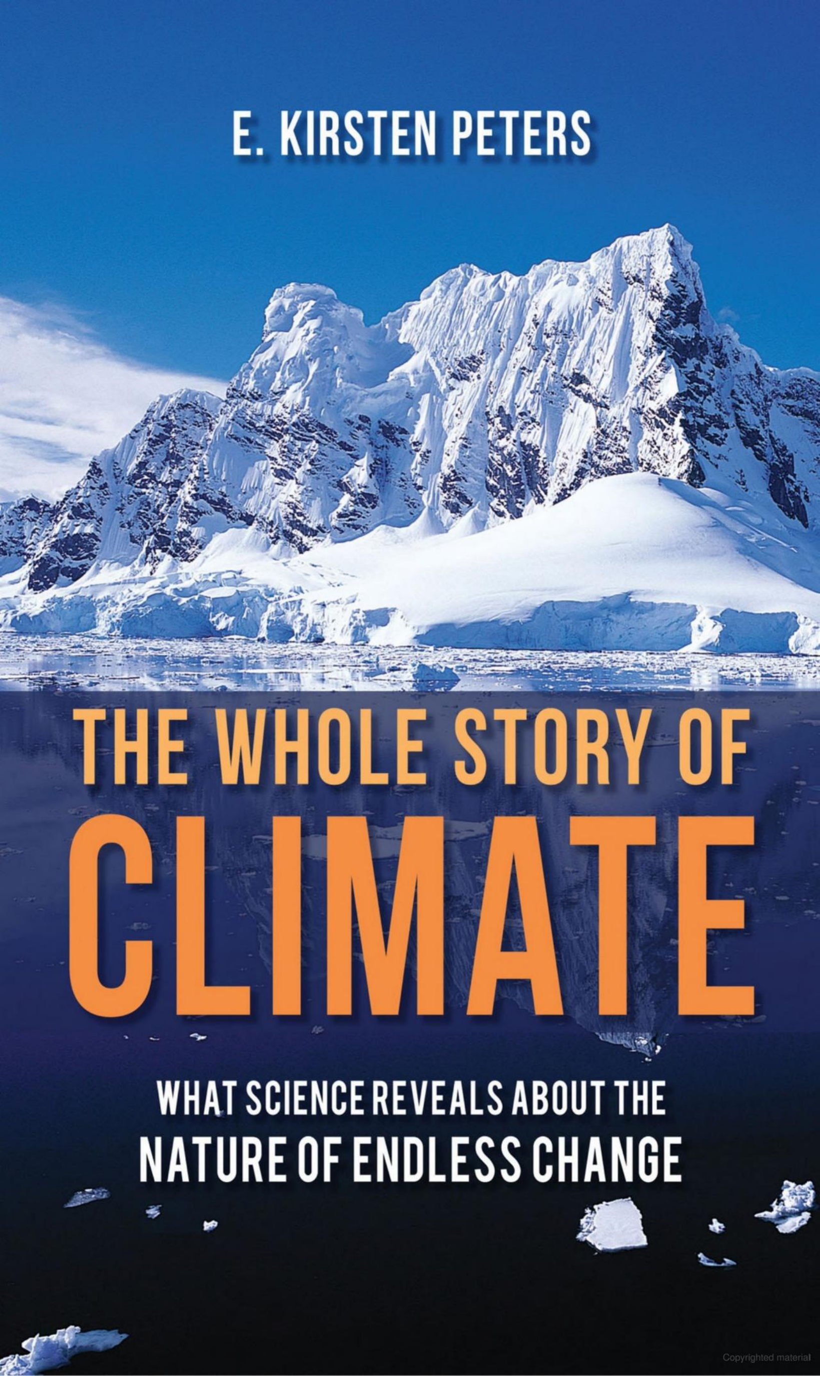

E. KIRSTEN PETERS

THE WHOLE STORY OF CLIMATE

WHAT SCIENCE REVEALS ABOUT THE NATURE OF ENDLESS CHANGE

THE WHOLE STORY OF CLIMATE

WHAT SCIENCE REVEALS ABOUT THE NATURE OF ENDLESS CHANGE

E. KIRSTEN PETERS

Prometheus Books
59 John Glenn Drive
Amherst, New York 14228–2119

Published 2012 by Prometheus Books

Cover image copyright © 2012 Media Bakery
Cover design by Grace M. Conti-Zilsberger

Inquiries should be addressed to
Prometheus Books
59 John Glenn Drive
Amherst, New York 14228–2119
VOICE: 716–691–0133
FAX: 716–691–0137
WWW.PROMETHEUSBOOKS.COM

16 15 14 13 12 5 4 3 2 1

Library of Congress Cataloging-in-Publication Data

Peters, E. Kirsten.
The whole story of climate : what science reveals about the nature of endless change / by Dr. E. Kirsten Peters.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-61614-672-6 (cloth : alk. paper)
ISBN 978-1-61614-673-3 (ebook)
1. Climatic changes. 2. Paleoclimatology. I. Title.

QC884.2.C5P48 2012
551.5—dc23

2012023389

Printed in the United States of America on acid-free paper

CONTENTS

1

FACING OUR CLIMATE ADVERSARY SQUARELY

Geologic evidence plainly teaches that Earth's climate has changed through staggering extremes of balmy warmth to bitter cold. And that's not just a description of ancient history, when dinosaurs roamed the world. Instead, it's the clear record of climate change during recent times, when fully modern *Homo sapiens* left Africa, spread around the world, and ultimately founded our varied cultures and civilizations.

What's even more alarming than the recent dates and staggering scale of climate upheavals is how quickly they have swept over the Earth. Many of these have not been gradual events, unfolding over dozens of centuries or millennia. Indeed, as we now know, most major climate changes in geologically recent times have occurred in a mere twenty or thirty years. In other words, in the span of a single human lifetime, Earth's climate has crashed from warm times much like the present to Ice Age conditions—or rocketed back again to warmth. In between these catastrophic changes there have been numerous smaller, but still substantial, climate shifts. Even these lesser events have been more than sufficient to quickly alter entire ecosystems, and most of them have been devastatingly fast.

The more scientists learn about the natural climate revolutions woven into the fabric of the planet, the greater our awe about how supremely fickle is climate on Earth. And climate upheavals have rearranged more than just entire temperature charts. Wind, precipitation, and other elements of weather have been as varied as temperature change. For example, what is now the driest part of the Sahara Desert was only four thousand years ago a lush and verdant landscape with lakes, fish, crocodiles, turtles, and people. But when climate turned yet another corner in Earth's long history, the rains shifted far to the south and the green splendor vanished, along with the people. Today, in the same spot, there is nothing but sand.

No full climate crash has occurred in the span of written history. That may be chance, or it may be that if there had been a fully global and rapid climate revolution, early civilizations would not have survived, so we would not be here. But, in any event, the simple fact that we don't have *written records* of natural and extreme global climate revolutions accounts for a large measure of the ignorance of even the educated public about the behavior of climate on Earth. But geologists can read the *physical record* of the enormous changes that swept over the globe before civilization was established and our written history commenced. The signs are plain once you learn to see them: Earth's global climate reverses, staggers, and stumbles, again and again, sometimes with changes that occur within the span of a single human life. What's worse, the Earth looks like she may be overdue for another, fully natural, climate revolution, as well as for more moderate and ongoing climate shifts.

The public has heard a great deal in recent years from the ranks of climate science, a discipline that's partially distinct from geology. There's much to be valued in the complex computer models that climate scientists use. But climate science is quite a recent branch of research, and climate scientists are not the only ones with professional opinions about the Earth. For almost two hundred years geologists have studied the basic evidence of how climate has changed on our planet. We don't generally traffic in computer models so much as direct physical evidence left in the muck and rocks of our planet. From those kinds of grubby facts, which this book will explain at a level any interested citizen can follow, we know a great deal about how climate has actually changed. As geologists, we also have evidence from many millennia and even millions of years under our belts, from periods of complete cycles of bitter cold to balmy warmth and back again to deep-freeze conditions.

Regardless of American energy policies and our greenhouse gas emissions, changes in climate—including both massive and moderate upheavals in temperature and precipitation—are going to be a part of Earth's future, just as they have been the bedrock of the past. That's why the public and American policymakers need to understand what geologists know of past climate changes. Failing to discuss the evidence of both massive and moderate natural climate change is like speeding downhill on a bicycle at fifty miles per hour while wearing a blindfold. We can, if we wish, spend the next minute tightening the strap on our helmet. But ripping off the blindfold seems a wiser first step toward giving us a chance of survival. And the only way to start to see around us clearly is to look at the record of what climate has done in Earth's past. Some of the facts we can draw out from the Earth's records are encouraging, while many are quite challenging. But it's surely better to be informed about how climate on Earth behaves than to willfully wear a blindfold at this critical crossroads of our history.

Please understand, geologists are not Luddites who say we should have no concern about our production of greenhouse gases, nor do we argue that what you've heard in the popular press about global warming is hogwash. But some of us believe you've been told only one isolated part of a much longer and richer climate story. To understand what might come next for climate—no matter our carbon policies or lack thereof—you need to understand what geologists know about Earth's past climates.

Here's a simple analogy: if you were facing a crippling medical condition, you might be well advised to seek the opinion of differently trained medical professionals—perhaps surgeons, internists, and pharmacists. In the same way, you are well advised to listen to what geologists—as well as climate and environmental scientists—have to say about Earth's recent temperature and precipitation changes. The framework of geological knowledge is different than that of many climate and environmental scientists, and the advice we offer may differ from that of our colleagues in these younger disciplines. It's not that any one group has a monopoly on everything that's valuable, any more than cardiologists are always right and internists are always useless. Rather, before you make decisions about a route to follow, it's to your advantage to be informed about the lay of the land around you.

At the end of the day, many geologists feel strongly that the best guide we have to the future is the evidence of the past. The Earth's past is the part of the picture that's most clear, providing the data that are least in dispute. The past is also the realm in which geologists excel; it's the part of the puzzle to which we've been devoted for many generations.

As it happens, many geologic principles can be quickly learned by amateurs. In just a few pages, this book will show you how geologists can literally see Earth's recent climates when we look out the window. You, too, can master this skill set, and you'll be able to understand the basic outline of climate, as Nature herself can show it to you around your house or during your summer vacation in the Rockies, New England, or around the Great Lakes. And I'll teach you what you need to know not through a list of facts, but by explaining the *story* of how geologists learned the basic principles that guide our science. In other words, this isn't a textbook, but a narrative, the story of what real-life geologists—complete with human limitations and foibles—learned as they examined the parts of the natural world influenced by climate change. It's an interesting detective story in its own right, but it will also give you the basic tools to see the climate evidence that, indeed, lies all around you.

Here's a warning: you may have to unlearn a couple of things you think you know. For example, many educated Americans live with the assumption that Earth's climate is quite static under natural conditions. The weather of our childhood, after all, felt like it was right and proper, the way the Earth was meant to be—and remain. But thinking of climate as a constant is grossly misguided. The weather of our childhood, in fact, was different from the weather endured by the passengers on the *Mayflower* and also different from that in which Viking raiders harassed the people of Europe a thousand years ago. The weather we knew when we were children—perfect and proper though it seemed—was but a single snapshot of the ceaseless and unfolding process of ongoing climate change.

The notion that climate should remain the same over time is at the core of much of the recent discussion in the public square. Change—including fully natural climate revolutions and more frequent and moderate climate shifts—is understandably frightening. We naturally shy away from it. That's why it's actually comforting to believe the message of extreme environmentalists in recent years. Their argument is that we humans are in the process of destroying the world as we know it through our production of greenhouse gases, that we are the sole cause of current climate change. From that premise it follows that if we slash emissions of carbon dioxide greatly enough, climate will stop changing. That's actually *reassuring* compared to the view offered to us by the Earth herself. The fact is, if human beings had remained hunter-gatherers throughout our entire history, never producing a single molecule of greenhouse gases through agriculture or industry, climate today would still be changing. It would be lurching toward higher temperatures, crashing toward vastly colder temperatures, or at least swinging toward something different from what has been. That's just the nature of Earth's climate. It's not to our liking, and it's not to say we should do nothing about curtailing greenhouse gas emissions, but surely we must look the basic facts of natural change in the face if we are to have useful policy debates in the public square.

Fortunately, most Americans have another and more useful childhood touchstone for memories when it comes to climate. Many of us recall the gist of books about the Ice Age that we read in grade-school libraries. Those books were decorated with images of saber-toothed tigers, giant ground sloths, and woolly mammoths. Behind a mammoth or two, in the distance, there was likely to be a sketch of a great glacier, perhaps with fissures lacing its edges. The world, it was clear in the books, had once been quite different, in terms of both climate and species.

Although such library treasures gave us some significant information about climate, it's also true that there's much more that's now known to science than the mere outline of the deep freeze you saw in grade school. In the past twenty years, scientists have found a richly detailed record of climate change in materials as humble as lakebed mud in North America and as pristine as glacial ice in Greenland and Antarctica. That physical record has shown us that major climate crashes are interspersed with the history of milder fluctuations. But “milder” is a comment based on the Earth's standards, not ours, because even milder changes have led to famines.

Here's just one example: a dose of natural climate change once hit the mightiest empire of the Bronze Age, the Egyptian kingdom of the River Nile and its broad delta. Some 4,300 years ago (2300 BCE), Egyptian civilization was flourishing, built on agriculture enriched by organized irrigation, rather than just the scratch-in-the-dirt approach to farming. Egypt's agriculture had led to population growth, big cities with educated elites, and well-trained and equipped armies. But, quite out of the blue, natural climate change hit the Egyptian empire, and it hit hard.

It wasn't that temperatures changed much in North Africa but that precipitation patterns were altered. We have basic written accounts of this “small” change in climate—small by the Earth's standards. As one written account makes plain, the famine and cultural collapse triggered by this relatively mild climate shift was so great that wealthy families in Egypt ate their own children. Thus, rapid climate change quickly brought the superpower of the day to the point that parents resorted to cannibalism—just so the adults could survive a few more weeks.

While Egyptians were eating their offspring, climate change was affecting other parts of the Earth, too. In general, the higher latitudes of the planet are likely to experience more temperature changes during dynamic times. It is possible that global temperature changes—and their related precipitation changes in Egypt—were one part of what reshaped ecosystems in and around the arctic of that day. It was around that same point that the last, isolated bands of woolly mammoths disappeared from Wrangel Island, off the Siberian coast. The mammoths, that great symbol of the Ice Age in your childhood, had clung on for several thousand years after the enormous climate upheaval that occurred ten thousand years ago, but they didn't make it through the blip that hit them in the Bronze Age.

For animals and for people, Earth's climate is an adversary the like of which many policymakers and environmentalists have not yet dreamed. Natural climate change is the elephant in the room within our public discussion of climate. In our rush to start thinking about limiting our production of greenhouse gases—a goal we will surely undertake to some degree—we've unfortunately left behind the reality of the history of Earth's climate. Natural climate change is fearsome to contemplate, to be sure. But the time has come to acknowledge the geologic elephant that's standing so near us. While we cannot tame or control the beast, we owe it to ourselves to recognize the facts of what Earth's climate is like. Planning for and adapting to climate change is as worthy a goal as limiting greenhouse gases, once we acknowledge how frequent and profound natural climate change is. No matter our political commitments, we can all surely come to better policy judgments about energy and climate by acknowledging the facts regarding how climate behaves. Doing so would certainly be better than prolonging our collective denial of what we are up against.

Here's a first, preliminary sketch of what climate on Earth has been like in the period so crucial to us. Consider it an overview to the facts of life when it comes to climate on Earth, and rest assured this book will explain how this sketch is known to geologists from the same basic physical evidence you will learn to see for yourself in your own backyard.

In recent geologic history, climate has been characterized by long periods of bitter cold during which enormous glaciers covered half of North America. Huge volumes of glacial ice formed during these frigid times. Ice sheets buried almost all of Canada, reaching down into the American Great Plains. The northern parts of the Midwest, the northern strip of the Pacific Northwest, and most of New England were engulfed in ice for tens of thousands of years at a time. As far south as California, glaciers in Yosemite National Park slowly formed at high elevations and flowed downhill, creating the majestic landscape that tourists appreciate today. Even sea level was different during these times of bitter cold. Ocean levels were much lower because so much water was “locked up” on land in the glacial ice. One important effect of the low seas was that people, and animals like the brown bear, were able to walk to North America from the Siberian end of Asia—changing whole ecosystems as they did so.

The public knows of the events just sketched as the Ice Age. Geologists don't use the term *Ice Age* because the interval actually encompassed both ice-cold periods and some vastly warmer times. To geologists, then, *Ice Age* is misleading, so we call the period the Pleistocene (pronounced Ply-stow-seen) Epoch.[1]

Geologists have been studying the evidence of the Pleistocene's climate for upward of two hundred years. The subject is relatively easy for us to learn about because the glacial evidence lies at the surface of the Earth. Geologists have cataloged hundreds of thousands of pieces of evidence about the timing, movement, and extent of glaciers from around the world. The glaciers, obviously, tell us about precipitation and vastly colder temperatures. From basic evidence, geologists have constructed a detailed nomenclature that describes the many different times within the Pleistocene during which glaciers retreated, advanced again, and then melted away to nothing at all. In short, we have a clear and detailed picture of the worldwide extent of Pleistocene glaciation and various intermittent warm spells that occurred along the way. And, finally, we have a whole library of facts about how very different most of the Pleistocene's climate was compared to the time during which the whole history of human civilization unfolds.

Let's start at the beginning. The worldwide glaciers of the Pleistocene Epoch were born in severe cold about 1.8 million years ago. That date presents an immediate problem for communicating effectively with many people. While geologists are used to considering great expanses of time, it can be a challenge for others to think about ancient dates measured in millions of years. A simple analogy might help. Imagine an empty, one-hundred-yard football field. The length of the football field will give us a way of visualizing the time during which extreme climate change has played out. Now add to the image a single referee standing in the end zone. The end zone with the referee will mark the present day for our analogy. The Pleistocene Epoch begins at the opposite end of the football field, away from the referee. That's one hundred yards down the field, at the point representing approximately 1.8 million years ago in time.

Most of the whole football field corresponds to times of bitter cold—with enormous ice sheets covering Canada, New England, the upper Great Plains, and so forth. But the Pleistocene was not a time of only monotonous cold. In fact, it alternated between long periods of cold—lasting roughly 100,000 years—and short periods of considerably warmer times—lasting about 10,000 years. To visualize this, imagine starting at the distant end zone of the football field, at the start of the Pleistocene. We can count out 5.5 yards in the direction of the present day and the referee. That's the distance that corresponds to about 100,000 years. Those 5.5 yards represent times of cold and worldwide glaciers. But the next half of a yard—just 1.5 *feet*—is a warm time, with glaciers melting away to nothing. That thin, warm slice of time is similar to present-day Earth. Again, the warm period lasts for only half a yard, compared to the preceding 5.5 yards of bitter cold, and the warm times are followed by a return to a long period of cold.

The alternation of cold and warm periods repeats down the entire length of the football field. The cycle is always a *long* period of cold followed by a much *shorter* period of warmth. The exact time intervals are not the same with each cycle, but the basic pattern remains as we move toward the present day, where our referee stands.

The final few yards of the football field are particularly important to us. About 6.5 yards away from our end zone is the next-to-last warm time on the field. Glaciers melted back to nothing during this time. Conditions were a bit warmer than the present day. One geologic name for this time is the Eemian. (Geological science is full of difficult names, and often even has multiple names for what is essentially the same period of time. The Eemian has some other names, too, but they are even more challenging to read or say, so we will stick with the simplest option and call that time by one name, the Eemian.)

If we were transported back to the Eemian, we would feel pretty much at home as far as temperature and climate. If anything, the Eemian would feel one full notch warmer than what we are used to in the present—an example, if you will, of natural global warming. In addition to the warmer global conditions, however, what would likely strike us as most odd would be many enormous herbivores and carnivores, much larger than anything we know today. The Eemian, if you will, is much like what you learned as a child about the Ice Age in terms of many species of flora and fauna, but minus the ice and the cold temperatures.

The warm Eemian time lasts for about half a yard, as usual, after which the Earth returned to bitter cold, with glaciers advancing over continents. The cold continues for several yards on the football field. Then, just 1.5 feet from the end zone where the referee waits, we reach another enormous climate change. Temperatures warm and glaciers retreat radically.

It is in this balmy time, the last half yard on the football field, that something special happens. We don't know exactly why, but it is at this time that we humans change our way of living. Instead of just being hunter-gatherers, we start to deliberately plant and tend crops. We domesticate animals. Soon after those major milestones appear along the roadway of our common history, people make pots, weave cloth, and then record their thoughts with abstract symbols. After that, as you know, we are off to the races as civilized peoples all around the world.

Because of our accomplishments during this last, warm interval, scientists long ago gave this narrow slice of time at the end of the football field a special name: the Holocene Epoch (pronounced Hole-oh-seen).[2]

From the Earth's point of view, the Holocene is *no different at all* from other brief, warm intervals in the Pleistocene, like the first one we mentioned, all the way back near the far end zone of the field, or the Eemian, which is only 6.5 yards from the referee. So, calling the current warm times by a different epoch name is a clear mistake! It simply makes no sense as far as the Earth is concerned. Nevertheless, we gave these last few inches of the football field an exalted status and a new label because we are so enamored with civilization. And because the present warm time is known the world around as the Holocene Epoch, we will use the term in this book.

We've just sketched a whole football field's worth of massive climate changes that occur in a roughly cyclic pattern. But there are also smaller but still staggering climate shifts that occur *within* the long times of bitter cold or the brief times of warmth. That's an important point, because those changes are more numerous and more frequent than the megatrends we've just spread out onto the football field. And frequent changes, of course, are not a good thing for us people. Beyond all that, some of the changes are rapid—so fast we sometimes call them rapid climate change events or RCCEs (pronounced “Rickies”). If we asked our referee to mark RCCEs on the football field by putting down a flag for each one, we'd have to provide him with scores of marker flags—real work for him, and not a comfortable picture for us.

Another disturbing point you may have noted is that the Holocene has already run for about ten thousand years. That means the Holocene is already a bit longer than a good many of the warm times on the football field. Thus, if the Earth continues to behave as she has for the past two million years, we must expect a return to bitter cold at some point, with ice sheets that reach as far south as Nebraska once again. And, as scientists have recently learned, the change to that bitterly cold climate regime is likely to be fast, happening over the course of a generation or two.

That, as they say, is the bad news.

But facts are facts, and they are worth facing squarely rather than trying to ignore in the confusion of bad faith. And, as you know, modern civilization may be changing Earth's climate history by putting such a quantity of greenhouse gases in the air that we are altering climate. In that case, we ourselves may break the cycle represented by the football-field analogy of time. Our own activities may inadvertently help us to avoid a return to crushing cold. That, on the whole, would be a good thing, as cold would end agriculture in most of the world's breadbasket regions, resulting in the deaths of potentially billions of people.

But it's important to note that if we do change climate through our airborne effluents, such a result would be simply chance. We surely didn't produce industrial carbon dioxide with climate modification in mind. And if we raise Earth's temperature substantially, we shall have to adjust to what Earth's climate was like *before* the Pleistocene Epoch, when there were no glaciers at all, anywhere on the globe. Much of Earth history, in fact, has unfolded in exactly such a hot climate, so it would not be a “new day” from the point of view of the Earth. But our civilization would surely be severely challenged to adapt to pre-Pleistocene levels of warmth, just as it would be hard-pressed to adapt to a return to the Pleistocene's bitter cold.

The last possibility we must note for the future is that the sudden change in greenhouse gas concentrations we humans have produced could “push” the inherently fragile climate system too far, causing it to snap. An analogy sometimes used to illustrate this point goes like this: A profoundly drunk man is pretty likely to fall down as he walks home from the bars. We can wait for such an event, watching the drunk as he staggers and careens down the sidewalk, or we can increase the chance of his falling sooner rather than later by giving him a shove. In the terms of this analogy, climate careens around chaotically on its own. We humans were not responsible for the many times it has “fallen” into dramatic changes in the past. But by increasing greenhouse gas concentrations rapidly in a short period of time, we have “pushed the drunk.” Climate may become a lot warmer in response to the spike in greenhouse gases we have created. But, as we shall see in this book, Earth's climate has many different elements that are always in play, influencing one another. Because of that, our emissions could actually make the climate stagger and fall in one of several different directions.

But while it makes sense to feel real concern about pushing the drunk, there is a framework to aid your thinking that geology can give you but that climate science simply lacks. Just for example, there is one special plea about carbon-dioxide production that geologists know well, a call to action we have long been making. We'll explore the idea more fully toward the end of this book, but here is the gist of it: we would readily eliminate a significant amount of carbon-dioxide production if we could put together an international effort to extinguish the almost-biblical plague of unwanted coal fires in mining districts around the world. Particularly in Asia, raging and smoldering coal fires both above and below the ground are a curse the world's poor endure each day. Most people don't even know these fires exist, but geologists do—we live and work in the mines with miners—and from Pennsylvania to Alaska in the United States, as well as in mining districts abroad, these smoldering fires are common.

Just as Americans put out the petroleum-well fires of Kuwait at the end of the First Gulf War, we could extinguish many or most of the world's unwanted coal fires, doing both local residents and Earth's climate a major favor. Such work would be vastly cheaper than decreasing carbon-dioxide emissions by putting solar panels on roof tops or sequestering carbon underground next to coal-fired electrical plants. You must allow a geologist a direct appeal that we immediately address the coal-fire problem, for we could benefit the globe at a tiny fraction of the cost of other ways of limiting greenhouse gas production. That's the kind of practical thinking you can get from geologists, and it's one of the reasons you need to hear from us, not just from climate scientists making computer models.

One truth above all stands out in geology. *If we think of climate change as our enemy, we will always be defeated.* That's because climate will always evolve, lurching to new warmer states or crashing into much colder ones. To geologists, it's death, taxes, and climate change that are the true constants of life on Earth. Our goal should not be to hold climate static, but to understand its fully natural but menacing and manic moods. Above all, we must adapt to climate. Included in that adaptation, of course, should be limiting human activities that provoke climate—like pouring greenhouse gases into the skies. But it's also true that we must be honest with ourselves, knowing that the climate of Earth will always change for fully natural reasons regardless of our energy choices. That kind of honesty should allow us to temper at least some of our climate and energy policies in light of their great costs to our economy. It behooves us, therefore, to keep our economy running as best we can so that we can afford to make the transition to a necessarily uncertain future.

And there is much climate science the public has not heard about. One recent hypothesis from an eminent climate scientist deserves special mention because it has not received nearly the attention in the media that the Intergovernmental Panel on Climate Change reports have—but it's actually much more fundamental and significant to our situation. There is plausible evidence that man-made climate change may not be new at all. The hypothesis now being vetted in the climate-science community is that human activities throughout thousands of years of the Holocene have changed climate—essentially fending off a return to giant glaciers here in North America. The argument is that human agriculture—even early farming done with slash-and-burn techniques and hand tools—was enough to increase the two principal greenhouse gases so that we crossed just over a critical climate threshold. Due to these agriculture effects over thousands of years, the argument goes, we've stayed just warm enough that glacial ice masses have not been able to re-form in Canada. We'll address that argument in a special chapter of this book, both because it's so significant in itself and because it's a good example of how science—at its best—unfolds through evidence and argumentation.

Through it all, this book will make clear to you the major assumptions that lie behind all climate predictions—the beliefs about what will happen next that may collapse when the Earth turns yet another small corner in the geologic history of climate. The past is our best guide to the future, and the past is the realm of geology. Personally, I can see the evidence of bitter cold winds of the Pleistocene just outside my house's windows in rural Washington State, and by the time you finish reading this book, you'll understand a great deal about the evidence of geologically recent and dramatic climate change, too; the evidence is available for your inspection from New England to New York and across the Midwest, from the plains of Nebraska to Colorado and Wyoming, and also in such places as the Sierra Nevada of California. If evidence matters to your view of the world, let me show you abundant and clear evidence of natural climate change, all of which is part of the framework needed for understanding recent climate shifts.

We humans can successfully move forward in the face of both natural and man-made climate change. But to do so intelligently and effectively, we must understand and acknowledge the dynamic nature of climate. Let us begin, then, with the story of how geologists learned about the Ice Age that came before the balmier times in which we now live.

2

THE ICE TIME

Louis Agassiz stands at one of the great transitions in intellectual history, the time in the early 1800s when men called “naturalists” could still comment on a wide range of questions in areas we think of today as biology, geology, chemistry—and even theology. After Agassiz's era came the “scientists,” professionals much more neatly divided into groups by discipline and specialization, fully separated from each other and much more divorced from religion. But in Agassiz's day, a wide range of different types of evidence and reasoning could still be pursued by a single individual, an approach that initially helped Agassiz's understanding of major climate change even as it ultimately crippled parts of his thinking.

It was a chance holiday that led Agassiz to recognize evidence of the Ice Age. But chance only favors the fertile mind, and Agassiz was most certainly blessed with the right intellect to make great strides in understanding the natural world when the opportunity arose. Agassiz's normal daily toil in his native Switzerland was demanding work examining fossils in dim rooms that taxed his mind and eroded his poor eyesight. He knew he needed a holiday each year from such labor, and so he chose to spend a few weeks outside in the summer of 1836, walking in the high meadows of the Swiss mountains. But summer holidays don't always proceed as planned, and what Agassiz saw high in the mountains changed the trajectory of his professional life because it taught him about thoroughly radical and quite recent global climate change.

Even prior to that significant summer, Agassiz was well on his way to becoming an early Stephen Hawking of science. Though young, he was already known to all the naturalists of his era because of his work on the fossil record of life on Earth. Agassiz and other naturalists around Europe were just learning to deduce the grand story of life, the history that leads from simple organisms in the sea to complex fish and then amphibians crawling forth on the land. After that, in quicker succession, come reptiles, dinosaurs, birds, and the eventual stunning successes of our own group, the mammals. Agassiz had the deep joy of discovering the story of life not from lines written in books, but from exquisitely preserved fossils that directly recorded the exotic and intriguing species of the past.

One pivotal group in the early history of life is the fish, and the thousands of species of ancient fish were the subject on which Agassiz was focused in the 1830s. Fish were the world's first highly successful group of vertebrates, and fish led in life's story to amphibians, the first large animals to live on land. Agassiz had set himself the task of finding whole fossil fish in stones from a variety of points in the geologic past. Part of his work was to correctly intuit where and how the fish fossils lay inside the stone that had preserved them for ages. He then broke the fragile fossils free of the surrounding rock and caught the first glimpse of ancient life, preserved for eons as if for Agassiz himself.

The work with hammer and chisel wasn't a simple exercise, nor did the newly exposed fossils speak to a linear history. Instead, naturalists like Agassiz learned of many odd and highly varied fish, like the jawless fish that had first arisen in the ancient seas and the fierce-looking armored fish that came later and were built more like tanks than like a familiar trout.

Agassiz was entirely devoted to his work with fossils. Once, quite famously, he faced a particularly difficult fossil, entombed within a stone. He could see just a small amount of the animal at one end of the broken rock. The question was where and how the rest of it lay within the stone. If he guessed wrong, Agassiz would destroy the fossil with the hammer blow meant to liberate it.

Agassiz's intuition of how that ancient fish lay within the stone was literally the best guess of anyone in the world at the time. But, from the small parts of the fish he could see, he knew it was an unusual fossil, and Agassiz hesitated before the block of rock. For days, the fish was on his mind, but he dared not take a chisel to the stone. Then, he dreamed of the fossil fish and sketched the specimen as soon as he woke, so vivid was the picture in his mind. Guided by his drawing, he successfully brought the fossil out of the enclosing rock, showing the world a specimen that fully matched the one his unconscious mind had generated for him in the sketch.

Agassiz was part of the first wave of naturalists to seriously study fossils, and he found the labor fruitful and gratifying. With the passing of each dark winter month in Switzerland, Agassiz made significant progress in a field that combines the best of the geological and the biological sciences. His fame grew across Europe as he published his findings in major tomes. When his books became known in the New World as well as the Old, the name Agassiz became synonymous with the study of nature literally around the world.

But spending year after year studying, cataloging, and drawing fossil fish is enough to wear down even the most dedicated and ambitious young professional. So when the chance arose in 1836 for Agassiz to take a summer walking tour in the Swiss countryside, he wisely took the opportunity afforded him. The intense work of explaining in detail the history of life on Earth could wait, after all, for the next long and dark Swiss winter.

If there is one supreme reason to visit Switzerland at the height of summer, it's to walk on the roof of Europe and see the glaciers that decorate the tops of Swiss mountains. On a warm July day, walking on the glaciers themselves is a diverting excursion.

Crevasses and scattered boulders are hazards on the course, but blue glacial ice underfoot and stunningly deep valleys thousands of feet below combine to make the spirits soar. Agassiz, who was trained to carefully study the world around him, found much to intrigue him regarding the glaciers. Like other naturalists, he hadn't thought a great deal about the history of Earth's climate up to that point. But the full significance of global temperature change hit him before his summer walking tour was done.

Prior to the 1830s, most naturalists had paid no more attention to high-alpine glaciers than a farmer might pay to an annoying snow bank that lingers in the spring on the north slope of a field. Pretty much all that was known about glaciers was that they were icy and that, in some years, a particular glacier might come a bit farther down a mountain slope than in other years. Glaciers in July looked to most people like cold, static bits of nature of no more interest than a lump of slush along the gutter of a city street in January. Agassiz shared the common view of glaciers before his holiday in the mountains. Fortunately, however, he didn't have a common mind.

As a native of the area, Agassiz was well familiar with the geography around him that summer. He had fished in the long, narrow lakes that occupy the region's deep valleys. An outdoor enthusiast since his earliest boyhood, he knew the basic geology of the rocks of the Alps and the Jura Mountains—the latter being the source of fossils that gave its name to the Jurassic Period of geologic history. Agassiz also knew—and had summarily rejected—the notion that his friend Jean de Charpentier advanced: that Switzerland had once been engulfed in thick, glacial ice during an epoch of endless winter. Indeed, it was in part to refute his friend's heretical idea that Agassiz had agreed to the summer walking tour in 1836. What could be better for an ambitious young man than having a break from fossils, taking in the beauties of the high elevations, and correcting the errors of a fellow naturalist, all at the same time?

De Charpentier's hypothesis about an ice-engulfed world was easy to scorn because it called for a radically colder climate on Earth in the geologic past. Agassiz—like virtually all the rest of humanity—thought that idea was simply impossible. There could be no real reason, he was sure, for considering the Earth's climate to be so capricious and once so very cold. He wanted to see his friend's reputed evidence, simply to find another way of explaining the rocks and meadows of the high elevations.

But as Agassiz discovered that summer, once you seriously start to look at a glacier and its surroundings, your eyes adjust to seeing a fully different Earth. The alternative world before you is built on a grander scale than you're used to, so seeing the bigger picture is a breathtaking transformation of perspective in itself. Beyond that—in a flash—the visual evidence requires that you accept the reality of staggering climate change. If you aren't used to manic highs, there's nothing like fieldwork in the geologic sciences to get you to a state very near them, and Agassiz quickly found his way to this new and quite different perspective.

The flash to the bigger picture is still the reason why college students taking a freshman geology class today sometimes fall into the thrall of their instructors—at least while pictures of beautiful glaciers and landscapes are shown on the screen at the front of the lecture room. And as certain hikers in the Rockies or visitors to northern national parks know at a visceral level, the Ice Age wasn't long ago at all, and it can literally be seen all around us. Epiphanies exist in science as surely as in emotional life, and glacial landscapes lead many people to wonderful visions of the wide sweep in space and time of major geologic processes. And at the core of both high-alpine beauty and ranger lectures in national parks is the simple idea that climate has been radically different, and quite recently so.

Agassiz's first step toward his new perspective was learning to actually see a glacier for what it is: a body of ice that's on the move. De Charpentier showed Agassiz clear evidence of glacial flow by taking him to a large boulder at rest on the ice. It was a massive stone, partly submerged in the glacier, and its elevation on the mountain in previous years had been noted. The boulder in the summer of 1836 was hundreds of feet farther down the valley than where it had been. On another glacier was an old hut built years before at a particular elevation. It, too, had moved hundreds of feet down the valley from where it had rather recently been. Thus it was that Agassiz understood the first point of evidence: glaciers are icy rivers that flow more slowly than a stream, but that flow downhill just as surely. And glaciers also carry quite a bit of material with them as they move.

In later summers Agassiz was the first person to ever measure exactly how glaciers flow. He drove a series of stakes directly across a Swiss glacier, from one side of a valley to the other, across the glacial ice in between. As the years went by, the stakes near the center of the glacier moved farthest down valley. Those at the edge of the glacier moved hardly at all. Those in between filled in an arc, bowed on the downhill side, showing that the ice in the center of the glacier moved downhill more quickly than the ice nearer the valley walls.

We moderns say that the lower and middle portions of the glacier flow *plastically*. They deform and flow like Silly Putty®, moving slowly but flowing as surely as a stream. But if a glacier is flowing down a Swiss valley, why doesn't the river of ice reach the plains below? Agassiz wrestled with that question in the several years to come after his first foray into the mountains. He studied the *termini* of glaciers—the places where glaciers end at their lowest elevation.

A glacier's terminus is marked by two things: a jumble of rocks melting out of the disappearing ice, and, at least in the summer, a rushing stream of meltwater. Sometimes, as Agassiz found, the terminus is marked by quite a high mound of rock rubble. Such mounds, he realized, are an indication the ice has been melting in the same basic location for several years, with the imbedded stones transported every year to the very end of the glacier and left at the terminus in the mounds of ever-increasing size. In other places in the high Swiss valleys, Agassiz learned to recognize the signs of recent glacial advances that had bulldozed through the old terminus and started the process of establishing a new one at lower elevations. And, on the other hand, some terminal mounds had been left stranded in a valley, a hundred feet or more lower than the modern glacier's terminus as the ice retreated up valley, year by year.

Agassiz came to understand that the terminus of a glacier marks the spot where the rate of ice melt catches up with the rate of ice flow coming down from higher elevations in the valley. The glacier, we could say in industrial terms, is a bit like an icy conveyer belt, carrying stones downhill. The stones are left where the belt system ends because the ice simply melts away in the summer sun.

One lesson that was clear to Agassiz about the terminal end of glaciers is worth bearing in mind today when images of melting glaciers are flashed across television or movie screens. The great melt off at a glacier terminus is impressive, especially in July, with meltwater streams gushing forth from the blue ice. Even more dramatically, glacial ice that reaches the sea “calves” off into icebergs at its terminus. But *such processes are fully natural* and have been going on throughout the whole life of the glacier. When glacial ice reaches the terminus, it stops flowing and melts away or calves off. That's the natural end of all glaciers, but it's one that can be exploited for significant visual effect for those with a bent to do so, which is something to bear in mind.

Agassiz rapidly came to understand that the individual stones that had been embedded in Swiss glaciers—the materials in the rubble that made up the terminus—were not like stones in streams in the plains below. The glacial stones were generally angular in shape rather than round, and they bore characteristic scratches on their faces. Modern backpackers and mountaineers immediately recognize both the angular shape and the grooved scratches on such rocks as characteristic of what is underfoot at high elevations everywhere around the world, from the Alps to the Andes. It is such scratched, angular rocks that make up the material in a glacier's terminus. The mound or heap of such material is known as a terminal *moraine* of the glacier. And, as Agassiz could plainly see, there are other types of moraines, too. Along the sides of many glaciers are long ridges or mounds extending down valley, parallel to glacial ice. They are made up of similar material as the terminal moraine, namely angular stones adorned with many scratches. These ridges are known as *lateral* moraines, suggesting their origin along the sides of glaciers. The stones in such moraines happened to be pushed to the edge of the glacier, where they have accumulated. They remain high on the valley walls until a time when the glacier grows substantially and engulfs them, moving them in the ice once more downhill toward the terminus.

Once Agassiz understood glaciers as rivers of ice with their own rules for moving and amassing stones, the lessons of geology came thick and fast. The scratches in the stones were evidence that the rocks in the glacial ice sometimes ground against bedrock below. The scratches on the individual stones were in random and varied orientation because the rocks had rotated many times as they were carried down the valley in the river of ice. The scratches in underlying bedrock, however, were all lined up, parallel to the axis of the valley, recording the direction of the glacial ice moving downhill. The glacier might flow like Silly Putty, but this was plastic flow that had serious teeth in it—teeth made up of stones ranging from the size of a grain of sand to the size of a small house.

Next Agassiz noted that some outcrops of bedrock had the parallel scratches but were also, on a greater scale, polished quite smooth. In other words, if you look closely at rocks in glacial landscapes you are impressed with their small grooves and scratches. But if you stand back, you see that for many feet in all directions, the bedrock has an undulating, smooth surface. Sometimes, at the right angle and in the summer sun, the surface is actually shiny like a mirror. It's as if the natural bedrock is like the polished marble blocks found in a bank building. On that polished surface, there can be some small scratches, but they don't negate the fact that, on a larger scale, the rock is smooth.

Looking at the glacial ice around him, Agassiz saw that a great deal of the rocky material in a glacier is quite small, nothing more than fine sand and silt particles. This, he reasoned, was the type of material that could smooth bedrock into a polished surface as a glacier moves over the rock below. Large particles in the ice might also scratch the same surface at some point. In other words, the glaciers represented a natural system that was sanding down the mountains of Switzerland, both polishing and scratching them. So substantial was the total erosional force of the glaciers that they had, over time, carved the stunningly deep valleys of Agassiz's home, all of which he saw with new eyes that fine summer of 1836.

A further point about the landscape also became clear. Switzerland's famous mountain peaks are composed of several distinct rock types. Agassiz could quickly see that isolated boulders in the lowlands looked like they were made of the same type of rock of certain distant peaks. The boulders range in size from those about the size of a cow to a few that are the size of a house. The rocks are called *erratic boulders*, and Agassiz saw that no simple stream could have washed the boulders to the lowlands where they rested. Streams don't move boulders the size of buildings, but rivers of ice can carry large boulders in them, as Agassiz had seen at higher elevations. It was quite evident to the naturalist that ancient rivers of ice had once carried the great rocks miles away from their places of origin high in the Swiss peaks.

Another point about the landscape that was suddenly explicable to Agassiz was a particular joy to him. He had grown up as a youthful angler in the many lakes of his homeland—an activity that later led to his interest in fossil, as well as modern, fish. The deep valleys of Switzerland host many long and narrow lakes, and Agassiz realized that what was holding many of the lakes in place were dams made up of old terminal moraines. Such moraines, cutting across valleys, are natural dams. After the retreat of the local glacier, with water flowing down valley in streams, long and narrow lakes can naturally form. Thus it was that ancient rivers of ice and modern streams and lakes began to be twined together in Agassiz's fertile mind.

Another delight is that the lake water itself in glacial landscapes holds evidence of the erosion of the mountains around them. High, glacial lakes are an opaque, turquoise-blue color in the summer—a favorite of modern photographers and the makers of postcards and inspirational wall posters. Because opaque water is not terribly appealing for drinking, however, hikers the world around learn a trick to clear the water. When making a camp at high elevations next to a glacial lake, experienced backpackers immediately scoop up a pot of lake water and let it sit undisturbed. In a few hours, the water's opaque quality diminishes as tiny rock particles—known to hikers and geologists alike as “rock flour”—settle out of the still water in the pan and form a layer on the bottom. The rock flour is suspended while it's in the lake because wind and waves keep the water stirred. It is the suspended tiny fragments of rock that interact with sunlight to produce the unique turquoise color of high glacial lakes. The rock-flour is direct evidence of the pulverizing, erosional force of glaciers. The rock-flour layer in the bottom of a hiker's pan is a tiny volume of what had once been the bedrock of the mountain, material turned to tiny grains by glacial ice grinding over the Earth through great stretches of geologic time.

Once Agassiz truly saw the picture of how the glaciers moved, what moraines and erratics signified, and what the scratches on the polished bedrock meant, he understood glaciers as a prime agent of erosion on Earth. That, in itself, was a great advance for geological science. But Agassiz's most significant insight was yet to come. Quite quickly, he began to look in the Swiss valleys much, much lower than in the neighborhood of the modern glaciers. It was as if his eyes were newly opened, and what he saw changed his understanding of climate immediately.

Agassiz found the now-familiar parallel scratches in polished bedrock dozens of miles below the glaciers of the peaks. He also found the same grooves on the smoothed bedrock of the walls of the valley, standing many hundreds of feet higher than the valley floor. Both lateral and terminal moraines, in just the same way, were in evidence many miles below the modern glaciers or high on the valley walls, and glacial erratics existed at low elevations. Once his eyes were opened to this simple evidence of past glacial action, Agassiz again and again saw the clear natural record left by ancient glaciers on a much greater scale than those of modern Switzerland.

The inference was as immediate as it was significant: at one time, vastly greater and thicker glaciers had filled high Swiss valleys, extending down to low elevations and spilling out onto plains. That could mean only that summers in some past time were extremely short, perhaps barely warm at all, and certainly fleeting. In those ancient times, glacial ice simply did not melt at any of the elevations where Agassiz saw it melting in his day. In other words, the climate of the past was dominated by long periods of cold more bitter than anything even a wizened resident of the Alps had ever experienced.

The evidence was plain, and Agassiz was fully convinced of it.

Soon he was telling his friends about what he had seen. Like all enthusiasts, he made some converts and alienated some other people. But he never looked back in his evangelism. He preached the news of climate change as he understood it and invited a number of colleagues to join him in studying glaciers the following summers. Many naturalists of the day took him up on the offer, and most were converted to his basic viewpoint in short order.

In the coming summers, Agassiz and company built a lean-to shelter on a glacier, using a giant boulder to serve as one wall of the structure, and they all went to work to better understand everything from the slow flow of glacial ice downhill to the patterns of meltwater that emerge from the terminus of a glacier each summer. They poured colored water into crevasses and noted where the color emerged farther down the glacier, and they measured the temperature of the ice at various points in the moving mass. Agassiz himself boldly dropped down on a rope into a great crevasse, exploring firsthand the body of the glacier to a depth of 120 feet. That journey, which most certainly put his life at risk because crevasses can close just as easily as they can open, showed exactly how determined the great naturalist was to learn about the newly discovered agent of erosion that testified so clearly to past climates. In short, Agassiz, who personally led all the summer expeditions to the Swiss glaciers, established himself as Europe's foremost authority on glaciers just as he was the clear authority on fossil fishes.

Oddly, Agassiz did miss one significant feature of glaciers that he literally stepped over time and time again. Glaciers are ice that's created from enormous quantities of compacted snow layers. Many glaciers show these former snow layers as distinct layers in the glacial ice itself. The ice layers are visible in many crevasses, but Agassiz apparently didn't think them significant. Much later in the history of science, as we shall see, the distinct layers of glacial ice gave us a clear annual record of climate change. In Agassiz's day the lessons of glaciers were much more general, simply speaking to the fact that the Earth had once known a vastly colder climate.

Agassiz publicly named the bitter climate of the past the *Eiszeit*, or Ice Age. That evocative name is the same phrase schoolchildren today use to describe the time in which the woolly mammoth and the saber-toothed tiger lived. But acceptance of Agassiz's basic insights did not come immediately, and the great naturalist himself was wrong about many aspects of the Eiszeit.

The notion of an Ice Age ran into stiff opposition from most naturalists of the day in part because it appeared to contradict so much of the fossil record of life. Most fossils—like the giant fern leaves in coal beds in Scandinavia or the great swimming and flying reptiles of the Jurassic period, named for the Jura Mountains—seemed to speak of a warmer, not a colder, climate during Earth's past. For ferns to grow in northern latitudes, or for great cold-blooded animals to ply the seas, clearly required that the world must have been a much warmer place in the past. All educated naturalists—including Agassiz—agreed on the basic idea that Earth's past was mostly much warmer than the present.

It's easy for us moderns to accept the two-part idea that ancient geologic history could have been warmer, while more recent Eiszeit times were bitterly cold. That framework of climate change is taught today to most schoolchildren, who learn about the warmer Earth of the dinosaurs versus that bitter cold of the globe in the era of the woolly mammoths. But such a view makes climate look much more variable than many naturalists of the 1830s could accept. It was one thing to picture the world as gradually, over millions of years, cooling from tropical warmth everywhere to more modern and temperate times. It was quite another to think of Europe as blessed with tropic warmth for ages, then plunged into bitter cold, and then resurrected to moderate warmth.

As Agassiz's fellow naturalists told him in no uncertain terms, the Eiszeit hypothesis raised a host of unanswerable questions. Why should Earth's climate change, and change once more, oscillating through geologic time in unpredictable ways? If one accepted the Eiszeit hypothesis, what would be next—claims for more radical climate shifts in one direction or another every time somebody turned over a rock? Surely, if climate could be stood on its head, then everything else we know about the world could be undermined as well.

Most naturalists in Europe thought that the evidence that Agassiz had recorded in such detail in the mountains showed only that climate *in Switzerland* had once been colder. Perhaps, for some reason connected with wind patterns or weather fronts, the Swiss mountains had for a time been quite a bit colder. But that didn't imply that the rest of Europe had experienced bitter cold, let alone the rest of the world. It was better to explain Swiss evidence as a local phenomenon, not something of global significance at all, argued Agassiz's many critics.

It didn't help matters that, in the hot light of the enthusiasm brought on by his alpine epiphanies, Agassiz made some pretty wild claims about the Ice Age. The Eiszeit, he wrote, was a time in which a vast glacier covered most of Europe, extending all the way from Scandinavia to the Mediterranean Sea. Agassiz had, in fact, never seen the Mediterranean, nor is there any evidence of ancient glaciers around it—no polished bedrock with parallel scratches in it, no moraines, no erratics, no tangible evidence of any kind of glacial activity. Agassiz's blunders, of course, opened all his ideas to blistering criticism.

Significant scorn as well as criticism was heaped on Agassiz's head for a number of years. The idea of radical climate change made many naturalists angry as well as skeptical. Some of Agassiz's counterparts actually interrupted his talk at a professional meeting, shouting out their objections and disrupting his presentation. That's an unusual event in professional life, in particular for science professionals. But Agassiz was sure he was right, and the power of his convictions sustained him through the significant disrespect and even outright scorn of some of his colleagues.

Agassiz's basic idea of the Eiszeit would have been a little easier to swallow if naturalists in the 1830s had had a clear understanding of the Earth's polar regions. One reason that American schoolchildren (and their parents) blithely accept the teachings of library books today about the Ice Age is that in modern times we have some pretty clear analogies for what Agassiz's Eiszeit was like. Indeed, most explanations of the Ice Age in schoolbooks refer to the great ice sheets of Greenland and Antarctica to sketch what much of the world was like millennia ago.

But naturalists of the 1830s had no clear descriptions of Greenland or Antarctica. Although men in Viking long boats and sailors in much later whaling vessels had doubtless glimpsed the coasts of Greenland near its midsection, brief visions of ice through the summer fog didn't equate to scientific observation. And there was simply no mechanism for transferring fragmentary knowledge from the hardy northerners who made brief sightings of Greenland's ice to naturalists living back in the heart of civilization.

In short, Agassiz could accept the notion of a Europe buried under a vast glacier, but his critics could not. They couldn't reason by analogy with Greenland simply because no one had clear knowledge of it, and they continued to tell Agassiz he was mistaking some kind of local climate phenomenon for a much larger one.

Not surprisingly, Louis Agassiz took to the roads of Europe in the 1840s both to look for evidence of the Eiszeit beyond the borders of Switzerland and to convert his international colleagues by personally explaining his arguments to them. Luckily for Agassiz, he went north, rather than south, from his home, and that meant his travels took him to regions that had been well and truly glaciated. His most important European foray, by far, was the one that took him to Great Britain. In Scotland and Wales he immediately found the familiar evidence of glaciers, this time in mountains where no modern glaciers exist. The polished bedrock with parallel grooves in Wales and the moraines flung across Scottish valleys all spoke clearly of the Eiszeit in Agassiz's mind. He recognized that some of the lochs in Scotland came from the same set of circumstances, which explained the narrow lakes that filled Swiss valleys. In short, even without active glaciers in the area, much of the British Isles showed clear evidence of the Eiszeit, just like his homeland.

Agassiz also made great headway in Britain on the human side of science. His observations and arguments won the Eiszeit converts, including the allegiance of the naturalist William Buckland. Buckland taught many budding young scholars at Oxford, and his belief in the Ice Age shaped the following generation of scientists in Britain. And, as a jewel added to the crown of the Agassiz visit, Buckland convinced the most significant naturalist of the day, Charles Lyell, of the reality of the Ice Age, using rocks near Lyell's own home.

As Buckland then wrote to Agassiz, “Lyell has adopted your theory *in toto*!!! On my showing him a beautiful cluster of moraines within two miles of his father's house, he instantly accepted it, as solving a host of difficulties which have all his life embarrassed him.”[1]

It was a significant conversion, although not as complete as Buckland thought that day. Lyell waffled a bit for a number of years about the significance of glaciers, but he did understand the importance of the Eiszeit hypothesis from that day onward and ultimately he became thoroughly convinced of it. Lyell's conversion was important because Lyell was the towering giant among British naturalists, the man to whom everyone in Britain's scientific circles looked for intellectual leadership. That point is shown by the fact that a young naturalist named Charles Darwin, when he could take only a few books with him on his round-the-world voyage on the HMS *Beagle*, chose to take the Bible and Lyell's book on geology. Converting Lyell to belief in the Eiszeit marked the turning of the tide that had been running against Agassiz and his hypothesis about radical climate change.

Naturalists, just like the professional scientists who followed in their footsteps, loved to resolve tenacious problems. The Eiszeit hypothesis could do just that, which is why Buckland and ultimately Lyell valued it so highly. As one example of the problem-solving power of the Eiszeit line of thought, we'll consider an ancient natural puzzle in Scotland that Agassiz was able to almost instantly resolve. The matter concerned a set of three perfectly parallel indentations in the walls of a certain valley. The parallel markings had puzzled Lyell, Darwin, and many others for as long as the history of British intellectual life records.

The three parallel markings are on the sides of Glen Roy in Scotland. If you stand at the bottom of the treeless valley (or glen), you are struck by the perfectly level markings on the valley wall above and around you. The indentations extend for as far as the eye can see—and that's a long way in the desolation of rural Scotland. Each of the three markings runs at one distinct elevation, without any ups or downs. The three markings are known as the “parallel roads” of Glen Roy because they look like roads laid out by the strictest of surveyors, each set to run at one—and only one—elevation, each cut into the walls of the glen.

The only agent that can make perfectly level markings on the land is a body of standing water. Both lakes and seas are well-known agents for cutting indentations into land, due to waves that dig into a hillside and mark the even and level shoreline extending at one and only one elevation for miles. And, indeed, the “roads” of Glen Roy are sandy, fitting with the notion that they were once the shoreline of some body of water. So far, so good. Evidently, the water responsible for the temporary beaches was at three different elevations over time, with each water level existing for long enough to allow waves to cut into the land and form a sandy stringer.

The valley or glen of the parallel markings opens onto another valley. That is, Glen Roy with its parallel and level hillside beaches leads to another and larger glen. The great puzzle that had stood unanswered for centuries was why the parallel shorelines of Glen Roy end abruptly near the mouth of that smaller glen. They simply stop, as if the body of water that once stood there had existed in some odd kind of half form, unlike a lake or sea that naturally has a shoreline running all the way around it.

One way to phrase the question behind the puzzle of Glen Roy is this: What could have created a deep lake in the valley, and done so in quite recent geologic time, and only created shorelines we can see on certain sides of that ancient lake? Let me put the matter in terms that help lead today's freshman geology students to the answer, and that also reflect the same kind of reasoning employed by Agassiz to solve the riddle. Rephrased in this manner, the question becomes: What natural agent could have dammed Glen Roy and some other glens nearby and then later simply vanished into the air? The answer is glacial ice. The Glen Roy markings, Agassiz argued, are a clue to the power of glacial ice to do more than simply wear down mountains, but to also create deep lakes held in place by ice dams.

Agassiz reported his solution to the puzzle of Glen Roy as soon as he saw the “parallel roads” and their setting. He did so via a letter to Professor Robert Jameson of Scotland, with whom he'd had contact in his travels in the area. As it happened, an issue of Scotland's most significant scientific publication had just been printed. Wanting to get the news of the solution out to the wider world as soon as he could, Jameson convinced a major newspaper in Scotland to run the story of how Agassiz's Eiszeit so elegantly solved what had been a puzzle for British naturalists that had stood for centuries. Both Lyell and his younger sidekick, Darwin, were convinced of Agassiz's explanation as soon as they heard of it through the press. Once the reality of the Eiszeit is accepted and a person learns to see long-vanished glaciers on the landscape, much that had been inexplicable can indeed be understood.

In short, Agassiz's journey to Great Britain was fully as rewarding to him and his hypothesis of radical climate change as it possibly could have been.

In 1846 Agassiz traveled much father from home, this time to North America. Once again, by chance, he had the good fortune to head into glacial lands. With his characteristic enthusiasm for the Eiszeit, as soon as he arrived by ship at Halifax, he began looking for the Ice Age in the New World.

As he wrote: “I sprang on shore and started at a brisk pace for the heights above the landing…. I was met by the familiar signs, the polished surfaces, the furrows and scratches, the line engravings of the glacier.”[2]

Next, continuing on to Boston, Agassiz found more of the same. Indeed, all of New England soon revealed itself to Agassiz's eye as one great moraine after another, with erratic boulders and other glacial evidence of all types stretching across the land from Maine south to Manhattan. And, gratifyingly, American naturalists hailed Agassiz's icy vision. So great was the opinion of so many Americans, in fact, that the Swiss naturalist soon became a professor at Harvard. When, a few years later, he made an expedition around Lake Superior, which was then an outpost in the American northwest, he again found evidence of glaciers all around him. Agassiz and his Eiszeit were even more triumphant in the New World than they had been in the Old.

So it was that in a short, twenty-year period, Louis Agassiz had established that glaciers had once buried much of Europe and a good measure of North America. It was a major accomplishment, built on his gift for observation and inference, his ability to hold fast to his vision despite intense attacks from colleagues, and his good fortune in traveling to lands that had, in fact, been extensively glaciated. Just two decades after that first telling summer in Switzerland, glacial ice was widely understood by many to have once been the dominant feature of the surface of the Earth from the midlatitudes northward. The Eiszeit had been proven real, evident to anyone with the basic training to see it, and it was apparently the result of substantial climate change on a global scale.

In addition to his other gifts, Agassiz had the ability to popularize science. In America he delighted crowds from Boston to the Carolinas with a series of lectures that explained the basics of the fossil record, as it was then known, and also taught people about the Pleistocene Ice Age. Living in an era when natural history museums were starting to flourish in Europe, Agassiz founded the Museum of Comparative Zoology at Harvard, an institution that still delights crowds with fossils from all parts of geologic history, including the time that glacial ice enveloped so much of the Earth.

But Agassiz himself didn't fare well as a research scientist from about the time of his trip to Lake Superior onward. He had key ideological commitments that precluded his scientific usefulness for the rest of the many years he lived in New England. He believed—as a theological matter more than a scientific one—that God was the cause of the Ice Age and that the Lord himself had sent the glaciers over the land to wipe out all traces of life. The woolly mammoth, the saber-toothed tiger, and even humble worms at the equator, from Agassiz's point of view, all perished in what he came to believe was a rapid descent into a deep freeze so profound that nothing at all survived. That hypothesis helped Agassiz make sense of his religious commitments, which we won't summarize here, but it ended his usefulness in investigating the Eiszeit. Thus the torch of research was passed to other men, including Lyell, still in England, and it fell to them to deduce what actually happened in the Ice Age.

Happily, with hardly a hiccup, the basic facts of Earth's climate in the Ice Age soon became integrated with the standard geologic timescale that Lyell had worked out for the Earth. The Ice Age occurred in what Lyell—using the evolving history of fossils as his guide—called the Pleistocene Epoch. The Pleistocene is the next-to-the-last epoch in all Earth history, the one that came immediately before our own, the Holocene.

In the analogy of Earth time as a football field, which we explored in the first chapter, the Pleistocene accounts for almost all the yardage on the field. Despite Louis Agassiz's shortcomings—and they were substantial—it's worth giving him credit for understanding the stupendous cold that dominated most of the time laid out on our field. Prior to Agassiz, naturalists and laymen alike assumed there had been no such bitter episode on the Earth. But after Agassiz had done his work from Switzerland to Glen Roy to Lake Superior, professional scientists and ordinary citizens alike came to appreciate the brutal cold of much of recent geologic time.

If you visit Harvard University, you can pay your respects to the mortal remains of Louis Agassiz in nearby Mount Auburn Cemetery. Agassiz lies buried beneath a twenty-five-hundred-pound boulder brought there, at what must have been considerable expense, from a glacier in Switzerland. We geologists care a lot about our headstones, and the one above Agassiz seems particularly fitting for the man who first recognized the Eiszeit by studying alpine glaciers and their erratic boulders.

Agassiz's accomplishments are remembered in a variety of ways in the geologic community. Perhaps most fittingly, his name is given to a giant, glacial lake that formed in the Pleistocene Epoch in northeastern North Dakota, northern Minnesota, Manitoba, and western Ontario. Glacial Lake Agassiz was the largest such lake in North America, several times larger than modern Lake Superior. Lake Agassiz was an immense body of frigid waters in the basin of the Red River, a stream that today has the distinction of flowing north out of the United States into Canada. The water was dammed up, forming an enormous lake, because the retreating continental ice sheet blocked its flow to the north. The outline of Glacial Lake Agassiz can be followed today across the plains as stringers of sand and gravel, from the long-ago beaches that lay around the southern edges of the vast, icy lake. Just as in Glen Roy, the evidence of a Pleistocene body of water held in place by an ice dam is plain, at least once the scales fall from your eyes and you can visualize massive climate change.

In time, after Agassiz's death, Harvard University decided to honor and remember the founder of its natural science department by creating the Louis Agassiz professorship, which is held by Harvard's most distinguished paleontologist. Several significant scientists have held the position named for the early naturalist. Perhaps most famously, for decades in the late-twentieth century, the Agassiz professorship was held by Stephen Jay Gould, a powerhouse of research, teaching, and the popularization of science through his magazine columns and books.

Agassiz changed the way scientists and laypersons understand and appreciate climate. Every childhood book you read about the Ice Age should have been dedicated to Agassiz, who popularized science just as much as he advanced it. The Pleistocene Epoch, however, was far from a monotonous deep freeze, and the Ice Age did not wipe out most species of plants and animals that graced the Earth, as Agassiz believed. How the great shifts in climate within the Pleistocene Epoch came to be understood is the subject of the next chapters.

3

STAGGERING COMPLEXITIES AND SURPRISING SIDE EFFECTS

By the time the sun was setting on Louis Agassiz, the great Swiss-born naturalist, a new era in American science had gathered a full head of steam. For the first time, men trained specifically as *geologists* were spreading westward across the growing country, first by the scores and then by the hundreds. Some of the geologists were employed at colleges. Others worked for major mining companies. But many other geologists spent highly productive professional lives in the recently formed state geologic surveys and in the national equivalent, known as the US Geological Survey.

Geologists of this era braved the elements to travel by horse up humble gullies and over majestic mountain passes. They paddled canoes along lakeshores and walked up arroyos. It was a romantic era of outdoor work and rapid intellectual progress for geology, a time when newspaper reporters wrote long stories about the staggering discoveries geologists were making about newly found fossils and natural resources.

The first goal of geological exploration in the 1800s was to produce reliable *geologic maps*. The men who dedicated their lives to this work risked their comfort and safety for the sake of being able to sketch in the blank parts of such maps—because they are the crucial tools geologists use to help us understand the Earth. A geologic map fulfills several purposes. At an elementary level, it shows the rocks in a region, telling us what lies immediately beneath our feet. It also points us toward where, still deeper in the Earth, that same rock bed likely trends. That's quite an accomplishment for a map based on what a field geologist can see only at the surface of the Earth.

Geologic maps are not academic matters. If you are a rural resident and are drilling a well for water, you want to hit material that's porous and permeable as well as water rich so that significant volumes of water can flow from the Earth into your well. That's information a geologic map can provide. Drilling wells is tough and expensive work, so any clues about the solid Earth that can minimize effort and maximize success are highly valuable to someone living in the country—or to a town or city government trying to provide drinking water to residents. Geological maps are also highly prized by prospectors and miners. As an example, consider an independent miner following a small silver vein in the mountains of the western United States in the 1800s. The vein could very easily disappear abruptly at a small fault. Given all that would have been invested to discover and follow the vein, the miner would urgently want to know in what direction—up or down, left or right—to tunnel in order to once more find the vein. A geologic map gives exactly that kind of information, making it a guide to the unseen world of the solid and opaque Earth.

Creating a geologic map is an exercise in making good surface observation coupled with reaching wise estimates of what likely happens beneath the Earth's surface. Those estimates rest on a great deal of experience with rocks and a thorough knowledge of how different types of rocks are born in the Earth. It's not trivial to create a good geologic map in complex terrain, but it's a skill that can be learned. Geologists are still taught how to make geologic maps in much the same way as the men of the 1800s learned their trade. That's why, if you tour the Rockies in the summertime, you can still come upon groups of young geologists in the making going through what's called field camp. The young people—college-level students, mostly—will be busy making measurements of rocks, veins, gravel beds, and much more. From their measurements, and using their knowledge of geologic processes, they'll try to deduce what lies beneath their feet in the third dimension of the solid Earth. At the end of their studies in a particular place, the “final report” from the students is their geologic map of the area, a record of their surface observations and a prediction of what lies underground.

In the 1800s, geologists produced hundreds and then thousands of geologic maps. And all of those maps, taken together, had major consequences. From long-lived water wells for towns to the underground mining of gold and silver ore, important work was accomplished in part due to accurate geologic maps that guided people toward what they wanted in the Earth. Historians think of the 1800s as one of expansion westward as the United States grew toward the Pacific, but it was also in a very real way a time of expansion *downward* as people increasingly learned to mine the Earth's natural resources at greater depths and in more complex geological terrain. And as American geologists undertook all this mapping work on which so much of practical life depended, so did their counterparts around the world. The age thus marked the first time ever that technically trained men fanned out to map vast portions of the Earth for the discovery of the natural resources that make modern life possible.

But there's another purpose beyond the practical that a good geologic map fulfills. The history of the Earth is revealed by the millions of specific rocks, fossils, and surface features spread around the globe. So, while groundwater and iron ore were definitely emphasized in the mapping effort that spanned the middle and late 1800s, geologists of the day always took time to investigate the abundant evidence that climate on our planet has been very different from what we know today.

Charles Whittlesey was one of the first American geologists to focus extensive amounts of fieldwork on the evidence of the Ice Age—or the Pleistocene Epoch, as it had come to be called in Lyell's language. His official portrait photograph shows a fiercely determined man with a narrow, flint-like face dressed in sturdy field clothes and holding a rock hammer at the ready in one hand. He looks both able and willing to deal with anything and anyone standing in his way. That's a fitting image, for his scientific work challenged the thinking of many geologists, and his work resulted in quite a few arguments. But Whittlesey's field evidence was both abundant and telling, and in time his colleagues fully converted to his way of viewing the world.

One of Whittlesey's first successes regarding climate was understanding that there must be a distinct southern limit beyond which Pleistocene glaciers had never passed. He went to work mapping out part of this “glacial boundary,” or the mother of all terminal moraines, in the Midwest. Today we know that the line of southernmost glaciation drops from western Pennsylvania across southern Ohio, then moves through southernmost Indiana and Illinois. It runs across Missouri near the middle of the state and from there heads into northeastern Kansas.

The ultimate terminal moraine is easy enough to recognize. North of it are glacial gravels and the jumbled and sometimes angular rocks with striations that Agassiz had learned to recognize. South of the glacial boundary is the countryside that has never been invaded by glaciers. In many ways, this type of basic mapping work by Whittlesey put teeth into Agassiz's general theory of the Ice Age. All too often Agassiz had been content to note glacial scratches on bedrock as he passed, but he generally didn't do the slow work of detailed mapping that shows clearly where and how glaciation had shaped the land. Whittlesey made the detailed case for Pleistocene glaciers across the Midwest. He worked like a patient district attorney amassing and explaining evidence to the jury, and in time Whittlesey emphatically won his case.

The facts about which American lands had been glaciated turned up some interesting sidelights. In western New York, and in Ohio, Indiana, Michigan, Wisconsin, and Illinois—land that had been buried by Ice Age glaciers—a few very lucky pioneers and later farmers found single diamonds in the gravels and sands around their homesteads. Most such finds were absolutely isolated occurrences. For example, a single diamond was found in Ohio, near where the state lines of Ohio, Indiana, and Kentucky all come together. No other diamonds were found in the area—and of course a lot of local people looked for them after one had been discovered!

Geologists quickly saw that the diamonds were in glacial debris, materials that had come south on the vast ice sheet of the Pleistocene. Each diamond was isolated because it was so far from its original source in the Earth. It didn't take geologists long to understand that if they wanted to find the source of the occasional diamond in the upper Midwest, they must look to central or northern Canada. And this is what geologists did, but without success for a very long time. Several generations of exploration geologists, in fact, scoured central and northern Canada for the ultimate source of the diamonds. Isolated gems were found occasionally, but not the diamond-rich rocks that had originally given birth to the long-but-thin trails of diamonds the great ice sheet had created.

When I was a college student at Princeton University in the early 1980s, the mystery of the diamond sources in Canada was still unsolved. Two Princeton geology professors thus spent a summer trying to follow the trail of diamonds “up ice” to the north. They returned with good stories and at least one minor insight into the puzzle—but without any diamonds in their pockets and without the discovery of the source of the gems. The honor of finding the special rocks from deep within the Earth that were the original source of the gems fell to other geologists, including those who have made a fortune in the famous Ekati and related diamond mines of the Barren Lands, about two hundred miles northeast of Yellowknife. The Ekati was discovered in the late-twentieth century—and other mines around it were developed shortly thereafter—a long time, indeed, after geologists of Whittlesey's time first realized that there must be diamond-rich rocks in Canada that had sent a few gems thousands of miles to the south courtesy of staggering volumes of ice.

Perhaps Whittlesey's greatest accomplishment is that he contributed evidence that the Pleistocene was more varied and complex than anyone had first thought. The first clear facts in favor of *repeated* climate changes in the Pleistocene came from humble water wells in the Midwest. As farmers and townsmen in those states dug downward into the Earth for water, they first shoveled their way through mixed glacial debris. Water in that layer often wasn't abundant enough to last through long summers, so the wells had to be extended to deeper levels. Whittlesey realized that well records were notable because a number of wells hit a layer under the glacial debris that contained wood. Then, beneath the wood-bearing layer was a still-deeper layer of glacial materials.

Whittlesey didn't speculate about the origin of the wood layer, although he recognized it as important. But another geologist, following immediately in Whittlesey's footsteps, was the first person to see the regional pattern and grasp what it meant. Under the surface of glacial gravels there was a layer recording a forested time that implied a completely different climate for the whole region. This balmier time—something like the present day—had lasted long enough *for soils to form and trees to flourish*. But the mild era was only an interruption in the great, bitter cold of the Pleistocene. In short, the Pleistocene was not a monotonous deep freeze. It was, instead, a period dominated by bitter cold but with interruptions of warmth similar to the present day.

It's worth an aside to mention that the evidence—glacial deposits immediately above and below an ancient forest—is of a type that allows geologists to infer what's called “relative geologic time.” No one in the 1800s knew exactly when the ancient forest had grown in the Midwest—was it fifty thousand or one hundred thousand years ago? But even without knowing specific dates, they could infer that the era of the forest came between two bitterly cold times marked by thick glacial ice that had buried the Midwest and deposited glacial gravels. Geologists thus could construct a sequence of events in relative order, saying that first there had been glaciers, then there had been a warm time with soils and a forest, then there had been glaciers once more, and finally there came our own warm times. These types of sequences create what geologists call the relative ordering of events in Earth history. Exact dates—fifty thousand versus one hundred thousand years—depend on other types of evidence, like the radioactive decay of elements. But simply working out the relative or sequential ordering of events in climate history teaches us a great deal.

The lesson to which Whittlesey had helped lead geologists was that Earth's climate had seen multiple climate flip-flops. But at first some geologists didn't want to believe it—anymore than an earlier generation in Europe had wanted to accept Agassiz's arguments. It's psychologically natural to question this kind of evidence. Major and repeated climate flip-flops undermine our confidence that the world will be hospitable to us tomorrow, something all of us want to believe. It had been difficult enough for many people to believe Agassiz's evidence that the world had once been engulfed by an Eiszeit. Now, just a couple of decades later, geologists familiar with the Midwest were asking people to accept the idea of repeated and massive climate changes that ran in both directions, back and forth.

But because the evidence of the water wells was both clear and direct, in a few years geologists were persuaded to accept the notion that the Pleistocene had contained at least one warm time very much like our own epoch. At a human level, this was not a comforting lesson, but science tends to compel its loyal practitioners to accept facts as facts, and professional geologists adapted to the new view of climate and moved forward. The critical wood-bearing layer between the glacial gravels became known to geologists as the *forest bed*. Once it—and its significance for climate—was fully accepted, the forest bed was traced into Indiana and other states, where it had originally been overlooked. The ancient wood spoke to what geologists came to call "the interglacial stage," the balmy time between major glaciations, the time so disturbingly like our own that was snuffed out by renewed bitter cold.[1]

A geologist named Thomas Chrowder Chamberlin, born in the era of Charles Whittlesey, noted the evidence of the forest bed. T. C. Chamberlin, as he is known, was to become a giant figure in American geologic circles, someone whose ideas are still taught to young geologists in the classroom and in summer camps devoted to mapping work.

Chamberlin was born—appropriately enough—on a glacial moraine along what was then the American western frontier in Illinois. When he was a toddler, his family moved by "prairie schooner" to Wisconsin, where they established the family farm near Beloit. After a few years in a log cabin, Thomas and his brothers helped build the foundation of a more permanent farmhouse—a foundation made of Ordovician limestone rich in fossils that had been quarried nearby. Thomas noted the fossils well, and his fascination with geology was born.

As a young man, T. C. Chamberlin started out in the world by teaching high school. His pedagogical approach was all but unheard of in his era—he would take his students outside to simply look at things. In a like manner, he himself continued to learn, and in time he became a professor at Beloit College and a member of Wisconsin's state geological survey.

Northern Wisconsin is covered with glacial debris. One distinctive feature of the moraines in the northern part of the state is the “kettle” country. A kettle is a dip in the land, a natural depression in the extensive moraines. Some kettles are small, just a few feet deep, while others are fifty to sixty feet deep and even farther across. Because Wisconsin is a wet place, many kettles are filled with water, forming numerous lakes. Some kettle lakes have outlet streams, but others do not, being isolated from streams that flow nearby but do not connect to the lake or its enclosing kettle basin.

If you travel south of the glacial boundary, you won't find many streams that pass near lakes but don't connect to them. Indeed, in most parts of the globe, streams either empty into lakes or drain water out of them. In Wisconsin's kettle country, however, nearby streams and lakes often seem not to know of each other's existence. That feels incoherent to anyone familiar with most of the landscapes of the world, and it's part of the topographic peculiarities that geologists call, rather evocatively, “deranged” terrain.

Chamberlin saw that the hummocky moraines of northern Wisconsin were responsible for the deranged drainage patterns of the area. The whole landscape consists of random piles of debris dotted with depressions tossed around like bits of confetti. Chamberlin had the insight to realize that these deranged features would be temporary on a geologic scale. In time, he reasoned, natural erosion of streams downward would regularize the land so that small streams would lead to larger ones and all lakes would have outlet streams that feed into larger rivers. The fact that this had not yet happened in the northern part of Wisconsin meant that the formation of the kettle country was geologically recent. As he traveled in other parts of the glaciated Midwest, Chamberlin saw that deranged drainage was much less pronounced, and in some places it was simply nonexistent. He deduced that northern Wisconsin had been shaped by a more recent glaciation that had not extended to all the glaciated Midwest. To put the matter another way, not all glacial advances in the Pleistocene were the same, and the most recent one had not penetrated as far south as some of the earlier episodes.

Chamberlin and other geologists of the time added to this understanding of multiple glaciations by mapping bedrock in the Midwest. They noted that some of the solid rock of the ground showed glacial scratches that ran in more than one direction. One clear set of striations might be aligned from due north to due south, but another set of parallel scratches on the same outcrop of bedrock might be at a 20 or 30 degree angle to the first. The implication is plain, and American geologists soon accepted the notion that the vast Canadian ice sheet over time flowed over the same spot in somewhat different directions. That likely meant that climate patterns were different even within one glacial epoch, driving ice in one direction for thousands of years, but then altering the pattern, likely because precipitation patterns changed.

Thus it was that in a matter of one generation, geologists had gathered evidence of Ice Age glaciers advancing and covering what had been temperate forests and flowing in varying directions and to different extents during the cold times. But more evidence of climate complexity was yet to come. A Canadian geologist published evidence from the Lake Ontario region of *three*, rather than two, distinct glacial layers separated by times of warmth like that of the present day. Soon, other geologists published evidence for *four* separate glaciations. Geologists could have naturally started to talk of the various glacial eras as the first, second, third, or fourth ones. This, however, would have led to confusion because not all glacial layers are present everywhere. For example, the “second” glaciation in a particular place in Iowa isn't the second one in northern Wisconsin. To clean up the inevitable miscommunication, geologists started to give proper names to the different glacial times.

Here we must face up to the unpleasant fact that names for *time* in geology are usually given based on a *place* where the evidence for those times is clear or abundant. That can seem like a strange custom, but it's the way the geological profession has gone about its business because it at least helps link events that may have occurred millions of years ago to a tangible place in today's world to which we can relate. So it was that American geologists came eventually to name the oldest or earliest glaciation the *Nebraskan*, the next one the *Kansan*, the penultimate glaciation the *Illinoian*, and the final or most recent glacial era (the one Chamberlin had worked on) the *Wisconsinan*.

While American and Canadian geologists were busy mapping the evidence of past climates in the New World, European geologists were doing parallel work in their homelands. They, too, quickly came to realize that the glaciers that had once buried their countries had been intermittent. They, too, gathered evidence for four major times of glaciations. As the North American and European geologists read each other's publications, geologists everywhere were confronted with the clear fact that climate on a fully global scale is highly fickle, oscillating between bitter cold times of glacial advance and times of much more moderate warmth and glacial retreat.

This book began by comparing recent geologic time to a football field. Most of the field is the Pleistocene Epoch, with all its complexities, and the Holocene Epoch is our current warm era. By the late 1880s, the basic outline of that sketch was becoming clear to geologists around the world. Earth's climate was evidently subject to radical changes, with repeated climate reversals. The total number of temperature flip-flops on the field, and the specific dates at which they occurred, was not yet known, but the basic picture and sequence of events could be seen by anyone.

In short, the natural human tendency to think of global climate as stable had been shown to be fundamentally naive. And our current warm times, given the dignified-sounding name of the Holocene Epoch, had been shown to be just like the short-lived balmy periods embedded in the much longer record of bitter cold and extensive glaciation of the Pleistocene. We are living, from this perspective, on borrowed time, waiting for the glaciers to advance once more and bury us just as they did the forest bed of the Midwest long ago. Science, for the first time in Western intellectual history, was predicting a clear "end to the world," at least an end to our world here at moderate latitudes.

It was a disquieting lesson.

But geologists had ways of comforting themselves—and anyone else in need of reassurance about climate. The stupendous change from balmy warmth to bitter cold, geologists in the late 1800s assumed, must take centuries or even thousands of years to unfold. So although the magnitude of climate change was breathtaking, and it certainly looked like the current warm times couldn't last forever, it was common for geologists in the era of Whittlesey and Chamberlin to assert that Americans had nothing to fear. A return to frigid temperatures like those of the Pleistocene would take dozens of generations to transpire. A thousand years for the great change seemed like a good rough estimate for a climate flip, and most of us can't drum up much concern for our society a millennium down the road.

We'll see in the coming chapters that the assumption of gradual climate change was simply incorrect. It was an assumption, after all, not a hypothesis grounded on evidence. But it took another century for indisputable evidence to arrive on the crucial point of how rapidly climate could flip-flop. Meanwhile, so as not to get ahead of our story, we'll return to the late 1800s because there are a couple more important lessons about climate to be learned from the first wave of geological mapping.

Geologists of T. C. Chamberlin's day came to understand several sidelights of extensive glaciation. One realm into which geologists waded was climate's inevitable impacts on sea level. The first piece of headway made in understanding sea-level fluctuations related to the fact that Scandinavia had long appeared to Europeans to be slowly but steadily *rising* out of the ocean. Visiting Denmark and Sweden, Lyell—the great British naturalist of Agassiz's day—had seen the old beaches or "strands" that stand on dry land in many places above modern sea level. In some areas there are several such beach strands, each higher than the last. The evidence of the old shorelines shows that either sea level is dropping or the land is rising. But which is it?

Naturalists like Lyell knew that sea level, as recorded in the shorelines of southern Europe, didn't show evidence of global sea-level decline. Thus, naturalists had admitted that lands like Scandinavia must be slowly rising. That phenomenon was difficult to explain, to be sure, but the facts of regional uplift seemed clear enough.

In the era of Whittlesey and Chamberlin, North American geologists published field evidence showing that the lands around the Great Lakes and Hudson Bay are also rising compared to sea level. The solid ground around Hudson Bay, for example, is slowly increasing in elevation, as is shown by the old shorelines that can be traced in places for many miles around the bay. The old shorelines stand away from the modern beaches and at elevations higher than modern sea level by dozens and scores of feet. Thus, the basic evidence of regional uplift is the same as in Scandinavia, but another aspect of the matter helped solve the riddle of what could cause regional uplift.

The Hudson Bay area, geologists knew, was near the epicenter of the great ice sheet that had grown in Canada and flowed down into the United States. The bay itself—the ocean water we have named after Hudson—didn't exist in the Pleistocene, when the whole region looked like modern Greenland, engulfed by glacial ice. The evidence from Hudson Bay clearly means that the land has been rising *after* the last glaciers left the area and *after* the sea flowed in to make the shorelines that record that rise. To put this another way, during the millennia of the Holocene Epoch—our current warm times—the whole surface of the Earth in the region has been flexing upward. The cause of the uplift, evidently, was linked to the departure of the glaciers.

Geologists realized that just as a large ship will bob upward as its cargo is unloaded onto a dock, so the Earth's crust flexes upward when staggering loads of glacial ice are removed from it as a result of melting. The Earth responds much more slowly to the change than does a ship, so the “bobbing up” process takes millennia. The land around Hudson Bay is therefore still rising, century by century, in response to the off-loading of glacial ice at the start of our epoch. In a similar fashion, all of Scandinavia is rising due to the lifting of the great weight of the glacial ice that used to engulf northern Europe. The rates of rising are similar, by the way, roughly a foot or two a century.

Ideas about sea level lead us naturally back to the flint-faced American geologist Charles Whittlesey. He hypothesized that global, as well as regional, changes in sea level must be related to climate change. Whittlesey estimated the total volume of glacial ice that had existed during the cold times of the Pleistocene in North America, Europe, and so forth. Water that was in those extensive glaciers, he reasoned, must have decreased the total water available to be in the oceans. So Whittlesey looked at the whole, global consequence to sea level caused by extensive glaciation.

Whittlesey published his estimate that global sea level had stood about three hundred fifty to four hundred feet *lower* during the glacial times of the Pleistocene than it does today. That was a shocking figure to consider in the 1800s, but it's an estimate that compares very favorably with actual subsea measurements of ancient shorelines from recent oceanographic studies. Such work shows that, during the cold parts of the Pleistocene, the Atlantic shoreline of the United States stood more than three hundred feet lower than it does today. New York's Hudson River, during those times, cut a significant and sharp valley—now under the sea—and that valley can be traced beneath today's ocean waves for a distance some sixty miles offshore, southeast of the city of New York. Other parts of the ocean shore of what's now New Jersey, Virginia, and the Carolinas stood one hundred miles to the east of where the sea and land meet today.

In short, natural climate reversals affect sea level in two ways. First, as continental-scale glaciers grow during cold times, more and more of the globe's water is "locked up" in enormous glaciers, causing global sea levels to drop tremendously. Oceanfront property in much of the world grows substantially outward toward the seas during these times as the ocean retreats from the land. Then, when climate reverses and warms once again, sea level on a global basis rises as meltwater from glaciers makes its way back to the ocean. Much oceanfront property shrinks as the seas rise and claim more of the solid land. But this global increase in sea level can be modified on a regional scale by the fact that removing great glaciers from the land compels parts of the solid Earth to flex upward. Thus, regional sea level around Hudson Bay and Scandinavia is dropping today with respect to the local landscape and dropping despite global sea-level rise in the Holocene.

The consequences of dramatic sea-level shifts due to climate change are far from academic. North America was peopled during the waning stages of the Pleistocene because sea level was so low that there was a land bridge between Siberia and Alaska. As archeological and even genetic evidence shows, people spread from Asia to Alaska and south through the rest of North America, taking advantage of low water levels. And people were not unique in this respect—the whole ecosystem of the late Pleistocene and Holocene was shaped by the consequences of sea-level changes. As an example, the Siberian brown bear also walked across the land bridge from Asia, spreading over time from Alaska down the coast of what's now Canada and the American Pacific Northwest. Evolutionary pressures on the brown bear stock led to the development of the inland grizzly bear. Likewise, in the waning part of the Pleistocene, natural selection led the northern polar bear to emerge from grizzly-brown stock. The tale of these three bears, dancing with climate and its effects, is just one example of the biological world's constant flux.

Whittlesey's pioneering work in estimating how much sea level dropped during times of extensive glaciation also ties into the fact that modern shorelines are not nearly as high as they have been in the geologically recent past. In the first chapter of this book we mentioned that the last interglacial time prior to the modern Holocene warmth—an interval called the Eemian, which occurred around 6.5 yards away from the end zone in our football-field analogy—was actually warmer than anything we know today. An extra-balmy Eemian, of course, must have melted more major glaciers than anything we've experienced in modern times, and that means that Eemian sea level must have been a good measure *higher* than what we know in the present. Indeed, we find clear evidence for exactly that in the southeastern United States, where the Carolina and Georgia old shorelines are about fifty miles inland and about 120 feet higher than modern ones, reflecting the significantly higher sea level of those warmer times. That empirical evidence of the scale of natural global warming and resulting higher seas may be worth noting as a general framework when you evaluate what you hear in the press about modest sea-level changes in modern times, such as the rise of one to two feet we've seen since 1850.

But to return to the 1800s, let us note that by the time of Charles Whittlesey's death, geologists were starting to recognize one more major consequence of the enormous climate changes of the Pleistocene. In what's now the western United States, south of the great ice sheet that dominated the northern half of the continent, geologists came across evidence of major and unexpected catastrophes related to consequences of the Ice Age differences in climate.

If you've been to the Great Basin area of Utah, you have an understanding of what an arid climate is like. But, as geologists quickly realized when they mapped the West, such aridity is only recent, and it relates directly to the climate change that buried the Midwest under glacial ice.

Grove Karl Gilbert was the single most significant research geologist of the late 1800s, the man above all others, who came to understand arid lands and how recent climate revolutions have shaped them. Geologists still genuflect when saying his name because he contributed to the solution of many different problems. He's the American version of what Lyell had been in England, a single geologist who shaped so many ideas of his day that it's difficult to understand how people understood the Earth before his time.

As it happened, G. K. Gilbert was a failed high-school teacher. He was a quiet person who never imposed his will on others. That temperament led him to disaster when he tried to teach teenagers in rural Michigan while he was a young man. But teaching's loss proved to be geology's great gain. Gilbert had a keen mind for understanding physical science and applying that knowledge to what he perceived in the world around him. He saw foundational and crucial evidence where others were mesmerized by details, and he reasoned effectively from physical science to its applications within geology. Gilbert was truly, as his chief modern biographer calls him, “a great engine of research.”[2] He also became a leader in the US Geological Survey, where his skills and insights became so highly valued over time that he was twice elected president of the Geological Society of America—an accomplishment that has never been repeated by anyone.

Gilbert cut his teeth as a geologist in the federally funded wave of exploration and mapmaking that helped shape the development of the American West. His life spans the time from when the United States still had a western frontier to the fully modern era of the early-twentieth century. Gilbert's major publication of 1890 recorded just how radically precipitation in North America was altered by geologically recent climate change. His piece focused on the Great Salt Lake and the land around it, and from field evidence he carefully and convincingly deduced important consequences of climate change, including consequences no one in the profession would have guessed before his day.

Today the Great Salt Lake of Utah is a briny and shallow pool in the bottom of a large, natural basin. There is no outlet stream leading away from the Great Salt Lake because it's fully enclosed by higher ground around it. If you walk from the briny shore toward the mountains you see in the distance around the lake, you will come to distinctive, ancient shorelines. Gilbert carefully studied these shorelines, including in places where there are enough of them to make a natural “staircase” on the hillside.

Clearly the lake had once been vastly deeper than what it is in modern times. That simple fact implies heavier precipitation patterns in the Pleistocene. Just as the sea around Greenland's great ice cap today is the site of many fierce storms, so land near the North American ice sheet of the Pleistocene was shaped by storms—and the heavy precipitation they bring.

Geologists call the freshwater lake that existed in Utah in the Pleistocene *Lake Bonneville*. The Bonneville Salt Flats, which you hear about in the news when race cars are tested, are on the flat floor of part of the ancient lake. In the Ice Age, the great lake rose and fell over time as precipitation and evaporation varied. It was these changes that led to the “staircase” steps of old shorelines in the hill slopes around the modern Great Salt Lake. At its height, Lake Bonneville was as large as one of the modern Great Lakes in the Midwest, a body of water that had substantial wave action as Pleistocene winds whipped its surface, leading to significant marks on the land.

Generally, lakes have outlet streams. Such lakes cannot rise significantly above their natural levels because, as the surface of the lake water increases a little, more water spills into the outlet stream, decreasing the lake's waters. Because Lake Bonneville had no outlet stream, however, it rose whenever precipitation exceeded the rate of evaporation from the surface of the lake. Over time, in the wettest stage of the Pleistocene, it rose to very great heights indeed. Its shorelines, as we know from the old beach strands, extended north beyond the borders of Utah into southern Idaho and westward from Utah into Nevada.

But obviously there has to be an edge or lip to a basin. Geologists of the 1800s wondered where the relative low point of the Great Basin's enclosure was, the place where lake waters might have overspilled the basin at some point in the Pleistocene. Gilbert, the excellent field geologist and engine of research, found that low place. In the process, he laid the groundwork for the discovery of a major side effect of climate change, one that geologists continued to bump up against in the West throughout the twentieth century.

The lowest point on the rim of the Salt Lake Basin is Red Rock Pass in southern Idaho. As it happens, highway departments as well as geologists appreciate relatively low ground in the midst of higher topography, so it's no surprise Red Rock Pass now has a highway that runs through it. But, of course, in Gilbert's day the highway didn't exist. He got to the pass in the same way he traveled all around the Great Basin, by horse or mule or on foot.

What Gilbert discovered at Red Rock Pass was what happens when an enormous lake overtops the natural dam that holds it back. In the late Pleistocene, when the lake's surface just reached the lowest part of the pass, the great lake started to overspill its container. At first, the amount of lake water running north across the pass and toward the plains of southern Idaho was small. But when water runs over the top of a natural dam, it has a tendency to erode the dam. And when Lake Bonneville's waters eroded that first inch or two of the Red Rock dam that had been holding back the great lake, a large volume of water started to pour out of the basin.

As it happened, the rocks of Red Rock Pass were fairly soft and unconsolidated. As that first gush of water from Lake Bonneville flowed over the pass, the water eroded the soft rocks a good bit more. That meant yet more water went over the pass, causing a feedback loop. Soon a catastrophic flood was emptying Lake Bonneville, with the floodwaters racing north across the plains of southern Idaho and into the deep canyon of the Snake River. The flood continued, with the torrent growing larger day by day as the feedback effect grew and grew. The Snake River was soon accepting vastly more water into its bed than it had ever experienced in even the heaviest springtime flood. Those floodwaters raced down the great canyon of the Snake, through the rugged terrain of central Idaho, and westward into what's now Washington State. Ultimately, the floodwaters rushed into the lower Columbia River and from there through the Columbia Gorge into the Pacific Ocean.

Today we have fully traced the erosive powers of the great flood from Lake Bonneville. There are numerous flood gravels—dozens of feet thick in some places in the Snake River canyon—that were created quickly in the violent event. The flood continued for many weeks, geologists have calculated, basing their work on the geographic dimensions of Lake Bonneville and the size of Red Rock Pass. Ultimately, when the down-cutting lake waters reached a firm rock layer at the pass, the flood slowed and naturally came to an end. Lake Bonneville had been greatly reduced in volume and surface area, never to be the same again.

As Gilbert realized, the catastrophic flood of Lake Bonneville occurred late in the Pleistocene Epoch, just shortly before our present warm era. When climate warmed substantially, the ice cap left the continent and rainfall and snowfall in Utah became much scarcer. The region's climate evolved toward what it is today, with cool winters and hot, dry summers. Gradually, evaporation from the surface of what was left of Lake Bonneville far exceeded the input of fresh water from rain and snow in the basin. The lake shrank each year, becoming more and more salty as it did so, ultimately becoming the shallow brine pool of modern times.

When Gilbert published his findings about the catastrophic release of much of Pleistocene Lake Bonneville's water to the north, his conclusions came as a surprise to geologists. As a profession, geologists had assumed that natural change was gradual, a point of view inherited largely from the writings of Lyell. Geologists would have preferred that climate change and everything related to it had happened gradually, with changes measured over centuries or millennia. But the evidence for the catastrophic flood from Lake Bonneville was clear, and the event was soon accepted as one of the surprising side effects of the wet climate of the region during the Ice Age.

Not long after G. K. Gilbert died in 1918 at the age of seventy-five, a young geologist named J Harlan Bretz began to muse that another catastrophic flood had shaped a much larger part of the northwestern United States. In the summers of the 1920s and 1930s, Bretz—accompanied sometimes by a mule to help carry his gear—hiked up the numerous braided or interlaced “coulees” of central Washington State. Grand Coulee is the largest and most well-known of the stark channels of the area. Bretz mapped it with care, but he also explored the scores of other, smaller coulees that cut across the region in a similar fashion. As the years went by, Bretz mapped most of the area, concentrating on surface features and coming to know them better than any other geologist of his generation.

The coulees of Washington State are just the most obvious feature of the “Channeled Scablands,” an area where soil is thin or absent and the land has been stripped to bare-bones bedrock. The region is unique in North America, a curiosity that attracts visitors to this day. Like the Wisconsin terrain mapped in the previous century and explained by T. C. Chamberlin, central Washington shows chaotic stream drainage worthy of the technical term *deranged*. Small streams don't lead to larger ones, at least not for very long distances. In fact, some small streams of the Scablands roughly parallel each other, an odd occurrence in all the “normal” parts of the world, where streams lead into one another. Although the area is fairly arid, there are a few small lakes, most located in significant depressions or pits. Streams that run only in the spring are often unconnected to the small lakes, bypassing them completely. All of those features are part of the deranged topography that led many geologists to assume that the area had been scoured by a tongue of the Canadian ice sheet that had flowed down from British Columbia. The Scablands, from this point of view, must be analogous to Chamberlin's kettle moraines in northern Wisconsin.

But Bretz quickly rejected the glacial hypothesis for the origin of the Scablands. The loose rocks of the region do not show the scratches and striations of glacial action. And although there are many ridges of gravel in the Scablands, Bretz believed they were not moraines. Instead, he interpreted what he saw in the Scablands as the product of catastrophic flooding on a scale much greater even than what Lake Bonneville's waters had unleashed.

J Harlan Bretz was unlike the gentle Gilbert, who couldn't control a high-school class. A forceful character, even at his weakest, Bretz loved to argue—and to go his own way. So, acting alone, and without any support from other geologists of the day, Bretz published a hypothesis of catastrophic flooding to explain the entire Scablands region. But, unlike Gilbert's work, Bretz put forward his idea without describing a *source* of the floodwaters he identified as having shaped the land.

A substantial argument about Bretz's views raged for decades in professional circles. Most geologists assumed Bretz was wrong, siding with colleagues who believed the region's topography could be explained by the gradual action of continental glaciers. The argument started to be resolved only in the early 1940s. At that point a young geologist named J. T. Pardee published air photos of western Montana. Taking photos from the air was a new technology, and the view from a few hundred feet above the Missoula area changed the dynamic of the argument that Bretz had begun.

Geologists had long known that during the Pleistocene a deep lake lay in western Montana. If you stand in Missoula, Montana, looking up at the giant hills around you, you can trace with your eye extensive horizontal markings on the land. The marks are old shorelines, cut into the hillside by wave action, as a closer examination of them above the city will demonstrate. The old shorelines run level but curve around all the mountain valleys of the whole region, providing a dizzying and complex array of evidence that shows one simple fact: a deep lake—more than two thousand feet deep—existed in western Montana in the late Ice Age.

Geologists of the 1800s had named the great Pleistocene lake Glacial Lake Missoula. They had traced the parallel shorelines across whole counties and had also noted that the shorelines simply ended in northern Idaho. Recalling Louis Agassiz's triumph in explaining the parallel shorelines on the sides of Glen Roy in Scotland—the marks that ended abruptly at the mouth of the valley—geologists had accepted the notion that a very large ice dam in Idaho had likely held back Glacial Lake Missoula. Just as in Scotland, the only natural agent that could have dammed the entire drainage of the land—and then wholly disappeared—was glacial ice. And, happily enough, there was abundant evidence of glacial ice in northern Idaho, where the ice dam must have been located. The lower Clark Fork River there intersects the Purcell Trench, a great lowland that leads down from Canada, and was doubtless a conduit of glacial ice, as bedrock scratches make abundantly clear.

Glacial Lake Missoula, like Lake Bonneville in Utah, was an enormous Pleistocene lake. But Lake Missoula's existence was enormously more fragile than Lake Bonneville's, because Lake Missoula was held in place by ice, not rock. Pardee's air photos elegantly showed enormous ripple markings west of Missoula, on what had been the floor of the great lake. The megaripples—on a scale so large they look simply like hills from the ground—showed clearly that Glacial Lake Missoula had not drained quietly, but rather had rushed westward in the late Ice Age. The ripples were created by currents, like the ripples you've felt on your feet when you've waded on sand in rivers—but the scale of the currents (and thus the ripples) was breathtakingly different. When geologists took in the full force of Pardee's off-scale photographic evidence, they realized that at some point all the waters of Glacial Lake Missoula headed west at the speed of a freight train. That could only mean that the Pleistocene ice dam that made the lake possible had collapsed.

Glacial Lake Missoula's catastrophic dam failure was the key that led geologists to accept Bretz's argument that most of central Washington State had been carved out quickly by enormously violent and deep floodwaters. Grand Coulee, and all the dozens of other coulees Bretz described, were formed not over millennia by glacial ice, but very quickly by the erosive powers of the catastrophic flood. The deep torrent of floodwater stripped the land bare of soil and carved the deranged drainage so characteristic of the region. Climate and biblical-scale catastrophe were, once again, closely linked. Indeed, once the eyes of geologists were opened about the source of floodwaters coming from Glacial Lake Missoula, they found evidence of *multiple* Bretz-like floods in the Channeled Scablands. Just as the acceptance of one forest bed helped lead to the discovery of other similar features in the Midwest, the acceptance of Bretz's basic hypothesis helped the next generation of geologists to see that Lake Missoula had formed—and catastrophically drained—multiple times as the ice dam that held it back formed and reformed late in the Pleistocene Epoch.

A question naturally arises about the two megaflood sources of the Pleistocene, Glacial Lake Missoula and Glacial Lake Bonneville. Which flooding events came first in the long sequence of events of the waning Ice Age? That question is of the same type that we saw Charles Whittlesey successfully address about the sequence of climate events shown by the forest bed of the Midwest. Geologists can answer such questions of relative time with the help of any location where two pieces of geologic evidence are in direct physical contact. To address which catastrophic Ice Age floods came first, geologists needed to find a place where the evidence of the two events was brought together in one location.

A simple gravel quarry in Lewiston, Idaho, fills the bill. It contains evidence of both the Bonneville and Missoula floods, and it allows even a casual observer to understand which flood happened before the other. The quarry lies next to the Snake River, where it is worked for gravels for construction projects, laying bare a cliff-like front in the deep, loose rocks. At the base of the quarry face are the rounded gravels set down by the Bonneville flood, rocks that are the same type as found in southern and central Idaho. Immediately above the Bonneville gravels are much finer sediments that flowed *up* the Snake River canyon when the wall of water from Lake Missoula reached the Snake. Like the gutter of a roof temporarily overwhelmed by a big bucket of water poured on the roof above it, the Snake River had run backward for a time, choked with Lake Missoula water and sediments during the flood Bretz had correctly described, if not explained.

The sequence of the two events is clearly shown in the gravels, with the Lake Missoula sediments lying on top of the earlier Bonneville gravels. The humble gravel quarry is thus a famous site in geologic circles, a place where you can directly see not just two catastrophes related to climate but also the simple types of evidence geologists use to deduce the sequences of events over the long reaches of geologic time. Like the forest bed of the Midwest, this kind of evidence is indisputable, compelling the observer to accept the description of a relative history of the Earth, including an appreciation of climate change and catastrophes spawned by climate.

From Whittlesey to Bretz, geologists carefully mapped evidence not just of repeated glaciations and intermittent warm spells, but also of global sea-level shifts, vast inland lakes, and catastrophic flooding. By the middle of the twentieth century it had become clear to geologists everywhere both that climate is key to the physical landscape in which we live and that repeated climate changes have created and then snuffed out ancient forests and sea coasts. Even staggering features like the Grand Coulee owe their existence to relatively modest side effects of the great monster that is global climate change.

There's certainly no going back to the comfortable illusion that we live in a world with a climate that's stable or at least predictable. Anyone familiar with geological research knows full well that repeated and substantial climate change is woven into the fabric of the world in which we live, and that such change has many and varied effects.

But now for some good news. Despite the challenges posed to all living creatures by major climate upheavals, it's also true that plants, animals, and people have survived and sometimes even flourished in the last two geological epochs, the highly variable Pleistocene and the modestly variable Holocene. In the next chapter we'll turn to the fossil record of some of your favorite animals from grade school—woolly mammoths, wolves, moose, and saber-toothed tigers—to see how they dealt with the extremes of climate change.

4

FROM WOOLLY MAMMOTHS TO SABER-TOOTHED TIGERS

Louis Agassiz, the first person to clearly recognize the signs of the Ice Age in Europe and North America, was in many ways an intellectual progressive. By accepting the facts that pointed to how fickle climate on Earth had been, he earned his place as a major figure among the founders of modern geology. He also was prescient in seeing the likely connection between climate change and the birth and demise of some wondrous species. In short, extinction and climate were closely linked events for Agassiz, and that connection of ideas has proven a fruitful one from his day down to this one.

As we have seen, Agassiz was not a perfect scientist. Some of his observations were quite fuzzy, and often his manic intensity about the Ice Age was simply too extreme to be useful. Important qualifications and serious refinements were all too often missing in Agassiz's work. And he also, as it happened, used theological arguments to address scientific questions—a recipe likely to lead to disappointing results.

When Agassiz was a boy, science and religion were freely mixed together. It was only in the later decades of his life that science became a profession that stood firmly on its own empirical feet, a matter on which theology could not—in the judgment of most intellectuals—usefully comment. While many naturalists and early scientists fully adjusted to that change of worldview, setting aside their religious convictions when they theorized about the natural world, Agassiz never quit blending science and religion as he had when he was young.

Still, despite the double handicaps of an extreme temperament and unfortunate early training, Agassiz got a number of important pieces right about fundamental geology, climate change, and the history of life. Agassiz's errors were significant, but his virtues were so great that they could have made up for even greater transgressions.

The reader may recall that Agassiz didn't start his career as a naturalist investigating glaciers in Switzerland. His true forte was fossil fish, an area he chose to study in part because the fish are the