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INTRODUCTION

An urban park bench is about the last place I would expect to find a fossil reef, but there's no mistaking the corals within the stone benches at Miami's Maurice A. Ferré Park. Instead of sitting on a bench, I'm stooped over inspecting one as joggers sprint past, music blares from somewhere, and kids shriek while playing in the grass nearby. As I look more closely at the large rectangle of stone that forms the seat of the bench, I can see the shapes of star coral skeletons, pockmarked with tiny stars where the coral animals once lived. And there are some with larger star shapes, called great star coral. The sinuous lines of brain coral wind across the left end of the park bench, and numerous fossil clam shells are suspended in the rock on the right side. The curved shells look like smiles in cross section. I stand up to find a dog walker looking at me as if I'm crazy. His suspicions are probably confirmed when I start taking photos of the bench. But I can't help myself—the fossil reef within it looks so much like the fossil reefs I used to study. This limestone rock, formed from a coral reef long ago, was excavated from a quarry and then made into benches for an oceanfront park in downtown Miami with a backdrop of skyscrapers, but it's still a fossil reef to me. It's a piece of coral reef history.

If you were to sit on the bench's fossil reef and look out to sea, you would get a view of the Port of Miami. A lineup of massive cruise ships takes up one side of the paved, human-built island at the port's center. On the island's other side are container ships and giant metal cranes that look somewhat like the AT-AT walkers from *Star Wars*. Despite the entirely unnatural concrete and steel environment of the port, and the potential dangers of pollution, extreme heat, and other human-caused problems, small corals live below the lines of ships. A few months before I found the fossil corals in this bench, researchers published a study about the living corals that are able to persist in the nonideal waters of the port.[1] There's other life in the port too. Coral City Camera, an underwater live stream from the seafloor below the port, regularly captures images of fish, rays, and dolphins as they swim by.[2] But not all marine life can survive the port. And even in parts of the ocean that are arguably far more natural than the port, it's become more challenging for tropical marine life to survive. Overall, the ocean is becoming a less hospitable place.

A stone's throw from the park bench and the port, other corals live in the Frost Museum of Science. There, researchers are growing small coral colonies in saltwater tanks to help species survive. Some of the new colonies are on display in an exhibit with blue-tinted light, each growing on its own tiny pedestal. Looking through the glass of the tank at the corals organized in rows is like looking through the glass wall of a hospital nursery to see the newborns. When I visited, staghorn coral and finger coral were growing in the nursery. If all goes well, one day those corals will be thriving in the sea.

The corals in the park bench lived in a past world without much, if any, human influence. The corals currently living in the Port of Miami are somehow persisting today despite our environmental mess. And the corals in the Frost Museum of Science will be used in the future to rebuild reefs we've destroyed. After spending more than a year writing about the past, present, and possible future of coral reefs, I felt it was apropos to find all three together in the shadow of the Miami skyline. All three are related—the stories of how reefs lived in the past, when they thrived and when they floundered, can help us understand reefs today and find ways to help reefs persist into the future, as we'll explore in this book.

The living corals in the port and in the museum, like those that we see snorkeling, are typically colonies of tiny organisms called coral polyps. Most living coral polyps within a colony are smaller than the eraser at the end of a pencil.[3] A tiny coral colony that's just getting started might have only a handful of polyps. An enormous colony will have many thousands of polyps. Coral polyps may be small, but these invertebrates, millions of them together within a reef, build limestone skeletons so large that some can be seen from space.[4] Their construction projects, coral reefs, become ocean epicenters of biodiversity, creating habitat for as many as a million species,[5] including tiny fish like bluehead wrasse that dart between branches of coral, damselfish that defend their territory with intimidating snapping sounds, sharks that loiter in sandy patches between corals, bright orange scallops that use long spines to wedge themselves in reef crevasses, turtles that soar placidly over a reef's colorful diversity, shrimp that make constant crackling noises, snails that cling to sea fans, lobsters that duck into holes, and countless microbes that are unseen by divers.

With thousands of coral polyps in a large colony, and hundreds to thousands of colonies in a reef, corals are powerful. Together, they are strong enough to buffer storm waves, protecting coasts, including our cities and towns, and creating habitat for reef life that prefers calm water protected from the waves. Yet reefs are in trouble today, in large part because corals have been weakened by warming seawater, pollution, overfishing, disease, and other problems (all of which we'll explore in the coming chapters). Some problems, like coral disease, are exacerbated by other environmental changes. Disease has been particularly problematic in the Caribbean—scores of corals have been killed by a disease that debuted in 2014 not far from the park bench and port. And extreme heat is too much for many corals to bear worldwide. For decades, climate change has caused widespread coral bleaching events that have weakened the corals; as I write this, corals are bleaching and dying en masse in particularly hot waters.

It isn't change itself that is problematic for these ecosystem-building organisms. Corals naturally live with change. They cope with cycles of tides and seasonal heat. They also live with regular oscillations between El Niño and La Niña—changes in winds and ocean currents that cause tropical climate and sea surface temperatures to swing warmer and cooler every few years. But these natural sources of change are cyclical—water warms and cools each year with the seasons, for example—unlike problems affecting modern reefs, which only increase over time in an unsustainable way. Predictions about how long coral reefs may hold on in the coming decades are becoming increasingly dire.

To get some perspective amid the current spate of problems, this book looks to the past, exploring the history of coral reefs. Fossil coral reefs make it possible to understand how reefs lived before human influence, helping us understand what today's reefs would be like if we weren't changing their environments. They give us a window into an alternate universe, where coral reefs are subject only to the stressors found in nature instead of the myriad problems humans have caused and continue to cause. This is not just a nostalgic desire to escape the current mess. Looking into the past can also help us understand what reefs need in order to have a future.

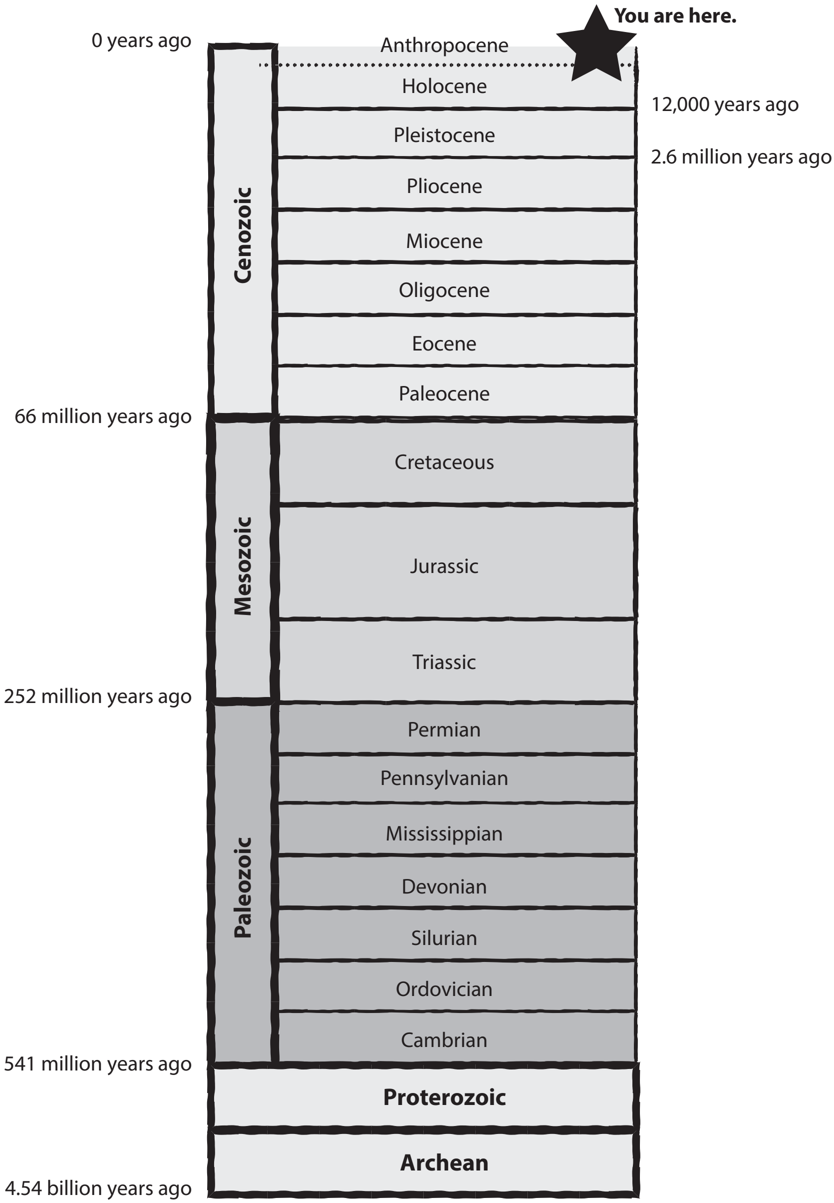
Research on the remains of long-dead reefs can also help us understand how reef ecosystems function over hundreds to thousands of years, at much longer timescales than those of studies that observe living reefs. By studying both fossil and living reefs, scientists can gain much stronger insight into how contemporary changes in coral compare to reefs across their long history. Understanding the past and present will in turn help us understand coral reefs' future—and maybe even how to save them. The stories of how past reefs persisted and when they didn't can help us understand how to play the long game: take actions now that will help coral reefs have a brighter future in hundreds and thousands of years, even if the near term is rough.

When they aren't in park benches, the remains of ancient corals and other reef life can be found fossilized in rock outcrops, often on tropical islands and coasts. Most of the fossilized reefs we'll explore in this book lived about 125,000 years ago, a time when there likely weren't even a million humans living on Earth, so they lived with little or no human disruption. We'll also look at the not-yet-fossilized skeletons of coral and other reef life that lived decades to several thousand years ago, which hold a record of both human disruptions and natural environmental changes. These, combined with fossil reefs and modern reefs, add up to a timeline of reefs. By tracking the history of reefs from before human influence to the present day, we can learn what has changed. What went wrong? And when did it start to go wrong? The answers, as we'll see, are often complex, without a single smoking gun.

If you are a fan of dinosaurs, trilobites, or other extinct fauna, even the oldest fossils described in this book will seem very young. This book focuses mostly on coral reefs that lived far less than a million years ago. While that's a very long time from a human perspective, it's nothing in the long span of over 4.5 billion years that is Earth's history (known as geologic time or deep time). The same coral species alive today also lived in reefs at this shallow end of deep time (with a couple of exceptions). By comparing contemporary corals with their relatively recent ancestors in the fossil record, we can easily see connections between the past and present.

While this book focuses on young fossil reefs, there are much older fossil reefs in the world. One of the oldest known fossil reefs sits in the middle of Canada and formed nearly three billion years ago from mounds of blue-green algae called stromatolites in a very different world.[6] There are fossil coral reefs in the US Midwest that formed in the Paleozoic era, approximately 460 to 360 million years ago. In the Guadalupe Mountains of Texas, a huge fossil reef, 400 miles long, is filled with fossil sponges, algae, and other creatures that lived about 275 million years ago, toward the end of the Paleozoic.[7] Reefs have existed for a long time, but it's the geologically younger reefs, with the same species that make up reefs today, that can best inform us about what today's reefs need and what their future may hold.

Earth's history is represented graphically as a stack of layers in the geologic timescale. It's like a map of deep time. The oldest layers, the Proterozoic and Archean, are on the bottom of the stack. The Cenozoic era is at the top of the stack with its most recent time layers: the Pleistocene and the Holocene, the latter of which started 12,000 years ago and appears to end at the top of the graphic. The top of the geologic timescale is the time we're living in now.



Geologic timescale.

We could be seeing humanity as a part of this long story of the planet, but more often than not, we explore human history and deep time separately. Yet both are made up of seconds, minutes, hours, days, and years. In deep time, the record is usually compressed, making the smaller increments of time indiscernible, but overall, time is time. This makes me want to wander the halls of geology departments and classrooms around the country and the world, adding "you are here" stars to the top of every geologic timescale posted in the style of way-finding maps on hotel room doors.

Our "you are here" star should be in a time period called the Anthropocene, but it's rare to find that word listed at the top of geologic timescales (except for the one in this book). More than two decades after atmospheric scientist Paul J. Crutzen proposed the Anthropocene as a new time period that we've entered because of our enormous effect on the planet,[8] the group of timekeepers that determines the official periods of geologic time, the International Commission on Stratigraphy, decided that, no, the Anthropocene will not become an official epoch of geologic time.[9] This was in 2024 after years of deliberation and research, after a subcommittee voted that we are, in fact, in the Anthropocene,[10] and after a four-year search for an appropriate start date landed on the mid-twentieth century.[11]

Perhaps the Anthropocene will eventually be added to the top of the stack of layers in the official geologic timescale. But even if it isn't, the Anthropocene still describes this time when human impacts are a dominant force on the planet, changing the climate and ecosystems worldwide, and this makes it a useful concept for this book as we plow through the many thousands of years at the current end of geologic time in search of coral reefs. No matter when, specifically, it started, we are most likely still at the beginning of the Anthropocene since it does not seem possible that humans will stop being a dominant force anytime soon, which begs the question: What will the rest of this time layer be like?

This book looks to answer this question for coral reefs, understanding how the story of coral reefs will likely continue through the Anthropocene given what we know about their past in deep time, their more recent history, and the present-day world at the current end of geologic time.

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I spent my childhood searching for shells on pebbled Cape Cod beaches. I spent my twenties doing much the same as a scientist working on my PhD, although most of those shells were within fossilized coral reefs on tropical islands. Over several years, I headed to the Bahamas for weeks to study the shells and skeletons of marine invertebrates that lived in coral reefs. I was a professional shell collector. And because most of the shells I studied were fossilized, I was also a time traveler, living in the past. I daydreamed about business cards that announced my twin specialties: Dr. Gardiner, Shell Collector and Time Traveler.

In the years since I left research science for the world of climate and geoscience education, I've focused on scary prospects for the future, like climate change and other looming disasters, rather than on the geologic past. For the most part, geologists and paleontologists look back in time, and climate scientists look forward (although there are climate scientists who study ancient climates and geologists who project into the future). I like both the past and the future, perhaps because I tend to have trouble living in the present. There's an anxiety to the present, especially when it's filled with unprecedented environmental problems like the warming climate and its ill effects.

Researching geologically young fossil reefs and seeing their living counterparts in decline just offshore, I found it impossible not to wonder about the ecosystem's future. And it was apparent to me that understanding the past can help us put the present-day trouble into context.

What I've learned while researching and speaking with experts for this book is that the future won't necessarily continue on a predictable trajectory. As we'll see, coral reefs are facing grim times and there will continue to be losses, but there's evidence that we can help turn this around. If we have the power to crumble reefs, we also have the power to fix them, and myriad scientists and conservationists are finding creative ways to apply our understanding of past and present coral reefs to help them have a future. The corals in the Frost Museum's aquarium are part of one such project. This book takes the stance that we can do a lot to improve the prospects for future coral reefs, especially if we use what we know about how reefs have survived in the past and take action on climate change.

In many ways, this book is a search for examples of coral reef perseverance. Stories of how reefs have survived in the past can hold clues to how reefs might survive climate change and other environmental challenges, now and in the future. As we explore these stories from the past, we'll find that over long timescales—millennia or even hundreds of thousands of years—coral reef ecosystems have been able to persist even when individual reefs could not, relocating and rebuilding where corals could survive, lying low when conditions weren't great. Yet this doesn't appear to be the case over short timescales, like the past several decades.

On short timescales, this perseverance is resilience. In ecology, the term "resilience" describes the ability of an ecosystem to recover from disturbances. For example, a coral reef with resilience is more likely to bounce back after a hurricane, even if it takes a few years. Resilience also describes the ability of animals to bounce back—the ability of coral to recover instead of dying after spending weeks or months in overheated water, for example. When it comes to resilience, we have something in common with corals: resilience also describes our ability to recover from stress or trauma and avoid post-traumatic stress disorder (PTSD). At a larger scale, resilience also describes the ability of our cities and towns to recover from extreme weather events and climate impacts.

There are plenty of unknowns about whether corals and reef ecosystems have enough resilience to recover from current challenges and future climate change. We don't know whether they'll be able to persist. Some say coral reefs may be among the first ecosystems to become extinct.[12] Yet the fossil record shows that reefs have been able to survive tough times over the long term. Learning what happened to reefs in the past can help us understand coral reef resilience and persistence, how the world shaped them, how they shaped the world, and what we need to do to help corals thrive now and in the future.

In this book, we'll explore fossil reefs at the fringes of tropical islands and dive into modern reefs to connect the past and present. In chapter 1 we'll look at the big picture of how coral reefs and other tropical marine life create limestone that preserves an often-detailed fossil record. This record in rock is what allows us to track reefs through time. Then in chapter 2 we will explore how the idea of uniformitarianism—that the present is the key to the past—helped lay the foundational understanding of coral reefs before Anthropocene reef declines started. As we'll see in chapter 3, the ecological patterns of modern reefs are also found in fossil reefs, an example of uniformitarianism, although living reefs have changed so much that the present is often no longer the key to the past.

We will then step back in time to explore disruption in reefs. This includes the tumult in modern reefs and what dead coral skeletons on the seafloor can tell us about changes in reefs (chapter 4), evidence of Caribbean reef transformation over decades and centuries, preserved in history archives and subfossils (chapter 5), and how reefs coped with environmental change long ago (chapter 6).

Evidence of how reefs have been able to persist over the long term can help us understand how the same strategies could allow reefs that have been decimated to someday return. In chapter 7, we'll explore how one of these strategies, protective refugia where corals shelter in place during difficult times, may help coral species survive. And in chapter 8 we'll see how reef restoration projects are creating human-built refugia, increasing the number of safe places to help reefs persist. In chapter 9, we'll explore other strategies—adaptation and acclimatization of corals to warmer temperatures—which could help corals survive as the climate warms, and how reef restoration projects have been speeding up this process through artificial selection. We'll then consider the possible future of coral reefs based on what we know of their past and present in chapter 10.

Some of the most well-studied fossil reefs in the world are in the Caribbean, which is one reason why this book tends to have a Caribbean focus, although reefs—past and present—from the Indian and Pacific Oceans and the Red Sea make appearances too. Fossil reefs in the Caribbean tend to be well studied because they are often found on land, which makes them easier for scientists to access and study than fossil reefs deep underground or underwater. Also, the first modern reefs to decline are in the Caribbean, with ecological transformations starting decades to centuries ago, which allows us to now look at this decline, and what went wrong, with the benefit of hindsight.

Understanding coral reefs' past, present, and projected future is a multidisciplinary effort. Tracing reef stories from the past to the present gets geologists, paleontologists, paleoecologists, and historical ecologists involved. Marine biologists, ecologists, and conservation experts typically focus on living corals and reefs. Since corals make limestone, geologists do research on living reefs too, not just fossilized ones. Plus, because corals are sensitive to their physical environment, oceanographers, chemists, and climate scientists are also involved in reef research. Many of the scientists highlighted in this book work in interdisciplinary ways to understand reefs. I find hope in the fact that so many experts are looking at questions from many different perspectives to help reefs have a future.

As with most environmental challenges we're currently facing, witnessing both the vulnerability and resilience of coral reefs today provokes feelings of both loss and hope. But knowing what has helped build reef resilience in the past lets us understand what can be done to help corals and other reef species. Just as it takes large numbers of animals to build a reef, it will take large numbers of people to help reefs survive an increasingly inhospitable world.

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