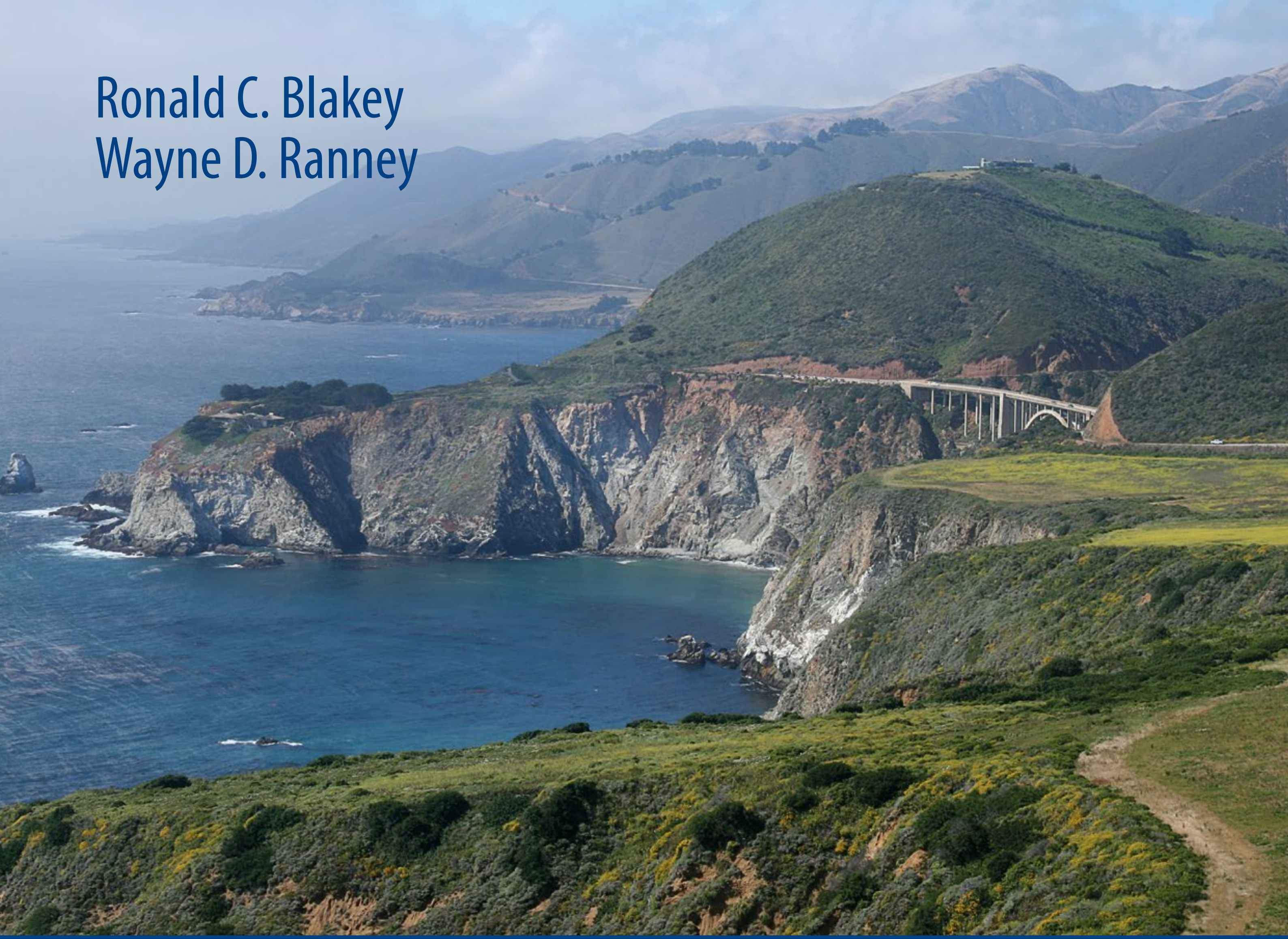

Ronald C. Blakey
Wayne D. Ranney

Ancient Landscapes of Western North America

A Geologic History with Paleogeographic Maps

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Foreword

You have before you a remarkable and ambitious book. The authors include the geologic development of the North American Cordillera, a region that extends some 5000 to 7000 miles from the Verkhoyansk Mountains in E. Siberia to Central or South America, and some 250 to 1000 miles across. Their imaginative and excellent maps and exquisite photographs complement the description of this vast region area, which has seen geologic and tectonic activity for at least the past 500 million years, and continues to present time in many regions.

I commend the authors to you as highly respected scientists. Ron C. Blakey, retired Professor of Geology at Northern Arizona University, has authored popular geological books and published numerous maps of the *paleogeography,* or ancient geography, of parts of or all of the Earth. Wayne Ranney, a geologist from Northern Arizona and former student of Blakey's, has authored a number of popular geologic books himself and led geological expeditions to various parts of the North American Cordillera and beyond. Now, working together, they have developed a comprehensive historic overview of the geographic, geologic, and tectonic development of the North American Cordillera.

This book notes that features of the North American Cordillera were key in the development of pre-American native societies and later the westward expansion of European settlers, including the following:

- Patterns of land, sea, and in the latest glacial times, ice and ice-free corridors strongly affected the patterns of human migration and settlement in North America. A brisk trade developed between Native American societies in such items as obsidian from volcanic centers for spear and arrow points, and marine shells for use as money.
- The Lewis and Clark expedition provided the first written accounts of the geology of the North American Cordillera in the early 1800s.
- In 1842, the J. C. Fremont expedition searched for, among other things, the mouth of the mythical Buenaventura River, which allegedly head watered in the Rocky Mountains and flowed through land that is now in Nevada and California to the Pacific Ocean. Fremont and his companions, including the American Mountain Man Kit Carson, instead discovered the Sierra Nevada of California, and proved that the Buenaventura River did not exist.
- Discovery and exploitation of rich deposits of gold in California in 1848 and silver in Nevada in 1859 arguably financed the Union in the 1860–1865 American Civil War. During the war, the California Geological Survey began a study of the geology of that state that ended in 1868.
- After the war, several well-organized national efforts on geologic investigation included the Hayden Survey in the Yellowstone region, the Clarence King 40th Parallel Survey from Eastern California to Wyoming, and the J.W. Powell survey of the Colorado River and neighboring regions. And in 1872, the American geologist Grove Karl Gilbert first discovered the link between active fault displacement and an earthquake (in Owens Valley, E. California), and the UC Berkeley geologist A. C. Lawson discovered the active San Andreas fault in 1895 south of San Francisco and after 1906 extended it from Northern to Southern California.

Over the decades, these investigations and subsequent work by other geologists developed a voluminous body of knowledge and ideas about the geologic development of the North American Cordillera. Such was the situation when the field became swept up in the Plate Tectonic Revolution in the late 1960s. As a result of the new understanding of plate movement, geologists embarked on the daunting task of reinterpreting the development of the North American Cordillera in the context of plate interactions along the continental margin.

Geology is a forensic science. Geologists try to understand the geologic history of a given region, to understand an experiment that they did not design, and that is still ongoing. There are no eye witnesses to ancient geologic events.

Blakey and Ranney skillfully lead the reader through some mind-bogglingly complex geologic history including the following:

- It is now generally accepted that until some 650 million years ago, the Cordilleran margin of North America was attached to other continental masses, now present in North China, Australia, and East Antarctica. Then the continents rifted and separated far apart as the Pacific Ocean Basin formed. The North American Cordilleran margin from about 500 million years ago (500 Ma) to the present time has experienced the interaction of plates in that ocean and with North America. At first, this margin may have been a simple Atlantic-style (rifted) margin. Later, it experienced the arrival of "exotic" terranes coming from the "Pacific" Ocean (but long before the formation of the Pacific Plate). These exotic terranes collided with and deformed the margin, giving rise to the folded and faulted rocks that we see today in many places. The maps in this book are admirable attempts to portray these events.
- For hundreds of millions of years, the North American Cordilleran continental margin experienced a long and complex history of plate convergence, collision of chains of islands or of so-called ribbon-continents, and horizontal movement of these formerly off-shore features either to the north or south, depending on the time. During such times, the North American Cordilleran region may have looked more like the present western Pacific from Indonesia to Japan, with several island chains, many convergent or subduction zones dipping in several directions, and ongoing collisions between the continent and island chains (island arcs).
- At present, the North American Cordilleran margin exhibits a convergent or subduction margin south of Alaska, a so-called transform fault west of much of Canada, a convergent or subduction margin off the Pacific Northwest, the famed San Andreas "transform fault" margin along much of California, and a convergent or subduction margin off southern Mexico and Central America.

In a speech in 2012, the former US National Academy of Sciences President, Bruce Alberts, urged his audience to "Be Creative: Take Risks." Inspired by Alberts's exhortation and as a confirmed "West-Coaster" and geological risk-taker, I would have been happy with even more coverage than Blakey and Ranney portray of the geologic story that gave rise to the California Gold Rush — the huge gold-bearing rivers draining westward off a Tibet-like or "Altiplano-like" highland in Eastern Nevada; more about ophiolites, which are fragments of ocean crust and mantle formed at spreading centers and now preserved on land abundantly in Mexico, California, Oregon, Washington, and British Columbia; and more portrayal on maps of possible collisions of the continental margin with subduction zones dipping away from it.

But these are only quibbles. On balance, Blakey's and Ranney's inspired book provides a comprehensive portrait of our current understanding of the geologic past of our western mountains, basins, and plains, and something of the life that developed there, too. Enjoy!

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Preface

Western North America is a vast place with a vast geologic history. Despite the incredible volume of knowledge concerning the region, there remain many problems to be solved – and many more lacking consensus. Clearly, the individual who first said “the more you know, the more you realize that you don’t know” may have been referring to the North American Cordillera. We approach this complex problem by presenting a series of maps that show what ancient Western North America might have looked like – *not necessarily what it did look like* – over more than two billion years of geologic history. The maps are based on the voluminous literature and attempt to integrate numerous hypotheses that concern the geologic evolution of the region. Therefore, sets of data often yield conflicting interpretations. Sometimes, two pieces of information gleaned from the same rock or outcrop suggest contrasting interpretations. In most cases, we chose not to present multiple maps that show contrasting interpretations – this endeavor is beyond the scope of this book. Therefore, compromise and ambiguity are both present in paleogeographic maps – that is why they present what the region might have looked like, not what it did look like. They are our interpretation – our synthesis.

How accurate are they? Certain aspects of Cordilleran geology can be clearly allied with given events, in given areas, at given times. Examples include specific location of ancient shorelines, volcanoes, canyons, mountains, river systems, ocean basins, and many other ancient elements of past landscapes. It does not take rocket science to plot a well-defined Late Cretaceous shoreline (with data from the geologic literature) in eastern Alberta or the Triassic channels of the basal Triassic Chinle Formation of Northern Arizona, or the Eocene-Oligocene channels that fed a submarine channel complex in the Sacramento Valley of California. Correctly interpreted ancient features of a landscape cannot be accurately plotted on a given map time slice unless their *age is accurately determined* and their *extent correctly mapped*. But the integration of thousands of elements from the ancient landscape through careful correlation and mapping allows reconstruction of ancient landscapes through the construction of paleogeographic maps. And that is what the maps in this book are based upon. However, interpretation of an ancient landscape at a given outcrop (or based on subsurface data) can be complicated by other factors: (1) younger geologic events alter or destroy older ones; (2) the dynamic crust of the Earth shuffles blocks of terranes, sometimes over thousands of kilometers. These two factors create doubt and generate multiple hypotheses regarding the reconstruction of ancient landscapes, especially in areas along the West Coast of North America where Mother Nature has hidden some of her past secrets well!

The purpose of this book is to use paleogeographic maps to illustrate the geologic history of Western North America. Coupled with text, photographs, and, diagrams, we present a chronology of geologic history from oldest to youngest – the direction that most geologists’ reconstructions and thought processes follow. For over a billion years, large parts of the Western Continent did not exist, but rather were represented by vast stretches of ancient ocean that would be catastrophically destroyed by later subduction and mountain building. Pieces of continents and ancient island arcs from faraway places – terranes – would change this picture by accreting to the western margin of the continent and adding to its extent. The subduction of one of the largest plates in Earth history, the Farallon Plate, generated immense volumes of igneous rock, volcanics and plutons, and further caused the continent to grow westward. Finally, as the

Farallon Plate all but disappeared under the continent, a new oceanic plate, the Pacific Plate (moving in a different direction from the Farallon Plate) intersected the Cordillera and caused a dramatic shift in tectonic setting – subduction turned to transform margin. The adjacent Cordilleran crust was stretched, broken, and flooded by volcanics in a way seldom seen in Earth history. Our purpose is clear – to illustrate these events in chronological order through a series of paleogeographic maps.

To facilitate our presentation of these maps to a broad audience, we provide a brief introduction of appropriate geologic principles followed by an introduction, primarily through photographs, to the area elucidated in this book. We begin our presentation of geologic history with the oldest preserved rocks in the West. We follow through geologic history to the present by covering broad, wide-ranging geologic events that are filled in with appropriate details. Much of the text presents a concise examination of geologic history supplemented by tables that add additional detail, terminology, and explanation. The photographs illustrate the rocks, terrain, and scenery of this incredible region. The maps show some of the locations that we mention in the text, but the large area covered and the complexity of names make it impractical to show every mentioned location. We suggest a search on your browser to ferret out some of these places. Our intent is to present a complex concept to a broad audience that ranges from those with interest in, but limited background with geology, to geoscience students and professionals. For those with limited background in the geosciences, the maps lead the reader through the patterns of change that mark deep geologic time. The text adds clarity and explanation and helps with navigation through successive geologic events that shaped the final landscape. Students and professionals in the geosciences will find that this book provides a broad introduction to Western North American geology and a comprehensive presentation of the geologic history of the region. The tables add detail that is presented in consistent manner from chapter to chapter. For some of the more complicated events in Cordilleran geologic history, a series of successive time slices are used to show the evolving paleogeography or paleotectonic elements.

Paleogeography is the ultimate synthesis of immense amounts of geologic data – like all scientific syntheses and interpretations, the product is only as good as the original data. These geologic data describe ancient events and the products – in this case landscapes – that result from geologic processes. Many geologic products cannot be recreated or repeated in a lab, especially with regard to the vast amount of time necessary for their production.

We acknowledge the many individuals who helped to bring this book to reality. Our colleagues at Northern Arizona University and Yavapai College shared much of their expertise as we prepared the manuscript. We especially thank the late Bill Dickinson who shared with Ron Blakey many of his views, insights, and experiences with Cordilleran geology and who provided to the entire geologic community some of the most innovative, meaningful, and important publications on the subject. Numerous friends and acquaintances urged us to write another book based on our earlier work, *Ancient Landscapes of the Colorado Plateau*. Ron Doering, a publishing editor at Springer Nature, heard about the proposed book and invited us to submit the manuscript to Springer. We thank the editorial staff at Springer for preparing the final product. Our wives, Dee Blakey and Helen Ranney, encouraged our work and kept us on track as manuscript preparation took longer than expected. Finally, we thank our teachers, mentors, colleagues, and students who over many years shared stimulating discussions both in the field and over a cold brew or two, providing us with knowledge, information, stimulation, and good old geologic debate.

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Contents

About the Authors

Ron C. Blakey is Professor Emeritus at Northern Arizona University where he taught in the Department of Geology for nearly 35 years. He retired in 2009. Ron received a bachelor's degree in Geology at the University of Wisconsin, a master's degree at the University of Utah, and a doctorate at the University of Iowa. The subject matter of both of his theses involved the sedimentary rocks of Southeastern Utah. Since that time, he has studied nearly every Permian, Triassic, and Jurassic sedimentary rock unit on the Colorado Plateau. His interest in paleogeography dates to his earliest publications in the 1970s in which he used pen and ink to illustrate past landscapes on the Colorado Plateau. Since then, he has written more than 40 professional papers. Computer graphics took his paleogeography a quantum leap forward and his interest in historical geology expanded to global Earth history. He has since prepared paleogeographic maps of North America, Europe, and the Earth. Several of his most recent publications include some of these maps. His interests include photography and beachcombing along the California Coast – he and his wife, Dee, now make their home in Carlsbad.

Wayne D. Ranney loves southwestern landscapes! (His liberal use of exclamation marks is a dead giveaway!) A 2-week vacation in 1975 led him to his first southwest residency in the bottom of the Grand Canyon where he worked as a backcountry ranger at Phantom Ranch. Living among the rocks for 3 years inspired him to formally study geology at Northern Arizona University, where he obtained both his bachelor's and master's degrees. While studying at NAU, he also worked as a river guide on the Colorado, San Juan, and Verde rivers. Wayne began working as a shipboard geology interpreter in 1989 and has traveled the world ever since, completing more than 100 expeditions that took him many times to the Arctic, the Amazon, Africa, and Antarctica. These far-flung adventures allowed him to see and learn about many different kinds of landscapes, but he always returned to the red rock cliffs and canyon country of his adopted home in Flagstaff, Arizona. Wayne currently works as a geology interpreter and trail guide for organizations such as the Smithsonian, the Museum of Nvorthern Arizona, and the Grand Canyon Field Institute. He is a former adjunct faculty member at Yavapai College in Prescott and Coconino Community College in Flagstaff, where he taught courses in southwestern geology. Wayne is an award-winning author who inspires readers to learn more about their home planet. He has written nine books - all about geology of the region - and has contributed articles for numerous magazines. He writes a popular geology blog at: earthly-musings.blogspot.com.

Introduction

1

Earth is a terrestrial planet whose history is recorded in rocks (Fig. 1.1). Like fingerprints left at a crime scene, the evidence for past landscape-forming events is strewn about Earth's surface – hidden in canyons, on mountains, and beneath lakes and seas. This history hasn't always been recognized and only when Renaissance-era scientists began to use newly acquired tools and their newly acquired knowledge about natural Earth processes did they begin to seek out evidence, first for a Biblical flood, then for events on a much grander scale. Although no evidence for such a flood was found, the idea that Earth's rocks contained evidence for its ancient past grew in the minds of these early scientists, setting them on a path that led to the development of the science of geology.

Soon fossils were becoming categorized and a coherent sequence of evolved life forms emerged. Past mountain building events were recognized and numerous sub-branches of the discipline were developed, such as volcanology, sedimentology and glaciology. In the 1960s a 50-year-old hypothesis first suggested in 1915 by German geoscientist Alfred Wegner – plate tectonics – sprung to the forefront of geology as the dominant theory that could explain myriad Earth processes (a theory is the strongest level of acceptance in science short of a physical law). This great leap forward was given additional support with the publication of results from the International Geophysical Year (1957–1958) and since then plate tectonics has dominated the understanding and focus of research for geologists. This is especially applicable in explaining the structure and functions of the Earth's interior, the non-random distribution of earthquakes and volcanoes, and the variable locations of the continents and oceans through time. Plate tectonics has evolved into a sophisticated paradigm that shows how the continents were assembled piecemeal by great and small collisions between sections or plates of its mobile, brittle crust (Fig. 1.2). Every landscape on our planet, whether it is spectacular or not, holds clues to its formation and a coherent, if still developing, story can be known.

It is the truly spectacular landscapes however, that seem to draw the most attention from the public at large and from around the world people of all backgrounds are drawn to the iconic landscapes of the American West. They are poets, painters, filmmakers, thrill seekers, movie stars, rock stars, Asians, Europeans, Pacific Islanders, and just about anyone who has ever seen a cigarette ad or car commercial. But perhaps no one group comes to the American West with such vigor and intensity of observation as geologists, who seek out its hidden secrets from the ancient past. Here, in a still actively forming terrain lie the answers to the origin of a huge and rugged portion of the North American continent. Geologists cherish this relatively accessible and always tantalizing landscape, home to active volcanoes, continental-scale river systems, forested or sun-splashed shorelines, its canyons, deserts, mountains, and high-alpine valleys, that stretch from the Pacific shore to the Sierra Nevada and Cascade crest, across the Basin and Range to the Rocky Mountains and the Great Plains. The American West seems to have everything and is loved and revered by people worldwide.

The story you are about to read is complex in many of its details but can be understood and appreciated by those who merely have a sense of curiosity and wonder about it. By using the paleogeographic maps contained in this book, one can literally see the sequential development of the Western landscape and take a trip on a virtual time machine, revealing scenes that are long gone from planet Earth, but whose stories are preserved in its rocks. As our modern society advances, more and more people are able to visit these places, and the stories that geologists can share with them are richer and more complete. This is one of the first books to tell the vast and varied history of the American West through using visually attractive and state of the art *paleogeographic* maps (literally, ancient geography). Using these as a guide, one learns how the basement rocks of the region were cobbled together from volcanic islands that accreted onto North America over a mind-boggling 200-million-year time period. One sees how the area now occupied by the Rocky Mountains was covered not once in seawater but numerous times and most recently just 70 million years ago.

R.C. Blakey, W.D. Ranney, *Ancient Landscapes of Western North America*, DOI 10.1007/978-3-319-59636-5_1

Fig. 1.1 The Cordilleran region is marked by spectacular rock outcrops. Seen here are plutonic and metamorphic rocks exposed by glacial scouring in a fjord in the Alaska Coast Range south of Juneau

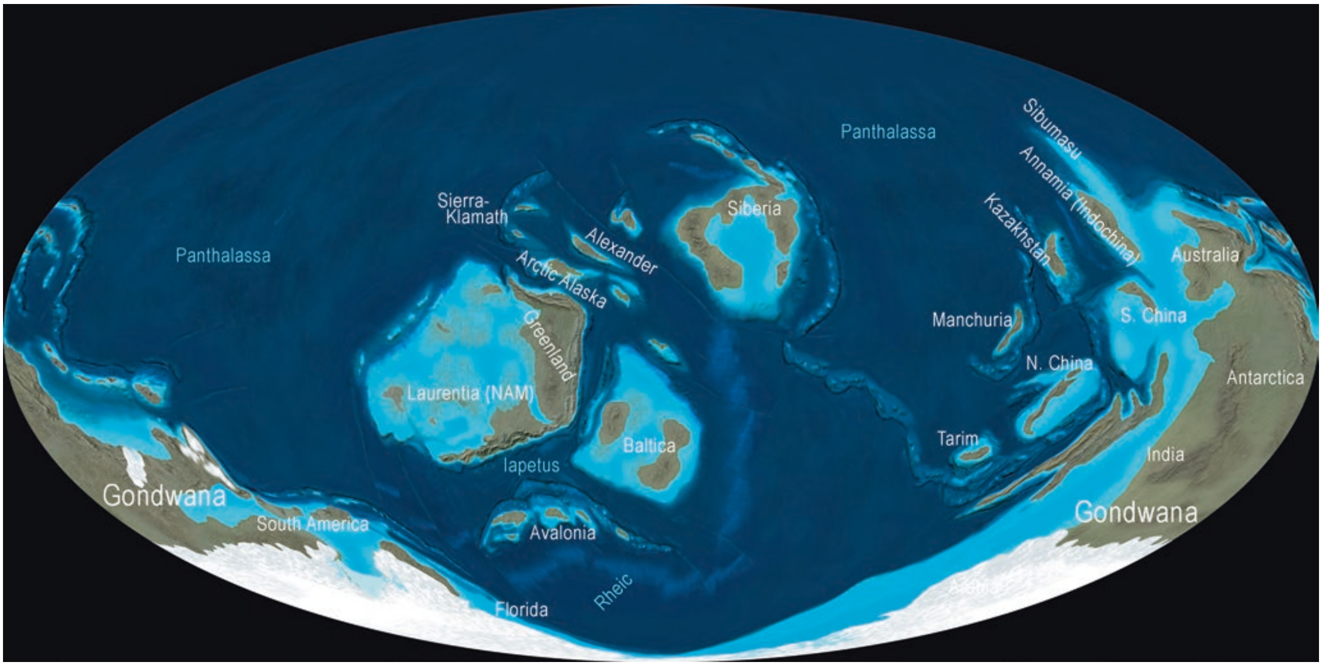

Fig. 1.2 The Earth's plates were scattered across broad oceans in the Ordovician (ca. 450 Ma) but close inspection suggests that collisions were eminent as North America (labeled as Laurentia (NAM) closes on Baltica (center) with Siberia above. Gondwana occupied the South Polar region. Global maps are shown in Mollweide projection, an equal area map developed in 1805 by German mathematician Karl Mollweide and commonly used in atlases today. Mollweide's map, which represents the whole world in an ellipse, has axes in a 2:1 ratio, and reflects the round character of the Earth better than rectangular maps

And how parts of the Los Angeles basin were submerged beneath 600 m of water only 3 million years ago, and when volcanoes erupted, faults were generated, and canyons carved in the last few million years.

Before starting this geologic story, some descriptive terms will aid in the use of the maps and as you read the text. Throughout the book the abbreviation *Ma* is used for Mega-annum or millions of years ago. Similarly, *Ga* stands for Giga-annum or billions of years ago. Thus, very old events can be described as happening either thousands of millions of years ago or billions of years ago (1,750 Ma can also be written also as 1.75 Ga). Geologic time is divided into various *Eon's,* *Era's, Period's*, and *Epoch's* (Fig. 1.3). There are three Eon's, the *Archean* (4,000–2,500 Ma), *Proterozoic* (2,500–541 Ma), and *Phanerozoic* (541 Ma to Present) and it is often useful to refer to these large subdivisions of time. The geologic Era's may have a familiar ring to them including, *Paleozoic* (541–252 Ma), *Mesozoic* (252–66 Ma), and *Cenozoic* (66 Ma to Present). Perhaps not as familiar however, are the periods that belong in the Archean and Proterozoic Eon's, with three in each and Paleo-, Meso-, and Neo- used as prefixes (i.e. *Paleo-Archean*, *Meso-Proterozoic*, etc.). The term *Precambrian* has no official standing in today's time scale but is still used when referring to the first 8/9th of earth history, or the time before complex life evolved, the base of the Cambrian.

The geologic Periods are the most widely used subdivisions of time and include names such as *Cambrian*, *Permian,* or *Jurassic*. Learning the names, sequence and age ranges for the time periods may seem tedious at first and perhaps even unnecessary. But anyone serious about moving forward in their quest to comprehend geology will need to have at least a rudimentary understanding of where the time periods are placed relative to each other, and for the important events that are often associated with them. The various geologic Epoch's within each time period are used mostly by professional geologists, who find these more detailed subdivisions of time useful. The exceptions are the seven Epoch's within the Cenozoic Era that are quite commonly used: *Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene* and *Holocene*. Some geologists propose another Epoch, the *Anthropocene*, denoting the time of greatest human impact on Earth resources. It either replaces the term Holocene (the last 12,000 years) or it begins from the year 1950 and onwards when a steep rise in carbon emissions began.

Like all continents, North America is composed of a core of ancient crystalline rocks called *cratons*, which formed in the early collisions between small continental fragments. A large part of the North American craton is also known as the *Canadian Shield* as it is widely exposed in the eastern 2/3 of Canada. The North American craton was formed entirely in the Precambrian and includes a subdivision known as the Slave province containing Earth's

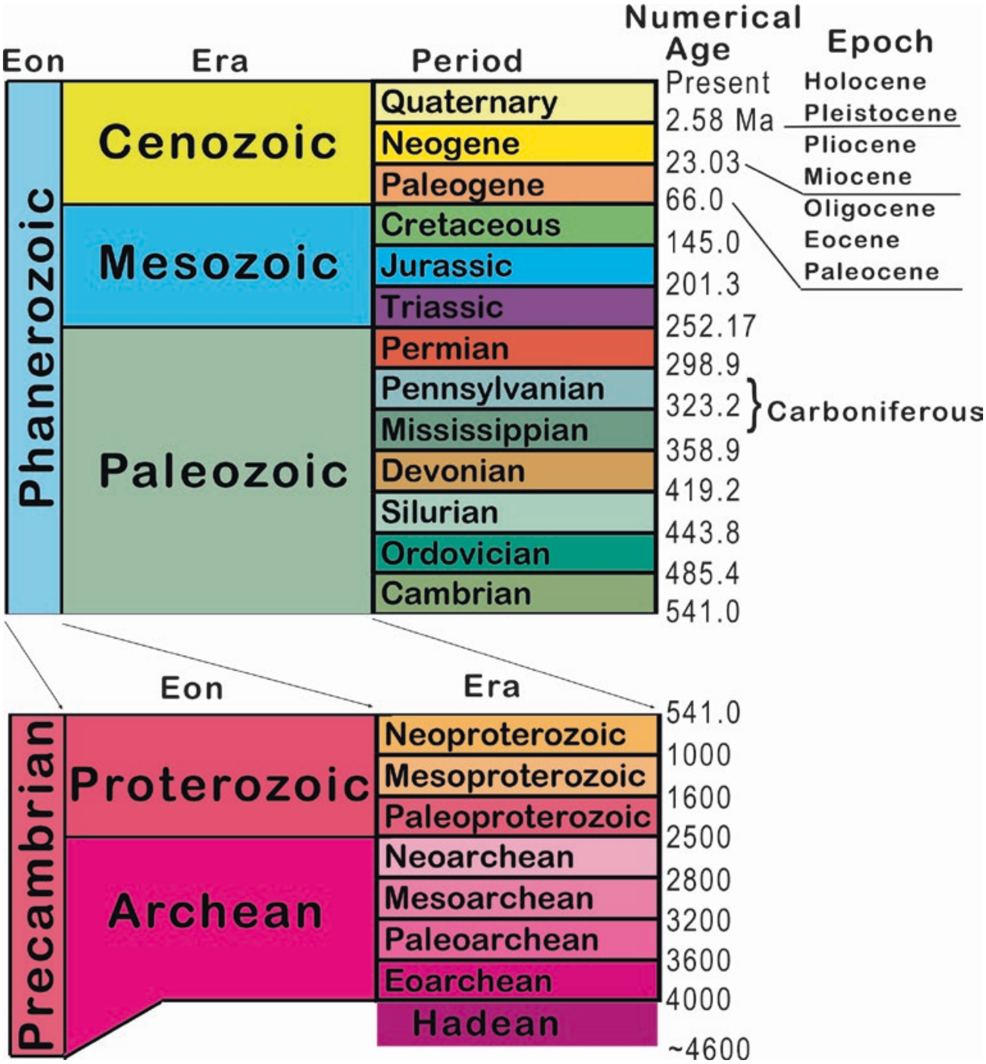

Fig. 1.3 The modern geologic timescale (simplified)

oldest rocks dated at about 4,000 Ma. The North American craton also includes Greenland, home to more of Earth's oldest rocks. Cratons may have a thin veneer of sedimentary rock that overlie them or they may be exposed at the surface as with the Canadian Shield.

Laurentia is a term synonymous with the North American craton and is used often on the paleogeographic maps as a name for the North American continent over various (usually older) periods of time. Laurentia was assembled piecemeal during the Archean and Proterozoic Eons, with its final assembly during the Grenville orogeny, 1.3–1.0 Ga (Fig. 1.4). Parts of it such as Greenland and the western British Isles were rifted away during the late Mesozoic and early Cenozoic era's, around 80–40 Ma. Laurentia as a paleogeographic term is commonly used from the Proterozoic to the Mesozoic. We refer to Laurentia on the global maps as a term for the ancient North American continent and use it synonymously for the craton, which includes the Canadian Shield and Greenland, the still-covered platforms and basins of the North American Interior, and the Cordilleran foreland of the

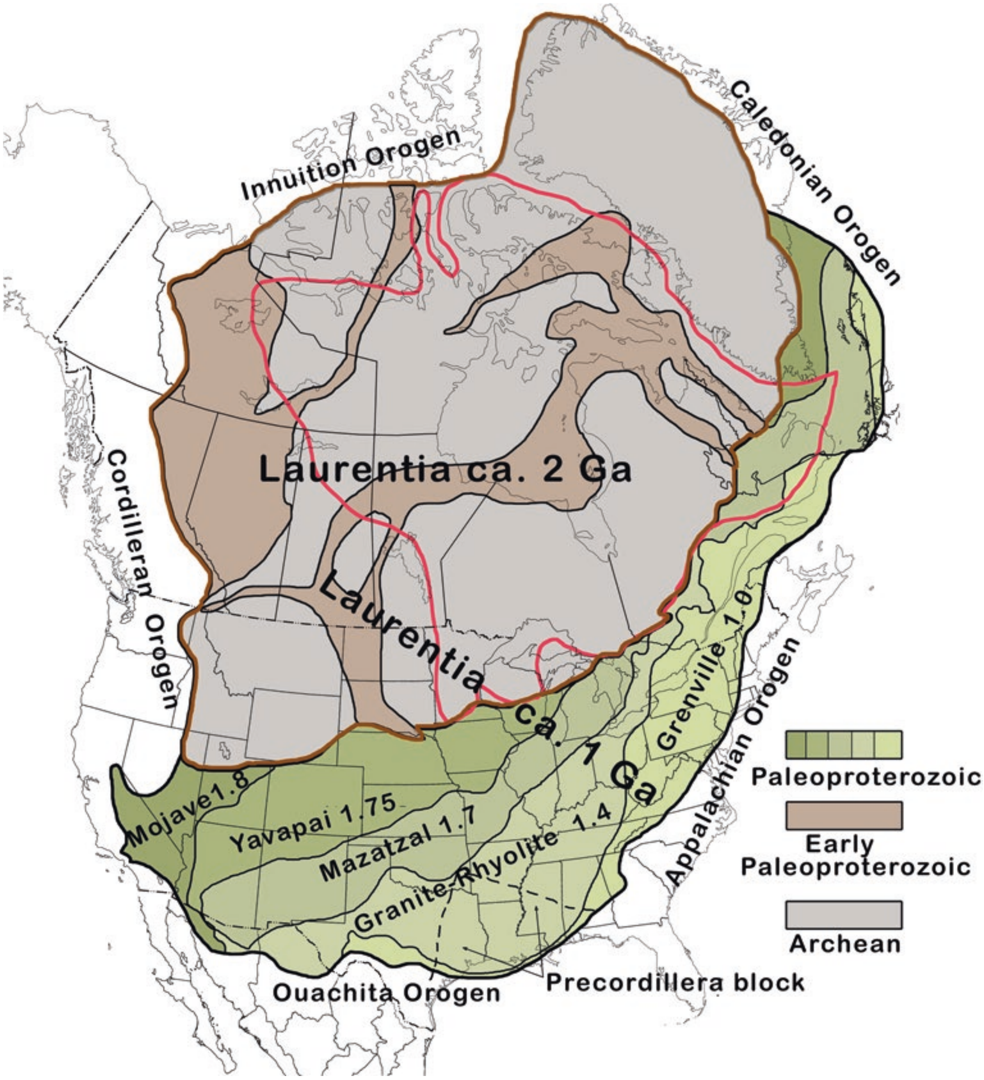

Fig. 1.4 North American (Laurentian) Craton. The earliest rendition of Laurentia formed approximately 2 billion years ago when several Archean cratons (*gray*) united in several continental collisions. The Early Paleoproterozoic bands shown in pale brown represent various orogens that stitched the Archean cratons and formed accretionary orogens in NW Canada; the result was earliest Laurentia – area within heavy brown lines. A series of accretionary and collisional events added Paleoproterozoic crust south and east of the original Laurentian craton. Note how the events young away from the original craton (ages of crust given in billions of years). The final Laurentian continent was formed by approximately 1 billion years ago (entire colored area). The Laurentian continent remained this size for over 1.5 billion years until Paleozoic orogenic events added additional crust. Greenland is shown restored to its position in Laurentia prior to Cenozoic rifting. Scotland, Western Ireland, and parts of Newfoundland are shown in their position within Laurentia prior to later tectonic events. The Cordilleran Orogen was built along and over Laurentian crust that included both Archean and Paleoproterozoic ages. The bright red line is the approximate extent of Canadian Shield – that area mostly uncovered by younger sedimentary rocks. Precambrian outcrops outside this line are the result of Phanerozoic uplift events that stripped away sedimentary cover

southwestern United States. Furthermore, as a plate tectonic term, Laurentia refers to ancestral North America from its initial assembly more than 2.5 billion years ago to the breakup of Pangaea approximately 200 million years ago.

Basement is a term used for the crystalline rocks (igneous and metamorphic) that compose the bulk or foundation of any continent. *Cover* or *sedimentary cover,* refers to the layered rocks that in many places overlie the basement. Use of the terms basement or cover does not imply any specific age. For example, basement rocks across much of North America are Precambrian in age, while much of the basement in the Appalachians is Paleozoic and in California's Coast Ranges it is late Mesozoic and Cenozoic in age. In a few places such as Grand Canyon or Death Valley, the oldest sedimentary cover is Proterozoic (the Grand Canyon Supergroup and Pahrump Group respectively), but most of the sedimentary cover in North America is Phanerozoic in age. In many places across western North America layered volcanic rocks comprise much of the "sedimentary" cover.

The term *North America* itself has several meanings (Table 1.1): (1) the exposed landmass that includes the United States (except Hawaii), Canada, Mexico, and some portions of Central America; (2) the North American continent including the crust that extends to the edge of the continental shelf whether above or below modern sea level; (3) the North American Plate, a much larger feature composed of both continental and oceanic crust extending across much of the Arctic Ocean to eastern Siberia in the Verhoinsk Mountains, the Atlantic Ocean eastward to the Mid-Atlantic Ridge, including the Bahamas, Cuba, Mexico and south to the Motagua Fault in Guatemala, but excluding crust west of the San Andreas Fault which lies on the Pacific Plate.

Other terms will be very useful to the reader and perhaps the most important is the word *Cordillera* or alternatively, the *western Cordillera*. This originally is a Spanish word defining any long, narrow mountain range or ranges (the word *corduroy* – literally King's road – formerly referred to a series of logs placed crossways on top of muddy roads). Many mountainous areas in Spain and its American colonies were named with the prefix Cordillera (Cordillera de Los Andes, Cordillera Oriental, etc.). Geologists liked the word and use it to describe the entire western margin of North and South America. In this book, the word Cordillera stands for all the western landscape in North America from the Pacific Coast to the eastern edge of the Rockies.

Table 1.1 North America: components and definitions

North America (continent – geographic landmass): the modern *landmass* that includes Canada and the Arctic islands, the United States (except Hawaii), Mexico, and plus or minus Central America depending on whose definition you follow

North America (continent – geologic, geophysical): includes the above *landmass and the continental crust submerged by modern sea level* out to the edges of the continental shelf-slope-rise – the area underlain by continental crust both above and below modern sea level. Most North American crust is 30–50 km (20–35 miles) thick

North American Plate (tectonic): a much larger feature that extends across much of the Arctic Ocean, includes Eastern Siberia to roughly the Verkhoyansk Mountains, the Atlantic Ocean eastward to the Mid-Atlantic Ridge, the Bahamas, Cuba, and Mexico southward to the fault bordering Honduras, *but excludes* Continental North America west of the San Andreas Fault – much of Southern California

Note: the boundaries of each of these has changed dramatically through geologic time and are changing slowly at present

Laurentia (ancient North America Plate): ancestral North America (including Greenland, and parts of the British Isles) from its assembly more than 2.5 billion years ago to the breakup of Pangaea approximately 200 Ma. The various oceans once part of this plate have been destroyed by tectonic processes

Cratonic North America: for the purposes of this book, this term is generally synonymous with Laurentia

Western North America: a general term lacking a definitive boundary used herein for the mountains and plateaus of North America from the High Plains to the Pacific Rim

Cordillera (mountains, region): *Cordillera – Spanish* = Mountain chain – defining any long, narrow mountain range or ranges. Many mountainous areas in Spain, and North and South America, were named with the prefix Cordillera (Cordillera de Los Andes, Cordillera Oriental, etc.).;

Cordillera (geologic): a mountainous setting related to or caused by a subduction zone in which the subducted plate is mostly oceanic material; only a small portion of accreted material is continental blocks

North American Cordillera: stretches 12,000 km from Central America (Honduras) through Alaska and into Kamchatka, Siberia; its width varies but ranges from nearly 2,200 km west of Denver to 700 km in parts of Canada and Mexico; elevations extremely variable to ~6,000 m; terrain includes rugged mountains, plateaus, volcanic cones, broad valleys to narrow canyons, wide beaches to ragged cliffs jutting out into ocean. We prefer a loosely defined eastern boundary

You will also note the word *terrane*, with its distinctive spelling meant to differentiate it from the more familiar spelling *terrain*, which stands for the shape of the land. A geologic terrane (or the plural, terranes) form discrete blocks of crust that can be shown to have a completely different history, age and rock type from crust found in adjacent blocks (Table 1.2). Terranes are often *exotic* or *suspect,* meaning that they have traveled far distances before colliding and *accreting* (attaching) to a larger mass. There are dozens of exotic terranes that have been identified throughout the Cordillera and these will be discussed in the text and shown on the maps. Often when terranes accrete to a continent they create compressive pressure that initiate a mountain building event or *orogeny*. There are at least six major orogenies that are discussed in the text and numerous smaller ones. Note that orogeny is the process or sequence of events and orogen is the product – the deformed rocks. In some usages, the difference is blurred or not important.

The names and types of faults involved in orogenic events are helpful to know. When the earth's crust is squeezed or compressed, *reverse faults* will dominate.

Table 1.2 Cordilleran terrane history

Terrane	Present location	Origin-history	Age of accretion
Yukon-Tanana	N BC, Yukon	Peri-Laurentia, rifted in Mississippian with opening of Slide Mountain Ocean	Early Jurassic
Quesnell	SE BC to N Wa	As above	As above
Stikine	BC to Yukon	As above	As above
Slide Mountain	E BC	Ocean that opened in Mississippian, closed in Jurassic	As above
Kootenay	SE BC	Deepwater offshore sedimentary rocks along W Laurentia, thrust over shelf in Devonian-Mississippian	Dev-Miss
Roberts Mountain	NW Nv to S Id	As above	As above
Okanagan	SE BC	Siberia-Baltica-Caledonian (zircons do not match W Laurentia), drifted along N edge of Laurentia in Ordovician-Silurian, along NW Laurentia in Devonian	Dev-Miss
Eastern Klamath	NC Ca	As above	As above
Northern Sierra	EC Ca	As above, some fragments possibly derived from Gondwana via S Laurentia	As above
Cache Creek	C BC > 1,000 km long	Late Paleozoic – Early Jurassic ocean and accretionary material sandwiched between Paleozoic and Mesozoic terranes; contains blocks with Tethyian fauna	Jurassic
Baker	EC Or	Probable Cache Creek equivalent; as above	As above
Trinity-Hay Fork-North Fork- Calaveras	NC Ca (Klamath-Sierra)	As above	As above
Alexander	SE Ak, W BC	Siberia-Baltica-Caledonian (zircons do not match W Laurentia), drifted into NE Panthalassa and merged with Wrangellia in Pennsylvanian	Middle Jurassic-Cretaceous
Wrangellia	SE Ak, W BC, Vancouver Island	Devonian oceanic arc in Panthalassa, merged with Alexander in Pennsylvanian, oceanic plateau in Permian-Triassic, merged terranes (Insular Superterrane) formed leading edge of Farallon Plate	As above
San Juan Island-N Cascades-Wallowa	NW Wa to NE Or	Triassic-Jurassic arcs (fringing and exotic?) and intervening oceanic material including ophiolites; merged with NA during Nevadan orogen	Late Jurassic
Western Klamath-Sierra	NW to NC CA	As above	As Above
Guerrero	Sonora, Baja, SW Mex, S Ca	Triassic-Jurassic intra-ocean arc assemblage; may be leading edge of Farallon Plate	Early Cretaceous
Marin Headlands	San Francisco Bay area	Cretaceous accretionary complex; oceanic-plateau limestone blocks derived from southern tropics	"Mid" Cretaceous
Franciscan-Chugach, and related units	SE Ak – Baja	Complex assemblage of accretionary material and trench deposits; extensive post-formation dismemberment and displacement – Chugach displaced 1,000 km northward; Franciscan west of San Andreas displaced several hundred kms in late Cenozoic, individual element such as Nacimiento terrane had several episodes of displacement	Late Jurassic – Paleocene
Siletzia-Yukutat	Or, Wa (core of Olympic Mtns), BC, SE AK	Oceanic Plateau and seamounts 56-49 Ma (Paleocene-Eocene) possibly formed over Yellowstone Hotspot when various ridges adjacent to Farallon Plate overrode it	Eocene (50 Ma)
Salinia	Cent Ca (most of Ca west of San Andreas F)	Southern continuation of Sierra Nevada; original position Baja, Mx	Offset to current location during late Cenozoic

These are fractures where one piece of crust is pushed over another part of the crust. If the angle is less than 45°, they are called *thrust faults* and these types of faults are important in the Cordillera's history from about 400 to 55 Ma. The block that has been shoved over another block is called the *allochthon* (Greek for "other earth"), and the part that stays in place and becomes buried by thrusting is called the *autochthon* (Greek for "native earth"). The opposite of a reverse fault is a *normal fault* where one block moves down relative to another and these tend to form when the earth's crust is stretched or extended. If a normal fault is less than 45° they are called *detachment faults* and some of these flatten with depth becoming *listric faults*. These extensional faults are important in the history of the Cordillera in the last 30 million years.

Regarding rock types and environments, most terms may be obvious to the reader. Sandstone is composed of sand-size grains but when deposited by the wind is called *eolian* sandstone or *eolianite* (Aeolus was the Roman god of wind). Deposits that accumulate in rivers or on floodplains are termed *fluvial* (from the French flueve, for river). Igneous rocks are either *plutonic* or *volcanic* (Pluto was the Roman god of the underworld and Vulcan was the Roman god of fire). These two terms can also be stated respectively as *intrusive* or *extrusive* (formed in the ground or on the ground). Volcanoes that form along a plate boundary are may be part of a *volcanic arc* (from the Latin *arcuare*, to bend like a bow), and examples include the Japanese Archipelago, the Aleutian chain, or the Andes Mountains. The term arc was adopted as these volcanic belts often have an arcuate shape.

Earth contains two types of crust and their differences in chemical composition and density defines *continental* and *oceanic* crust. Continental crust contains more of the lighter elements such as silica and alumina, while ocean crust tends to be richer in iron and magnesium, making it denser and heavier. This simple difference has huge consequences in the way each type encounters the other during an orogeny. For example, when ocean crust collides with continental crust, their differences in density and temperature will cause the ocean crust to *subduct* beneath the continent. The process of *subduction* therefore, is where ocean crust is shoved beneath the edge of a continent, typically compressing the continental crust and forming a volcanic arc on top of it. This is an important process in the history of the western Cordillera.

This book covers a vast area, over immense intervals of time (Fig 1.5a, b). Broadly, we consider all western North America as the North American or western Cordillera (Table 1.3). Many of the maps extend eastward into the central portions of North America and some show the entire continent. Our previous book, *Ancient Landscapes of the Colorado Plateau*, covered many details of the Plateau and the adjacent Southern Rocky Mountains. Therefore, our area of emphasis in this book will be those landscapes found west, northwest and southwest of the Plateau, specifically western Utah, southern and central Arizona, all of Nevada, California, Oregon, Washington and Idaho, western Montana, Wyoming, as well as southeastern Alaska in the United States, British Columbia, Alberta, and the Yukon in Canada, and Baja California and Sonora, Mexico. Figures 1.6, 1.7, 1.8, 1.9, 1.10, 1.11, 1.12, 1.13, 1.14, 1.15, 1.16, 1.17, 1.18, 1.19, 1.20, 1.21, and 1.22 display some of the diverse modern landscapes across the North American Cordillera.

Three series of paleogeographic maps are used to illustrate the unfolding geologic history of the western Cordillera. A global series is used sparingly to show the setting of North America relative to other worldwide events; a North American series is used both in whole and cropped versions to show broad events across the Cordillera and those regions adjacent to the Cordillera; and most maps are a western series focusing on the American Southwest and Pacific Borderland. The emphasis in the book revolves around the use of the paleogeographic maps and the accompanying text (with figures, photos, diagrams, boxes and sidebars) meant to facilitate the understanding of the many details displayed on the maps. Those less familiar with geology or less concerned with detail will want to read the text and then refer to the maps.

Fig. 1.5 Maps of the Cordilleran region. (**a**) States and provinces within the Cordillera region and vicinity. *Dark yellow line* delineates the eastern boundary of the greater Cordilleran region. *Light yellow line* defines part of the Cordillera emphasized in this book. (**b**) Major subdivisions within the Cordillera and adjacent regions mentioned in the text and described in Table 1.3

Table 1.3 Overview of modern components of landscape and geology, western North America

Alaska Range – Aleutian Range – Chugach Mountains, SE Alaska. – Area of various accreted terranes bounded by large transform faults (Fig. 1.6)
Canadian Shield – Large region of *North American Craton* that consists of Precambrian crystalline rocks mantled by Pleistocene glacial deposits
Yukon Plateau – Area of variably deformed rocks that forms broad plateau between mountains to east and west
Mackenzie Mtns. – Fold belt that marks NE extent of *Sevier orogen*
Alexander Archipelago – Series of islands along Alaska-British Columbia coast mostly comprised of Alexander Terrane, an exotic terrane derived from Baltica or Siberia (Fig. 1.7)
Coast Mtns. (Canada) – Coastal mountain chain comprised of mostly Mesozoic granite batholiths and deeply dissected by glacial fijords. Granites stitch the rocks of Insular to those of Intermontane Superterrane (Fig. 1.8)
Haida Gwaii (Queen Charlotte Is.) – Vancouver Is. – Large islands mostly composed of rocks of Insular Superterrane (Fig. 1.9)
Canadian Rocky Mtns. – region of strongly compressed and folded and faulted mostly sedimentary rocks, deformed in Mesozoic and Cenozoic, especially during *Sevier orogen* (Fig. 1.10)
Great Plains – part of *cratonic North America*. A vast elevated region underlain by flat-lying, relatively undeformed sedimentary rocks that range in age from Late Precambrian to Cenozoic
Olympic Mtns. – Mostly Cenozoic accreted terrane that formed as oceanic plateaus and seamounts (Fig. 1.11)
East Pacific Rise – Mid-ocean ridge that formed boundary between Pacific and Farallon plates; at present, along western North America, only a small remnant is preserved between two large transform faults
Cascade Volcanic Range – large volcanic mountains, mostly Cenozoic, from N Washington into N California. The Cascade arc was formed by subduction of the Farallon Plate under western North America (Fig. 1.12a)
Snake River Plain – Columbia Plateau – basaltic lava flows from S Idaho into Oregon, Washington, and N. Nevada – mostly Late Cenozoic. These huge volcanic fields mask large areas of Cordilleran region and complicate interpretation of geologic history in region (Fig. 1.12b)
Northern Rocky Mtns. – These complex mountains include fold belt of *Sevier orogen* and granitic rocks of Idaho Batholith (Fig. 1.13)
Central Rocky Mtns. – Southern Rocky Mtns. – Strongly folded and faulted former crust of *North American Craton*. Largest uplifts are cored by Precambrian rocks – uplifts separated by large Cenozoic basins with thousands of meters of fluvial-lacustrine (lake) deposits. Mountains were formed during *Laramide orogen* (Fig. 1.14)
Klamath Mtns. – Large mountainous massif along California-Oregon border – complex history of accreted terranes, subduction zones, and granite batholithic intrusions
Basin and Range – block-faulted mountains separated by Late Cenozoic sedimentary basins; S Oregon to SE New Mexico and Central Utah to E California. The mountain blocks consist of thick Paleozoic and early Mesozoic sedimentary rocks and middle to late Cenozoic volcanic rocks. Age of faulting youngs from SE to NW. The thick sedimentary rocks were deformed in the Mesozoic *Sevier orogen* and extended and faulted in the Cenozoic *Basin and Range orogen* (Fig. 1.15)
Cordilleran thrust belt (Sevier Thrust Belt) – Cretaceous thrust and fold belt that extends length of Cordillera from Alaska to Mexico; modified by later extensional tectonics across *Basin and Range*
Cordilleran Batholiths – immense band of granitic rocks from NW Canada and SE Alaska south to N Washington (Coast Plutonic Complex) through C Idaho (Idaho Batholith), through E California (Sierra Nevada Batholith), S California into Mexico (Peninsular Batholith) (Fig. 1.16)
Central Valley of California – broad lowlands separating Sierra Nevada from Coast Ranges – **Sacramento Valley** to north and **San Joaquin Valley** to south
San Andreas Fault Zone – transform fault zone that forms plate boundary between North American and Pacific Plate; trends southward to SE from N of San Francisco to Salton Sea (Fig. 1.17)
Coast Ranges (US and Mexico) – mountains of variable size and form that comprise the western margin of continent and Cordillera, W Washington and Oregon, W California, NW Baja, Mexico (Fig. 1.18)
Sea of Cortez (Gulf of California) – Young sea underlain by oceanic crust – formed by transform motion of Baja California (Fig. 1.19)
Colorado Plateau – Plateau of uplifted and locally folded (monoclines) and faulted rocks that was once part of *North American Craton* – minor deformation during Laramide orogen; faulting and igneous intrusions (laccoliths) during Cenozoic. Extreme dissection of region provides some of best exposures of sedimentary rocks on Earth (Fig. 1.20)
Arizona Transition Zone – Series of block-faulted mountains that expose one of largest Precambrian outcrop belts in North America (type areas of Mazatzal, Yavapai, and Mojave orogens). Most mountain ranges mantled by Paleozoic sedimentary rocks, Cenozoic volcanic rocks, or both. The region has crustal thicknesses and a geologic history intermediate between those of *Colorado Plateau* and *Basin and Range* (Fig. 1.15e, f)
Sierra Nevada – Large mountain massif that parallels California-Nevada border – complex rocks and structures record long history of accretion, granite intrusion, and Cenozoic uplift (although exact timing of uplift is strongly debated). Intensely dissected by Pleistocene glaciers (Fig. 1.16d)
Mojave Desert – Sonoran Desert – Highly extended former North American cratonic crust later intruded by Mesozoic granites and deformed during both *Sevier and Laramide orogens*. Extreme Cenozoic extension has greatly modified these areas (Fig. 1.21)
Mogollon Rim – The linear escarpment that marks the southern boundary of the *Colorado Plateau* – extensive exposures or Paleozoic sedimentary rocks (Fig. 1.20f)
Transverse Ranges – E-W-oriented mountains formed when blocks west of *San Andreas Fault* rotated and collided with rocks on North American Plate (Fig. 1.22)
Channel Islands – Islands within *California Continental Borderlands* uplifted by tectonic events related to motions along *San Andreas* and related faults (Fig. 1.22a)
California Continental Borderlands – Continental shelf off Southern and Central California – part of Pacific Plate. Complex geologic history records Mesozoic subduction and Cenozoic extension
Peninsular Ranges – Southern extension of *Sierra Nevada* that has rifted and translated NW along *San Andreas Fault* and spread from mainland Mexico across *Sea of Cortez*. Major rock type is Mesozoic batholithic granite (Fig. 1.16a–c)
Sierra Madre Occidental – Major mountain range initially formed during *Sevier orogen* that became major Cenozoic volcanic center
Sierra Madre Oriental – Mountains of east-central Mexico that mark eastern edge of Cordillera west of Gulf of Mexico coastal plain

Many people might think that the western landscape (or the western Cordillera if you want to start speaking geologically) has been formed in only the last few tens of millions of years. They would be surprised to learn that this landscape has been "under construction" for hundreds of millions or even billions of years. But to a geologist old just means better! And because the oldest rocks are sometimes exposed in the bottom of a deep canyon or on the summit of a high mountain peak, it means you get to see a lot more other geology on the way there. We invite you to take a trip on a virtual time machine and learn about the evolution of the great American Cordillera.

Fig. 1.6 Features of the Alaskan Coast. (**a**) Coast plutonic complex in wall of fjord south of Juneau; (**b**) Coast Range east of Petersburg, AK showing heavily glaciated peaks; (**c**) Mouth of fjord near Petersburg; (**d**) Mountains south of Juneau composed of several accreted terranes

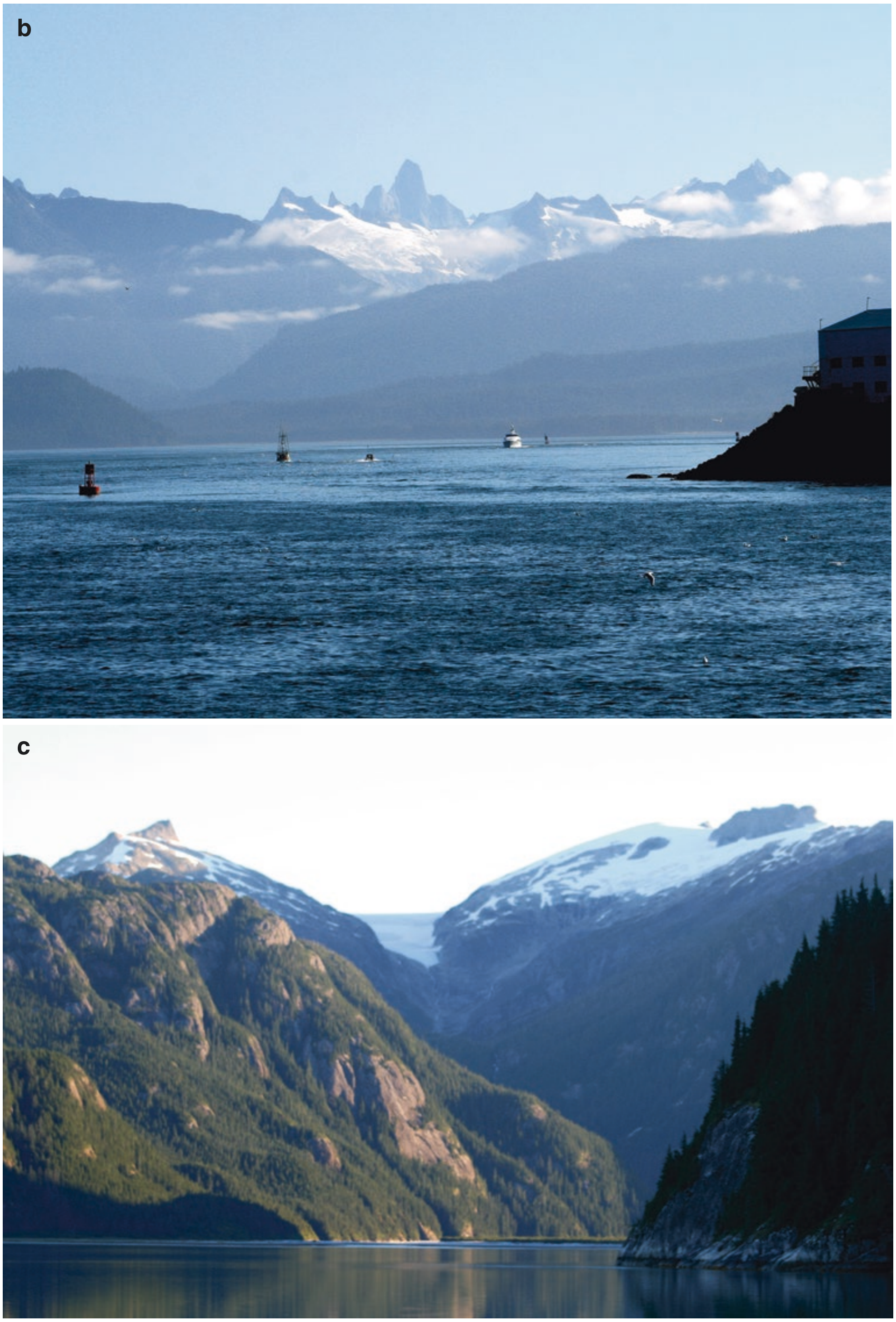

Fig. 1.6 (continued)

Fig. 1.6 (continued)

Fig. 1.7 Features of the Alexander Archipelago, a far-travelled accreted terrane. (**a**) View west from cable car at Juneau across northern Admiralty Island. (**b**) Admiralty Island near Alaska Brown (grizzly) Bear Preserve

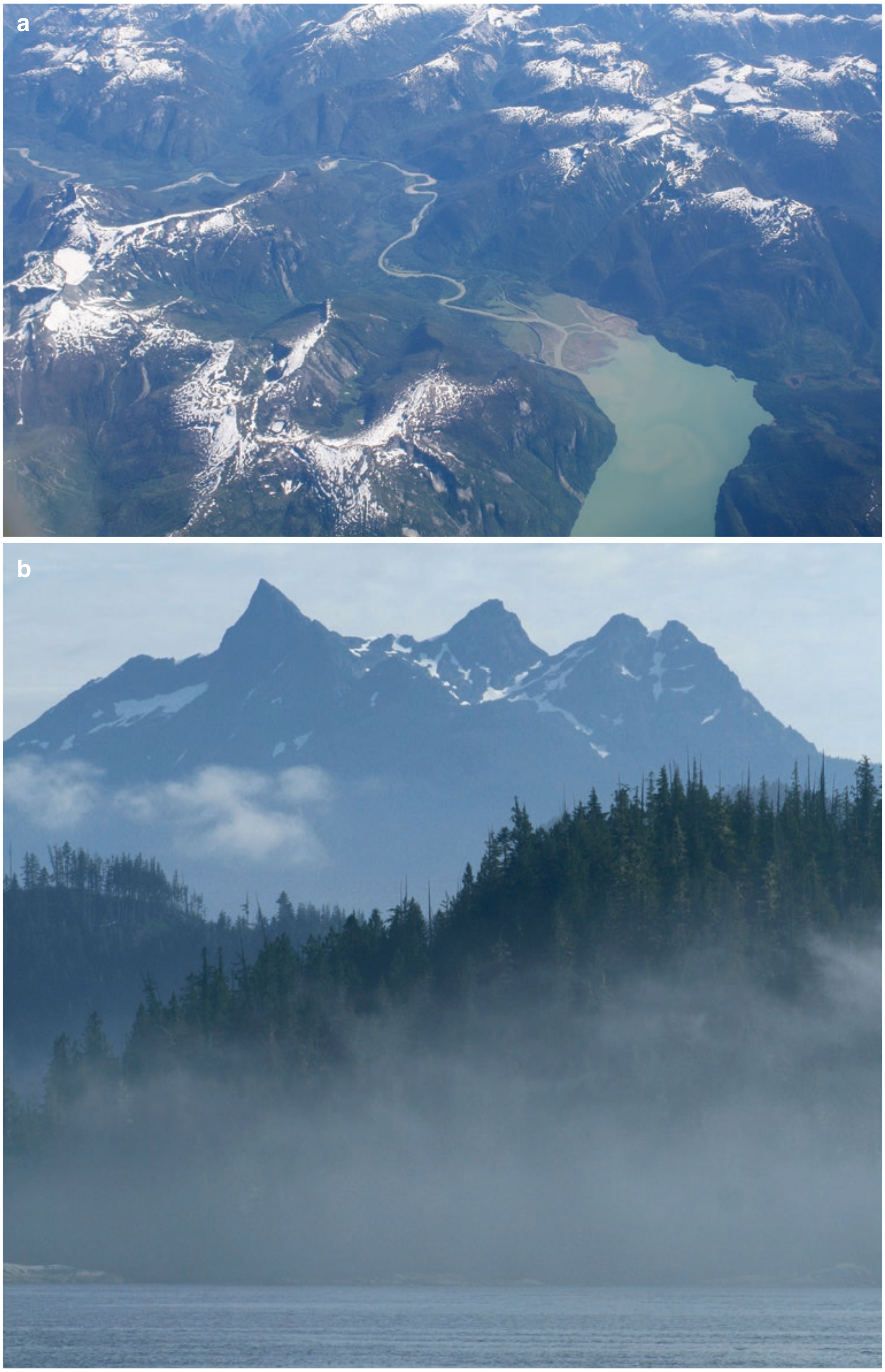

Fig. 1.8 Features of Coast Mountains, British Columbia. (**a**) Fjord penetrates deeply into tall, glaciated peaks composed of Coast Plutonic complex. (**b**) Coast Mountains viewed from Inner Passage south of Prince Rupert

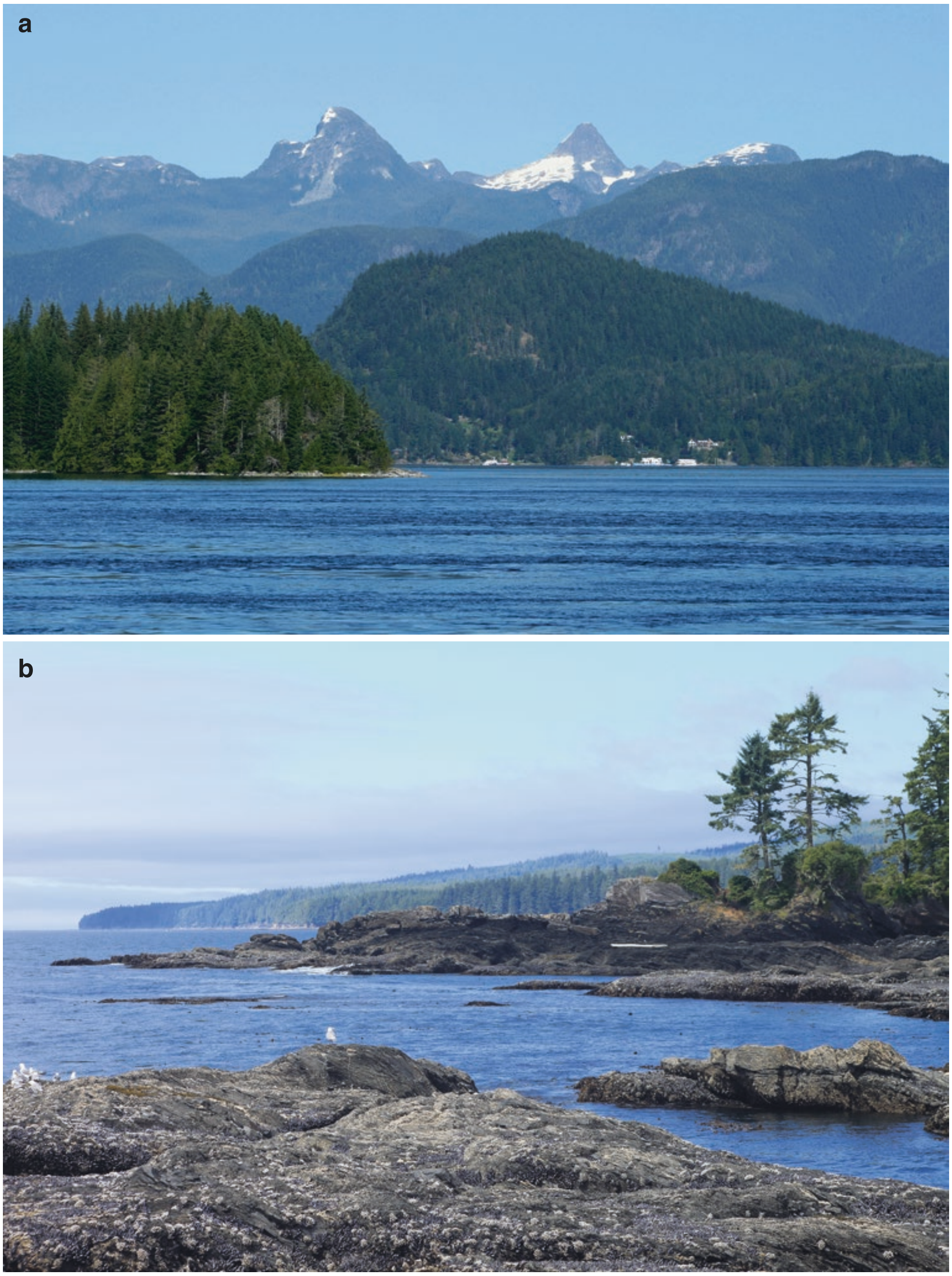

Fig. 1.9 Features of Vancouver Island. Most of Vancouver Island consists of the accreted terrane Wrangellia. (**a**) High peaks of northern Vancouver Island viewed from Inner Passage. (**b**) Nanaimo Basin near Victoria with Cretaceous sedimentary rocks in foreground; the tides can race through these channels at more than 12 miles per hour