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INTRODUCTION

Every summer, after 11 months of work in a laboratory buried deep in the bowels of the Smithsonian's National Museum of Natural History in Washington, DC, I have the chance to do what every paleobiologist dreams of doing when they decide to become a paleobiologist: fieldwork. The opportunity to find fossils of organisms that lived tens or even hundreds of millions of years ago casts a spell that is both potent and universal, as such fossils provide a road map to the origins and evolution of life on our planet. When we stare at a fossil, whether it is a billion-year-old stromatolite cemented into a Montana cliff or a *Tyrannosaurus rex* toe bone from the hills of Wyoming, we pause and reflect. Perhaps we think of our own very fleeting lifespan—not of our individual life but that of our species. Or perhaps we are drawn to the near infinite number of events that were required for the evolutionary processes that gave rise to the fossil. We may wonder how the organism died and how the fossil, whether made of stone, encased in amber, or mummified by desiccation, could have possibly survived these millions of years.

It was a specimen from the Kishenehn Formation in northwestern Montana, the fossil of a mosquito, that led me to ask a very different question. This was no ordinary mosquito. It was

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the beautifully preserved fossil of a blood-engorged mosquito—the first ever found. We have all watched as a mosquito pushes its proboscis though our skin, searches for a tiny blood vessel, and begins to transfer blood into its abdomen. If we are patient, we see the abdomen of the insect expand and darken. If we are quick, we see with what little force the blood-engorged mosquito can be smashed into unrecognizable fragments, a smear of blood spread over our skin. The chances that a blood-engorged mosquito, blown up like a taut balloon, would survive, intact, through the long and complex fossilization process are next to nothing. Examining this impossible specimen through my hand lens, I thought of Michael Crichton's *Jurassic Park*. Could there be DNA present? Perhaps even dinosaur DNA? No, of course not. The rocks were too young. But might some trace of blood, some ancient biomolecule that was once an integral part of the insect, have been preserved? Answering this question would lead to two unexpected events. First, when my colleagues and I published a paper that described the preservation of 46-million-year-old remnants of hemoglobin in the abdomen of the fossil, and I was interviewed by National Public Radio, the fossil became fleetingly famous—at least as famous as a fossil insect can be in our dinosaur-centric world. Second, I became engrossed in the rapidly growing science of ancient biomolecules—the study of DNA, protein, pigments, and other organic material that has been preserved across millions of years. This fascination led me to write this book, so I could share some of the field's awe-inspiring discoveries and explain how this focus on ancient biomolecules is completely changing the game of paleobiology.

For hundreds of years, paleobiologists have relied on a single tool with which to study, classify, and understand fossil organisms: comparative anatomy. It is a powerful and surprisingly

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discriminating instrument. The molars of modern humans and Neandertals can be easily distinguished. Muscles, tendons, and ligaments leave behind "scars" where they attached to bones, which can be used, for example, to establish ages of individuals of the same species. Through a histological examination of dinosaur bones, scientists have even been able to determine that a dinosaur was not only female but pregnant. In the past, phylogeny—through which we seek to understand the evolutionary relationships of one organism to another—has been based solely on the morphology of the fossilized remnants of extinct animals.

Now, though, we can peer into the past by examining several different kinds of ancient biomolecules. We have ancient DNA. And not just degraded fragments of DNA but entire ancient genomes: the very source of evolution. Access to ancient genes has already allowed us to study evolution at the molecular level; the oldest sample to date, nearly 1.8 million years old, has been used to trace the early Pleistocene evolution of rhinoceroses. Ancient DNA has also allowed scientists to synthesize ancient proteins and show that their function differed from their modern counterparts.

We also have ancient proteins, which are even older than ancient DNA. While most scientists agree that the oldest ancient protein sequences to date are about 3.8 million years old, there are data that suggest that sequenceable proteins can be isolated from the bones of *T. rex* and even older dinosaurs, some over a hundred million years old. These sequences of ancient proteins help us document, albeit indirectly, mutations that occur in DNA. They also augment classical morphology-based classification of long-extinct animals and plants.

But what about ancient biomolecules from really deep time? While we may never have DNA or even protein sequences from

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300-million-year-old mollusks, corals, or crinoids, scientists have documented an amazing array of other kinds of ancient molecules: cellulose from plants, chitin from the exoskeletons of arthropods, and pigments as beautifully colored as those produced by organisms that live today. Our ability to identify ancient pigments, for example, has allowed us to reconstruct the color patterns of organisms such as feathered dinosaurs. These latter ancient biomolecules do not contain genetic information, but they still shed light on a wide range of questions about ancient functions and behaviors: If a 500-million-year-old organism produced a brilliant red pigment, does that mean that they—or perhaps their predators—could see and react to that pigment? When did color vision evolve? Was the evolution of skin and feather pigmentation involved in the evolution of sexual display and courting behavior?

In our examination of ancient biomolecules, we will travel back to the very origins of life, as well as to some of the most interesting places on Earth. We will travel to Yoho National Park in Canada, where we will examine the iconic organisms of the Burgess Shale; to the amber mines of the Dominican Republic, where we will find a very different environment than that depicted in *Jurassic Park*; and to Clarkia, Idaho, where we will split 15-million-year-old shale to expose leaves whose greenish color foretells the presence of the photosynthetic pigment chlorophyll. We will accompany scientists as they collect these fossils and follow them in the lab as they extract and characterize ancient biomolecules from fossils from deep time.

We will begin our journey by spending a bit of time with my blood-engorged mosquito, as a means of introducing the methods and materials involved in this new frontier of science. Then, in chapter 2, we will see just how far back in time ancient biomolecules are able to take us. The rest of the book is broadly organized

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by the different ancient biomolecules: in chapters 3 to 5, we will discuss ancient pigments, which help us understand the colors of ancient life, as well as the evolution of color vision. In chapter 6, we will turn our attention to ancient biometals. While you might not think of metals as biomolecules, they have shown wide application to the study of ancient life; chapters 7 and 8 tackle one of the most illuminating types of ancient biomolecules, proteins, which shed light on a wide range of topics—including evolutionary, behavioral, and physiological aspects of life in the past. The degree to which they extend into deep time also provides one of the more controversial topics in the field of paleobiology. After discussing proteins, we turn to perhaps the holy grail of ancient biomolecules: ancient DNA. Our ability to document changes in DNA through deep time has uncovered the genetic history of the evolution of many species, including, as we will discuss in detail, that of our own. Our discussion so far has primarily concerned the animal kingdom, but in chapter 11, we look at what we can learn about early plant life. We will learn of the amazing diversity of ancient plant biomolecules and about the field of chemotaxonomy to which that diversity has given rise. We will conclude our journey by turning our gaze from the past to the future: what new discoveries will the science of ancient biomolecules reveal? Will ancient genomes allow us to produce viable embryos and clone long-extinct animals? Will we be able to make proteins that existed billions of years ago? While I cannot, of course, provide a definitive answer to these questions, one thing is certain: by the time you finish this book, you will never think of a fossil in the same old way again.

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