Ronald C. Blakey
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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.

1 Introduction

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.

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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

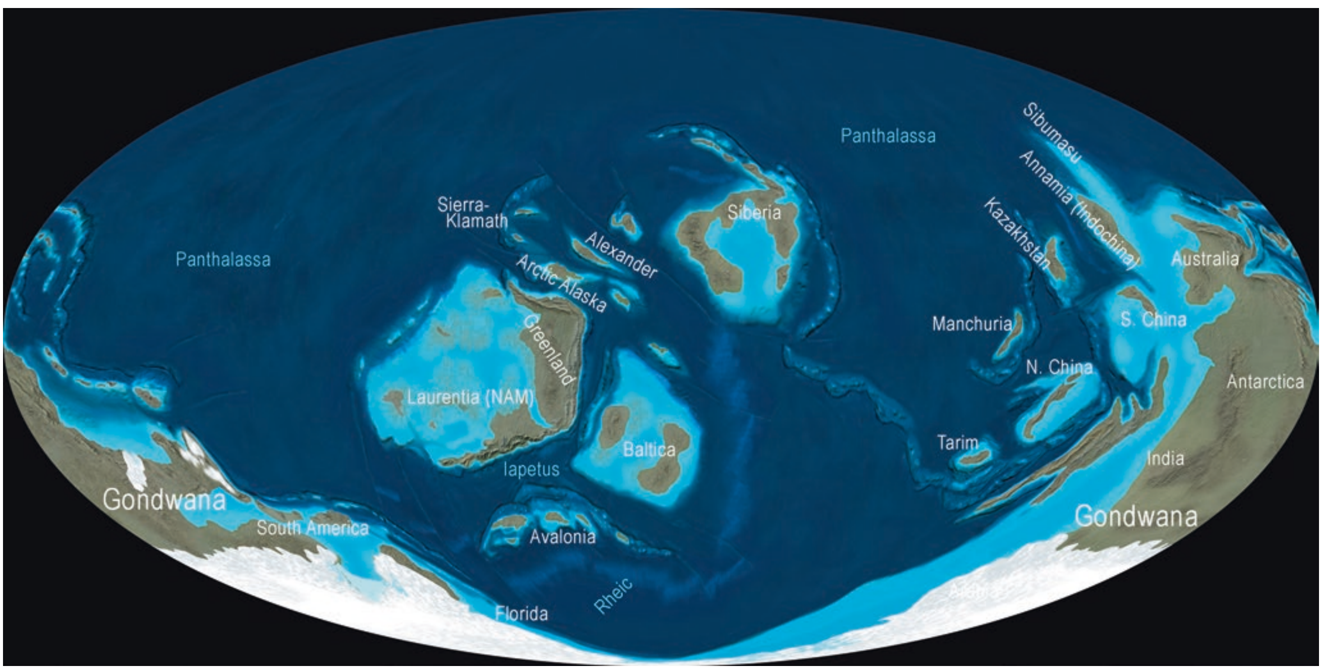

Fig. 1.2 The Earth's plates were scattered across broad oceans in the Ordovician (ca. 450 Ma) but close inspection suggests that collisions were eminent as North America (labeled as Laurentia (NAM) closes on Baltica (center) with Siberia above. Gondwana occupied the South Polar region. Global maps are 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

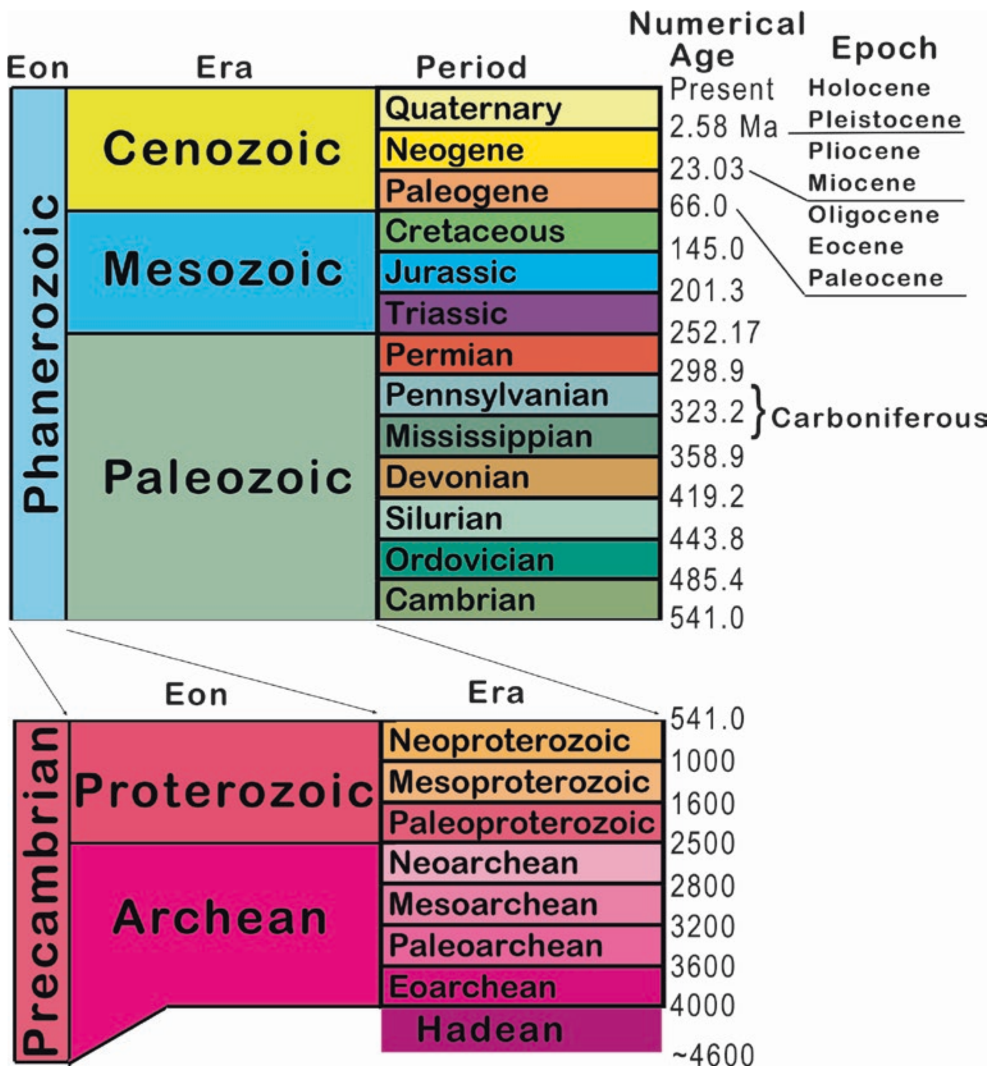

Fig. 1.3 The modern geologic timescale (simplified)

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

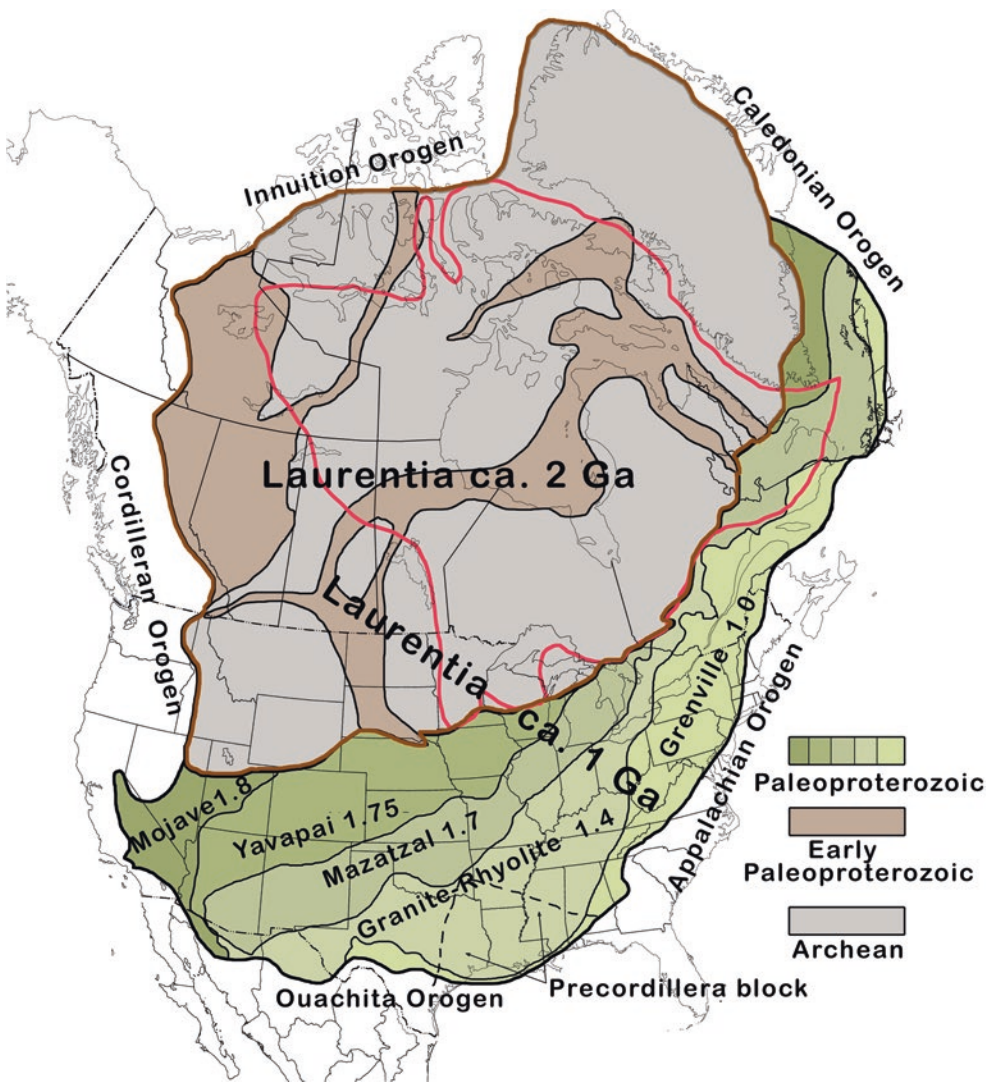

Fig. 1.4 North American (Laurentian) Craton. The earliest rendition of Laurentia formed approximately 2 billion years ago when several Archean cratons (*gray*) united in several continental collisions. The Early Paleoproterozoic bands shown in pale brown represent various orogens that stitched the Archean 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.

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 1.1 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

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*

Table 1.3 (continued)

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

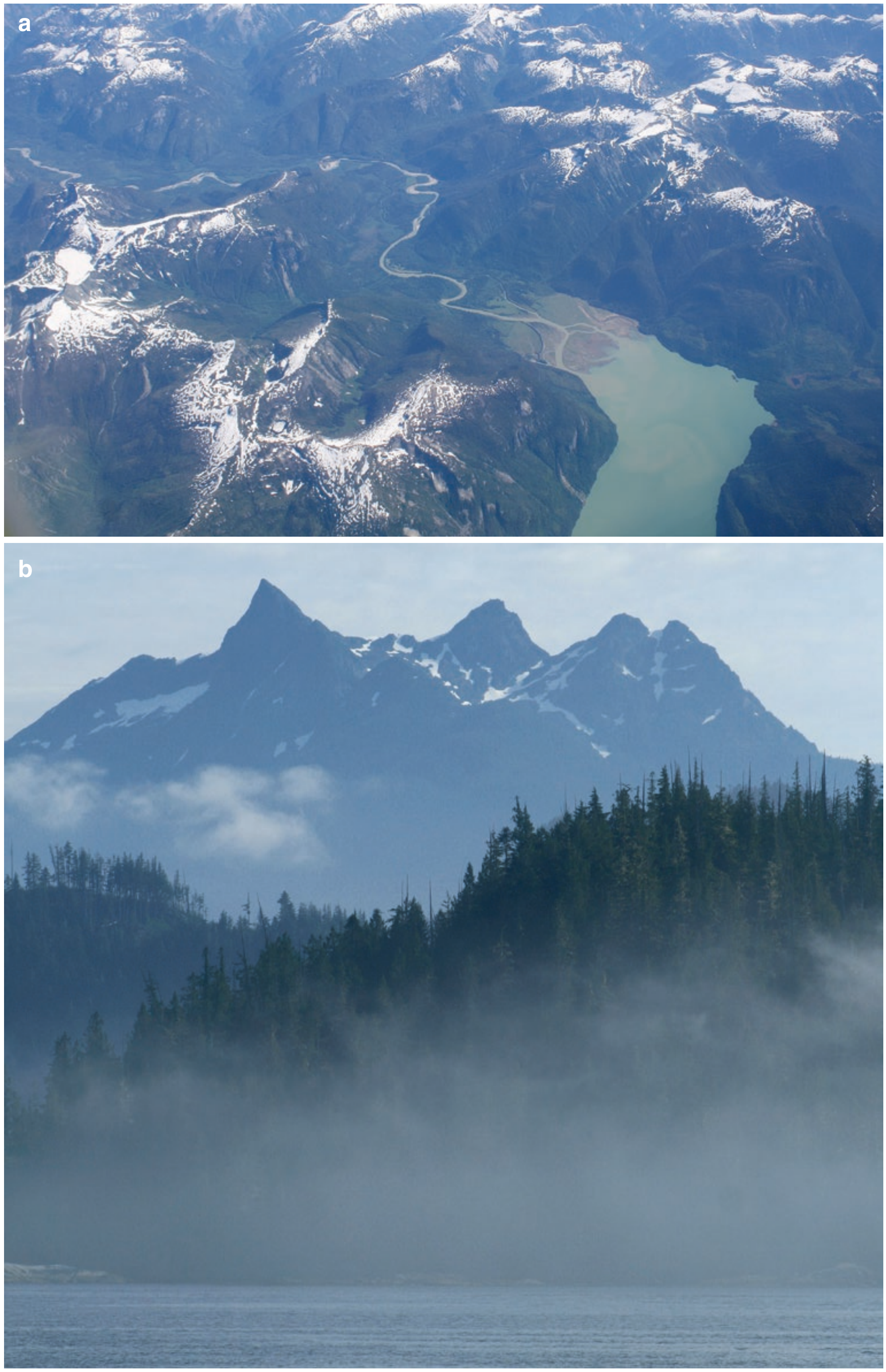

Fig. 1.8 Features of Coast Mountains, British Columbia. (**a**) Fjord penetrates deeply into tall, glaciated peaks composed of Coast Plutonic complex. (**b**) Coast Mountains viewed from Inner Passage south of Prince Rupert

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

Fig. 1.10 Features of Canadian Rockies from the air. (**a**) Folded and thrust-faulted ridges in NE British Columbia. (**b**) Glaciated ridges composed of Lower Paleozoic sedimentary rocks; note bedding

Fig. 1.11 Features of Olympic Mountains. View is from Olympic core, composed of accreted seamounts and other oceanic materials, towards Cascades with Mt. Rainer in background

Fig. 1.12 Features of Cascades and Columbia Plateau. (**a**) Mt. Rainier, a dormant late Cenozoic volcano mantled with alpine glaciers. (**b**) Columbia Plateau SW of Portland in the Oregon Wine Country. The dissected plateau is composed of thousands of feet of lava flows, mostly basalt

Fig. 1.12 (continued)

Fig. 1.13 Features of the Northern Rocky Mountains. The high peak is composed of Precambrian sedimentary rocks thrust over softer Cretaceous shales in the valley, Glacier National Park, Montana

Fig. 1.14 Features of the Central and Southern Rocky Mountains. (**a**) Archean gneisses comprise the iconic peaks of the Teton Mountains in W Wyoming. (**b**) Proterozoic quartzite and schist comprise the ragged peaks of the Needles Range, San Juan Mountains, SW Colorado

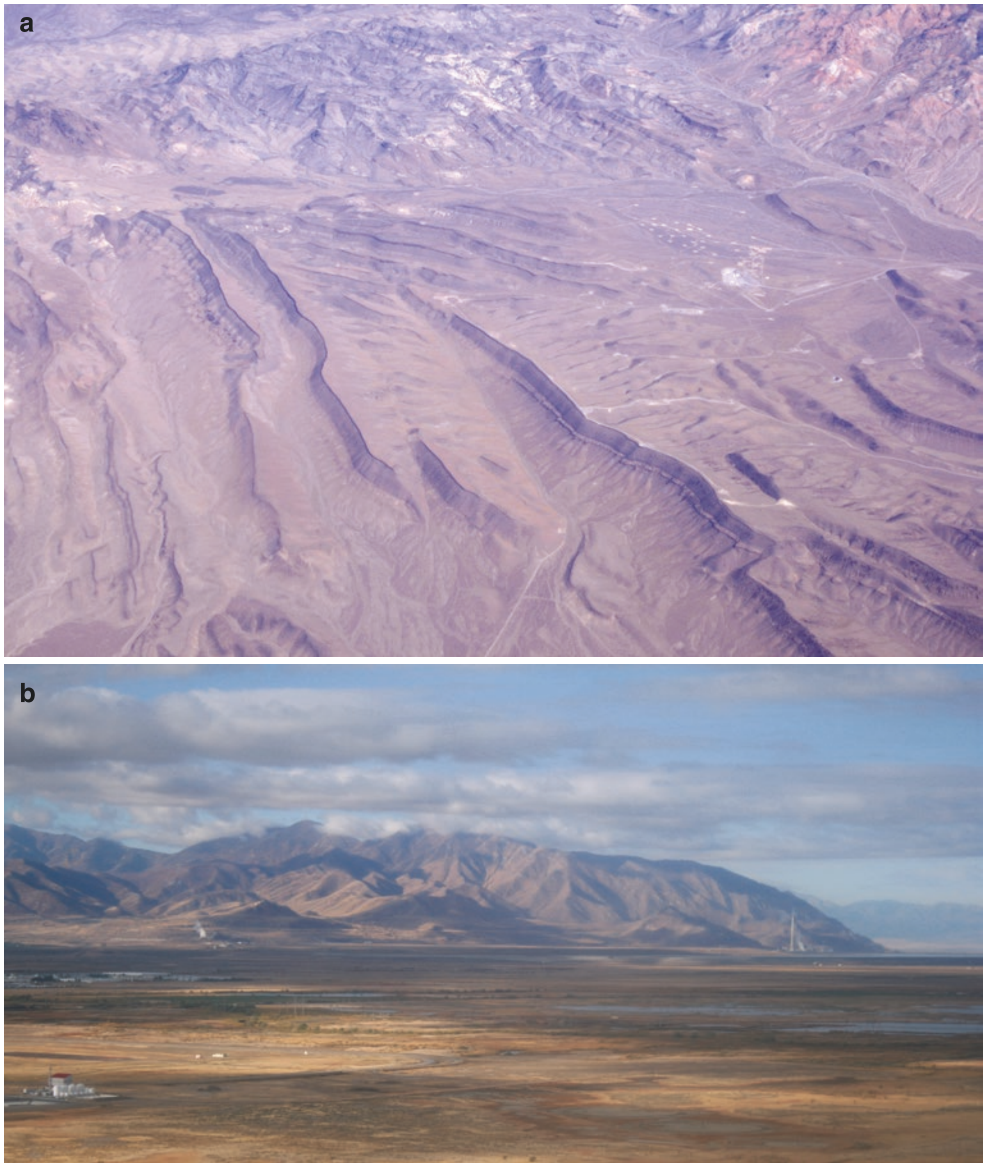

Fig. 1.15 Features of the Basin and Range (B and R), one of the largest and most diverse portions of the Cordillera. The following six photos emphasize this diversity. (**a**) Youngest B and R is located near boundaries of Nevada, Idaho, and Oregon; faults cut Cenozoic sediments and volcanics. (**b**) Oquirrh Range SW of Salt Lake City is part of faulted Sevier thrust belt – thousands of meters of Pennsylvanian and Permian rocks are thrust eastward over the craton. The thrust belt was then cut by normal B and R faults. (**c**) Hoover Dam on the Colorado River near Las Vegas lies in a subsiding graben structure known as the Colorado River Trough – thousands of meters of Miocene and Pliocene sediments and volcanics filled the trough. (**d**) Papago Buttes and the Phoenix Mountains lie within the oldest portion of the B and R around Phoenix. The buttes consist of middle Cenozoic sandstone and conglomerate derived from early B and R block faulting. The Phoenix Mountains expose Proterozoic schists and granites. The well-named Camelback Mountain forms the right skyline – the Camel Head exposes the same strata as the buttes in the foreground. (**e**) The Tonto Basin east of Phoenix lies within the Arizona Transition Zone, an area structurally transitional between the Colorado Plateau and Basin and Range. Oligocene and Miocene gypsiferous sandstone and mudstone, thousands of meters thick, lie within the basin. Proterozoic quartzites in the Mazatzal Mountains, type area for the Mazatzal orogen, form the skyline. (**f**) The Bradshaw Mountains form a large block of Proterozoic rocks in the central Arizona Transition Zone. This is part of the type area for the Yavapai orogen, Yavapai County, Arizona

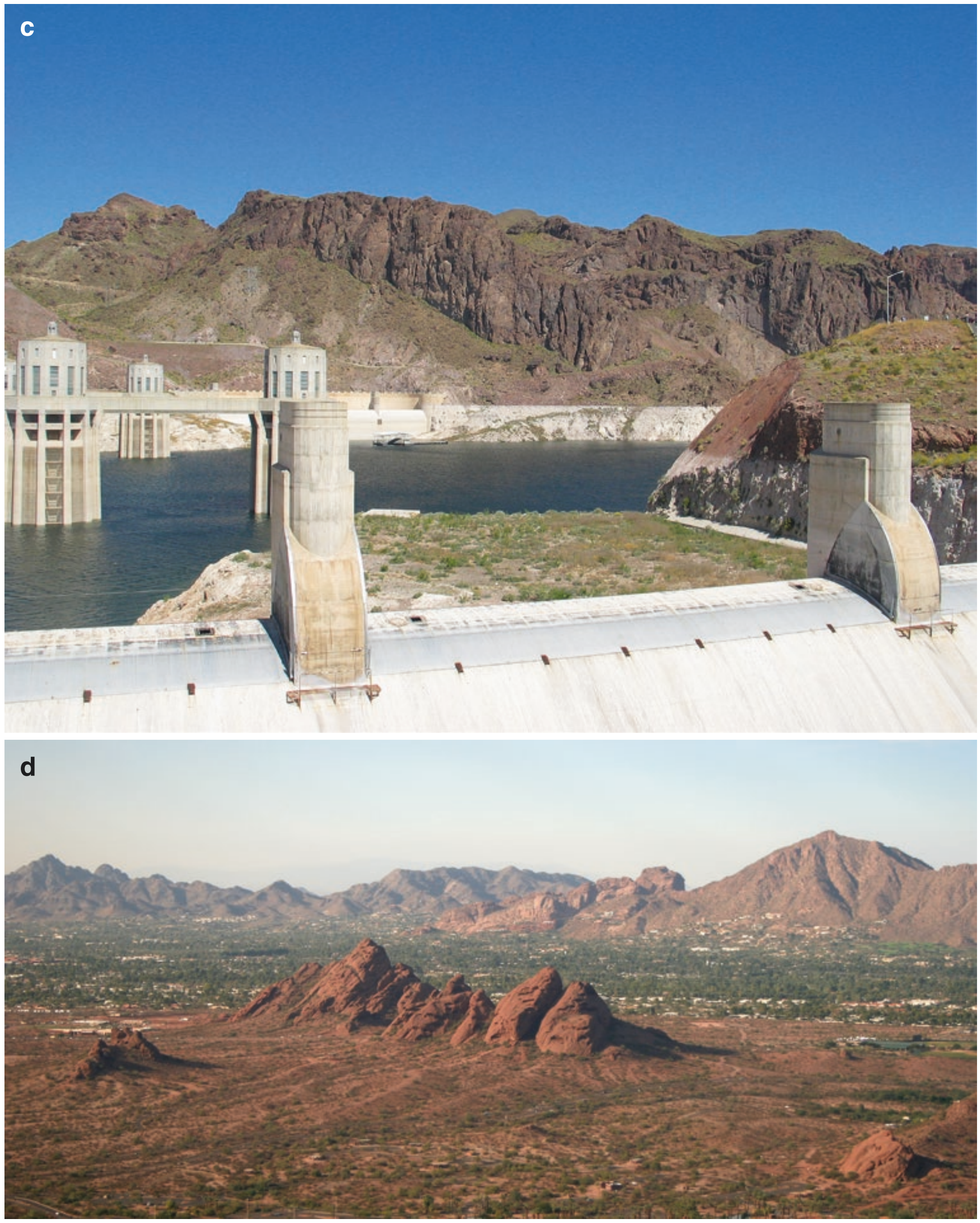

Fig. 1.15 (continued)

Fig. 1.15 (continued)

Fig. 1.16 Features of the batholitic belts of the Cordillera. Immense Mesozoic plutons (batholiths) comprise mostly granite and related rocks that formed during the subduction of the Farallon Plate beneath North America. (**a**) The San Jacinto and Santa Rosa Mountains near Palm Springs, California mark the northern flank of the Peninsular Ranges; Mesozoic granite intruded Precambrian gneiss and schist. (**b**) Large granite outcrop in Peninsular Range, Baja California, Mexico. (**c**) Peninsular Range east of San Diego with Coachella Valley (Salton Trough) in background. The San Bernardino Mountains (Transverse Range) form the skyline in the clouds and the San Andreas Fault runs through the valley (*upper left* to *right-center*). (**d**) Half Dome, Yosemite National Park, exposes massive plutons in the Sierra Nevada Batholith

Fig. 1.16 (continued)

Fig. 1.16 (continued)

Fig. 1.17 Features along the San Andreas Fault. View westward across Carizzo Plain and Soda Lake. Fault runs parallel to photo through the dry lakebed; rocks of Salinia on Pacific Plate form mountains in background

Fig. 1.18 Features of Coast Range, Oregon and California. (**a**) SW Oregon coast near Cape Sebastian exposes rocks equivalent to Franciscan rocks in California. (**b**) Volcanic rocks of accreted terrane Siletzia near Canon Beach, Oregon. (**c**) Big Sur, one of the most rugged coastlines in California, is held up by trench and accretionary prism deposits of the Franciscan melange. (**d**) Morro Rock at Morro Bay, California, the westernmost stock (small pluton) of a dozen or so that run NW-SE through western San Luis Obispo County. The Oligocene plutons formed beneath long-eroded volcanoes. (**e**) Quintessential California shoreline with dunes in foreground and iconic turquoise lifeguard station and pier at Pismo Beach. Mountains across San Luis Bay are part of Nacimiento Terrane. (**f**) Eocene Torrey Sandstone and Delmar Formation, Swami's Beach, Encinitas, California. Eocene rocks of San Diego County provide much information on early Cenozoic history of western Cordillera

Fig. 1.18 (continued)

Fig. 1.18 (continued)

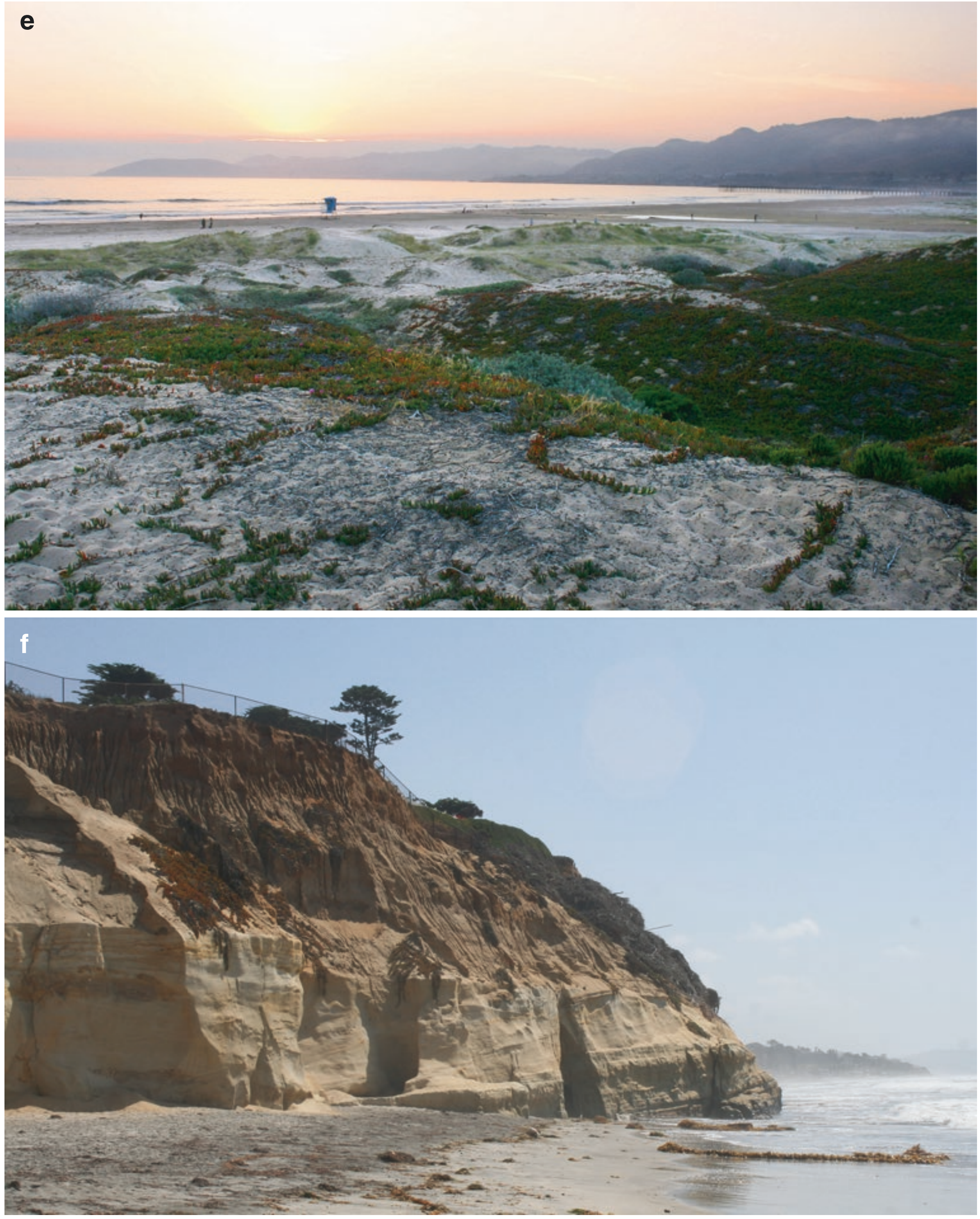

Fig. 1.19 Features of Sea of Cortez. Northern Sea of Cortez (Gulf of California) at Rocky Point, Sonora, Mexico; Mountains of Peninsular Range in background across one of the youngest oceans in the world

Fig. 1.20 Features of the Colorado Plateau. The Colorado Plateau is a convenient tectonic benchmark with which to compare tectonic displacements in the Cordilleran region to the west. Other than a slight Cenozoic rotation, the Plateau has remained fixed on the North American craton; all landscapes to the west and south of it have been tectonically displaced tens to thousands of kilometers. The following photographs record some of the salient features of the Plateau. (**a**) Waterpocket Fold (a monocline) exposes Triassic and Jurassic sedimentary rocks in Capitol Reef National Park, Utah; volcanic-capped High Plateaus in background. (**b**) Flank of Henry Basin, eastern Capitol Reef NP, with Upper Jurassic and Cretaceous rocks forming the landscape; laccoliths of Henry Mountains in background. (**c**) Henry Mountains, the global "type" laccolith showing bowed Jurassic and Cretaceous rocks that were tilted by the Eocene-Oligocene intrusion. (**d**) Arial view of Grand Canyon, Arizona, the quintessential Colorado Plateau landscape. (**e**) Bowknot Bend on the Green River in Canyonlands National Park, Utah; a classic view of the results of rapid late Cenozoic canyon cutting. (**f**) Mogollon Rim ramparts at the southern margin of the Colorado Plateau near Sedona, Arizona. The cliffs, 1,000 m high, are composed of Permian sedimentary rocks

Fig. 1.20 (continued)

Fig. 1.20 (continued)

Fig. 1.20 (continued)

Fig. 1.21 Features of Sonoran and Mojave (Mohave in Arizona) Deserts. Both regions have been tectonically extended more than twice their original extent. (**a**) Providence Mountains, Mojave Desert, SE California; dipping Paleozoic sedimentary rocks form most of the mountains in this scene; massive Mississippian limestone forms the most prominent cliff. (**b**) West-facing ramparts comprised of Early Miocene rhyolite welded volcanic tuffs, Superstition Mountains near Mesa, Arizona. The iconic saguaro cactus is the indicator plant for the Sonoran Desert. (**c**) Mesozoic volcanic flows, tuffs, and sediments form this part of Organ Pipe National Monument, Arizona. The cactus in the foreground is the parks' namesake with a forest of saguaros behind

Fig. 1.21 (continued)

Fig. 1.22 Features of Transverse Ranges, Southern California. The Transverse Ranges, one of two major E-W mountain ranges in North America, mark the collision between the Peninsular Range and rotated continental blocks on the Pacific Plate with the North American Plate. The San Bernardino and related ranges are on the North American Plate and the Santa Rosa, San Jacinto, San Gabriel, Santa Monica, and Santa Ynez mountains and the northern Channel Islands are on the Pacific Plate. Total length of ranges is over 400 km. The ranges were dramatically elevated in the Pliocene-Pleistocene (Pasadenan orogen). (**a**) Anacapa Island, the smallest of the northern Channel Islands, exposes Miocene volcanic rocks. (**b**) Point Mugu is the western margin of the Santa Monica Mountains. Miocene sedimentary rocks and interbedded volcanics comprise the point. (**c**) The Santa Ynez Mountains expose steeply tilted Cretaceous and Cenozoic rocks along the entire length of the Santa Barbara coast. These rocks were rotated over 90° counterclockwise (CCW) and transported several hundred kms north during the last 15 million years. (**d**) The San Gabriel Mountains were captured by the Pacific Plate from a location SW of present-day Yuma, Arizona and moved NW along the San Andreas Fault to the north edge of Pasadena. Precambrian rocks in the range were ripped off the Laurentian craton. Exposed across the range is one of the most divers suites of rocks in North America representing the craton, Mesozoic arc, Franciscan subduction zone, and Cenozoic sedimentary basins

Fig. 1.22 (continued)

Fig. 1.22 (continued)

Principles

2

This chapter will present a brief overview of geologic principles germane to the geologic history of the Cordilleran region. Given the numerous books and websites that cover geologic principles, terminology, and processes, we keep this overview as brief as possible and refer the interested reader to sources that expand on these topics. The references at the end of this book provide a list of sources used to compile the text, maps, and other figures. They also provide additional information to the interested reader, some highly technical and some not so much.

2.1 Terranes

The fundamentals of terranes and terrane analysis developed out of studies of the North American Cordillera in the 1970s and have expanded to most orogenic regions on Earth. The number of terranes in the Cordilleran region is large and varies depending on the nature of the study that delineates the various terranes. By 1990 hundreds of terranes had been defined but more recent studies have tended to group terranes, realizing that recognizing new terranes in every new study was becoming counterproductive. Another problem was that a given terrane was given a different name in subsequent studies, further muddying the pot. The terranes tracked in this book are shown in Fig. 2.1 (see also Table 1.2). For the most part, these are terrane names widely used in the recent geologic literature.

The investigation of a suspect or exotic terrane involves the use of many types of geologic data. Fossils for instance, provide information about the environments in which rocks on a terrane were deposited and then be compared with those on adjacent terranes or continents. For example, in the 1960s and 1970s, paleontologists working with fossils found on Vancouver Island, British Columbia determined that the Permian and Triassic-age fossils there were distinctly different from those on the nearby North American mainland. This led to the idea that rocks on Vancouver Island were formed in a much different place and were thus labeled as suspect or exotic. They are now recognized as belonging to a well-known terrane, *Wrangellia*, first named for exposures in the Wrangell Mountains in southeast Alaska. The fossils were preserved in rocks that formed hundreds to several thousand kms offshore from North America.

In addition, *paleomagnetic* data (evidence for the ancient position of the north magnetic pole when the rocks formed) can be used to determine the latitude of an area at any given time. In the example above, the Triassic rocks of Vancouver Island (Wrangellia) were deposited much closer to the equator than the adjacent rocks they accreted to. This in turn is used in conjunction with differences observed in the geologic strata and in the Wrangellia example, Triassic limestone was deposited on an oceanic plateau and contrasts sharply with rocks of the same age south in Washington (the structure of these rocks has sharp contrasts as well).

Additional tools may be used to confirm that a given region is part of a suspect terrane. One such method involves the analysis of the mineral *zircon* ($ZiSiO_4$), common in granite and some volcanic rocks. Zircon crystals reveal the crystallization age of a granite rock or the eruptive age of a volcanic rock or ash layer. When zircon grains are eroded from their host rock, they are said to be *detrital* zircons (from the Latin *detritus,* meaning to wear away), and as these detrital zircons are quite durable and very resistant to chemical weathering and physical abrasion, they are often reworked through numerous depositional and erosional cycles. Although this reduces their effectiveness in dating the layered rocks in which they are found, the age of the zircon is always the <u>*same age or older*</u> than the layered rock that holds it (Fig. 2.2). Even if the zircon is reworked many times, its

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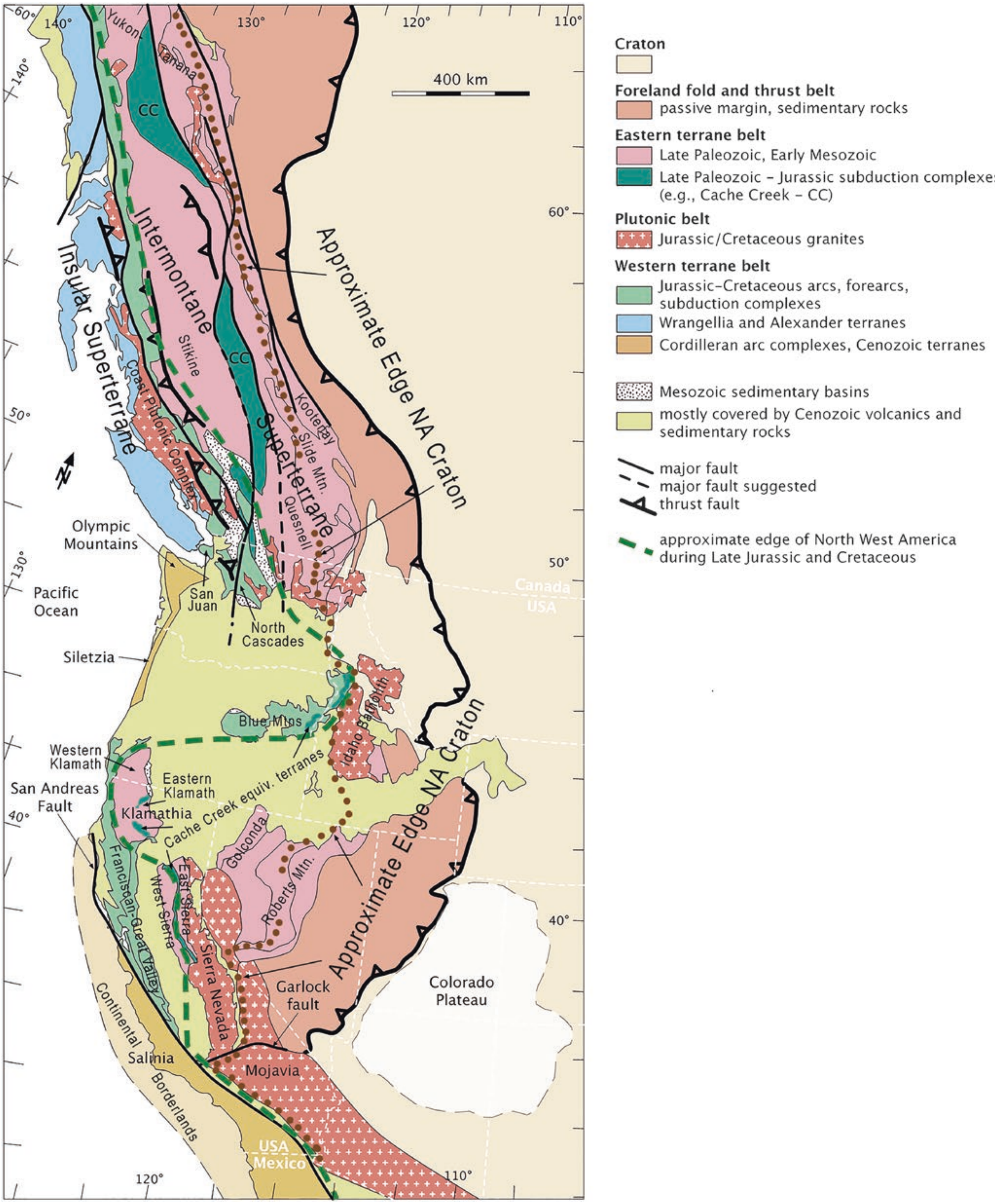


Fig. 2.1 Map of Cordilleran region showing distribution of terranes. Note large areas covered by Cenozoic volcanic and sedimentary rocks; these areas mask complex terrane relations and complicate terrane correlation and interpretation. Although Salinia was juxtaposed by the San Andreas Fault in the Late Cenozoic, it is clearly part of the Sierra Nevada-Mojavia terranes as indicated by rock type and internal structure (Modified from Frisch et al. 2011)

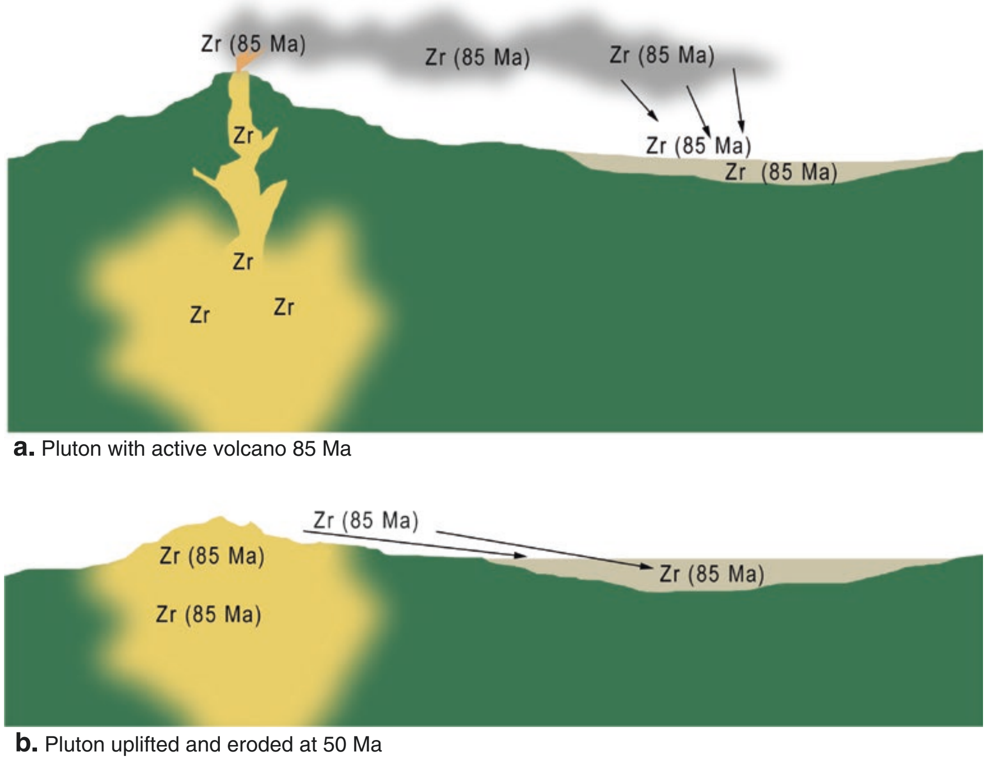


Fig. 2.2 Simple cross sections showing relations between zircon source and age of sediments. (**a**) Zircons in pluton incorporated into volcanics that cool at 85 Ma as they exit volcano. Zircons in volcanic ash settle into sedimentary basin. Age of sediment is the same as that of the incorporated volcanic ash. Zircons can be used to date age of sediments. (**b**) Millions of years later, pluton that cooled at 85 Ma is exposed at surface. Zircons in sediment reflect age of pluton, not the age of the sediments. In this hypothetical example, the sediments formed at 50 Ma but contain zircons that yield age dates of 85 Ma, the age of the pluton. In **a**, the zircon ages are the same as the age of the sediments in which they are incorporated – the zircons reflect the age; in **b**, the age of the sediments are younger than the age of the included zircons. The zircons in **a** will be mostly angular with little evidence of reworking; the zircons in **b** will be rounded and worn

age of crystallization is locked into the crystal and this can be useful in terrane analysis (Fig. 2.3). An example is that igneous rocks in North America that date between 700 and 600 Ma are extremely rare, therefore, a suspect terrane that contains detrital zircons of these ages is unlikely to have been formed in North America.

An obvious question might be, "Where do terranes come from?" The answer is that they can be classified on their inferred origin (Figs. 2.4 and 2.5): (1) *Continental fragments* (or blocks) form when crust is rifted from a larger continent. Modern examples from small to large include the Seychelle Islands block (India), Madagascar (Africa), and Greenland (North America); (2) *Volcanic arcs* commonly form exotic terranes and these are classified as *continental* (i.e. Andes; Andean-type arcs), *fringing continental* (i.e. Japan arc or the Aleutian arc), and oceanic (i.e. Marianas arc). These can be *peri-Continental* (having an original connection to the continent in which they later accreted, such as the Mesozoic-age Quesnell arc of British Columbia), or long-travelled terranes such as the Paleozoic-age arcs now found in the Sierra Nevada and Klamath Mountains of California; (3) *Oceanic plateaus* – thick portions of oceanic crust formed as seamounts from hotspots. Numerous such features are present today in the Pacific and Indian Oceans (i.e. the Ontag-Java Plateau currently colliding with northeast Australia). Modern hotspots include the Hawaiian Island chain and Iceland; (4) *Abandoned mid-ocean ridges* – formed when an active ridge "jumps" to a new location, these are thicker than normal ocean crust but thinner than oceanic plateaus. Several ridges or rises in the modern oceans are thought to be abandoned ridges. A part of the modern Shatsky Rise in the northwest Pacific Ocean is believed to have collided with and subducted below western North America in the Late Cretaceous generating, among other events, the uplift of the Colorado Plateau and the Rocky Mountains. Figure 2.6 illustrates some of the complexities associated with terrane analysis as they approach and dock with a larger continent.

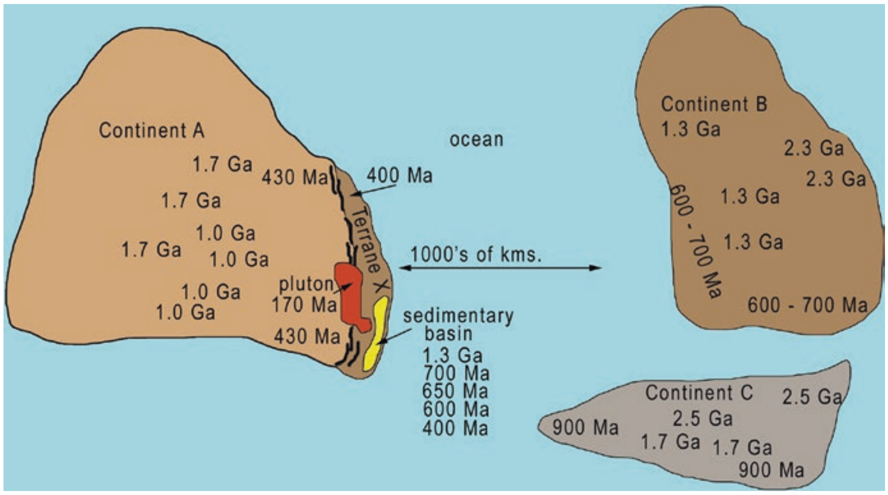
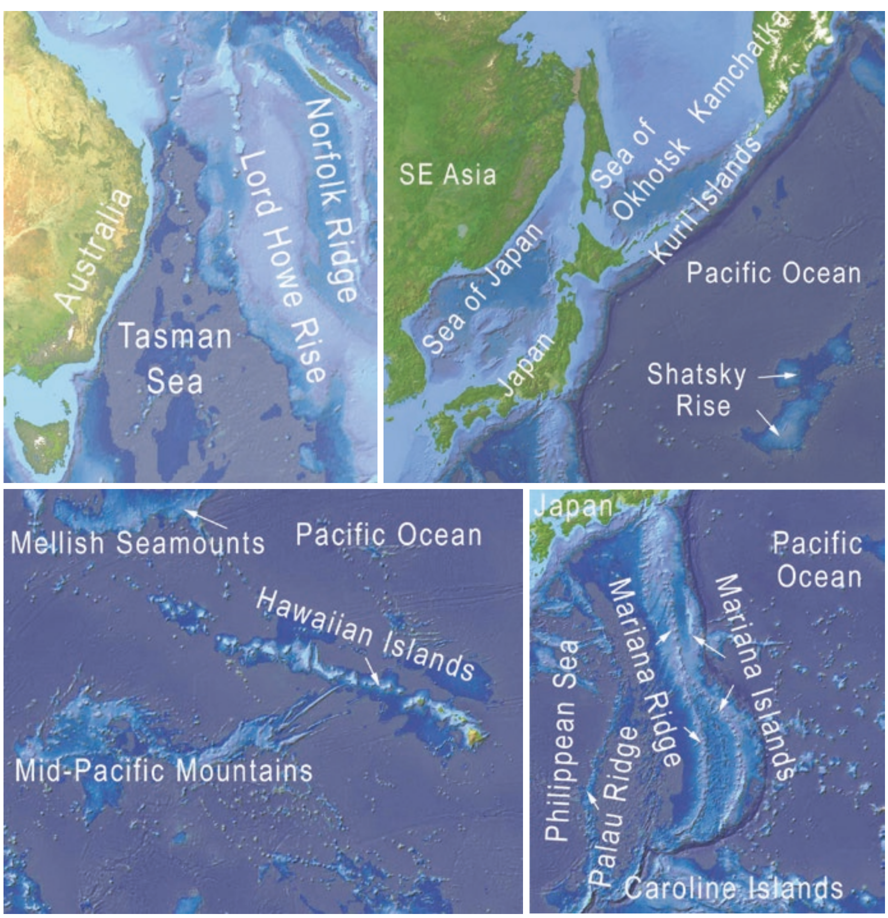


Fig. 2.3 Simple map showing several continents, one with accreted terrane. The age dates given for continents (**a–c**) are from granites on the respective continents (*Ma* millions of years ago, *Ga* billions of years ago). Terrane X is an arc with an age of 400 Ma with a sedimentary basin that contains detrital zircons of the ages shown. The heavy black lines between Continent A and Terrane X mark folded and faulted rocks, an orogen. A granite pluton with an age of 170 Ma cuts the orogenic belt and both the terrane and continent. Before detrital zircon (DZ) data was available, geologists would have debated whether Terrane X was exotic to Continent A or an arc adjacent to the continent. However, the DZ dates in sedimentary rocks deposited on the arc indicate that the sediments in the basin did not come from Continent A. Of the continents shown, Continent B provides the best fit for the source of the zircon grains. A strong hypothesis for the history of Terrane X could go something like this: the arc formed on or adjacent to Continent B at 400 Ma; after this time, the arc separated from B – the sedimentary basin may be rift-related with grains derived from B as well as the arc. The terrane rifted and drifted and accreted to A. The orogen between the two formed during accretion. The sedimentary basin was not active at this time as no grains derived from A are present. The pluton formed after terrane accretion as it cross cuts the orogenic boundary. Such a pluton is said to be a *stitching pluton*. The sedimentary basin was not active at this time as no 170 Ma grains are present. Based on this data, the terrane accreted after 400 Ma (likely well after this) and before 170 Ma; this interval is also the range of sedimentation in the sedimentary basin



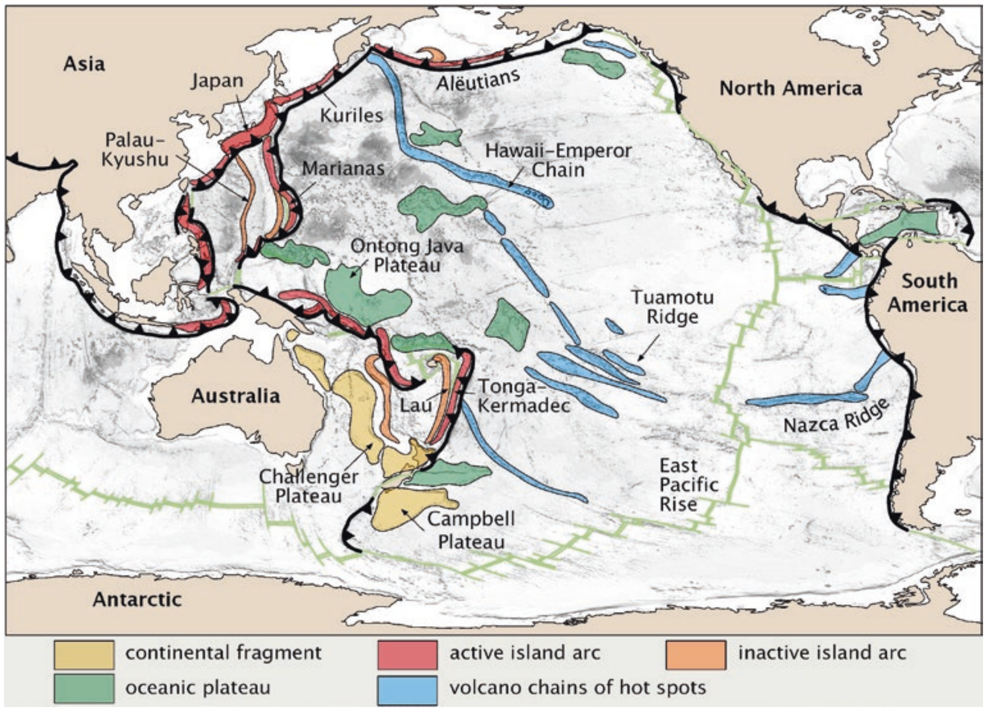


Fig. 2.5 Generalized map of various features within Pacific Ocean basin. The colored areas represent various tectonic features that will eventually be accreted into subduction zones and adjacent continents. Many of the accreted terranes in the Cordilleran region had origins similar to those shown on the map. Examples of each type in Cordilleran history are: *continental fragment* – Alexander terrane (part of greater Wrangellia) in Jurassic; *oceanic plateau* – Wrangellia (part of greater Wrangellia) in Jurassic; *active island arc* – antler orogen in Dev-Miss; *inactive island arc* – Jurassic accretion during Nevadan orogen; *volcanic-hot spots* – accretion of Olympic Mountains and Siletzia in Early Cenozoic (Modified from Frisch et al. 2011)

Fig. 2.4 Maps of Central and Western Pacific Ocean showing examples of present features that may become terranes in the geologic future. The Lord Howe Rise and Norfolk Ridge are continental fragments rifted from Australia when the Tasman Sea opened; the Kuril Islands and Japan are arcs separated from Asia by back-arc oceans (Sea of Japan and Sea of Okhotsk); Shatsky Rise is a Cretaceous mid-ocean ridge (now extinct) – the other half of this rise is believed to be the thickened ocean slab that subducted under California in the Late Cretaceous; the Mellish Seamounts, Mid-Pacific Mountains, and Hawaiian Islands are oceanic plateaus formed by hot spots – the Big Island of Hawaii is located over a major hot spot; the Mariana Islands are an oceanic volcanic arc and the Mariana Ridge is the back-arc ridge-spreading center; Palau Ridge is an extinct ridge; the Caroline Islands are a hot-spot-generated oceanic plateau with various miscellaneous components. These various ridges and rises are potential future terranes and the seas between them could form potential ophiolites

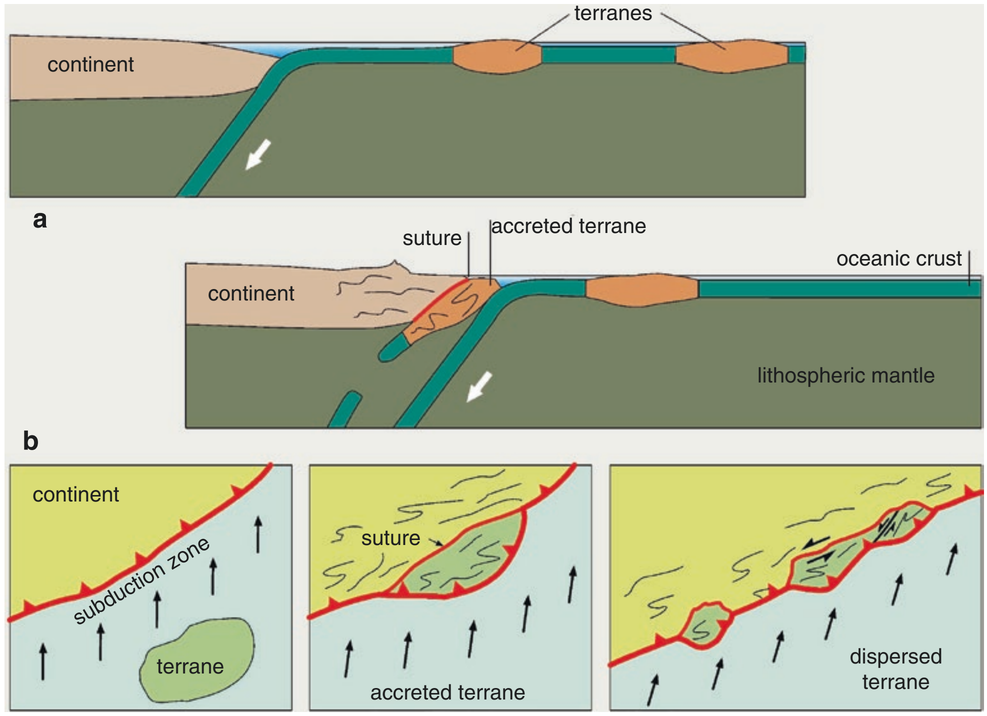


Fig. 2.6 Cross sections and map views showing possible sequence of events during terrane accretion. (**a**) Cross sections – two terranes approach continent; first terrane docks and subduction "jumps" outboard as second terrane approaches. (**b**) Map views – Terrane approaches and docks along continent; subduction "jumps" outboard; oblique convergence of ocean plate creates transform faults that disperse terrane in two or more pieces (Modified from Frisch et al. 2011)

2.2 Sediments and Sedimentary Processes (Fig. 2.7)

Continental environments are those found on land including rivers, lakes, eolian settings, and alluvial fans. These are composed mostly of quartz-rich sandstone and mudstone or shale. The most common environments represented in Cordilleran geologic history are river deposits, eolian and related settings. They are abundant across the Colorado Plateau and Rocky Mountains regions but tend to be relatively uncommon elsewhere in the western Cordillera.

Shoreline environments such as beaches, barrier bars, and tidal flats consist mostly of sandstone and mudstone or shale. These deposits are valuable indicators of ancient shorelines and are especially common along the margins of the Cretaceous Western Interior Seaway and in Eocene rocks along the Pacific Coast of the United States.

Offshore marine environments consist of mud and minor amounts of sand deposited beyond the shoreline, below wave base on the marine shelf, but above bathyal and abyssal depths. Portions of shelves can be affected by currents and storms and are subject to reworking by burrowing of bottom-dwelling organisms (known as bioturbation).

Deep marine environments such as slope-rise, submarine canyon and fan, abyssal plain, and trench yield a wide range of deposits depending on the dominant processes that affect a given area (Fig. 2.8). Turbidity flow deposits (*turbidites*) and related deep-water slump deposits are commonly associated with submarine canyons and fans and consist of rhythmically bedded sand, mud, or gravel in which individual beds can extend for great distances. Turbidites form some of the most distinctive deepwater deposits and are common across western North America. Channelized sandstones and interbedded conglomerates characterize submarine canyon and fan-head deposits that typically become finer-grained away from the canyons apex into fan-shaped (in map view) turbidites. *Abyssal deposits* form in deep water (thousands of meters deep) and consist of the finest mud and clay. They may contain thin sandstone beds adjacent to deep sea fans and turbidites. *Trench deposits* vary depending on the type of sediment delivered to the trench and the tectonic processes within it. Because trenches are located at convergent plate boundaries (typically subduction zones), the setting is very complex and the deposits tend to be mixed, hence the French term, *mélange* meaning mixture). These mélange deposits can include material scraped off the subducting plate, submarine slumps derived from the steep trench walls, and submarine fan deposits. Volcanics derived from an arc are typically added to the mix. Some mélange deposits are partly subducted and metamorphosed under great pressures to form blue-green rocks called *blue schists*. These metamorphic rocks can be tectonically mixed with non-metamorphosed sediments and volcanics. Mélanges are locally common where trench deposits are preserved, but not all trench deposits form mélanges.

Volcanic sediments can be mixed with any of the above sedimentary rocks, especially in the vicinity of volcanic arcs. The volcanic material can be ash, volcanic grains, and inter-bedded volcanic flows; volcanic material can be fresh

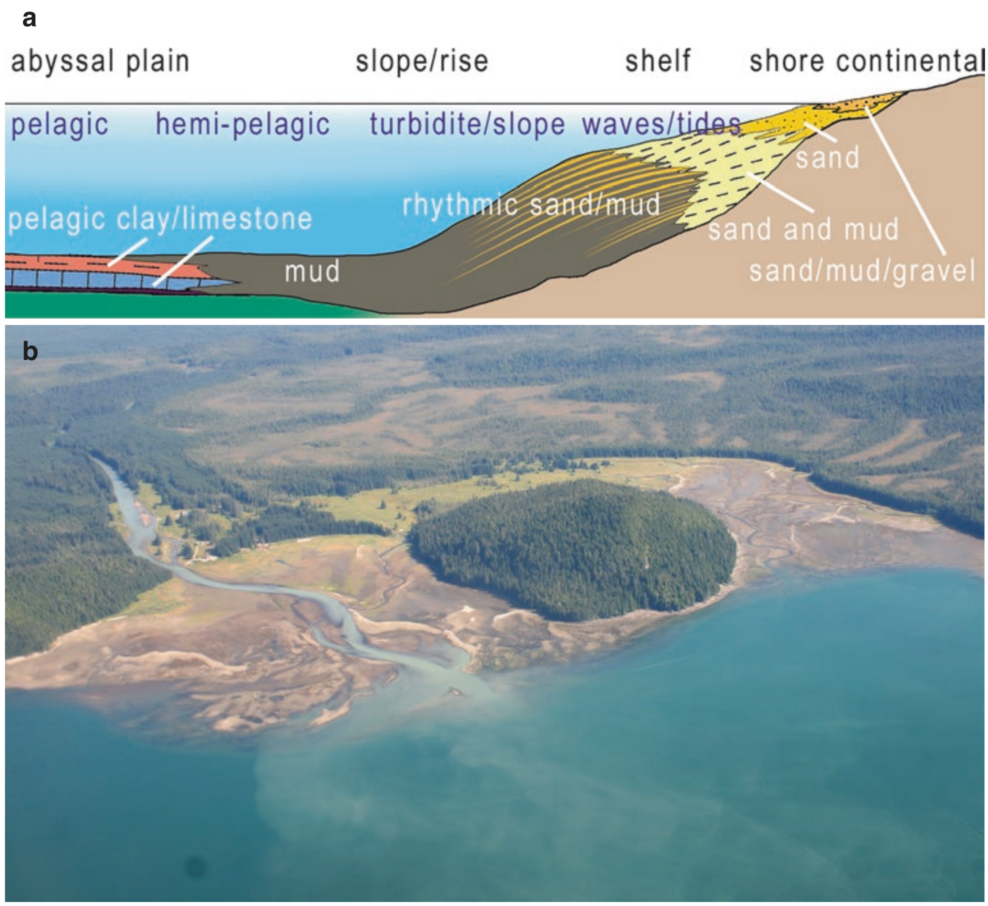


Fig. 2.7 (**a**) Marine depositional settings widely represented within the Cordilleran region. In areas with adjacent volcanic activity, interbedded volcanic flows and volcanic dikes and sills are common and sands and gravels contain abundant volcanic grains. In regions with minor terrigenous input and clear, warm water, carbonate rocks (limestone and dolomite) are common (Modified from Frisch et al. 2011) (**b**) Shoreline along the British Columbia Coast. The fluvial system discharges onto a small coastal plain building a delta. Note the plumes of sediment that expand into offshore settings to settle as mud on the sea bottom. If submarine slopes are steep enough, turbidity flows may be generated. This type of depositional setting was common across the Cordilleran region throughout much of its geologic history

(directly derived from volcano) or reworked from existing volcanic rock. Many sedimentary rocks of the Cordilleran region have small to significant percentages of volcanic material. Presence or absence of volcanic material can indicate how close a sedimentary deposit was to an active volcanic arc.

Clastic rocks are any sediment derived from fragments of other rocks or minerals (*clast* means fragments or broken pieces) and the plural *clasts* simply refers to the individual grains in a clastic rock. Examples of clastic rocks, from coarse- to fine-grained are conglomerate, breccia, sandstone, siltstone, shale, and claystone. The term *clastic rock* refers to sedimentary rocks composed of sand, mud, or gravel – clastic material derived from land – synonymous with *terrigenous* (of the land). Most clastic rocks were deposited near land; exceptions include abyssal clastics that may be sourced by volcanic ash or blowing dust. Turbidity currents can also deliver clastic material to distal, deeper marine environments.

Carbonate deposits consist of *limestone* (calcium carbonate) and *dolomite* (calcium and magnesium carbonate). The global ocean is saturated with dissolved calcium and magnesium so carbonate rocks form in many of the above mentioned marine settings. However, when abundant clastic material is present, carbonate deposition is precluded – carbonates tend to form most prolifically in areas where sand or mud is minimal. Limestone forms by the life-processes of algae or the remains of calcium carbonate secreting organisms that form shells, both larger animals as well as microscopic organisms. Broad, shallow marine shelves in sub-humid to arid environments (with a lack of nearby rivers) are some of the best settings for carbonate deposition and carbonate precipitation is enhanced in warm water. During the early and middle Paleozoic, ideal conditions for the deposition of carbonate occurred across much of central and western North America and vast carbonate deposits dominate the rock record. At times, the broad shelf extended from Kansas and Colorado westward to central Nevada.

Oceanic plateau deposits commonly consist of sediment and volcanic material deposited on these submarine plateaus. Because oceanic plateaus are build-ups on the ocean floor, they are areas of shallower water than the surrounding abyssal plains. If the water is warm and shallow, significant limestone deposits will form on the plateaus. Oceanic plateau limestone typically lacks any material derived from a continent; however, as plateaus approach continents, land-derived muds begin to appear interbedded in the rock record. The Triassic limestone of the Wrangellia terrane was likely formed atop such an oceanic plateau.

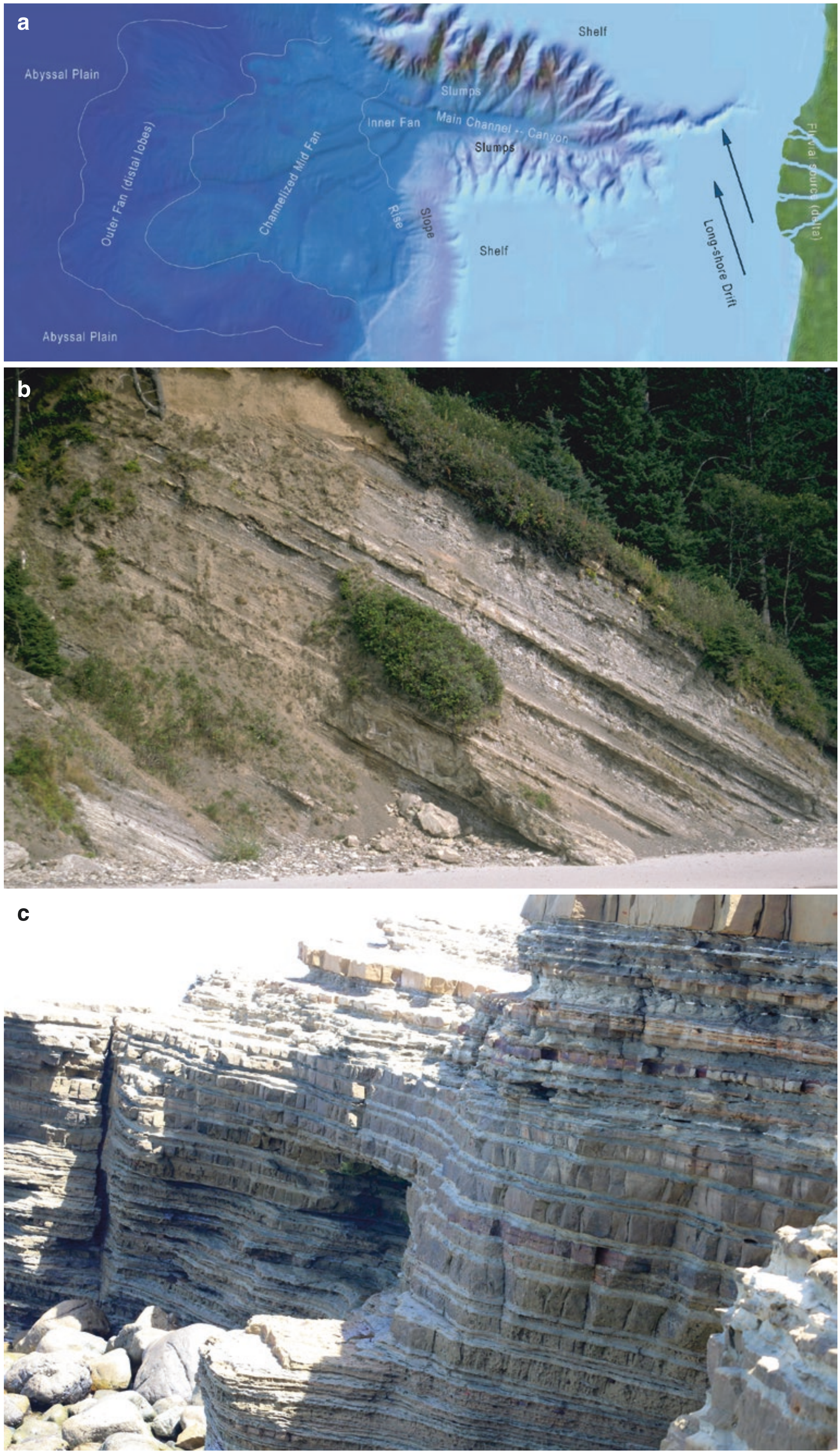


Fig. 2.8 (**a**) Map view of typical submarine fan, modified from digital map of modern fan. Sediment supplied by river systems enters submarine canyon; storms and/or earthquakes feed sediment down the canyon and onto the fan where the sediment radiates out from the inner fan. Grain size decreases distally across fan. Sediment type for given portions of fan as follows: slumps – chaotic masses of sediment deposited by gravity processes; main channel-channelized sand and gravel with abundant cut and fill structures, bedded to massive; inner fan – similar to channels but more sheet-like; grain size decreases distally; mid fan – sand-dominated turbidites locally cut by channels; outer fan – mud-dominated turbidites, channels rare; abyssal plain – fine turbidites that grade distally into muds and clays. All contacts gradational. Coarsest grain size in channel and on fan dependent on grain size supplied to canyon from river and shelf. (**b**) Eocene turbidite deposit near Canon Beach, Oregon. (**c**) Cretaceous turbidite deposit at Point Loma, San Diego; resistant ledges (6–10 cm) are sandstones that fine upwards into recessed mudstones

2.3 Igneous Rocks and Processes (Fig. 2.9)

Intrusive or plutonic rocks are formed when *magma* (molten rock) invades pre-existing rocks at depth, and then slowly cools and crystallizes to form minerals visible to the naked eye. *Plutons* are areas where these magmatic intrusions have occurred and the term refers both to the actively forming intrusion and the solidified granite rock found later in the crust. The most common igneous rocks are described below:

Granite is a light-colored plutonic rock composed mostly of the minerals feldspar and quartz (Fig. 2.9b). Large granite bodies

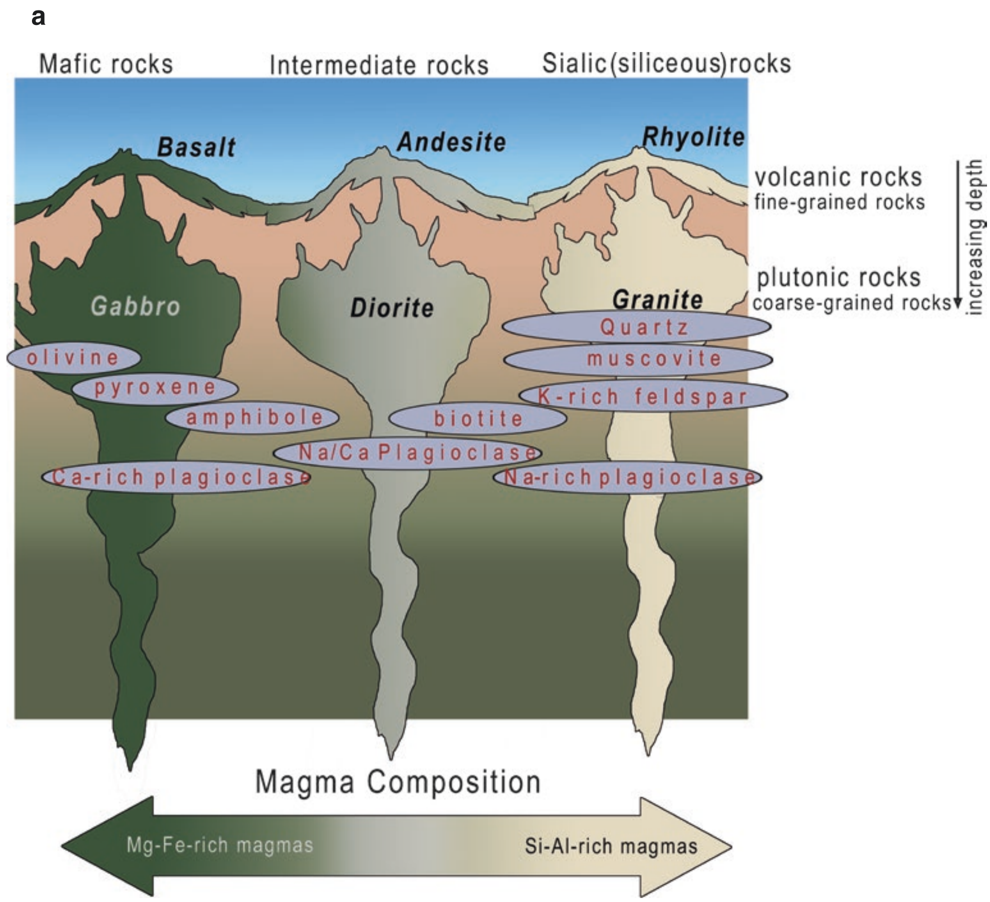
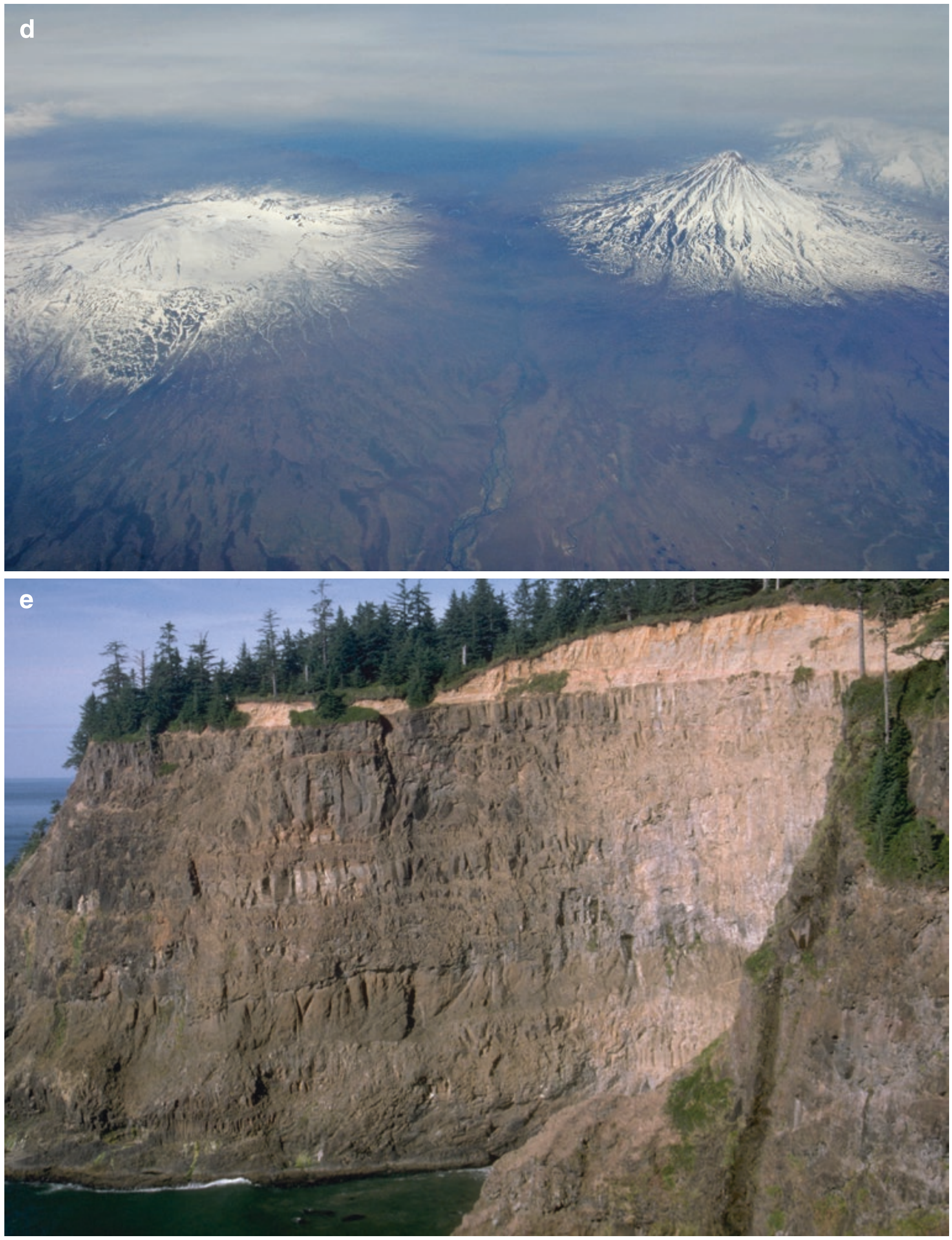


Fig. 2.9 Igneous rocks. (**a**) Diagram showing a simple classification of common igneous rocks. Magma compositions range from mafic (Mg/Fe-rich) on left to sialic (Si/Al-rich) on right. Grain size is controlled by whether magmas cool at depth – plutonic or intrusive igneous rocks – or at the surface – volcanic or extrusive igneous rocks. Classification is based on a combination of grain size (coarse vs. fine) and mineral composition, shown by ovals with mineral names. Examples: coarse-grained igneous rock composed of quartz, muscovite, K-rich feldspar, and Na-rich plagioclase is a granite; a fine-grained igneous rock composed of olivine, pyroxene, and Ca-rich plagioclase is a basalt. (**b**) Granite exposed north of Durango, Colorado – abundant orthoclase feldspar yields pinkish-orange color. (**c**) Dike composed of granite – thin white band is quartz vein, Inner Passage, British Columbia. (**d**) Volcanoes in Kamchatka arc – dominant composition is andesite. (**e**) Basaltic lava flows form cliffs carved by Pacific Ocean, Point Lookout, Oregon

Fig. 2.9 (continued)

Fig. 2.9 (continued)



are called *batholiths* (with a size greater than 250 km^2) and may mark the root of a volcanic arc such as the Sierra Nevada in California, the Peninsular Range batholith in Baja California, or the Coast Plutonic Complex in British Columbia and SE Alaska (Fig. 2.9c). Smaller granite bodies are called *stocks* (less than 250 km^2). *Diorite* and *gabbro* are igneous rocks that form dark-colored plutons composed of minerals such as hornblende, pyroxene, amphibole, olivine, and dark gray feldspars. Diorite is associated with some arcs; gabbro tends to form from melted oceanic rocks, although gabbroic bodies are important constituents of the Peninsular Ranges batholith.

Extrusive or volcanic igneous rocks (Fig. 2.9d) form when magma reaches the earth's surface and is called *lava*. In the extrusive environment minerals cool and crystallize quickly so they are mostly small and invisible to naked eye. Not all volcanic rocks originate from prominent volcanoes however, and some can flow for very long distances (Fig. 2.9e) from the linear *fissures* or *vents* from which they erupt. Ejected explosive components of volcanic eruptions form *ash* (mostly dust-size material) and *scoria* (pea-size fragments, also referred to as *cinders*). Ash deposits can settle over landscapes or oceans thousands of kms from their source. Extremely hot and concentrated ash will often fuse or weld together as it settles out of an eruption to form *welded tuff*. Volcanic rocks are abundant in the western Cordillera and this region contains some of the greatest concentrations of volcanic rocks on Earth. Put simply, 350 million years of subduction under the western margin of North America generated a huge volcanic pile!

Basalt is a dark-colored volcanic rock composed of pyroxene, olivine, and dark feldspars. Basalt forms in numerous geologic settings but is most common where the crust is stretched or extended to allow it to reach the surface directly from the mantle below (ocean crust is mostly composed of basalt and gabbro). Basalt is widespread throughout the Cordilleran region and curiously is the most common rock type on the planet, covering about 62 % of its surface, mostly on the world's ocean floors.

Andesite is a medium-colored gray volcanic rock composed of amphibole and gray feldspar. Andesite (named after the Andes Mountains, also a Cordilleran-type mountain range) is the most abundant volcanic rock within arc complexes. However, many large Cordilleran arc complexes such as the Sierra Nevada of California and the Coast Plutonic Complex of Canada have been uplifted such that their andesite volcanic carapaces have been eroded to expose the granite plutons below.

Rhyolite is a light gray, pinkish or pale red volcanic rock composed of light-colored feldspar and quartz. Rhyolite is common in volcanic arcs that are built on continents. Arc-related melting at the base of continental crust (largely composed of granite and related rocks) becomes enriched in quartz and feldspar as it rises through the crust, producing rhyolite as the resulting magma; as these magmas reach the surface, the viscous rhyolite tends to form domes in contrast to the widespread sheets of basaltic lava flows. When mixed with water, rhyolite magmas tend to generate very explosive volcanoes with much ash and scoria forming welded tuff. These ash beds can be rich in zircons, making them excellent candidates for radiometric dating. Ash beds found adjacent to or interbedded with fossil-bearing strata allows the fossils to be accurately dated. With thousands of fossil beds now dated, the modern geologic time scale is now replete with reliable, absolute ages.

2.4 Ophiolite

Ophiolite is not a specific rock type but rather a suite of rocks representing ocean crust that has been shoved up onto the margin of a continent. The process in which ophiolite forms is called *obduction*, which can be thought of as the inverse of subduction. Well-preserved ophiolites display a specific sequence of ocean crust from bottom to top and provide some of the best evidence for the composition and structure of ocean crust (otherwise difficult to sample). However, many ophiolites are greatly deformed as they are found between colliding continental plates or associated with faults at terrane boundaries. In either case, ophiolite represents ocean crust that was trapped between colliding blocks.

Ophiolites do not necessarily represent large ocean basins that closed between continents or terranes; indeed, small areas of ocean crust can form ophiolites. Examples include backarc extension between arcs and continents, and small ocean basins formed between continental blocks that are rifted apart relatively short distances. Subsequent closing of such ocean basins can preserve ophiolite sequences. It should be noted that whenever continents collide, or continents and arcs, or arcs collide with each other, that most of the ocean floor between the colliding blocks is subducted and therefore removed from the geologic record. Only a small portion is trapped as ophiolite and so these rocks are generally poor indicators of the original ocean width between colliding blocks.

2.5 Metamorphic Rocks

Metamorphic rocks (literally "changed form") are derived from any pre-existing rock through heat and/or pressure. These rocks are widely distributed throughout the Cordillera and the common processes and sequences of events associated with them include: (1) metamorphism caused by deep burial through crustal subsidence (heat and pressure); (2) intrusion of large igneous bodies such as batholiths where heat from the batholith metamorphoses the surrounding country rock; (3) subduction where rocks are carried downward and intense pressure and increased heating causes metamorphism; (4) orogenic processes (mountain building) where rocks are compressed, sheared, intruded by magmas, and/or deeply buried. All are generally followed by uplift, erosion and surface exposure. The first three types are typically more local in extent or unevenly distributed whereas the fourth is commonly of regional extent commonly extending for thousands of square kms. Figure 2.10 shows a simple classification of metamorphic rocks with several examples.

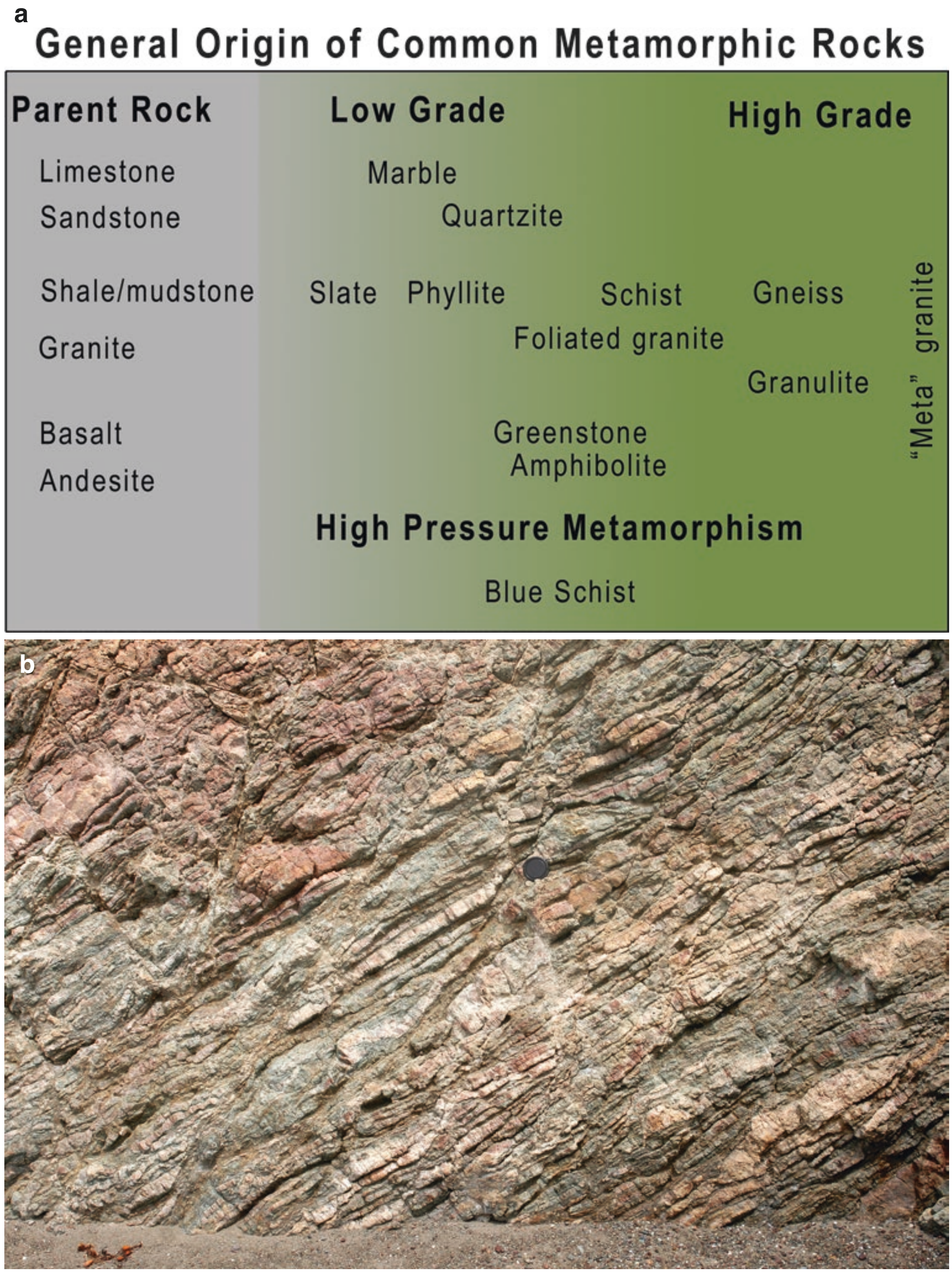


Fig. 2.10 Metamorphic rocks. (**a**) Chart showing common metamorphic rocks and their relations to parent rock and grade of metamorphism. If the parent rock consists of a dominant lithology, low to moderate grades of metamorphism produces the new rock to the right. High grade metamorphism results in more complex relations and commonly involves mixed lithologies of parent rock. High pressure metamorphism is common in subduction zones where parent rocks can be various mixes of sedimentary and volcanic rocks. (**b**) Schist in Franciscan assemblage, San Simeon, California. (**c**) Gneiss in San Gabriel Mountains, California; bands represent segregations of *light*- and *dark*-colored minerals. (**d**) Quartzite ridge in Mazatzal Mountains near Payson, Arizona

Fig. 2.10 (continued)

2.6 Cordilleran Margins

Cordilleran-type margins are active plate boundaries that are typified by protracted interaction between oceanic and continental plates. There are two classes of active plate boundaries: (1) *subduction zone* plate boundaries involve the subduction of oceanic plates beneath continental or other oceanic plates – they may or may not be accretionary in nature (Fig. 2.11); and (2) *transform boundaries* occur where two plates move laterally past each other (Fig. 2.12). As is the case with the modern North American Cordilleran margin, both margins commonly occur simultaneously lateral to each other (Fig. 2.13). Figure 2.14 displays a series of cross sections that show the enduring active plate boundary of western North America.

Figures 2.11, 2.12, 2.13, and 2.14 present basic information important to the remainder of the book and should be referenced as necessary. Much information will follow concerning the Cordilleran margin as we present the geologic history of western North America.

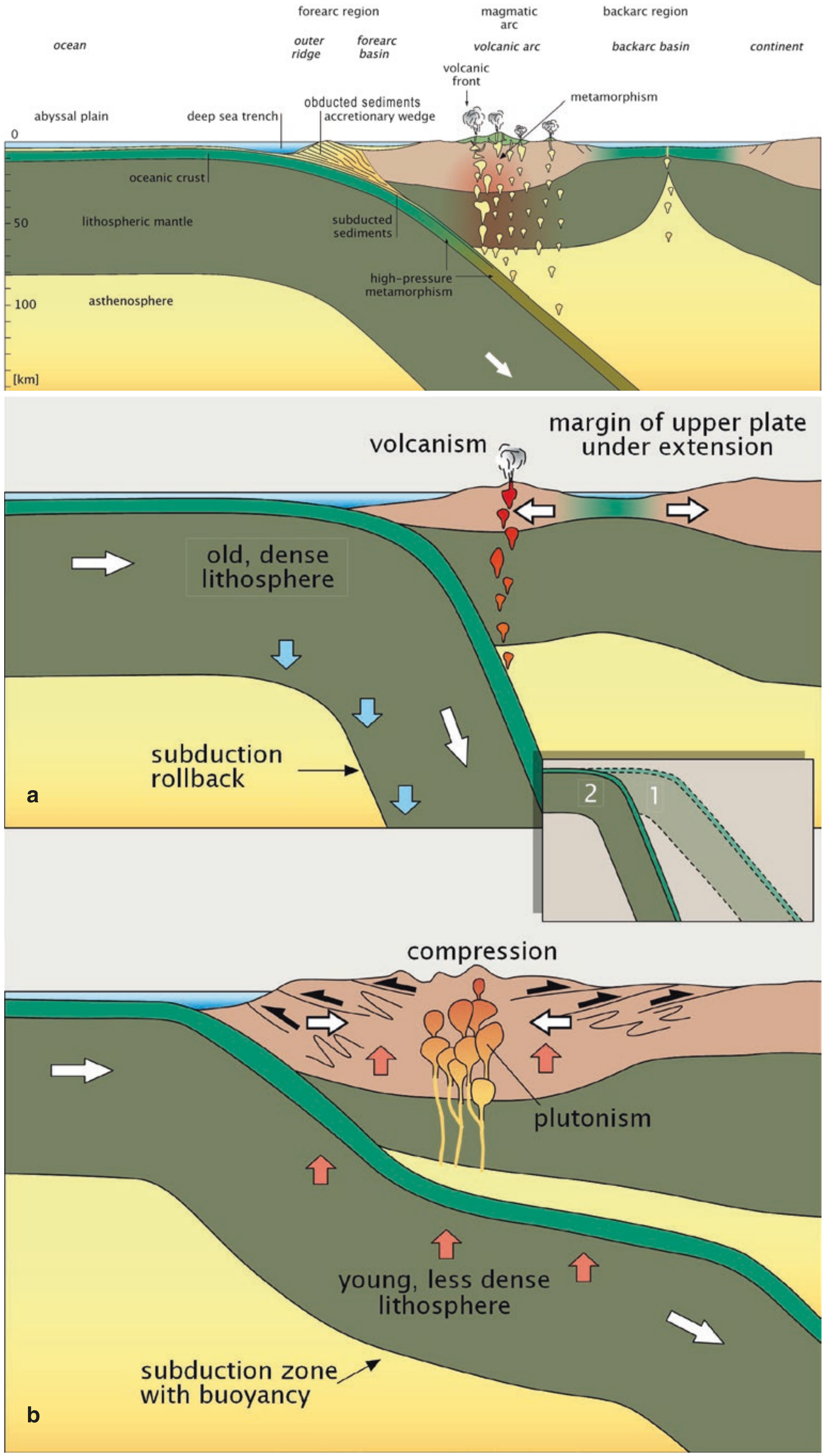
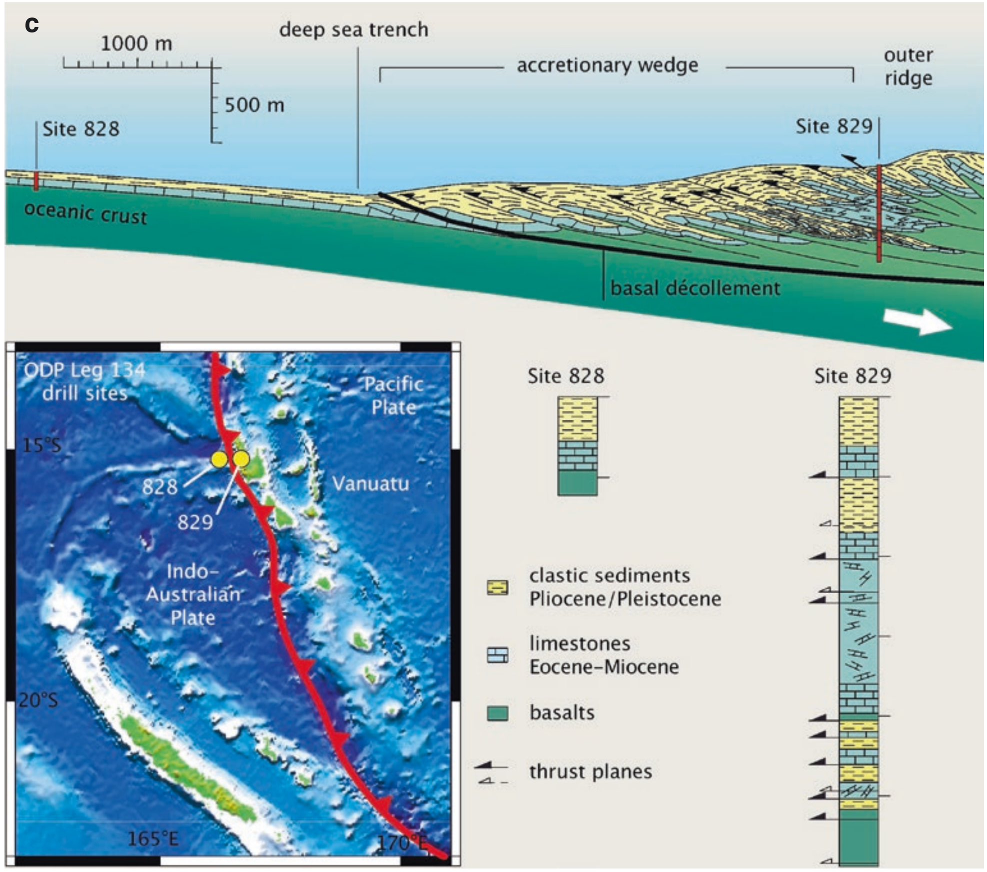


Fig. 2.11 Subduction zones. (**a**) General cross section of subduction zone; subduction of the ocean crust and its lithospheric mantle triggers partial melting of asthenosphere in upper plate which generates magmas that rise to surface to form volcanic arcs. The deep-sea trench marks the location of the plate boundary in map view. The accretionary wedge forms as sediment and surficial volcanic materials are scraped off as they enter the subduction zone. (**b**) Slab behavior related to angle of subduction. *Upper*: Dense slab rolls back from previous location (inset shows time 1 vs. time 2) creating extension on upper plate and formation of back-arc basin with oceanic crust potentially forming; longterm rollback may rift arc from continent forming new plate. *Lower*: Less dense slab subducts at lower angle and causes drag and compression on upper plate; long-term low-angle subduction generates mountain building and crustal thickening on upper plate. (**c**) Modern forearc region with well-developed accretionary wedge near Vanuata in the SW Pacific where Australian Plate is being subducted under the Pacific Plate. *Thin* Cenozoic limestone and clastic sediments of *lower plate* are scraped off in deep sea trench and added to accretionary wedge on *upper plate*. Note trench-directed thrusting in wedge stacks successive layers with oldest sheets on bottom of stack. Various tectonic breccias and melanges comprise the wedge. Deep Sea Drilling Program sites mark where data in cores has been retrieved. Map shows location of plate boundary and deep sea cores. Note that material being scraped off is approximately 100 m thick but resulting accretionary wedge is over 500 m thick (Modified from Frisch et al. 2011)

Fig. 2.11 (continued)



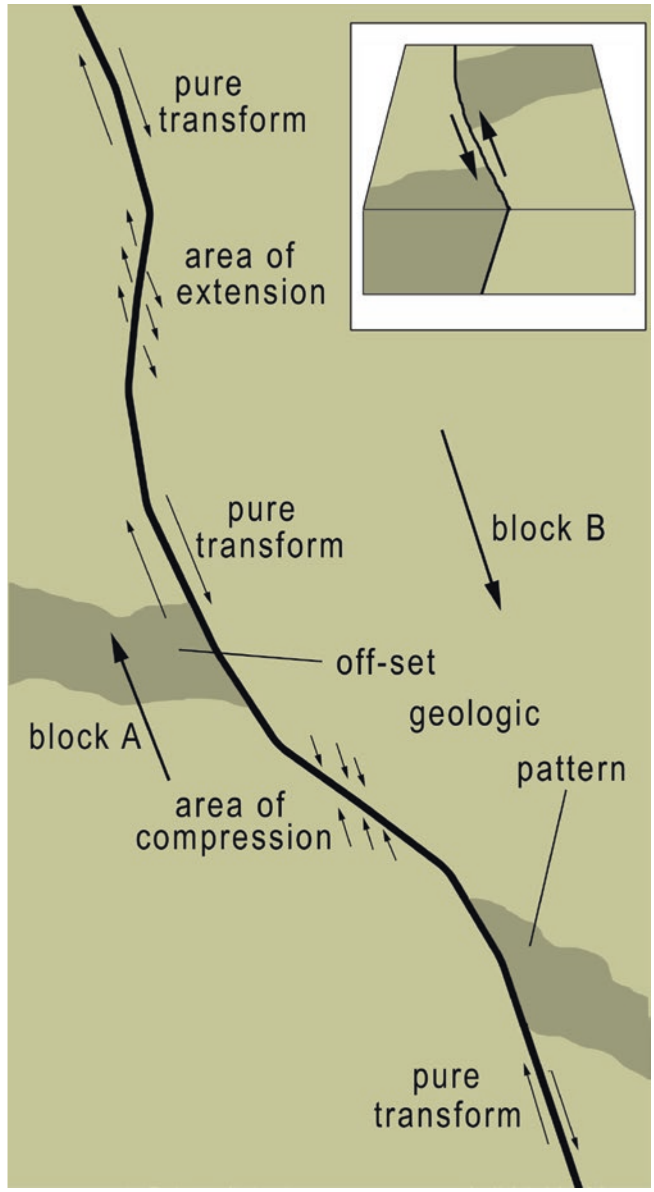


Fig. 2.12 Diagram showing features typical of transform faults. Map view shows variations in fault trend and resulting changes in stress along the transform. Pure transform occurs where block offset is parallel to trend of the fault; extension and compression occur when the fault trend becomes oblique to block offset. Areas of compression are areas of uplift and areas of extension are marked by linear depressions. The darker pattern represents an offset geologic pattern. Insert: simple block diagram showing 3-D geometry of transform faults. Note that map illustrates a dextral (*right-lateral*) fault and that the insert is a sinistral (*left-lateral*) fault

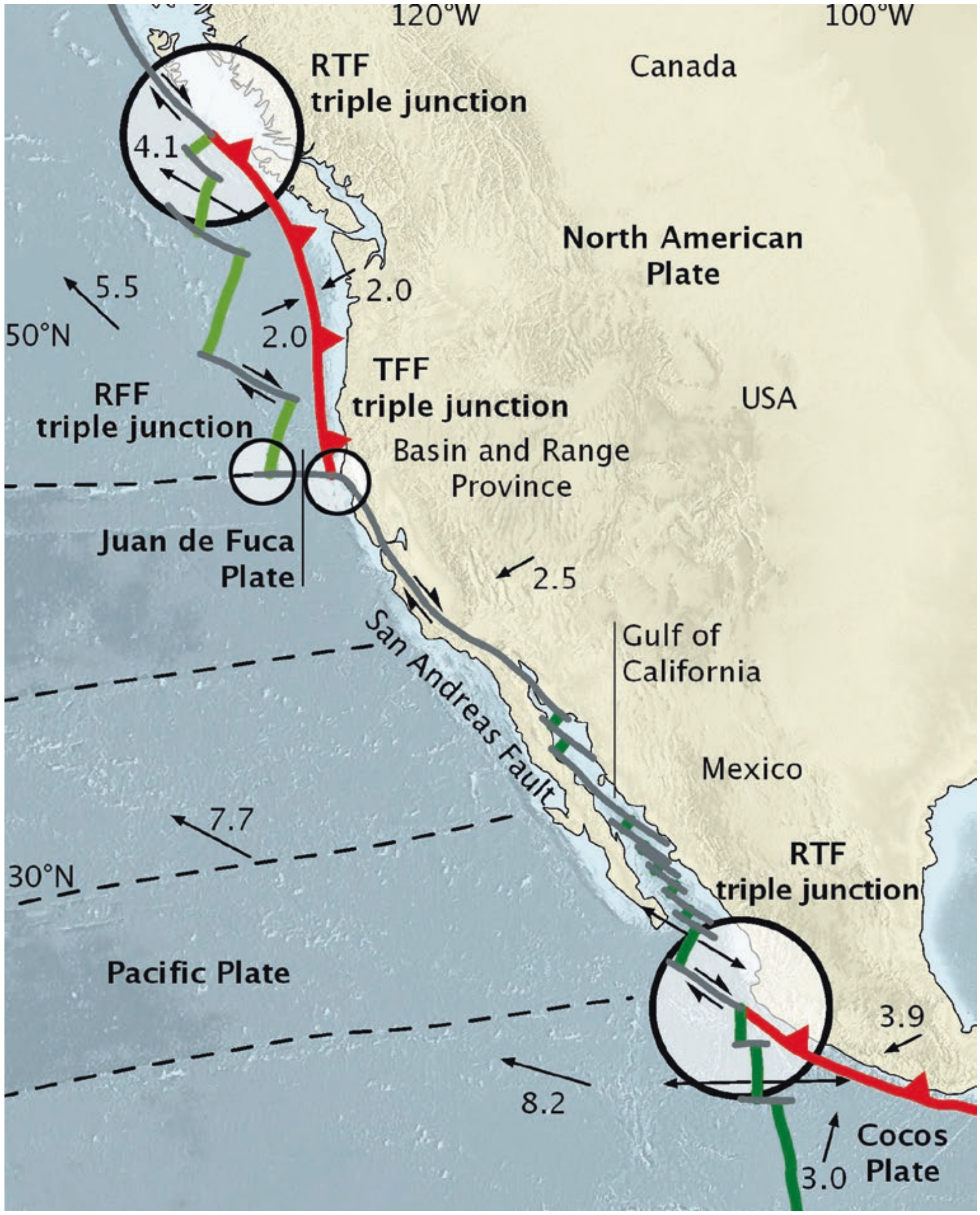


Fig. 2.13 Present tectonic setting of western North America showing first-order tectonic elements. Triple junction abbreviations: *R* ridge, *T* trench, *F* transform fault. Numbers show plate velocity in cm/yr. Both subduction and transform margins are present (Modified from Frisch et al. 2011)

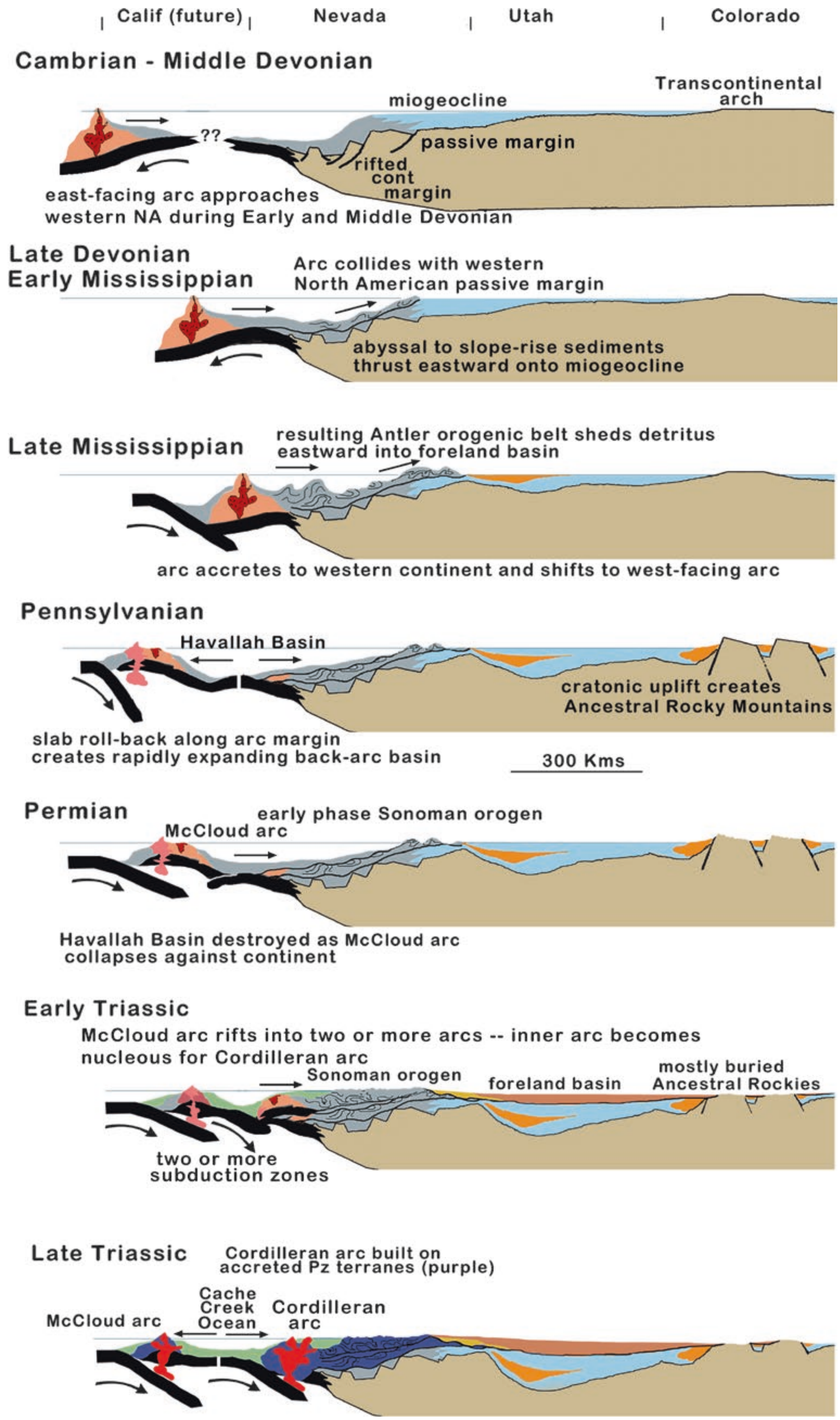
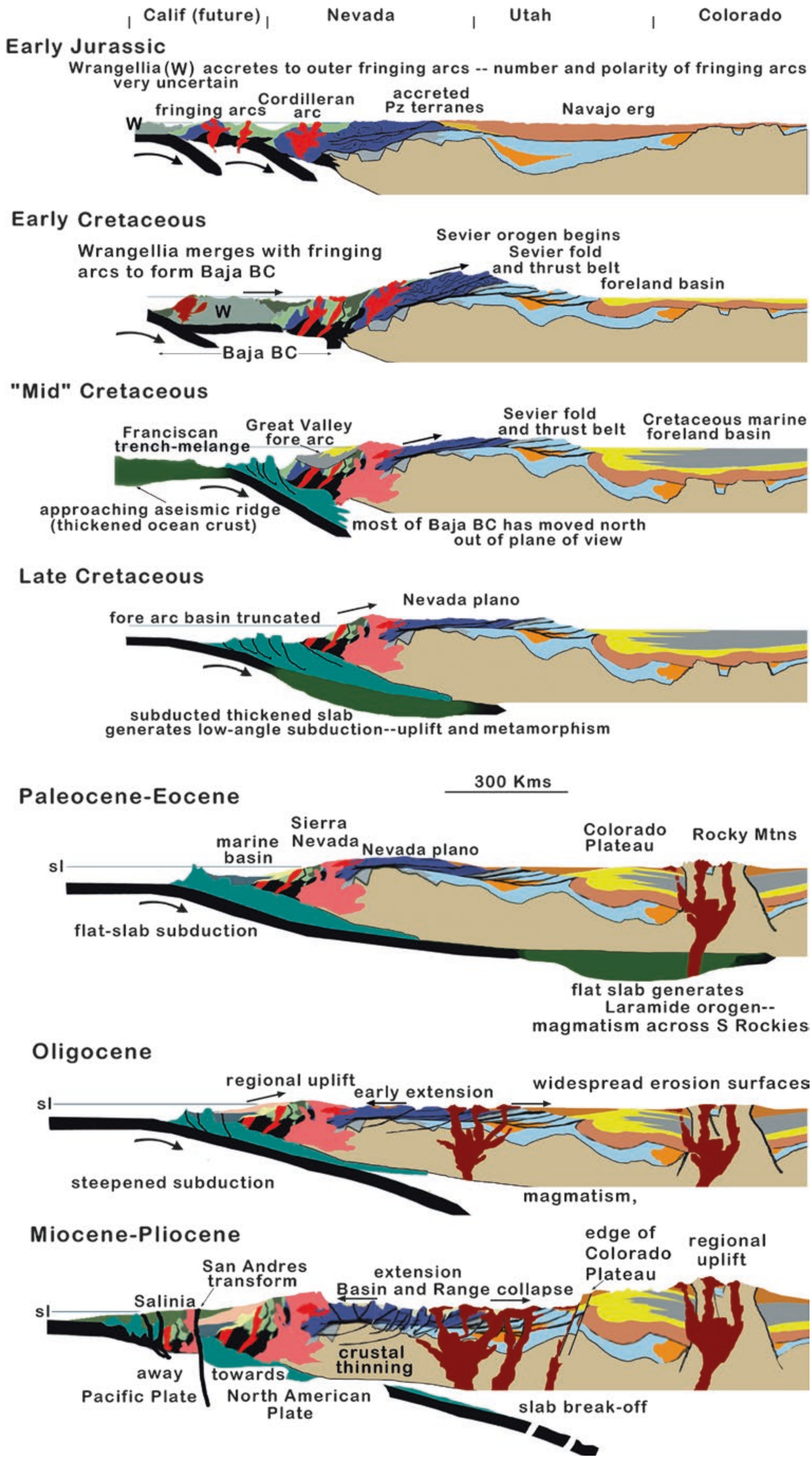


Fig. 2.14 Restored panel cross sections of North American Cordillera showing last 500 million years

Fig. 2.14 (continued)



3 The Cordillera's Foundations: Paleoproterozoic and Mesoproterozoic Periods: Ca. 1800–1000 Ma

3.1 Beginnings

Throughout the long course of earth history, the continents have continually rearranged their positions, size, and shapes, and the familiar outlines observed today serve merely as fleeting snapshots in the long cavalcade of time. We may think of these shapes and arrangements as permanent fixtures on Earth's surface but this is only an illusion revealing more about our own temporal and spatial limitations as tiny human beings. The continents move about and drift across Earth's surface and their motion is derived from the slow but inexorable churning of the *mantle* below, the layer that immediately underlies the crust. When the mantle moves, it pulls on the undersides of the continents, dragging them across the surface at about the rate fingernails grow, roughly 2–5 cm per year. The mantle is in motion, at about the same rate, because of radioactive decay near the core-mantle boundary. This generates heat and as it escapes upward it churns the mantle. Stripped to this essential fact, it is radioactive decay in the Earth that creates heat, setting in motion the mantle and the plates of crust that overlie it. This simple but important starting point helps in understanding how the western Cordillera evolved.

Fig. 3.1 Paleogeographic map of Paleoproterozoic North America. Map shows North America during Mazatzal orogen ca. 1680 Ma. Maps showing paleogeography greater than 600–800 Ma are extremely hypothetical

3.2 Basement Rocks

Landscape development of the Cordillera begins during an interval of time very far removed from the present (Figs. 3.1, 3.2, and 3.3; Table 3.1). The basement rocks in Wyoming and Montana – granite, schist and gneiss – were formed and already in place by the end of the Archean, about 2500 Ma. These old rocks were part of the craton or Archean nucleus of ancient North America, whose southern edge lay along a line that generally follows the present state line between Wyoming and Colorado. This is the location of the Cheyenne belt, a major discontinuity in the fabric of the Cordillera's basement and the location where additional crust would become attached to the edge of the continent beginning around 1800 Ma. It was along this line that various slivers of crust drifted into and collided with the underbelly of North America, adding real estate to the continent and providing a foundation upon which younger sediments would be deposited.

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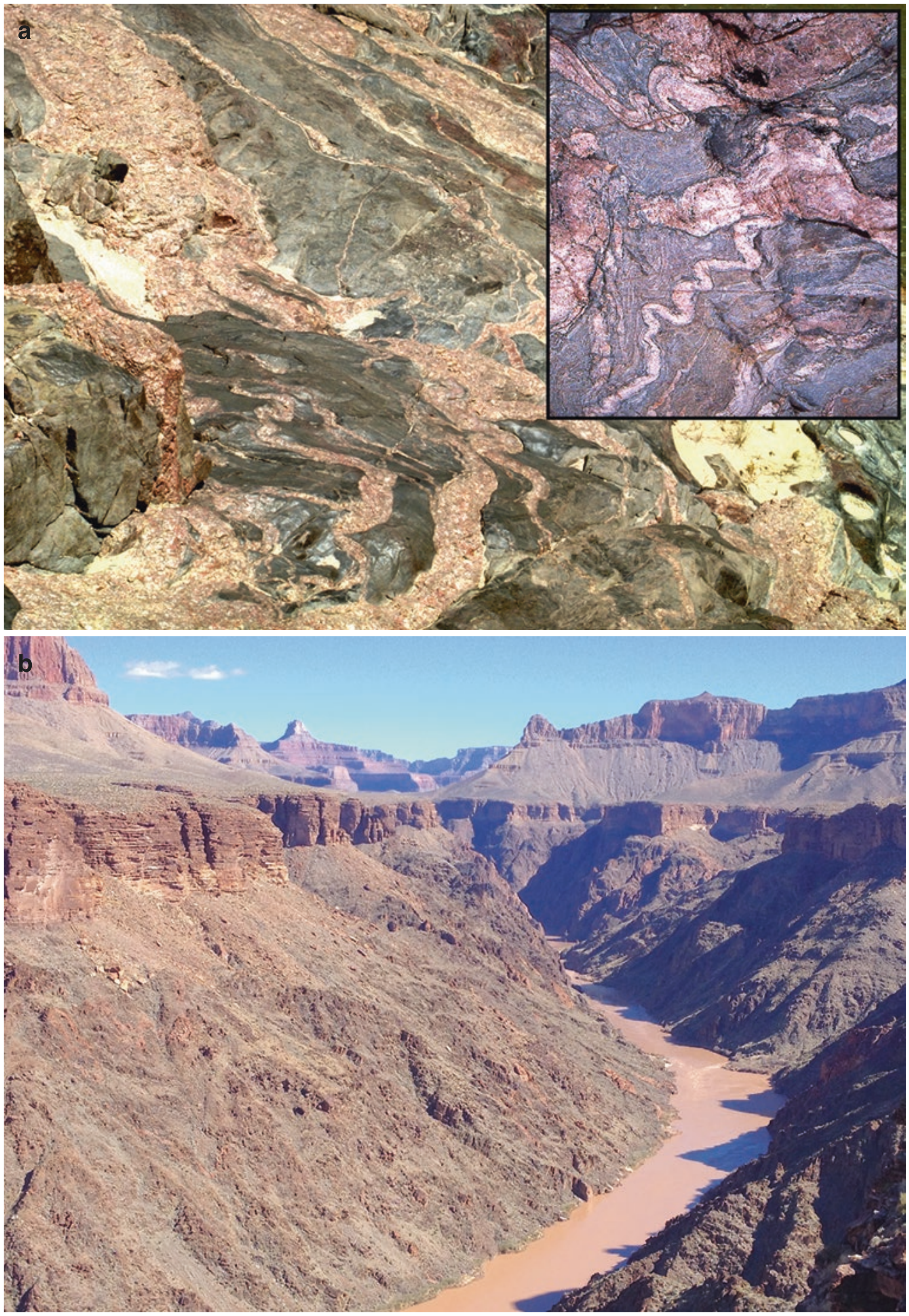

Fig. 3.2 Precambrian rocks of Grand Canyon. (**a**) Gneiss in western Canyon metamorphosed during collision between Mojavia and Yavapai (view is 4 m high); *inset* – close-up of banding (view is 1 m across). (**b**) Cratonic basement – Vishnu Schist was planed by erosion and subsequently covered by Paleozoic sedimentary rocks. Contact has over 1 billion years of the rock record missing. (**c**) Wall of Vishnu Schist with lighter pods and veins of granite that cross-cut the schist. Within the Inner Gorge of the Grand Canyon are medium- to high-grade metamorphic rocks formed during the collision of island arc rocks with the North American craton around 1.75 Ga. (**d**) The Mazatzal Quartzite exposed in the namesake mountains was deformed and metamorphosed during the Mazatzal orogeny (ca. 1680 Ma). (**e**) Quartzite and schist in Unaweap Canyon near Grand Junction, Colorado. (**f**) Uncompahgre Quartzite near Silverton, Colorado. Most Precambrian rocks in Colorado belong to the Yavapai Province and were metamorphosed ca. 1750 Ma

Fig. 3.2 (continued)

Fig. 3.2 (continued)

Fig. 3.3 Paleogeographic map of Mesoproterozoic North America. Map shows North America prior to final assembly of Rodinia ca. 1100 Ma. Positions of adjacent continents are extremely controversial

Table 3.1 Events 1700–1000 Ma

Time span	Paleoproterozoic and Mesoproterozoic (*Ca.* 1800–1000 Ma) growth of western North American continent
Geologic – tectonic setting	Archean nucleus of Laurentia expanded significantly
	Arc and microcontinent collision and accretion
	Major continental growth and mountain building occurred during Mojave (*Ca.* 1800 Ma), Yavapai (*Ca.* 1750), Mazatzal (*Ca.*1680)
	Continental collision from *Ca.* 1400–1000 Ma occurred during assembly of supercontinent Rodinia followed by rifting and continental break-up
Boundary of western north America	*Ca.* 1000 Ma, the western margin of Laurentia trended N-S through Central Nevada
Terranes	Numerous terranes and arcs accreted during the Paleoproterozoic orogens. Most accreted along S Laurentia
Sedimentation patterns, trends	Generalities: oceanic and arc-related sediments and volcanics preceded orogeny and siliceous sediments, now quartzites, followed major mountain building
	Varied sedimentary rock types formed in rift basins and passive-margin continental shelves
Igneous/ metamorphic events	Major batholithic formation and metamorphism related to orogenic events
	Volcanics common in rift basins and island arcs
	Immense volume of granites *ca.* 1400 Ma

Keeping this in mind, there are three phases to understand about the development of the basement here. (1) Rocks in Montana, Wyoming, and the northeastern part of Utah were already formed from microcontinent collisions by 2500 Ma. (2) Accreted to this ancient nucleus were basement rocks now located in Colorado, New Mexico, Arizona, and the other parts of Utah (Figs. 3.1, 3.2, 3.3, and 3.4). (3) And a final piece, located today in the entire western half of the Cordillera and containing parts of British Columbia, Nevada, California, Washington, Oregon, and Idaho, did not have basement rocks until much younger pieces of crust are attached piecemeal after about 375 Ma. During the Precambrian, the western half of the Cordillera was underlain only by ocean crust, which is usually destroyed by plate tectonic processes and unable to preserve longer spans of Earth history. These three basement zones delineate the undercarriage of the North American Cordillera.

Fig. 3.4 Mesoproterozoic rocks in Arizona and Montana. (**a**) Apache Group below Roosevelt Dam, east-central Arizona. (**b**) The Meso- and Neo-Proterozoic Grand Canyon Supergroup represents deposition during both the assembly and fragmentation of the Rodinian supercontinent. (**c**) The Belt Supergroup in Glacier National Park, Montana. This is the Grinnell Formation, deposited as nearshore sandstone, shale (now metamorphosed to argillite), and siltstone

Fig. 3.4 (continued)

3.3 Proterozoic Orogens

Large portions of the southwestern basement were accreted to North America when a volcanic arc located off of its southeast margin, drifted north as thin slivers of land. A terrane called Mojave (or Mojavia) was the first to collide and accrete to the continent about 1800 Ma. Next was a terrane called Yavapai and it accreted at about 1750 Ma, while another terrane called Mazatzal accreted at about 1680 Ma (Fig. 3.1). During the collisions, the sediments and volcanic rocks that had formed in the intervening ocean basins were compressed and warped to depths approximately 15–20 km – this process altered the rocks to schist and gneiss. Rocks deeper in the crust melted entirely and then rose buoyantly into the deforming crust to produce intrusive batholiths, dikes, and sills of granite. In this manner, new crust was added to North America (Fig. 3.2).

Modern analogs of this ancient tectonic setting include the Japanese, Philippine or Indonesian archipelagos that are positioned at the edge of the continents of Asia and Australia. In the coastal and oceanic settings, sediments and volcanic rocks accumulate. The arcs form when a subducted slab of ocean crust partially melts to form silica-rich magma, which then rises to the surface and erupts as explosive volcanic material (think of Krakatoa). In this manner, continental crust is formed and added to the margins of the continents. As the collision process advances (if or when Australia and Asia collide), both the sediments and the ocean slab they ride on are shoved downward where they become heated under pressure, changing the former surface rocks into metamorphic rocks. The modern analogs mentioned here allow geologists to recognize where these processes have acted before.

When the basement rocks of Mojave, Yavapai, and Mazatzal were accreted to the North American continent, a large mountain range formed on earth's surface. This mountain range may have existed in one form or another for a mind-boggling 400 million years, from about 1650 to 1250 Ma. Like most tectonically-formed mountains, they had to grow in two vertical dimensions – upwards as mountains on the surface and downward as a mass of continental crust protruding deep into the soft, pliable mantle. Many mountain belts grow this way and achieve *isostatic equilibrium* (a state of gravitational balance that is achieved when less dense crust rides atop denser mantle). Two important factors are *density* and *thickness* of the lithospheric mass – the plate. Compare how high a pine 2×4 rises in water vs. an oak 2×4. Then consider the same between a pine 2×4 vs. a pine 4×4. When the mountains are progressively eroded and the mass on top is removed, the crust buoyantly rises – carefully stack two pine 2×4's on top of each other and float them in water. Then remove the top 2×4 and watch what happens – the lower 2×4 pops up. Thus, as mountains are eroded, increased uplift is facilitated and repeated uplift and erosion occur in a positive feedback loop. This explains how rocks that initially formed 15–20 km deep were brought back to the surface as metamorphic rocks.

If the crust is pulled apart and the mountain belt is greatly extended, uplift can be greatly accelerated through a process called *tectonic erosion* in which large sheets of upper crust are pulled away, thinning the crust and causing the lower

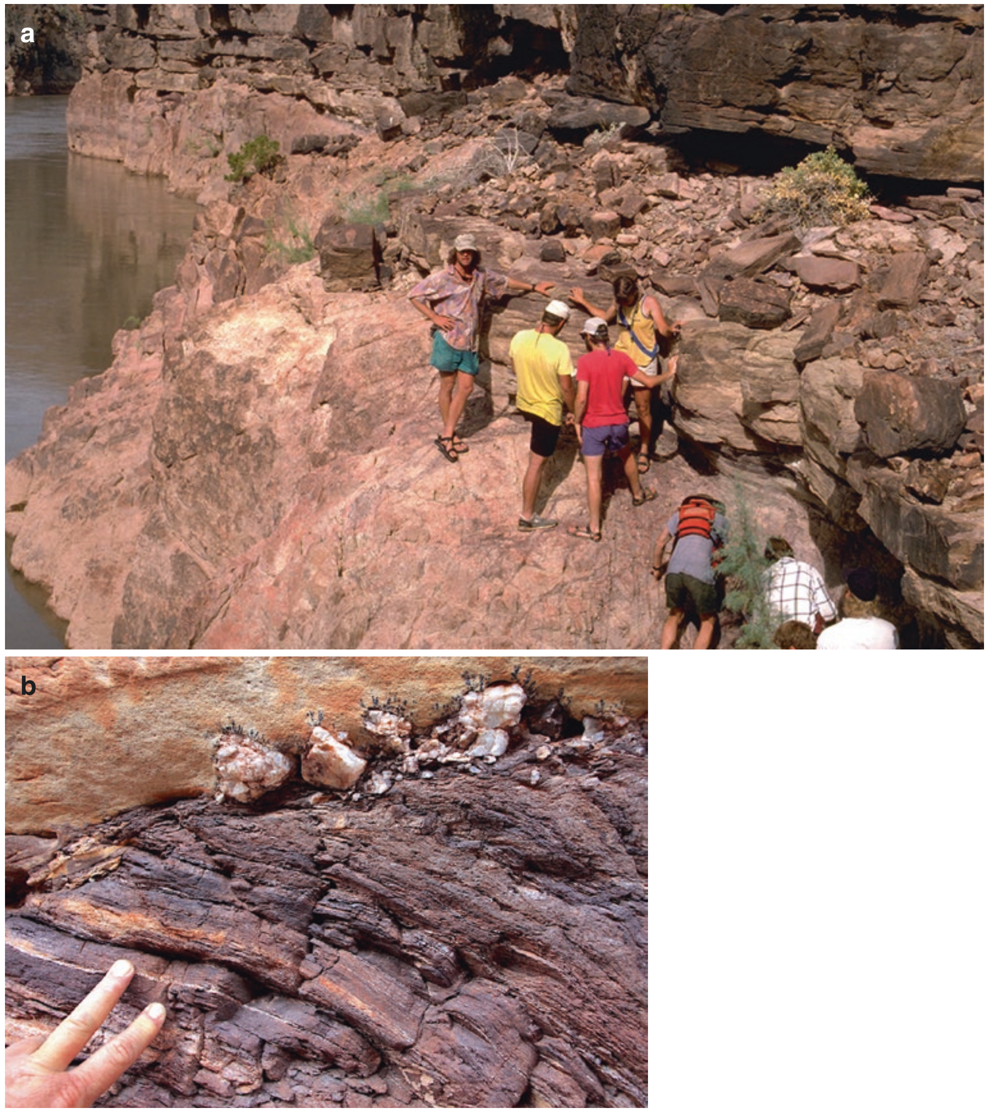

Fig. 3.5 The Great Unconformity. (**a**) Students examine the profound Great Unconformity in western Grand Canyon. The surface was developed on schists, gneisses, and granites that range from *ca.* 1800 to 1750 Ma and represent the roots of long-eroded mountains. Erosion attacked the mountains, wore them down several times, and created a surface exposed to additional weathering and erosion for untold hundreds of millions of years. The Cambrian transgression, *ca*. 515 Ma in this region, deposited sand, gravel, and mud to create the Tapeats Sandstone as a series of shoreline bars, beaches, and tidal flats – the places the trilobites knew. Following the subsequent history of deposition and erosion, the unconformity was exposed *ca*. 6 million years ago. Revealed was an infinitely thin horizon that failed to record over 1 billion years of Earth history. Many geologist report that the hair on the back of their necks rises when they cross the surface! (**b**) Close-up of contact showing pebbles derived from underlying Zoroaster Granite reworked into overlying Tapeats Sandstone

crust to rise rapidly – the metamorphic zone. More on this in Chap. 10 where *metamorphic core complexes* are discussed.

As the Yavapai and Mazatzal orogenies matured and the rocks were being worn away, a larger continental mass from the west collided with and accreted to western North America beginning about 1400 Ma. This was composed of various amalgamated fragments of the modern-day continents of east Asia, Australia and Antarctica. When this block attached to North America it created a supercontinent called *Rodinia* (a supercontinent not to be confused with the younger and more widely recognized Pangaea which will be discussed later). The amalgamation of Rodinia must have contributed to the height of the already formed mountains in the southwest Cordillera and initiated a period of deposition on its margins.

As the mountains wore down to near sea level, irregular topography underlain by Archean and Paleoproterozoic crystalline rocks stretched from modern day Alberta to Sonora, and from central Nevada to the Great Plains and beyond (Fig. 3.3). The landscape was locally low enough that sediment began to accumulate across the Cordillera in various basins. These basins captured shallow marine, fluvial and eolian sediments that today are sandwiched between the basement rocks below and younger rocks above (Fig. 3.4). They are found in the depths of Grand Canyon (the Unkar Group), central Arizona (Apache Group), Montana and Idaho (the Belt Supergroup), and in British Columbia (the Purcell Supergroup). Only *stromatolites* (algae fossils) are preserved in these sedimentary sequences, showing the antiquity of this history.

The eastern Cordillera now had a bedrock foundation that stretched through central Nevada from southeastern California to Alberta. This is the foundation upon which broad and extensive sheets of sediment would later accumulate (Fig. 3.5).

4 The Cordillera's Long-Lived Passive Margin: Neoproterozoic to Middle Devonian Periods: Ca. 1000 Ma–400 Ma

4.1 Break-Up of Rodinia

With a foundation in place along Laurentia's western margin, a new phase in the Cordillera's history began (Table 4.1). As Rodinia split from North America beginning around 1000 Ma, it opened the *Panthalassa Ocean* (Greek for "all of the sea"). This opening was a seminal event in the Cordillera's history as it initiated a long-lived *passive margin* setting. This is a tectonic environment where earthquake and volcanic activity is mostly absent, as opposed to *active margins* where considerable tectonic activity occurs. This allowed for the deposition of a huge thickness of near-shore and carbonate marine sediments on the newly formed continental shelf and slope-rise. The Eastern Seaboard of the United States is a good modern analog for this type of setting.

The Cordilleran landscape was composed not only of exposed land on the continent but also portions submerged beneath the Panthalassa Ocean. Both were part of the same tectonic plate that extended west to the rift where Rodinia had split apart. Tectonic plates can contain both oceanic and continental crust and a similar comparison is made today where the North American plate extends east to the Mid-Atlantic Ridge. In the Neoproterozoic, the western edge of the continental crust trended from southeastern California northward through central Nevada and along the provincial boundary between British Columbia and Alberta. Continental crust was located to the east of this and oceanic crust to the west. There may have been a few slabs of continental crust left stranded offshore of Laurentia when Rodinia split (Fig. 4.1); today Madagascar is an example of a continental sliver that was left after the split between India and Africa.

Table 4.1 Events 1000–400 Ma

Time span	Neoproterozoic to Middle Devonian (*Ca.*1000 Ma–400 Ma) passive margin sedimentation of western North America
Geologic – tectonic setting	Following break-up of Rodinia, western NA faced a broad ocean, the Panthalassa (*Gr.* all of the ocean)
	NA and this ocean on same plate – no plate margin/boundary.
	Western NA continental margin was stretched during and following rifting and became site of thick shelf and slope-rise sedimentation – a passive margin
Boundary of western North America	Margin of *continental crust* trended N-S through central NV, northward along the BC-Alberta boundary and S into SE CA
	Little tectonic activity
	Likely, stranded blocks of the rifted margin lay offshore as microcontinents (*cf.* Madagascar)
Terranes	Rifting was dominant process – no terranes approached WNA until the Middle or Late Devonian
Sedimentation patterns, trends	Extensive sandstone deposits mark Neoproterozoic and Cambrian shorelines; mudstones (shales) deposited farther offshore; carbonates (ls and dolomite) blanketed shelves where water was clear
	From Ordovician through Middle Devonian carbonates dominated from shore to shelf margin
	These thick carbonates dominate many ranges in modern Basin and Range
Igneous/ metamorphic events	Minor to absent in most areas.
	Rare volcanics may represent seamounts or approaching arcs late in the interval

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Fig. 4.1 Paleogeography of North America *ca.* 750 Ma during opening of Iapetus Ocean along the East Coast during break-up of Rodinia. Portions of South America and Africa lie to the right of and below Laurentia

4.2 Passive Margin

As Rodinia drifted away, down-dropped basins formed on the edge of Laurentia and Neoproterozoic sediments are preserved in Grand Canyon (Chuar Group) and Death Valley (upper Pahrump Group). The Chuar Group rocks reveal when *heterotrophic* life (organisms that do not make their own food but rely on nourishment from other organisms) appeared around 700 Ma, while stromatolites tell of warm, shallow marine environments. Elsewhere on the globe, evidence for a S*nowball Earth* is found, a period of time when ice age conditions were prevalent even at tropical latitudes. The timing is between 720 Ma and 650 Ma and may have lasted for 350,000 years or less. Recent zircon studies in the Chuar rocks show that they might fall within these Snowball Earth events, although no primary evidence for glaciation has been found yet.

As the crust continued to extend by rifting, it caused these rocks to become faulted as sediment poured into the widening rifts. Today, the Pahrump and Chuar groups are always found as tilted beds in the landscape (Fig. 4.2). As the Precambrian came to a close, passive margin conditions persisted in the Cordillera for the next 200 million years. In this setting, thick layers of sediment accumulated in shallow seas and along the continental slope. Vast portions of the American West display these rocks in canyons and mountain ranges, some of which have been folded and faulted in later events.

At the dawn of the Paleozoic Era and the Cambrian Period (*ca.* 541 Ma), new and exciting life forms begin to appear in the fossil record. Prior to this time life was simple, single-celled organisms such as cyanobacteria, blue-green algae, and protozoa. Over a period perhaps as short as 20–25 million years, life forms developed with protective shells that could be preserved in sediment and provide protection from predators and ultra-violet radiation from the sun. They developed eyes for seeing their prey, and appendages and mouth parts to pursue and eat other animals. Corals, sponges, mollusks, and crustaceans developed in this relatively short period of time. In one particularly interesting and unique setting, soft-bodied animals were preserved in the Burgess Shale (around 508 Ma) of the Canadian Rockies. The shale is presumed to have been deposited at the base of a limestone reef, where the animals would have found abundant food and shelter from predators. Farther south, the Cambrian and Ordovician rocks in western Utah and eastern Nevada expose these events in some of the most fossiliferous rocks on planet Earth.

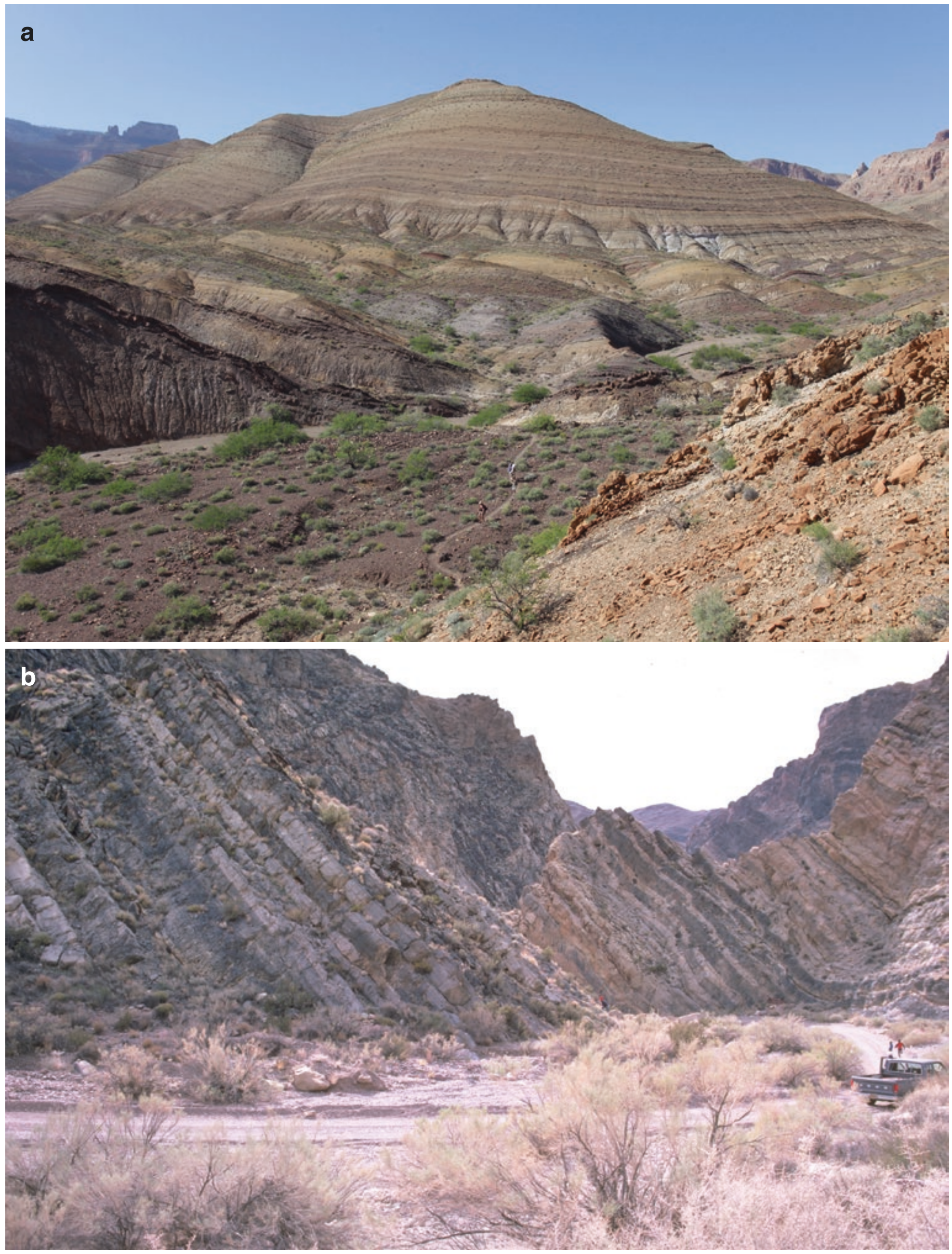


Fig. 4.2 Neoproterozoic rocks. (**a**) Chuar Group in eastern Grand Canyon was deposited in a wide variety of marine, lacustrine, and fluvial environments. (**b**) Pahrump Group in Death Valley, California. The Cambrian-Precambrian contact probably lies within the tilted ridge of marine rocks

4.3 Transgression

During the Cambrian, western Laurentia had a very simple geography with terrestrial settings to the east and marine settings to the west. This strand line extended from modern day Sonora Mexico to Alberta Canada (Fig. 4.3). Today, this line runs north to south but in the Cambrian, North America was positioned 90° clockwise from its present orientation, such that the shoreline in the Cambrian ran east and west and was located about 10° south of the equator (Fig. 4.4). Through time the sea transgressed over the continent to cover more and more of the Laurentian margin. At first, coarse sand was laid down in near-shore, perhaps beach settings, across the eroded Precambrian basement (Fig. 4.5). Occasionally the sea encountered the tilted remnants of Meso- and Neoproterozoic sedimentary rocks. Spectacular exposures can be seen in the depths of the Grand Canyon in Arizona or in Whirlpool Canyon along the Green River in northern Utah (Fig. 4.6). In many places, the Cambrian sands buried an undulating topography left over from latest Precambrian time.

Fig. 4.3 Paleogeography of North America *ca.* 540 Ma. As Iapetus widens and arcs approach Eastern North America, the western margin remains passive

As the seas transgressed further east (or south as it would have been back then), either by rising sea levels or subsidence of the continental edge or both, finer-grained sediments were deposited that commonly inter-finger with the sands. These in turn grade from shale to limestone as clastic sedimentation waned and the seas became clear, warm, and shallow. It can be shown that early Paleozoic sedimentation in the Cordillera was influenced by a so-called *Wasatch Line*, a tectonic hinge trending from Salt Lake City on the north to Las Vegas in the south. To the east of this line relatively thin continental shelf deposits give way to a total lack of deposits farther east, while west of the line, marine shelf and slope-rise deposits dominate and the rock record becomes much thicker (Fig. 2.7a). To demonstrate, in the Grand Canyon about 300 m of Cambrian strata are preserved. But only 65 km to the west in Nevada lies the most complete Cambrian section in the world, attaining a thickness of nearly 8000 m. These relationships are consistent to that observed farther north in Montana and beyond the international boundary in Alberta. The same trends are documented for Ordovician, Silurian and Lower and Middle Devonian carbonates that dominated the shelf environment from the rocky shore to the shelf margin and the slope-rise.

The take home message from this interval of time is that quiet, passive margin conditions existed in what is now the Cordillera region and perhaps most of Laurentia from about 1000 Ma to 400 Ma (Fig. 4.7). No suspect terranes drifted in from exotic locations to attach to North America. During the Ordovician and Silurian periods, most of the cratonic mass of Laurentia was inundated with shallow marine seas (Fig. 4.8). As shallow marine conditions dominated (Fig. 4.9), the evolving life forms found here attest to the near-perfect conditions for their existence and ultimate preservation. Some geologists have postulated that it was indeed these long-lived passive margin conditions that set the stage for this evolutionary leap, for without the right environments life might have taken a different trajectory on our planet. How incredible to think that the mechanical interior workings of the Earth could have such profound effects on the design of life that is recorded in its rocks.

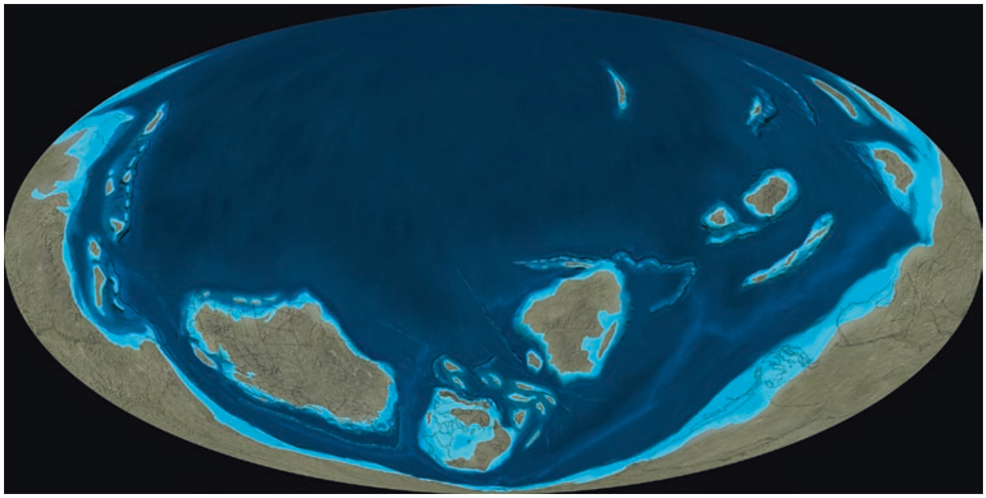


Fig. 4.4 Global paleogeography at the beginning of the Cambrian *ca.* 540 Ma. North America is the isolated continent near *lower-left* side of the map (notice state and province boundaries) with Baltica (Northern Europe – country outlines) and Siberia to its *right*. Gondwana wraps around the margins of the map. All global maps shown in Mollweide projection (see Fig. 1.2).

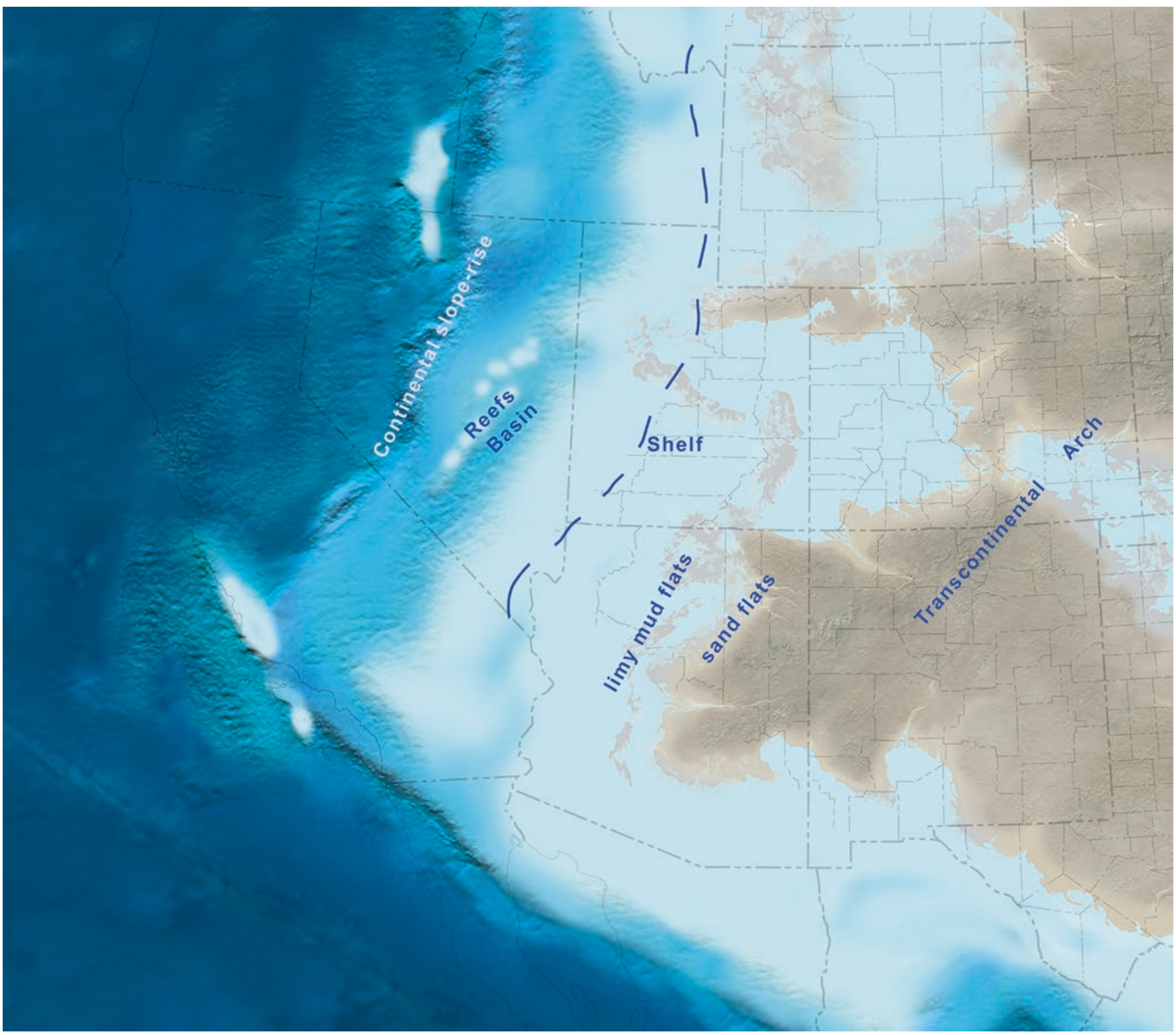
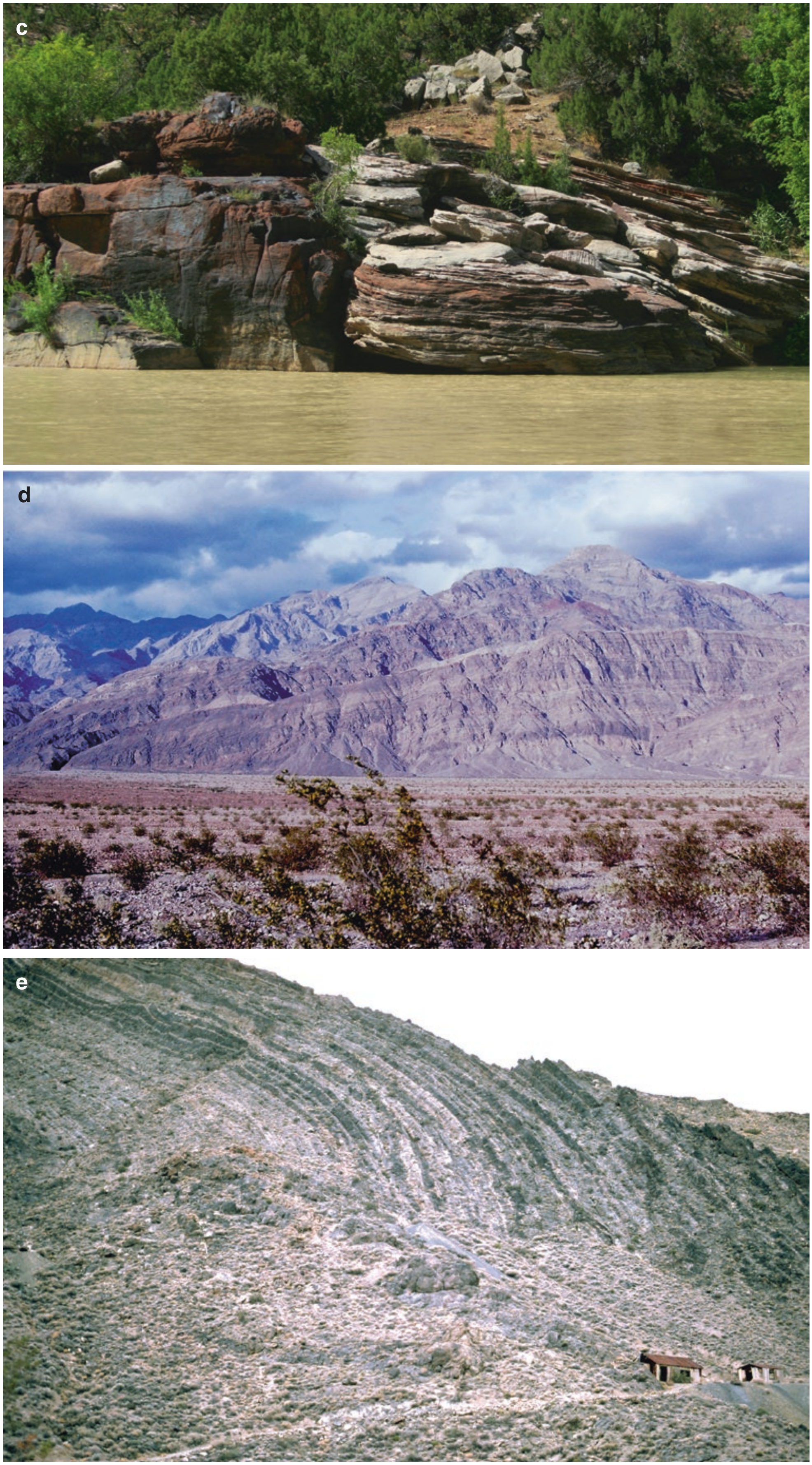


Fig. 4.5 Southwest North America during the Cambrian transgression ca. 505 Ma. The dashed line represents the Wasatch Line. The Transcontinental Arch was a linear belt from Arizona to Minnesota that subsided less than the surrounding areas exposing land on and off during the Paleozoic. The area in Nevada holds some of thickest Cambrian deposits anywhere. The *light-colored* areas shown off the continental rise-slope represent hypothetical continental blocks partly rifted from North America

Fig. 4.6 Cambrian rocks. (**a**) Cambrian shelf deposits within Grand Canyon include the basal Tapeats Sandstone (ledgy cliff above river) and the Bright Angel Shale (overlying slopes). Muav Limestone forms ledges and cliffs below Redwall Limestone sheer cliff (*left–center*). Cambrian rocks thicken to the west in Nevada across the Wasatch Line (Fig. 4.5). (**b**) Bright Angel Shale in Grand Canyon. (**c**) Cambrian deposits in Whirlpool Canyon, Dinosaur National Monument, Colorado. Here the Cambrian Flathead Sandstone (*right*) laps onto and pinches out against a topographic high composed of Proterozoic rocks (*left*). (**d**) Thick Cambrian rocks near Death Valley. (**e**) Cambrian limestone and dolomite (*darker bands*), SW Nevada

Fig. 4.6 (continued)



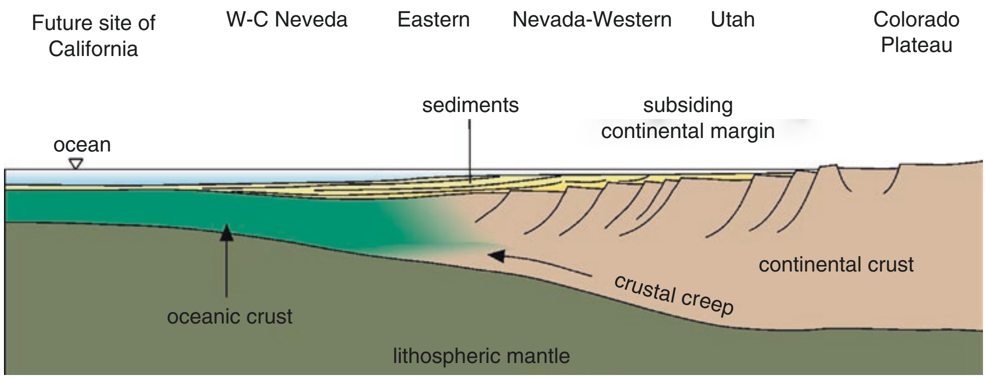


Fig. 4.7 Generalized cross section of a typical passive margin. Diagram shows relative thicknesses but is not to scale. Locations in Cordillera relative to the model are shown for reference. Crustal creep refers to the "plastic" stretching of the lower crust in contrast to brittle faulting of the upper crust. Western North America was dominated by this tectonic setting from the Late Precambrian (time approximated here) into the Devonian, an interval of nearly 1.5 billion years. By Late Cambrian, marine deposits blanketed most of the Colorado Plateau and adjacent Rocky Mountains. In Western Utah and Eastern Nevada, the deposits exceed 6000 m in thickness. Younger Paleozoic strata continued to be deposited in like fashion adding thousands of more meters of sediment (Modified from Frisch et al. 2011)

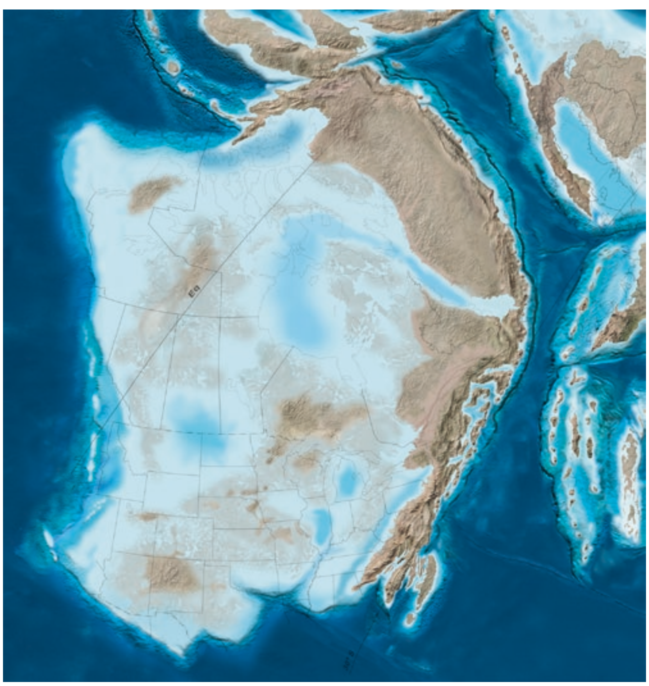


Fig. 4.8 North America during global marine highstand in Late Ordovician *ca.* 450 Ma. The west coast remains passive margin blanketed by thick carbonates as terranes close in on east and north coasts (present coordinates) – note Ordovician equator

Fig. 4.9 Thick early Paleozoic limestone and dolomite in the Spring Mountains west of Las Vegas. These mostly Cambrian rocks were deposited west of the Wasatch Line and are many times thicker than equivalent rocks to the east. These outcrops were thrust over Jurassic sandstone in the Sevier orogen

The Antler Orogeny and the First Suspect Terrane: Middle Devonian to Late Pennsylvanian: Ca. 400–300 Ma

5

5.1 Arrival of Exotic Terranes

From the Neoproterozoic through the Middle Devonian, a passive margin setting along Laurentia's western edge resulted in great thicknesses of shallow marine carbonate rocks (limestone and dolomite), and lesser amounts of near-shore clastic rocks (sandstone and conglomerate). The extent of this passive margin sequence both temporally and spatially is impressive, lasting nearly 600 million years and trending from southeastern California to Alberta Canada. The passive margin conditions however, came to a crashing halt with the arrival of a series of exotic terranes at the Cordillera's margin. With time, shallow marine carbonates were thrust faulted in allochthonous (*Gr. "other Earth"* – rock or block of rock transported from outside its present position) blocks over their stationary, autochthonous (rocks that lay where they were formed) cousins.

Beginning in the Middle Devonian and continuing into the Mississippian, slivers of exotic crust arrived at the western edge of Laurentia either by way of a northern route across the Arctic region or perhaps by way of a southern route around Texas (Fig. 5.1). Rocks in this terrane display characteristics commonly associated with a source area in the today's North Atlantic region, the northern Appalachia area or the Caledonian Mountains (today's British Isles and Scandinavia). To conceive of such a far traveled terrane may be difficult at first but remember that ancient Caledonia was beginning its initial collision with eastern North America (the Appalachians and the Caledonian Highlands share a common history). Studies of included zircons held within the exotic rocks testify to their far-flung and fairly certain eastern origin.

The former passive margin setting was now the site of subduction as the slab of exotic crust became attached to the continental shelf (Fig. 5.2). This mountain building event is called the *Antler orogeny*, as evidence for it was first recognized in the Antler Peak area of the Battle Mountains in northern Nevada. The orogeny, however, had other far reaching effects with associated assemblages found in the Northern Sierra and Klamath terranes in northern California, the Black Rock terrane in northwest Nevada, the Izee and Olds Ferry terranes of Oregon and Washington, and the Kootenay, Stikine, and Yukon-Tananna terranes of Canada and Alaska (Tables 1.2 and 5.1).

In the area of the classic Antler Orogeny, two assemblages are identified that are contemporaneous: a thinner eastern

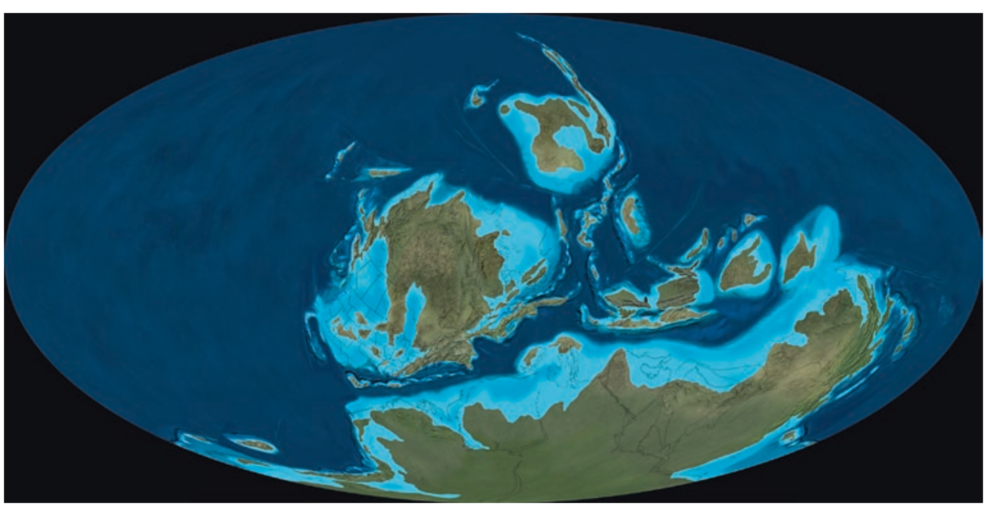


Fig. 5.1 Global paleogeography during the Late Devonian *ca.* 370 Ma. Complex global paleogeography reflects a major global plate-tectonic reorganization. Numerous Devonian terranes and arcs will merge in the Carboniferous to form the supercontinent Pangaea. Note the arcs moving into western North America

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Fig. 5.2 Late Devonian paleogeography of North America *ca.* 375 Ma. Terranes and arcs approached and accreted to Eastern North America – some of these terranes drifted into the northern and southern Cordilleran region. Note the extensive reef complexes in Alberta and the channeled nature of the continental shelf-slope-rise. These channels formed during the Early Devonian global lowstand and became an important habitat for the evolving early fishes

section containing passive margin, fossiliferous carbonates, and a thicker western assemblage with greatly deformed layers of chert, other silicic rocks and volcanic debris. The precise geometry and direction of travel of the Antler terrane is complex and even some strike slip motion may have been involved. It's also possible that microcontinent remnants from the Rodinia rifting may have been squeezed into the mix. Complications arise because much later faulting disrupted and obscured significant parts of the outcrops and for these (and other reasons) various and sometimes competing ideas have been proposed.

Stated simply, as chains of island arcs and/or microcontinents moved into the area on the upper plate, they were accreted to the western edge of Laurentia by subduction that dipped to the west beneath the microcontinents and/or arc rocks. This initiated thrust faulting – as the suspect terranes were shoved to the east, they forced the continental slope-rise deepwater-deposited rocks over and above the coeval shallow water carbonate shelf deposits. Locally, the main thrust fault is called the Roberts Mountain thrust (likely a zone of thrusting and not a single plane). The actual site of the thrust belt is well east of the accreted terranes; accretion occurred at the continental margin but the thrust belt was located above the continental shelf at least 100 km farther east.

Table 5.1 Events 400–340 Ma

Time span	Middle Devonian to Middle Mississippian (*ca.* 400–340 Ma) Initial terrane accretion and Antler orogen
Geologic – tectonic setting	Chain of volcanic arcs approached WNA from the north through the present-day Arctic region and/or the south along the southern margin of NA
	Terranes have many geologic characteristics found in Northern Appalachian-Caledonian Mountains of modern N Atlantic region
	Detrital zircons in terranes provide strongest evidence of exotic origin relative to WNA
	Terranes approached on the upper plate of subduction zone and collided with and were thrust over NA passive margin
Boundary of western North America	Passive margin was lower plate as accreted arcs and microcontinents were thrust over NA continental margin
	Complex arrangement of accreted terranes, perhaps complicated by stranded microcontinents that lay off WNA
	Entire mass of outboard material accreted to previous passive margin and subduction reversed direction (now east-dipping under newly accreted terranes and NA margin)
	Subduction steepened and caused trench roll-back (movement away from NA margin) which, in turn, caused extension and tectonic collapse of Antler-Kootenay Mountains
	Eventually, extension produced back-arc oceans – Havallah and Slide Mountain
	NA western margin once again became passive
	Complexity of these events is still poorly understood
Terranes	Antler-accreted terranes now form portions of following terranes: CA – Northern Sierra, Eastern Klamath; NV – Black Rock; OR-WA – Izee, Olds Ferry; Canada – Kootenay, Stikine, Yukon-Tanana
Sedimentation patterns, trends	Craton and craton margin (miogeocline): mostly carbonate with west-derived Dev-Miss clastic sediments shed from Antler orogen
	Extensive reef complexes in Alberta
	Antler sequence (Roberts Mountain allochthon): deep water clastics originally marginal to NA thrust onto miogeocline
	Terranes: early and middle Paleozoic cherts, volcanic-rich clastics, deepwater clastics, cherty carbonates
Igneous/ metamorphic events	Scattered early and middle Paleozoic volcanics and arc plutons preserved in accreted terranes

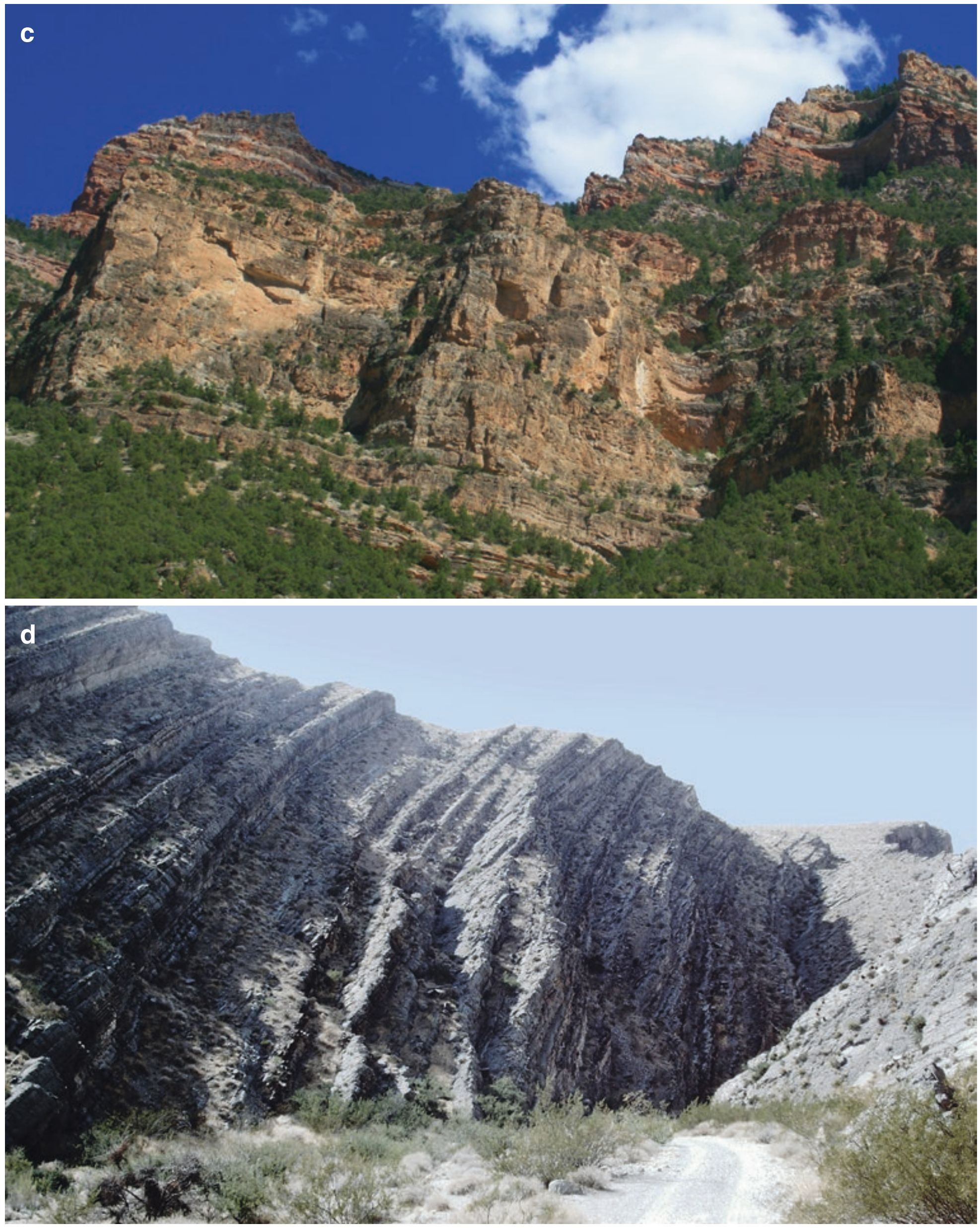
5.2 Great Carbonate Shelves and Meteor Strike

The tectonic excitement during the Antler orogen occurred in equatorial latitudes – in fact much of the Cordilleran region was tropical during the Devonian and Mississippian. This facilitated deposition of carbonate shallow marine deposits, including expansive coral reefs. In Alberta, Canada great Devonian reefs are the target for oil prospecting. *Evaporites,* rocks that form from the evaporation of sea water and produce layers of salt and gypsum, are also common and suggest hot, arid conditions. Graptolite and radiolarian fossils are also found in this part of the Cordillera and suggest adjacent deep water environments. Great swaths of the western Cordillera have Mississippian age carbonates that are widespread in outcrop or buried in the subsurface (Figs. 5.3 and 5.4). These include the Redwall Limestone (northern and central Arizona), the Escabrosa Limestone (southern Arizona), the Monte Cristo Limestone (Nevada), the Leadville Limestone (Colorado), and the Madison Limestone (northern Utah, Wyoming and Montana). Each of these are essentially the same deposit having only been formally described and named in a time before their lateral connections could be deciphered.

Another phenomenon of note that occurred at this time in the Cordillera was the Alamo impact event, a large meteorite strike that impacted Earth about 65 km north of Las Vegas near the small town of Alamo. Rigorously dated at 367 Ma, the precise dimensions of the *bolide* (a geologic term for the impactor) and its trajectory are obscured by much later geologic events. However, it surely was quite large given the dimensions of the disrupted strata. The strike hit in the shallow marine environment during deposition of the Guilmette Formation and created the Alamo mega-breccia, a contorted mass of broken limestone and huge landslide blocks. After the impact, huge tsunamis further disrupted the otherwise quiet water marine deposits. Much of the debris, including shocked quartz, elevated iridium levels, and spherules (all indicators of impacts) was then cemented in place to preserve evidence of the impact.

Fig. 5.3 Devonian and Mississippian rocks. (**a**) Devonian Ouray Formation overlies angular unconformity on Precambrian quartzites at Ouray, Colorado. (**b**) Mississippian Redwall Limestone in Marble Canyon, Arizona. This lithology typifies the Mississippian from Kentucky to SE California and from Arizona to Alberta. (**c**) Madison Limestone (direct Redwall equivalent) in Whirlpool Canyon, Utah, Dinosaur National Monument. (**d**) Tilted Monte Cristo Limestone in Arrow Canyon near Las Vegas, Nevada

Fig. 5.3 (continued)



5.3 Trench Rollback and Back-Arc Spreading

By the end of the Mississippian, accretion ceased – no additional terranes arrived at western Laurentia between 340 and 310 Ma. As the Antler orogen matured, the angle of subduction flipped directions and now dipped to the east beneath the Cordillera (Fig. 5.5). The cause for this switch is unclear but may involve plate reorganizations after the orogeny. Evidence suggests that this dip angle was steep causing the trench to roll away from the continent to the west. This trench "roll back," exerted extensional stress in the crust causing the mountains in the Antler orogen to collapse. The area was then flooded with sea water and the crust subsided.

The pressure exerted by trench roll back initiated the development of the Havallah and Slide Mountain *back-arc* basins (Table 5.2), a type of tectonic setting that was a surprising revelation in the early days of plate-tectonic studies. Subduction normally creates compression in the crust as two plates collide, but evidence indicated areas where exten-

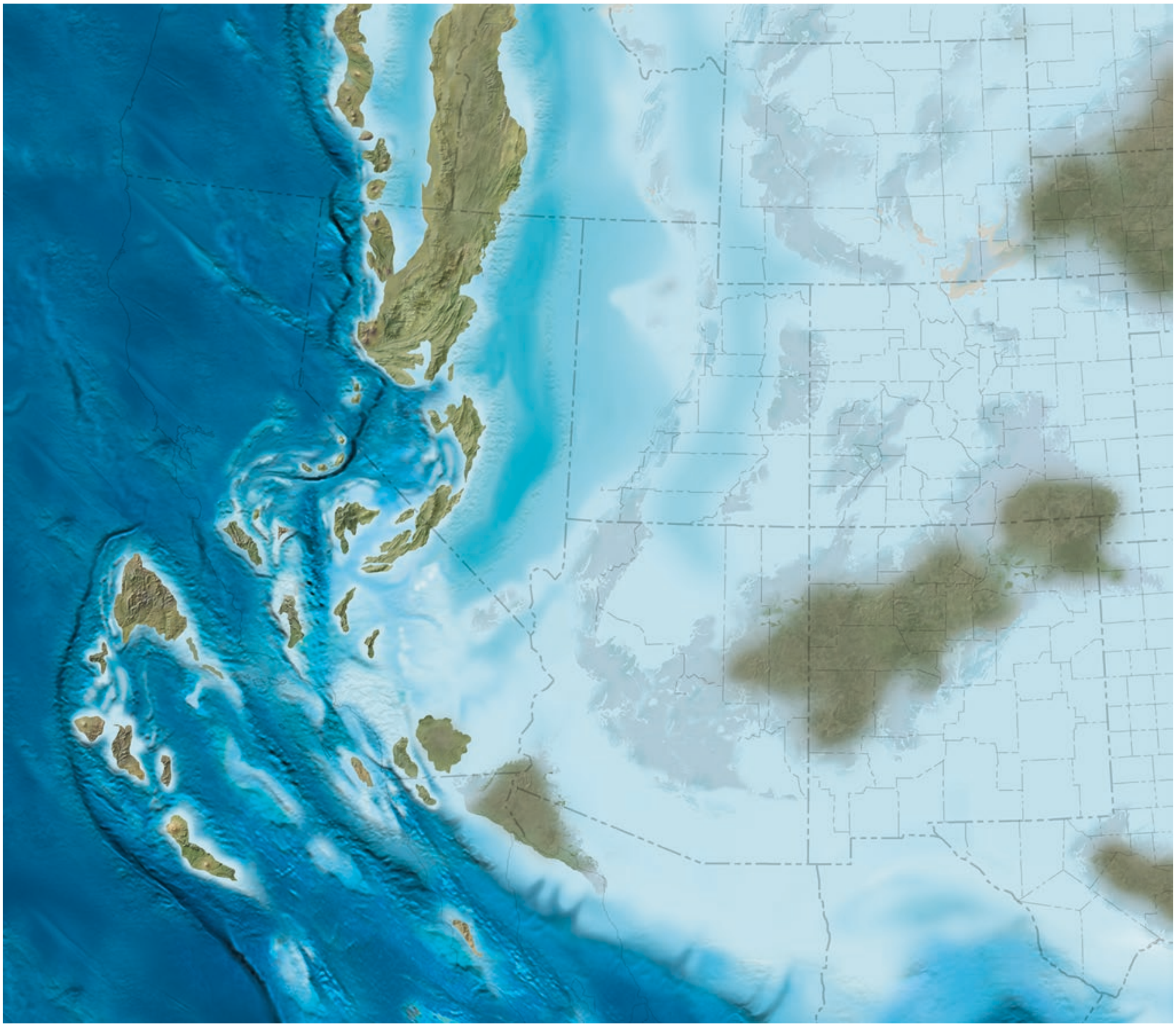


Fig. 5.4 Mississippian paleogeography, *ca.* 340 Ma, of SW North America. Exotic terranes approach and accrete to the previous passive margin. Bits and pieces of these terranes are now exposed in the Northern Sierra Nevada and Klamath Mountains of California. After terrane accretion, subduction switches so that Panthalassa Ocean plates subduct under western North America. Colliding terranes forced continental-margin sediments over previous passive margin forming Roberts Mountain thrust (allocthon). Antler orogen commences and a foredeep basin forms on the continental margin east of the mountain belt. Pure Mississippian carbonates such as Redwall Limestone form on shelf to east

sional collapse occurred parallel to and landward of the subduction. Momentum in the down-going slab apparently exerts a suction action on the overriding plate, causing the crust to extend and collapse. Back-arc basins are commonly found at present in the western Pacific near Japan and the Philippine archipelagos.

As the Antler uplift was further eroded, detritus shed from it was washed into surrounding basins. Continued back-arc pressure caused the Havallah basin in central Nevada to deepen, extending north into Idaho and beyond. The Havallah sequence is 1200 m thick and was named for exposures in the Tobin Range (the Native Indian name for the Range was Havallah). The Slide Mountain sequence of southern British Columbia is equivalent to the Havallah sequence. The margin of Laurentia expanded westward into central and western Nevada after the Antler orogeny.

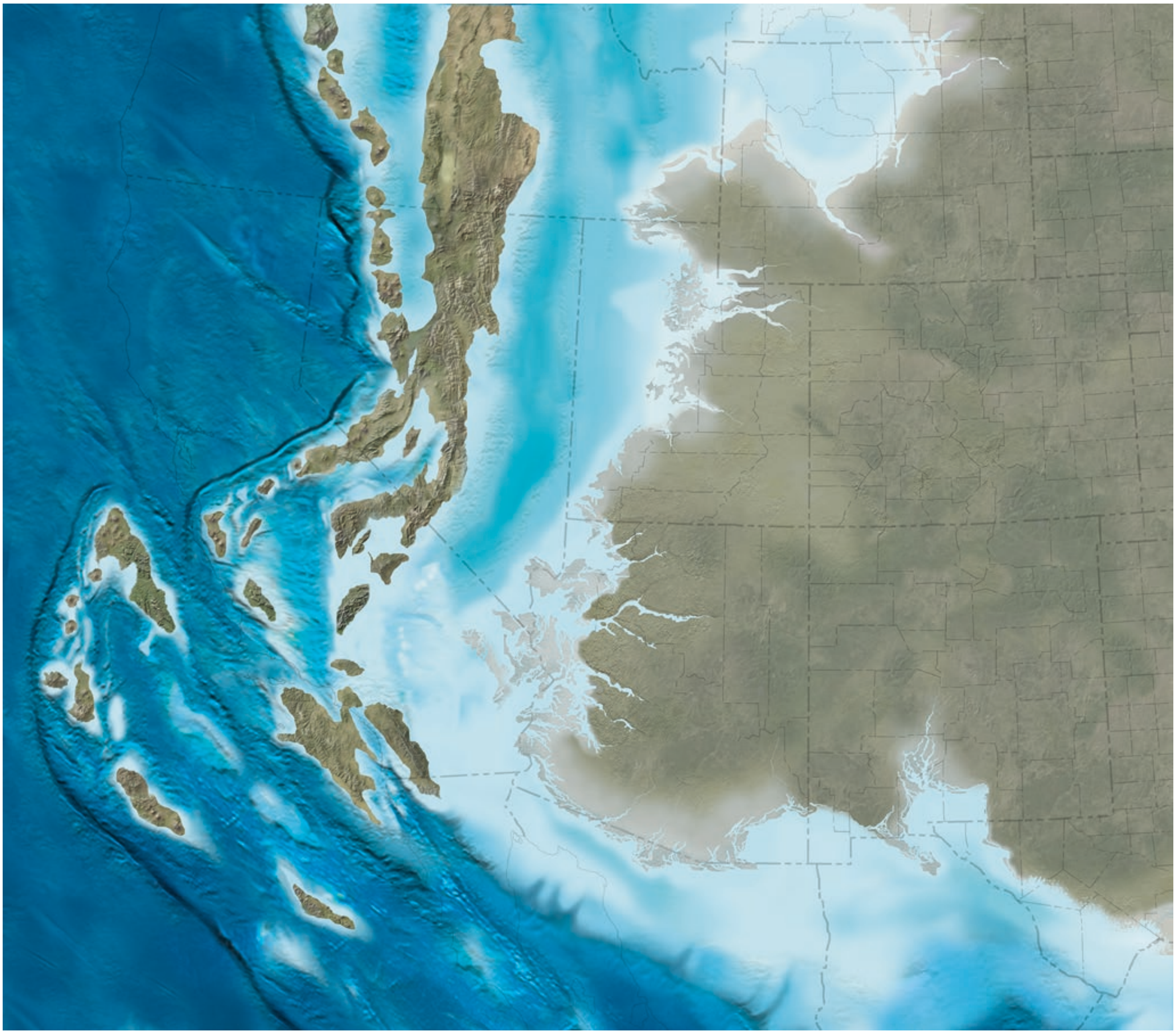


Fig. 5.5 Paleogeography of SW North America at *ca.* 325 Ma (Late Mississippian-Early Pennsylvanian). East-dipping subduction zone has oversteepened and the trench has rolled back to the west. This caused the subduction zone to migrate westward pulling recently accreted terranes away from North America and forming a back-arc ocean, the Havallah basin. Emergent land to east resulted from global sea level fall and emerging tectonic unrest

Table 5.2 Events 340–300 Ma

Time span	Late Mississippian to Late Pennsylvanian (*Ca.*340–300 Ma) Opening of Slide Mountain-Havallah oceans
Geologic – tectonic setting	Assembly of Pangaea
	Ancestral Rockies formed on western craton
	Trench roll-back caused rapid subsidence of Antler Mountains and led to back-arc rifting in Antler hinterland
	Previously accreted terranes rifted and drifted west from NA margin as elongate, west-facing arc complexes (e.g. Quesnell, Stikine, Yukon-Tanana)
	Havallah and Slide Mountain basins opened and formed oceans of uncertain width (100–1000's of kms)
	Rifted margin of NA became passive margin again, although Pennsylvanian compressional events occurred in central Nevada
Boundary of western North America	Rifted margin on eastern Slide Mountain and Havallah oceans
	New margin was parallel to and west of early Paleozoic margin
Terranes	No new terranes added to WNA
	Rifted arcs drifted westward into Panthalassa Ocean
Sedimentation patterns, trends	Shelf – mixed sandstone (abundant eolian) and carbonate; evaporates on W Laurentia indicate aridity
	Miogeocline – mixed clastics and carbonates as much as 8–10 km thick in Oquirrh, Wood River, and Bird Spring basins
	Mixed shallow shelf and deeper water deposition including local turbidites
	Havallah and Slide Mountain oceans – deepwater clastics near NA margin and on backside of rifted terranes
Igneous/metamorphic events	Uncommon – this is great mystery as Ancestral Rockies uplifts broke continental crust. Why no volcanics?

5.4 Assembling Pangaea

During the latter part of the Paleozoic Era, Africa, Europe, and Scandinavia moved towards Laurentia to amalgamate the supercontinent Pangaea. Africa's arrival brought with it the entire assemblage of the *Gondwanan* supercontinent, including Madagascar, India, Australia and Antarctica. Remember that Australia and Antarctica had previously left North America around 1000 Ma in the break-up of Rodinia – these continental blocks subsequently traveled around the Panthalassa Ocean to become part of Gondwana.

From the Late Mississippian through the Early Permian, closing of the Rheic Ocean, an ocean located on Laurentia's southeast quadrant, signaled the arrival of South America against Laurentia. This had huge effects in the western Cordillera – much of Mexico was accreted during this event. Microcontinents, including portions of crust that are now part of modern Central America, were also caught up in this collision. In addition, the basement rocks beneath Florida arrived along North America from their previous location on Gondwana (African portion).

One of the initial mountain-building events in this collision is the *Marathon-Ouchita orogen*, named for rocks in the Marathon basin of west Texas and the Ouchita Mountains in central Oklahoma. Folded strata provide evidence for a collision here but ripple effects were felt in northern New Mexico, Colorado, and eastern Utah. Buckling of the crust caused the uplift of the *Ancestral Rocky Mountains* and the disruption of the long-lived near-shore and shallow marine environments that preceded it (Fig. 5.6). With the uplift, the Paleozoic sedimentary cover was eroded to expose the Proterozoic basement core. The Ancestral Rocky Mountains delivered large amounts of terrestrial, coarse-clastic sediments to the adjoining basins, including the Paradox (southwest) Maroon (central) and Fountain (east) basins. To the south and west of the Ancestral Rocky Mountains, other basins received sediment that graded distally into fine-grained sediment; what you would expect to find the farther away from the mountain front (Fig. 5.7).

Near the end of this interval, most of western North America returned to passive margin conditions, having incorporated the Antler terrane as part of Laurentia. Localized compressional events were still occurring in central Nevada but the larger extent of Laurentia contained a shoreline that ran generally from south to north in western Arizona through central Utah and Wyoming. The stage was set for significant events related to the amalgamation of the supercontinent of Pangaea.

Fig. 5.6 Evidence for the Ancestral Rocky Mountains and continental unrest during the Pennsylvanian. (**a**) The Uncompahgre Uplift in Unaweep Canyon near Grand Junction, Colorado. The Proterozoic schists and gneisses are directly overlain by Triassic and Jurassic sedimentary rocks; the entire Paleozoic is missing here but present a few tens of kms to both the east and west. The Proterozoic rocks were exhumed during the uplift and erosion of the Ancestral Rocky Mountains. (**b**) Pennsylvanian Fountain Formation near Colorado Springs, Colorado is a coarse-grained sandstone and conglomerate shed from the Ancestral Rocky Mountains

Fig. 5.7 Pennsylvanian sedimentary rocks. (**a**, **b**) The Oquirrh Group is a thick (6000 m+) sequence of Pennsylvanian and Permian rocks deposited in the Oquirrh Basin of NW Utah. The rocks were thrust eastward over the craton during the Cretaceous Sevier orogen and later exposed in the Wasatch Mountains near Provo. (**c**) The Bird Spring Basin north and west of Las Vegas, Nevada was another major Pennsylvanian basin. Thousands of meters of Pennsylvanian rocks are exposed in Arrow Canyon. (**d**) The first major flux of eolian sediment entered the Western Interior in the Pennsylvanian. The Weber Sandstone in Dinosaur National Monument, Utah and Colorado is an example

Fig. 5.7 (continued)

6 The Amalgamation of Pangaea and the Sonoma Orogeny: Early Permian to Early Triassic – Ca. 300–240 Ma

6.1 Pangaea

With the amalgamation and assembly of Pangaea in the late Paleozoic, a hypothetical visitor could have traveled entirely by land from the western edge of the supercontinent in Nevada, across Laurentia and the Appalachian crest, to the plains of Eastern Europe, across the Ural Mountains in Russia, and then southward through Africa, India, Australia, and Antarctica (Fig. 6.1). The equator now trended from just south of Arizona through Texas, North Carolina, on to Algeria and out to the Paleo-Tethys Sea, a part of the Panthalassa Ocean.

Such a landmass had huge repercussions on Earth's climate. Across much of North America during the Pennsylvanian Period, a moister sub-tropical climate prevailed and the great coal deposits of Appalachia were formed. The Permian, however, aridified across much of the Pangaea landmass and resulted in widespread desert sedimentation. The worldwide occurrence of red beds in the Permian attest to this fact – red beds form by an interaction of oxygen with iron-rich minerals in sediment that is deposited in areas with an arid climate. These arid conditions persisted throughout the Cordillera region and continued north into the Hudsons Bay area in northeast Canada. Arid conditions were mitigated by the rain shadow of the Appalachian/Caledonian highlands.

As Pennsylvania mosses died out in the increasingly arid climate, seed-bearing plants called *gymnosperms* developed in the Permian. Cicadas and beetles also made their first appearance now. Giant-finned *Dimetrodon* belonging to a large group of reptiles known as *synapsids* roamed the southern Cordillera with fossil remains coming from New Mexico and west Texas. The larger synapsids went extinct at the end of the Permian, a period when the largest known extinction occurred. Up to 96% of marine animals, including trilobites and bryozoans, and 70% of land animals, disappeared in an event that was likely caused by extreme volcanism in Siberia (the Siberian Traps), a possible meteorite impact, a reduction of shallow marine shelves as sea level dropped rapidly, or a combination of factors. The disappearance of the synapsids created a vacuum in the ecosystem to which some even larger reptiles would soon take advantage of.

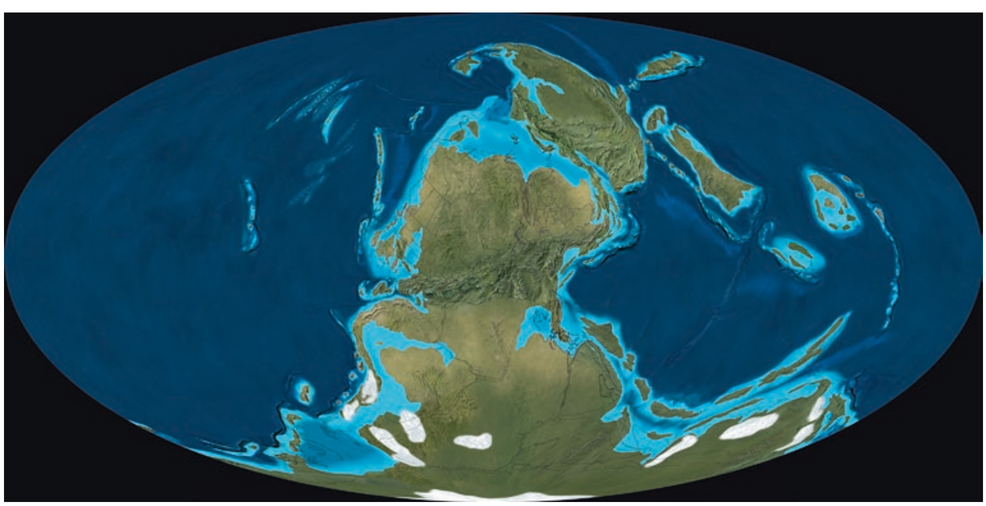


Fig. 6.1 Global view of Pangaea at 300 Ma. Note widespread, extensive mountain ranges in Northern Hemisphere that mark recent continental collisions. Pangaea has two parts, Laurasia to north and Gondwana to south – The Tethys Sea bifurcates the two on the eastern side

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6.2 The Back-Arc Closes: Sonoman Orogeny

At the beginning of the Permian, the Slide Mountain and Havallah basins were the site of shallow seas lying between island arcs and microcontinents to the west of Laurentia (Table 6.1). These microcontinents were peri-continental terranes, previously attached to the continent in the Antler orogeny, but rifted away as the back-arc basins developed Fig. 6.2). As the Permian marched on, the island arcs and peri-continental terranes docked once again with the continent as the back-arc basins began to close (Fig. 6.3). Subduction resumed as the basins closed and the terranes reattached to Laurentia. This event is known as the *Sonoman orogen*, taking its name from the Sonoma Mountains in northwestern Nevada, between Winnemucca and Golconda.

During the Sonoma orogeny, the once flat-lying deposits of the Havallah basin were greatly compressed, folded and deformed. As one can imagine, a frustrating yet ultimately rewarding aspect of doing field geology in areas that are highly deformed is the need to "undo" the effects of these deformation events. This permits an understanding of the original orientation and position of an exotic terrane. Today the Havallah carbonate rocks are much deformed, faulted and smashed, and that deformation had to be "looked through" to understand their originally quiet origins in the Havallah basin. The Havallah rocks were shoved over Laurentia on the back of the Golconda thrust fault. An additional exotic terrane was located west of Sonoma and is known as the McCloud arc, but its volcanic arc rocks would remain offshore of Laurentia until accretion later in the Jurassic.

A key point to note in these musings about exotic terranes is the idea that terranes can accrete to one another well before they accrete to the continent. The Cache Creek, Stikine and Quesnell terranes, and the Intermontane superterrane, in British Columbia serve as an example (Table 1.2). The Cache Creek Ocean was formed in the Permian but contains fossils that show affinities to the *Paleotethys Sea* halfway around the world near southeast Asia. Therefore, some of the Cache Creek terrane, probably rocks that originated on oceanic plateaus in the Paleotethys, was incorporated into rocks now present in British Columbia that were initially formed over 7,500 km distant; the journey took about 50 million years. While on the move, the embedded plateaus and the Cache Creek Ocean attached to the Stikine and Quesnell terranes; the resulting Intermontane superterrane accreted to North America in the Jurassic. This important insight has helped geologists understand the complexities of how accreted terranes traveled, evolved, and arrived in the Cordillera.

Table 6.1 Events 300–240 Ma

Time span	Early Permian to Early Triassic (*Ca.* 300–240 Ma) Second terrane accretion event and Sonoman orogen
Geologic – tectonic setting	Broad ocean basins – Slide Mountain to north and Havallah to south began to close in early Permian
	Offshore terranes included blocks that were previously accreted to North America during Antler orogen and later rifted away as ocean basins widened
	During Permian, these terranes drifted back towards east to approached the west edge of North America
	Complex, controversial subduction patterns; some models have subduction zones dipping west and others have them dipping east towards the continent – likely some subduction reversal
	Terranes closed and collided with western North America to generate Sonoman orogen. Intervening deep-water sediments of Havallah Ocean were thrust over WNA (Golconda allocothon); this pattern reminiscent of older Antler orogen
	As orogen progressed, subduction jumped outboard of the accreted terranes (Sonomia to south and Quesnellia to north) and dipped eastward under North America – McCloud Arc
	This fundamental change in tectonic processes laid the foundation for development of the Cordilleran arc
	Most major ensuing subduction throughout the Mesozoic and Cenozoic was east-dipping
	During Permian, SW NA was truncated by transform fault that transported a large fragment to the SE to become the Caborca terrane of W Sonora MX – distance of movement controversial
Boundary of Western North America	Early in interval, WNA was passive margin separated by ocean crust from terranes to west – width of oceans not well constrained
	Following terrane collision, subduction jumped to west under accreted terranes and boundary evolved to subduction zone that dipped under WNA
	Offshore fringing arc remained offshore along US portion of margin – McCloud arc
Terranes	Closing of Slide Mountain-Havallah ocean docked several terranes, including some previously docked in Antler orogen
	In Canada, there is strong evidence that the accreting terrane doubled back on itself (an oroclinal bend) trapping the Cache Creek Ocean between Quesnell to east and Stikine to west
	Some of these terranes were repositioned, mostly via transform movements, during Mesozoic and Cenozoic events
	Present locations from S-N: CA – Northern Sierra, Eastern Klamath; NV – Black Rock; OR-WA – Izee; Olds Ferry, Canada – Kootenay, Quesnell, Stikine, Yukon-Tanana

Table 6.1 (continued)

Time span	Early Permian to Early Triassic (*Ca.* 300–240 Ma) Second terrane accretion event and Sonoman orogen
Sedimentation patterns, trends	Craton and craton margin: mixed clastic and carbonate deposits; redbeds and eolian sediments dominate Permian with redbeds grading west into carbonates during Triassic
	Thick clastic and carbonate deposits in miogeoclinal basins of ID, UT, and NV
	Cordilleran margin: varied, mostly deepwater, commonly chert-rich with volcanic-rich clastics
	Cache Creek assemblage: the Cache Creek is a complex trench, accretionary prism, melange, and oceanic sequence that accreted to WNA during and after Sonoman orogen; in Canada, it forms a terrane sandwiched between Quesnell and Stikine terranes
	Scattered amongst the various terranes are blocks of shallow water limestone (McCloud Ls of Klamath Mountains), some with Permian fossils exotic to NA
Igneous/metamorphic events	Arc-related volcanism was present throughout much of the Cordillera
	Permian and Triassic plutons are present in S CA and adjacent MX

Fig. 6.2 Most of North America at *ca*. 300 Ma (Pennsylvanian). North America suffered collisions from all sides as Pangaea was assembled. The Slide Mountain Ocean opened as back-arc spreading severed major terranes. Note eolian dune fields across much of Western Interior

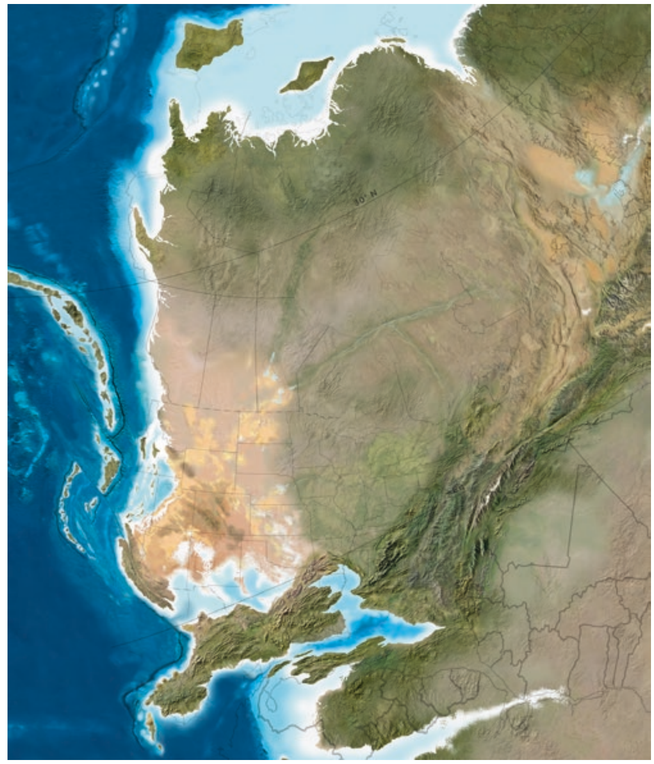

Fig. 6.3 Western North America *ca*. 280 Ma (Early Permian). Slide Mountain and Havallah oceans shrink as subduction reversal returns rifted terranes to North America. Quesnell, Yukon-Tanana, and Stikine at west edge of map will comprise the Intermontane superterrane. Islands to their south, today form various terranes in Sierra Nevada and Klamath regions. Dunes and redbeds blanket much of western North America

6.3 Sedimentation Across an Arid Landscape

The Permian landscape was varied and marked by extreme aridity – the Ancestral Rocky Mountains dominated the Cordilleran landscape to the east and the Sonoma arc rocks in the west. The Permian Cutler Group of western Colorado and eastern Utah (Fig. 6.4) are part of this package, grading southwest into various fluvial and eolian units in northern Arizona. To the southeast in New Mexico and Texas, Permian seas generated an immense reef that later desiccated as the Permian seas retreated and vast evaporate flats covered much of the Southwest.

As the Permian waned and the Triassic appeared (Fig. 6.5), much of the Western Interior from Alberta to Arizona was a vast arid plain that lay at sea level, with only remnant uplands of the eroded Ancestral Rockies to break the monotony (Fig. 6.6). Vast river systems and coastal

Fig. 6.4 Permian rocks of western North America. (**a**) Dark redbeds and lighter eolian sandstones comprise the Cutler Group in Southeastern Utah along upper Glen Canyon. The uppermost Permian sandstone forms the bench atop the foreground mesa at right. In the background, Triassic and Jurassic rocks are present. (**b**) Permian limestone reef forms the prominent butte in the Guadalupe Mountains. The reef advanced over offshore, deeper water limestone and mudstone in the foreground. (**c**) Thick Paleozoic sedimentary rocks west of Grand Canyon deposited along Wasatch Line. Note onlapping Miocene sediments at right that at one time probably buried the ridges in the foreground

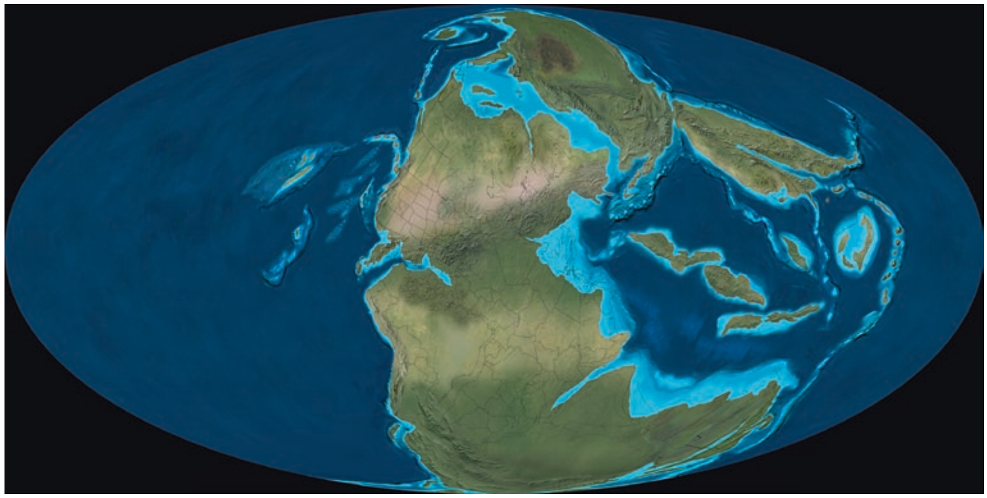

Fig. 6.5 Global paleogeography of the Pangaean Earth at *ca.* 250 Ma (Permian-Triassic boundary). Large, dark mass in Siberia at top of globe is the Siberian traps, one of the largest volcanic fields on Earth

Fig. 6.6 Early Triassic (*ca.* 245 Ma) paleogeography of western North America showing oroclinal bend that developed when Slide Mountain Ocean closed. The ocean between the closing limbs is called the Cache Creek Ocean and today forms the controversial Cache Creek Terrane. The collision generated a significant orogeny across Western Canada that is equivalent to the Sonoman Orogeny in the US. The subduction zone and arc in S Ca and W Az and into Mexico marks the nascent Cordilleran arc. Much of the Western Interior is blanketed by fluvial and coastal plain redbeds of the Moenkopi Formation and equivalent rocks

plains were the sites of some of Earth's most extensive red bed deposits. In this harsh system that deposited the Moenkopi Formation (Fig. 6.7a) and other red beds, the ancestors to both the dinosaurs and mammals developed and evolved. An inland sea expanded into Idaho, Utah, and Nevada (Fig. 6.7b) and in this sea and others like it around the globe, mollusks flourished and became the dominant marine invertebrate group for the Mesozoic and Cenozoic, and replaced the decimated groups at the end-of-Permian extinction.

Meanwhile farther west in the Cordillera, the Sonoman orogen climaxed as terranes accreted to the western margin. The Sonoman orogen, tectonically very similar to the older Antler orogen, was more notable for its rearrangement of the tectonic setting of western North America than for its mountains. In fact, by the Late Triassic, most of the mountains had subsided and many were covered by Upper Triassic and Jurassic marine deposits. Overall, the time surrounding the Paleozoic-Mesozoic boundary was not a quiet interval but more tectonic excitement was on its way.

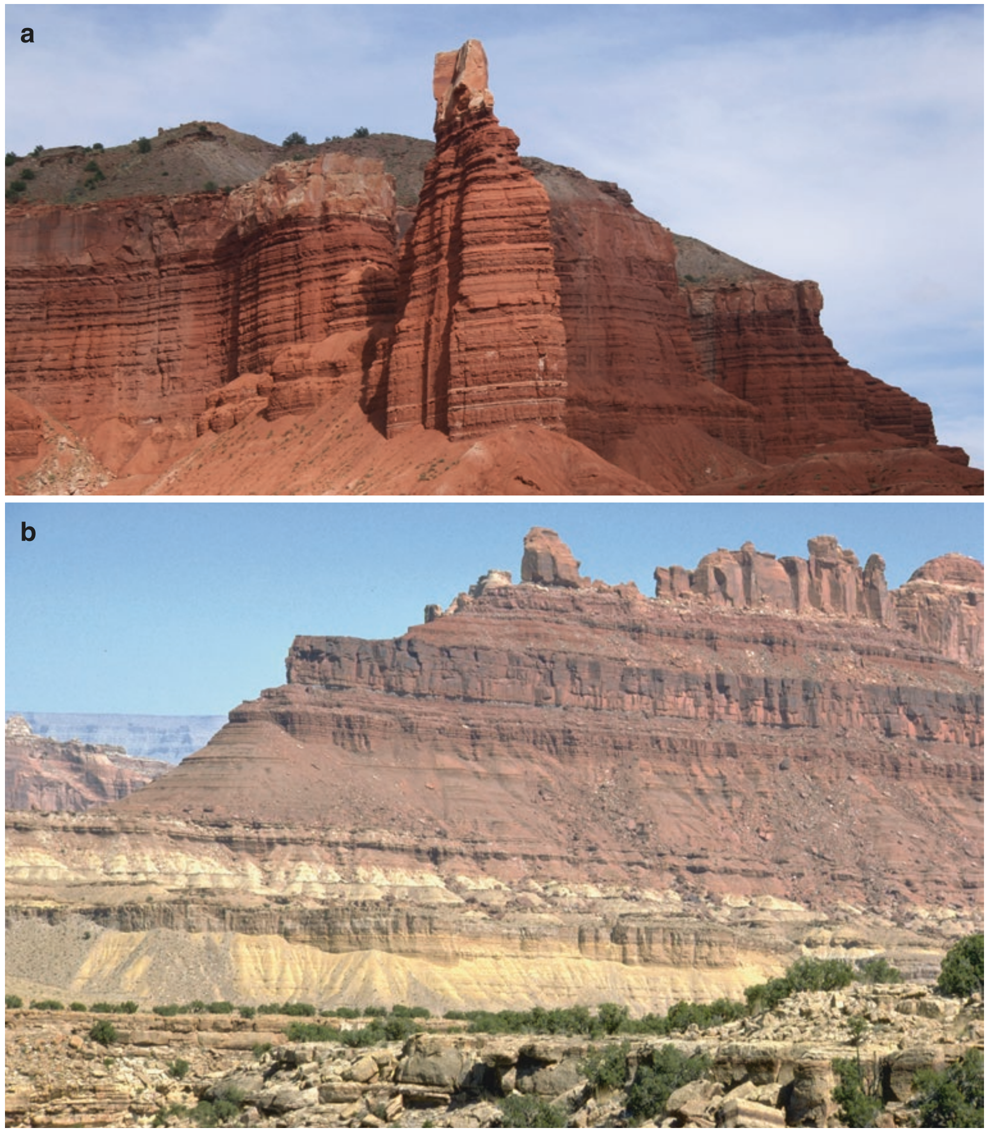

Fig. 6.7 Triassic redbeds and limestone on the Colorado Plateau. (**a**) Lower and Middle Triassic Moenkopi Formation in Capitol Reef National Park, Utah. Most deposits seen here formed on an arid coastal plain. Upper Triassic Shinarump Conglomerate Member of Chinle Formation caps the pinnacle. (**b**) The entire Moenkopi Formation in the San Rafael Swell, Utah consists of marine limestone and mudstone in lower part (tan units) and deltaic and coastal plain deposits (redbeds) above. *Dark red* cliff marks base of Chinle Formation; Jurassic rocks form upper cliff

The Arrival of Wrangellia and the Nevadan Orogeny: Late Triassic to Late Jurassic: Ca. 240–145 Ma

7

7.1 Introducing the Cordilleran Arc and Subduction Zone

The accretion of the Antler and Sonoma terranes in the Cordillera during the Paleozoic and Early Triassic was merely a prelude to the number of terranes and the scale of activity that would occur during the Mesozoic. Pangaea achieved its greatest extent around 250 Ma but not all of Earth's continental crust was attached to it. Perhaps up to 15 % of the planet's continental make-up existed as detached microcontinents, lying in the warm tropical waters of the Paleotethys Sea or Panthalassa Ocean. Some of these microcontinents would ultimately make their way to North America, arriving as terranes that resulted in large orogenic events. The fragmentation of Pangaea, ultimately yielding the various continental fragments that are familiar shapes on a globe today, signals a worldwide plate reorganization that brought on these changes. Included in this reorganization is the birth of the Atlantic Ocean as Africa and Europe drifted eastward, and the opening of Gulf of Mexico when South America drifted south (Table 7.1 and Fig. 7.1).

When the breakup of Pangaea initiated, North America began a westward drift that continues to this day initiating subduction along its western margin (with the breakup, Laurentia as a paleographic term is a thing of the past and will not be used going forward). The earliest Cordilleran arc is now known to be Permian in age based on igneous rocks in parts of Central and Southern California and Sonora, Mexico. The arc grew during the Triassic Fig. 7.2) – arc-derived sediment is known from the Upper Triassic Chinle Formation in Petrified Forest, Arizona. By Early Jurassic, the arc was a dominant structure at the margin of SW North America (Fig. 7.3) reaching northward towards Idaho and the Canadian border, perhaps joining the developing arcs of British Columbia. During the early history described above, the immense Panthalassa Ocean was subducted under North America, including its most infamous embayment, the Cache Creek Ocean with its Tethyan fauna. The Cache Creek Ocean closed in the Early to Middle Jurassic when Stikine accreted to Quesnellia to form the Intermontane superterrane (Fig. 7.4). Figures 6.2, 6.3, 6.6, 7.2, 7.3, and 7.4 illustrate the complex assembly and accretion of the Intermontane Superterrane.

However, following closure of the Cache Creek Ocean, a new player entered the scene from the west – this new plate comprised the largest plate on Earth at the time, the *Farallon* plate, named after the present day islands located 45 km offshore from San Francisco. Subduction of the Farallon plate is arguably the single most important event in the evolution of the present day North American Cordillera; all accreted terranes that attached to North America since the Late Triassic have come on the back or leading edge of the Farallon plate. Its arrival was sometime in the Jurassic. Our maps follow recent plate models that suggest that the incoming Wrangellia and Guerrero Terranes were on the leading edge of the Farallon Plate. As Wrangellia approached and accreted to the Cordilleran margin, subduction was directed eastward under Wrangellia and the Farallon Plate commenced its long history of subduction. Farther south, as Guerrero accreted to Southern California and Mexico, subduction jumped outboard of Guerrero and the Farallon Plate also dipped eastward. Thus, by Early Cretaceous, all Cordilleran subduction was eastward-dipping under North America.

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Table 7.1 Events 240–145 Ma

Time span	Late Triassic to Late Jurassic (*Ca.* 240 Ma – 145 Ma) Fringing arcs, initial docking of Wrangellia, and Nevadan orogen
Geologic – tectonic setting	Time of plate reorganization as rifting marks birth of the Atlantic Ocean and opening of Gulf of Mexico
	Most of NA is above sea level during Late Triassic and Early Jurassic
	Growth of the Western Interior Seaway extended into Utah by the Middle Jurassic
	Major development and expansion of Cordilleran arc; arc was built on cratonic NA in Arizona but was an offshore marine arc farther north. Cordilleran arc in the US probably correlates with arc built on Stikine off coast of Canada
	The Cordilleran region is marked by a series of poorly understood fringing arcs outside of (west) the Cordilleran arc. The geometry, location, polarity, and history of the fringing arcs are uncertain. The oceanic crust between them formed several ophiolite sequences in CA and OR as the arcs collapsed and accreted to NA in the Late Jurassic. This accretion, probably in concert with the collision of Wrangellia, is thought to be responsible for generating the Nevadan orogen
	Arc accretion occurred when Wrangellia (aka Insular) collided with western North America; initial collision was with fringing arcs followed by accretion to NA contininent.) first with the fringing arcs and then with the margin of WNA
Boundary of western North America	Complex and rapidly evolving – perhaps analogous to the complex history and evolution of arcs and continents in Cenozoic of SW Pacific.
	Cordilleran arc extended from SW MX to C NV as a continental Andean-style arc but graded northward into a Japan-style marine arc
	To the north, Stikine was bordered by an arc-subduction complex, the Bridge River
	Unclear whether Cordilleran and Stikine arcs were continuous. The maps herein show them offset by transform
	Trench system that bordered this arc system marked the boundary of NA until Wrangellia collided late in interval
	The accretion of the Coast Range ophiolte caused a westward jump in the Cordilleran subduction zone
	As Wrangellia approached WNA, it bulldozed through the fringing arcs and eventually accreted to NA greatly modifying the margin
Terranes	Intermontane Superterrane (Quesnell, Cache Creek, Stikine, and Yukon-Tanana) was fully assembled and docked with NA by the Middle Jurassic
	Insular Superterrane, Wrangellia, Alexander, and several minor terranes, initially collided in the Late Jurassic
	Collision initiated along southern terrane margin and then closed northward through early Cretaceous
	Merger of southern margin of Wrangellia with fringing Jurassic arcs created a complex terrane assemblage referred to as Baja BC
Sedimentation patterns, trends	Western NA craton, typified by the Colorado Plateau region and vicinity, was site of extensive eolian sedimentation throughout much of interval (e.g. Navajo Ss)
	Both fluvial and marine deposits are sandwiched between eolian intervals
	Jurassic sedimentary rocks are generally absent across the central Cordilleran region but widespread to the west
	Sandstone and limestone was deposited across western NV in marine shelf and basin settings
	Forearc basin was site of mostly deepwater sandstone and mudstone deposition with local interbedded volcanics – oldest Great Valley units are Late Jurassic
	Trench accumulated deepwater sand and mud commonly tectonically mixed – melange – oldest Franciscan complex is Jurassic
	Fringing arcs and basins between them were sites of deepwater sandstone, mudstone, chert, and volcanics
	Several ophiolite (oceanic crust assemblages) sequences are preserved across western Cordillera
Igneous/metamorphic events	Continental arc rocks across W AZ, S CA, and S NV consist mostly of rhyolite and granite
	Jurassic plutons and volcanics continue northward through the Sierras into British Columbia
	Scattered plutons and volcanics mark various fringing arcs
	Metamorphism is widely associated with larger plutons in the arc and within the subduction zone
	Metamorphic events occurred across much of region during Nevadan orogen

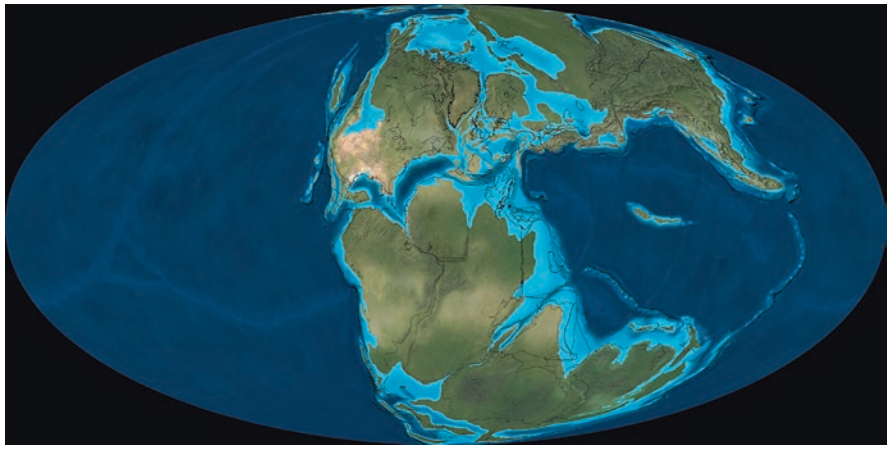


Fig. 7.1 Global paleogeography at *ca*. 160 Ma. The opening of the Central Atlantic Ocean and Gulf of Mexico signaled the beginning of the end of Pangaea. The bright area in the SW US marks the location of Middle Jurassic ergs – Entrada Sandstone adjacent to Western Interior Seaway

Fig. 7.2 Western North America during Late Triassic (*ca.* 220 Ma). Large rivers drain Eastern North America to deposit Chinle and related formations across Western Interior

Fig. 7.3 Early Jurassic (*ca.* 180 Ma) Paleogeography of western North America. The gigantic Navajo erg covers much of the Western Interior from Wyoming to Arizona and spills westward into the Cordilleran arc. The map shows the Intermontane folding in on itself closing the Cache Creek Ocean between the two limbs (see also Figs. 7.4 and 7.5), Stikine to west and Quesnell to east with Cache Creek Ocean between. The McCloud arc lays to the south. Two exotic terranes, Guerrero to south and Insular Superterrane to north approach western continent in Jurassic and accreted in Jurassic and Cretaceous

Fig. 7.4 North America showing hypothetical arrangement of complex arcs and terranes *ca.* 170 Ma (Middle Jurassic). Cordilleran arc generated voluminous volcanic and plutonic rocks. Off-shore fringing arcs of uncertain geometry and polarity accreted in Late Jurassic Nevadan orogen. Guerrero arc and Insular Superterrane (just off *upper left* of map) collided first with fringing arcs and then accreted to North America in Late Jurassic and Cretaceous. Widespread Jurassic ophiolites formed in the complex oceanic setting and were obducted onto North America during terrane accretion. Note embryonic Central Atlantic Ocean and Gulf of Mexico

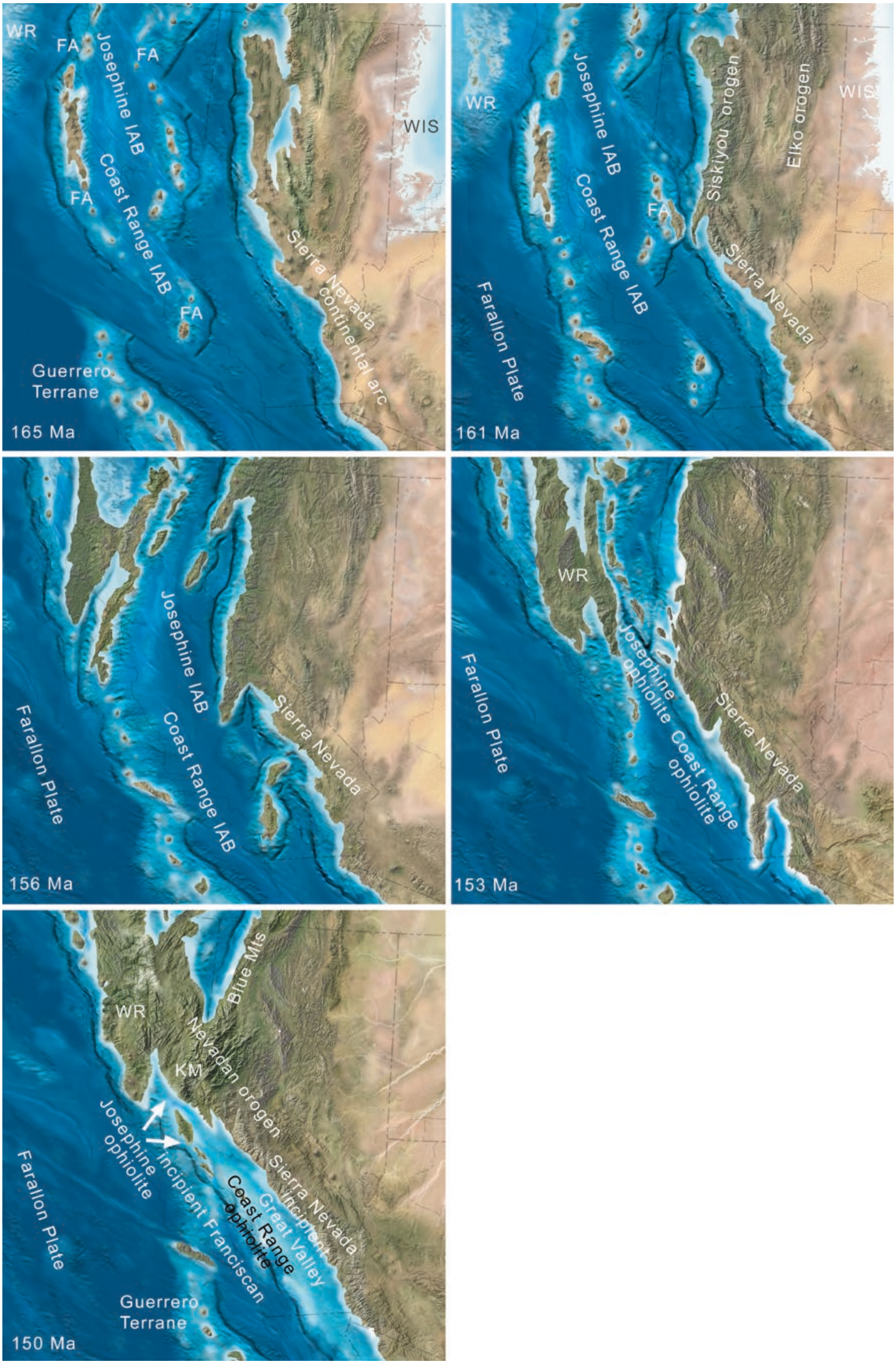
7.2 The Continental Arc

Given this broad introduction to the Cordilleran Arc, we now focus in on some of the details that illustrate its development. During the Late Triassic and Jurassic, the descending slab was heated at depth and partially melted to produce arc volcanism at the surface. The continental arc (the surface expression) existed as a line of silica-rich volcanoes that stretched along the edge of the continent from Sonora Mexico to northern Nevada, parallel to the trench located offshore. This setting was like the modern-day Andes Mountains and the coupled offshore Peruvian trench in South America. North of Nevada and into British Columbia, the volcanic arc trended offshore but was likely connected to the continental arc in the south. A complex set of fringing arcs was also present offshore of the Cordillera; although they would end up as part of the continent, their geometry and history is uncertain.

The subduction and continental arc setting continued unabated into the Middle and Late Jurassic. A protracted interval of subduction can alter the continental margin. First, voluminous plutonic and volcanic material generate new continental crust. The hot new crust pushes against and rises through pre-existing rocks creating deformation and metamorphism of the older rocks. Second, incoming terranes collide with and deform the continental margin. Either or both processes generate orogen. The first such event in the Cordillera occurred in the Middle Jurassic and resulted in thrusting and metamorphism near Elko, Nevada and is called the Elko orogen. Events farther west in Oregon are called the Syskiyou orogen. Thrusting depressed the crust to the east creating a subsiding basin in Utah and Idaho called the Utah-Idaho trough. The earliest marine incursion of the Western Interior Seaway deposited thick Jurassic sediments there.

This event was followed by a larger, more widespread deformation known as the *Nevadan orogeny.* This major mountain building episode was most pronounced between about 160 and 150 Ma (Fig. 7.5) and produced the first important and volumetrically extensive plutonic and extrusive rocks in the western Cordillera. Many of the granite batholiths in the Sierra Nevada were formed during this event. Jurassic arc-generated rocks range from Baja, Sonora, western Arizona, southern California and southern Nevada northward into British Columbia (Fig. 7.6). These granite intrusions in conjunction with compression led to metamorphism of the surrounding rocks – Jurassic metamorphic rocks are widespread across the Cordillera.

Fig. 7.5 Paleogeographic time slices of SW North America showing possible sequence of events during Middle and Late Jurassic. The maps show the hypothetical, complex, and controversial accretion of arcs and terranes, the accretion of Wrangellia, and the accretion/obduction of the Coast Range and Josephine ophiolites. See Figs. 7.2, 7.3, and 7.4 for the broader picture. 165 Ma – Interarc spreading between Jurassic fringing arcs (*FA*) opens an obliquely spreading ocean – the basins in which the major ophiolites will form (IAB). 161 Ma – Accretion of arcs and/or a stronger coupling between the subducted and overlying plate generate the Siskiyou and Elko orogens. Note the closing of Wrangellia (*WR*). 156 Ma – Wrangellia collides with the outermost fringing arcs driving the closure of the interarc basins. 153 Ma – The Josephine and Coast Range ophiolites begin to collide/obduct with the Cordilleran margin. There is lack of agreement as to whether the collision of Wrangellia helped drive the Nevadan orogen; it is also unclear as to whether the ophiolite obduction could generate such an orogeny by itself. 150 Ma – The ophiolites are accreted/obducted and the subduction zone jumps 50–100 km west of its previous location. The ophiolite forms the basement for the Great Valley sequence and accretion outside the trench initiates Franciscan events. The Guerrero Terrane will accrete in the Early Cretaceous creating similar tectonic elements farther south. Note that the Blue Mountains, Klamath Mountains (KM) and Sierra Nevada are much farther south than their present locations


WR
FA
Josephine IAB
FA
WIS
FA
Coast Range IAB
Sierra Nevada continental arc
FA
Guerrero Terrane
165 Ma
WR
Josephine IAB
Siskiyou orogen
Elko orogen
WIS
FA
Coast Range IAB
Sierra Nevada
Farallon Plate
161 Ma
Josephine IAB
Farallon Plate
Coast Range IAB
Sierra Nevada
156 Ma
WR
Josephine ophiolite
Farallon Plate
Coast Range ophiolite
Sierra Nevada
153 Ma
Blue Mts
WR
Nevadan orogen
KM
Josephine ophiolite
Incipient Franciscan
Coast Range ophiolite
Incipient Great Valley
Sierra Nevada
Farallon Plate
Guerrero Terrane
150 Ma

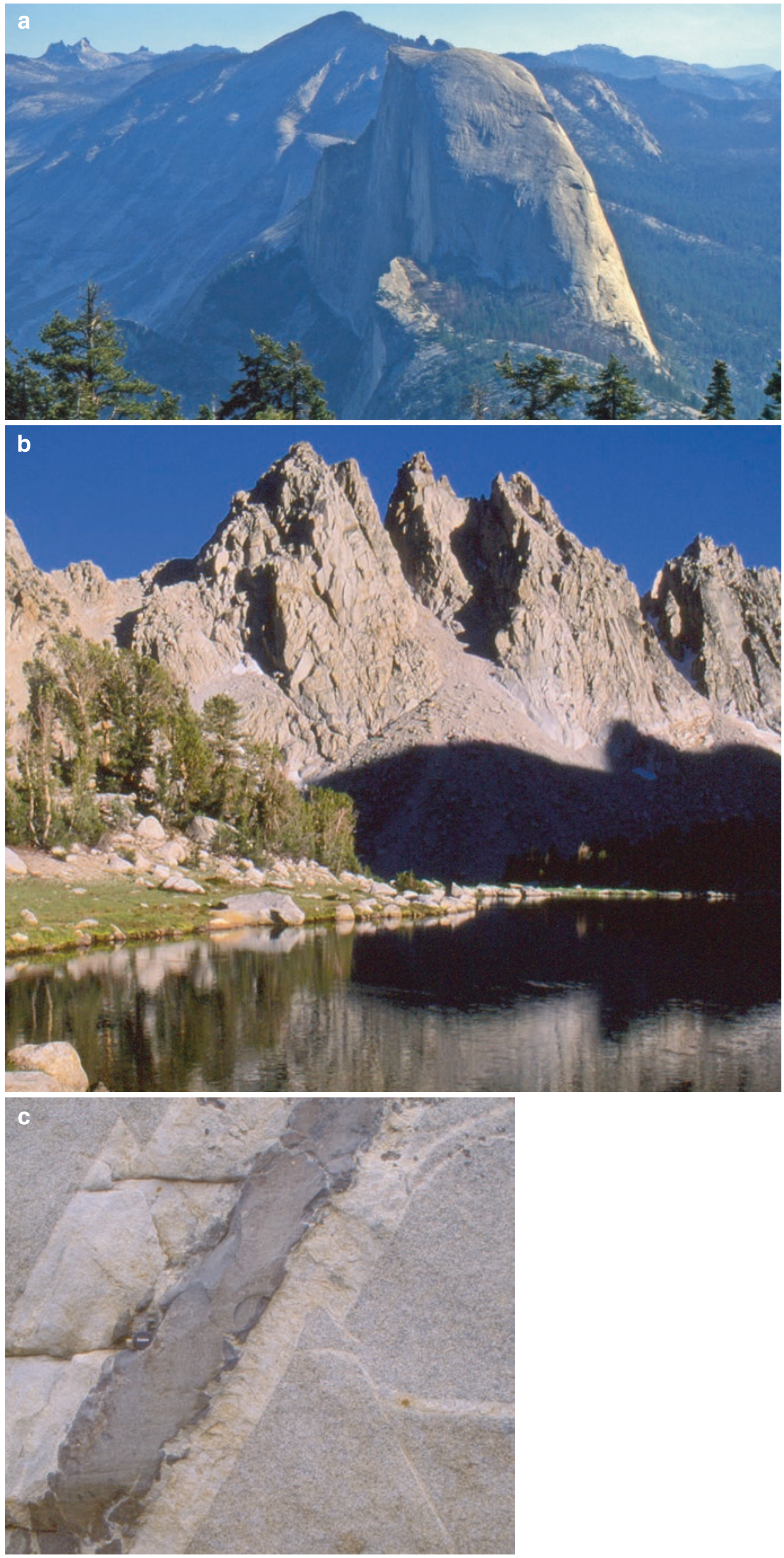
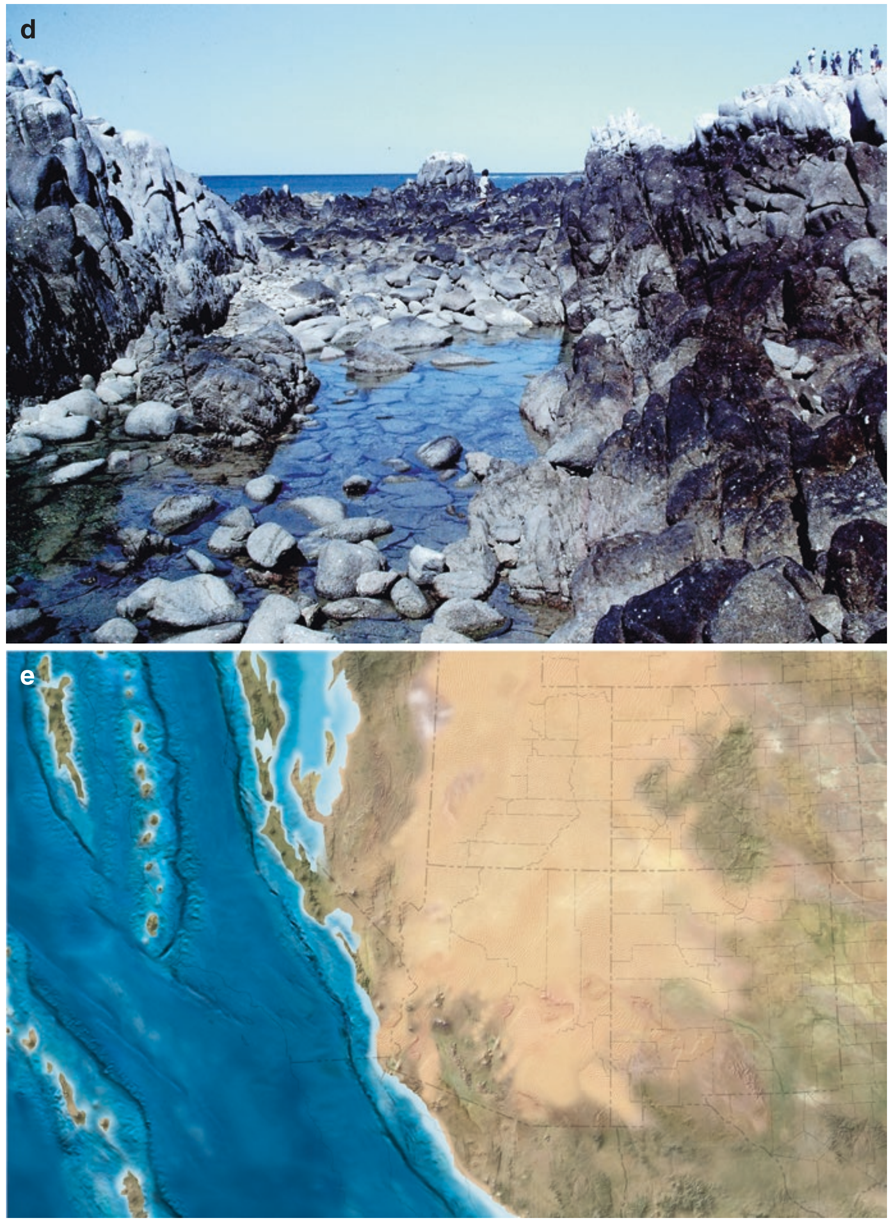


Fig. 7.6 Plutonic rocks of the Cordilleran arc. The oldest large plutons in the Cordilleran region are Jurassic. (**a**) Half Dome, Yosemite National Park. (**b**) High Sierras. (**c**) Dike in Sierras showing several stages of intrusion and cooling. (**d**) Jurassic pluton at Rocky Point, Sonora, Mexico. (**e**) Detailed paleogeographic map showing SW extent of Early Jurassic Navajo erg interfingering with Cordilleran arc volcanics. These relations are preserved in S Arizona and E California where eolian deposits of the Jurassic Aztec Ss are interbedded with Lower Jurassic volcanic rocks

Fig. 7.6 (continued)



7.3 A Myriad of Oceanic Arcs

In the north, the arc was built on the assembled pieces of Quesnell, Cache Creek, Stikine, and Yukon-Tanana, which by Middle to Late Jurassic were firmly attached to western North America. Termed the Intermontane Superterrane, its original latitude was northern Oregon, at least on its southern margin, hundreds of kms south of present locations (Fig. 2.1). As it collided with the continent in the Middle Jurassic, *ca.* 170–160 Ma, a major event occurred to the south as several slivers of ocean crust were obducted onto the continental margin in Oregon and California to form the Coast Range Ophiolite (Fig. 7.7). Recall that obduction is the inverse of subduction with ocean crust riding up and over the edge of the continent. Controversy still surrounds its origin and method of obduction, but consensus remains that this ophiolite formed the floor of the Late Jurassic and Cretaceous forearc basin in which the Great Valley sequence was deposited. The five time slices shown in Fig. 7.5 illustrate one of the plethora of models used to explain these events.

7.4 New Exotic Terranes

Following accretion of the Coast Range Ophiolite, another important event followed – the arrival of the superterrane called Wrangellia. Named for excellent exposures in the

Fig. 7.7 Large blocks of the Coast Range Ophiolite encased in Franciscan melange near San Simeon, California. The ophiolites yield Jurassic radiometric ages and the Franciscan here has been dated as Upper Cretaceous. The interpretation is that blocks of the ophiolite were exposed east of the trench and were incorporated into the Franciscan as jumbled, semi-coherent blocks called olistostromes. Presumably the blocks slid and tumbled through thousands of feet of water to reach the trench (see Fig. 2.8, *slumps*, for a possible setting). (**a**) Overview of outcrop. (**b**) Close-up of pillow lavas, a common element in ophiolites

Wrangell Mountains of southeast Alaska, it was one of the first terranes not only to be recognized, but known to be exotic to North America as well. As the concept of exotic terranes was first perceived in the 1970s and early 1980s, Wrangellia was a kind of poster child for suspect terranes and as such may be the most famous of all the Cordilleran terranes. (At a professional conference in 1983 we remember the speaker showing a photograph of a helicopter sitting on a remote mountain pass in Alaska. Completely different rock types were obviously present on either side of the pass and the speaker only half jokingly said, "The throw on the fault here is about 7,500 kms")! As Wrangellia moved east, it attached first to other fringing arcs and ultimately collided with the continent to create a complex terrane assemblage that some geologists refer to as *Baja British Columbia* (Figs. 7.8 and 7.9; more about this in the next section). Today, remnants of Wrangellia lie mostly along the outermost portions of the continents' edge in the Wrangell Mountains of Alaska and on Vancouver Island, British Columbia. Related rocks outcrop in Hells Canyon, Idaho but their relationship to the main Wrangellia terrane remain uncertain.

Far to the southwest in Mexico, a terrane known as Guerrero approached the ancient coastline taking its name from the nearby Mexican state (Fig. 7.5). This terrain is a composite of smaller terranes that may have been built in the Panthalassa Ocean during a period of volcanism in a back-arc basin, before it docked as a composite terrane with the mainland. Two opposing hypotheses are proposed for the origin of Guerrero. The first postulates formation as an arc either on or adjacent to western Mexico. Backarc spreading drove the arc into the incoming Farallon Plate which then accreted Guerrero to the mainland. The second hypothesis suggests that Guerrero formed as an oceanic island arc like the Mariana Arc, likely on the leading edge of the Farallon Plate. Backarc spreading as seen today in the Mariana Arc likely complicated the assemblage. The arc complex obliquely collided with Mexico and Southern California into portions of the existing Cordilleran Arc. In either scenario, the

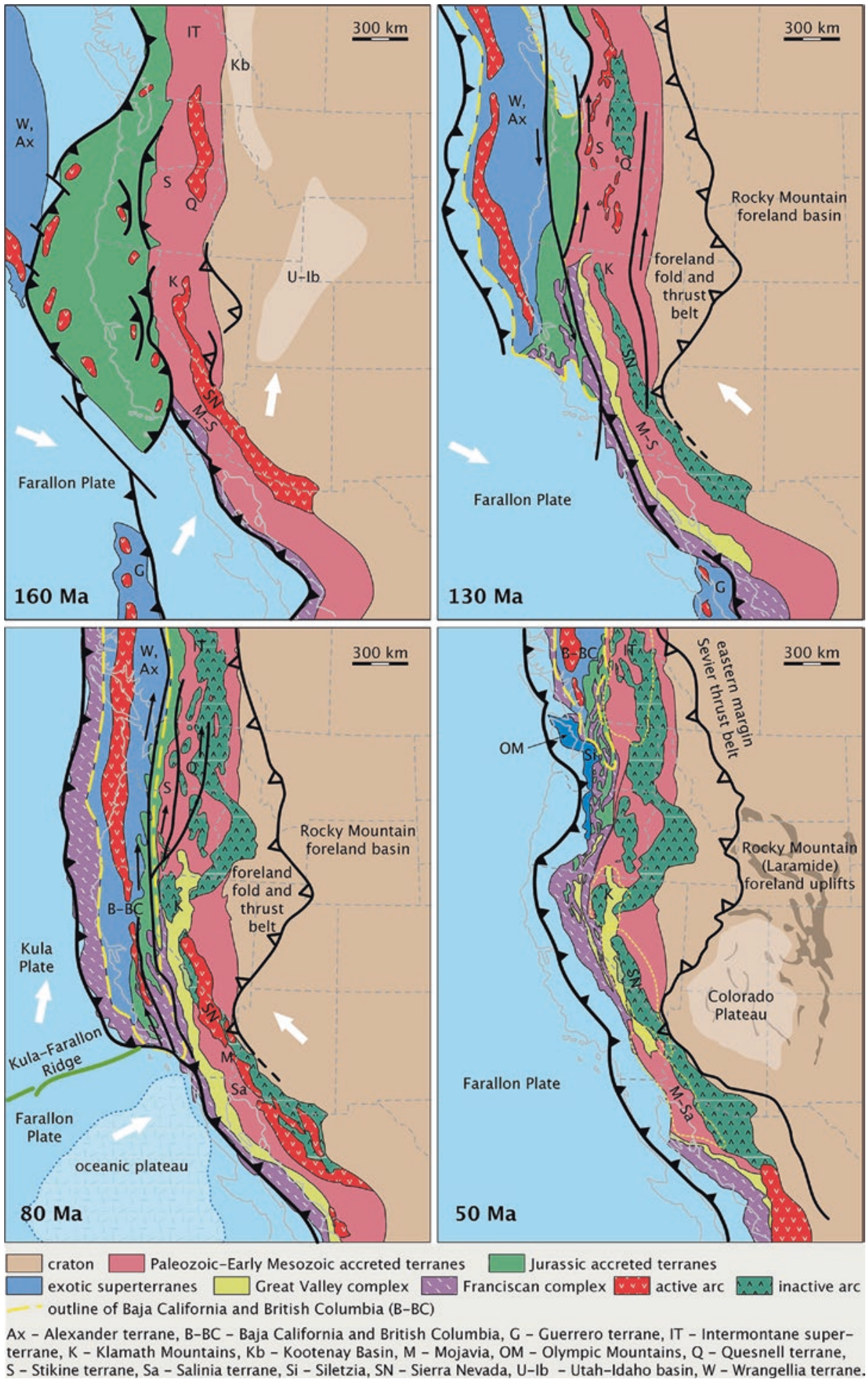


Fig. 7.8 The complex journey of Wrangellia and Baja BC. Paleotectonic/paleogeographic maps showing evolution of Cordillera, with emphasis on Wrangellia/Baja BC, from Middle Jurassic to Early Eocene. **160 Ma** – Wrangellia collides with several fringing volcanic arcs that bounded western North America; this collage formed the nucleus of Baja BC. **130 Ma** -. *Left*-oblique collision welds Wrangellia, Baja BC; note sheared junction as Wrangellia migrates southward. **80 Ma** – major plate change to right-oblique movement of Farallon Plate; Kula Plate splits off to north. Wrangellia-Baja BC drift north. Oceanic plateau approaches SW North America. The location of the southern margin of Baja BC at this time is strongly debated – some models have the southern tip farther north at latitudes of S Oregon or even S Washington. **50 Ma** – Wrangellia and Baja BC at or near present locations; Siletzia accretes to form Olympic Mountains; the subducted oceanic plateau is under the Colorado Plateau as the Central and Southern Rockies form; note how Southern and Central Rockies bend around presumed subsurface location of subducted slab (Modified from Frisch et al. 2011)

Fig. 7.9 The San Juan Islands consist of Jurassic deepwater volcaniclastic sediments, submarine volcanic flows, ophiolite fragments, and melange-like rocks that suggest formation adjacent to or between island arcs. Some geologists believe that the rocks in the islands are remnants of the fringing arcs that lay off the western Cordillera in the Jurassic and were sandwiched between approaching Wrangellia and western North America; some would call this Baja BC

amalgamated complex formed the foundation for the Cretaceous Alisitos Arc, that portion of the Peninsular Ranges batholith in Baja, Mexico. The northern portion of Alisitos Arc rocks extends into San Diego and Orange Counties, California as the Santiago Peak Volcanics.

7.5 Transcontinental Rivers, Explosive Volcanism, and Enormous Ergs

Most of North America was above sea level during the Triassic and Jurassic with terrestrial sedimentation dominant across the Colorado Plateau (Fig. 7.10). A continental-scale river system extending from the Ouchita/southern Appalachian region to the central Cordillera is preserved in parts of the Moenkopi, Chinle, Moenave and Kayenta formations. The Chinle Formation forms most of the colorful scenery of the Painted Desert and Petrified Forest areas on the Plateau and encloses North America's oldest dinosaurs. The Late Triassic Shinarump Conglomerate Member of the Chinle Formation records the very first arrival of coarse-grained sediment from the *Mogollon Highlands*, the initial uplands formed in the southern Cordillera during the Late Triassic (note that the term Mogollon Highlands is also used for Cretaceous uplifts in the same area).

Although the descending slab of the Farallon plate was basaltic in composition, the slab was only partially melted. Partial melting is a complex process that tends to enrich the silica component of magmas. Additionally, the slab also carried silica-rich sediment on top of it that was derived from vast eolian systems on the continent. Explosive volcanism results from silica-rich magmas – rhyolite, dacite and andesite (the more silica in a magma, the more viscous it becomes and thus the more explosive). Interestingly, the volcanoes were not towering edifices such as those that dominate the modern Cascades, but rather low volcanic centers, rich in calderas and volcanic domes, and enclosed in a graben-like structure that made them even lower in elevation. One of the most interesting consequences of the silicic volcanism is that as the ash rained down into the Chinle Formation to the east, it enriched the deposit with silica. When large trees in the Chinle fluvial setting were uprooted in floods, they became driftwood logs that were buried in the silica-rich soil. Groundwater gradually replaced the carbon atoms in the wood with silica atoms and the famous Petrified Forest was formed.

Voluminous eolian sequences show that the Triassic fluvial settings in the southwest Cordillera gave way to arid conditions in the Jurassic (Fig. 7.11) and one of the most intriguing transitions is recorded in the Moenave/Wingate sequence, where Early Jurassic rivers disappeared as wind-blown sand encroached from the north. The Wingate *erg* (erg is Arabic for sea of sand) was followed by the Navajo, Page, Temple Cap, Entrada, Zuni and Bluff ergs, all with well-preserved southeast- to east-dipping cross-beds that reveal northerly to westerly Jurassic wind directions. Southwest North America was positioned about 15–20° north of the equator and within an arid climate belt. Zircon studies in these eolianites show that the sand originated on the western slopes of the Appalachians, then traveled in fluvial settings towards Montana and Wyoming; the rivers desiccated on the hot Jurassic plains. The sand was then carried by the wind to the southwest and onto the future Colorado Plateau.

Slightly more humid conditions commenced in the Late Jurassic and the world renown Morrison Formation marks a change back to fluvial and lacustrine conditions. This widespread deposit extends from Arizona to Montana and records environments dominated by a Late Jurassic fauna, including *Stegosaurus*, *Camarasaurus*, *Allosaurus* and the

Fig. 7.10 Triassic and Lower Jurassic fluvial deposits on the Colorado Plateau. (**a**) Chinle Formation in Petrified Forest National Park, Arizona – note petrified wood "talus" in foreground. (**b**) Kayenta fluvial deposits underlie the Navajo Sandstone eolian deposits. Note the south-dipping crossbedding in Navajo at Coyote Gulch, Utah

large vegetarian sauropods *Apatosaurus* and *Brontosaurus*. In the world-famous bone beds at Dinosaur National Monument in northwest Colorado and northeast Utah, a ridge of upturned sandstone exposes the most ecologically complete assemblage of a Late Jurassic fauna on the planet. The rocks indicate an environment not unlike the Serengeti in Africa today with rivers, lakes, and strong seasonality. The 1,500 fossil bones here may represent the dying gasps of the animals when a water hole dried up beneath the hot Jurassic sun.

This interval of time was a seminal period in the growth and expansion of the western Cordillera and many mysteries still remain to be solved concerning its complex tectonic history. Many Jurassic processes would continue into the Cretaceous Period with additional significant changes to the landscape.

Fig. 7.11 Jurassic eolian and fluvial deposits. (**a**) Moenave Formation near Tuba City, Arizona contains both fluvial deposits (flat-bedded sandstone) and eolian sandstone (large cross beds) and represents the transition from dominantly fluvial deposits to eolian deposits as ergs swept across the Colorado Plateau from the north. (**b**) Jurassic strata exposed as tilted beds in the Henry Mountains of Utah. The eolian Navajo Sandstone is overlain by marine limestones of the Carmel Formation as the Western Interior Seaway entered the region (compare Figs. 7.3 and 7.4). (**c**) Fluvial deposits of the Morrison Formation in Capitol Reef National Park extended from Arizona to Southern Canada as vast amounts of sediments were shed eastward off the Nevada Mountains; this is the real Jurassic Park. (**d**) Jurassic eolian sandstone in the Aztec Sandstone north of Las Vegas is equivalent to the Navajo Sandstone on the Colorado Plateau. The dark gray units in the background are Cambrian dolomites thrust over the Aztec in the Sevier orogen

Fig. 7.11 (continued)

8 The Continental Arc, Sevier Orogeny, Western Interior Seaway and Flat-Slab Subduction: Cretaceous Period: Ca. 145–65 Ma

8.1 Break-Up of Pangaea

The long-lived subduction zone on the Cordillera's western margin that began in the Late Triassic was well underway at the dawn of the Cretaceous. In fact, the rate of plate motions across there globe was accelerated and faster plate motions heightened the rate of terrane accretion and accretionary prism formation along the continent's western edge. This increase in plate velocity initiated an orogenic event that had huge results on the landscape development of the Cordillera, the long-lived and widespread Sevier orogen (Table 8.1).

The planet likely experienced a "heat wave" during the Cretaceous and the idea does not just refer to climate (although more about that below). Rather, the rate of sea floor spreading in both the Atlantic and Pacific oceans increased—an event probably related to an increase in heat flow as pent-up energy trapped beneath Pangaea escaped as the continents rifted apart. The increased rates of spreading in the Atlantic pushed North America westward at a faster rate and subduction rates were increased along the Cordilleran margin. Outboard terranes were brought to the continental edge more rapidly and with more force. Why in the Cretaceous? During the extant of Pangaea over 150 million years, heat was trapped beneath the supercontinent because continental crust acts as a blanket to trap heat below. Fracturing of this crust, perhaps better termed rifting, allowed trapped heat to escape towards the surface and new oceans formed. The Central Atlantic, Gulf of Mexico, Canadian Basin, and Indian were all new oceanic spreading centers that caused continents to divide and separate (Fig. 8.1). This relatively aggressive escape of heat from below generated huge volcanic centers or *large igneous provinces*. More cubic volume of igneous material per unit time may have been created in the Cretaceous than in any comparable time in the Phanerozoic. Rapidly spreading oceans moved continents at accelerated rates. However, this rate of spreading was balanced by increased rates of subduction. As a result, the largest Cretaceous plate, the Farallon, was rapidly subducted under western North America. Needless to say, the geologic effects were pronounced. We now describe some of these effects.

Table 8.1 Events 145–100 Ma

	Early Cretaceous (*Ca.* 145–100 Ma)
Time span	Docking of Baja BC and early Sevier orogen; growth of Western Interior Seaway
Geologic – tectonic setting	Rate of seafloor spreading in Atlantic Ocean greatly increased during Cretaceous
	Rapid westward motion of NA resulted in huge volumes of subducted ocean crust from the Farallon Plate
	Due to rapid westward motion of NA, trench rollback was unlikely; rather, friction increased and compression occurred across Cordilleran region
	Collision of Insular Superterrane coupled with subduction processes resulted in Sevier orogen, a protracted mountain-building event that lasted throughout Cretaceous – almost 80 m.y.s.
	Dominant tectonic elements from Late Jurassic into the Paleocene, W to E: (1) trench, (2) forearc basin, (3) magmatic arc (arc), (4) backarc – foreland basin

(continued)

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Table 8.1 (continued)

	Early Cretaceous (*Ca.* 145–100 Ma)
Time span	Docking of Baja BC and early Sevier orogen; growth of Western Interior Seaway
Boundary of western North America	Western margin of NA lay along Cordilleran subduction zone – geometry at any given location is dependent on model that is chosen for Baja BC history
	Model herein: Wrangellia/Baja BC accreted near the present latitude of NC Ca and drifted S several hundred km in the Cretaceous before drifting N in Late Cretaceous and Paleocene-Eocene to its present location
Terranes	As Baja BC docked along N Ca, a second terrane, Guerrero, approached S CA and Mexico – our maps suggest that both were on the same plate – leading edge of Farallon Plate
	Throughout extent of Franciscan subduction, numerous terranes much smaller than Baja BC entered the subduction zone to expand the Franciscan complex – some of these are totally exotic to NA and include large blocks of tropical-deposited limestone, probably originally deposited on oceanic plateaus and seamounts
Sedimentation patterns, trends	See details of trench, forearc, and Foreland basin deposits in Table 8.2
	Sand, mud, and gravel are dominant sediment types throughout the Cretaceous across western North America
	Depositional systems ranged from continental – chiefly fluvial – to deep marine
	Cretaceous deposits are rare in the Sevier hinterland
	As the Gulf of Mexico opened, rifting extended westward across S AZ into SE CA; the Bisbee Basin to the SE was a marine basin comprising sandstone, mudstone, and limestone; the McCoy Basin to the SW contains continental sandstone and mudstone
Igneous/metamorphic events	Arc system: plutons mostly granites and granodiorites
	Ages vary along strike of arc, in general oldest at east margin, younger to west (Late Cretaceous plutons migrated back towards east)
	Volcanics mostly rhyolites, dacites, and andesites
	Huge volumes of volcanics eroded as batholiths unroofed
	Metamorphism associated with (1) Sevier orogen, (2) batholithic intrusions, and (3) Franciscan subduction

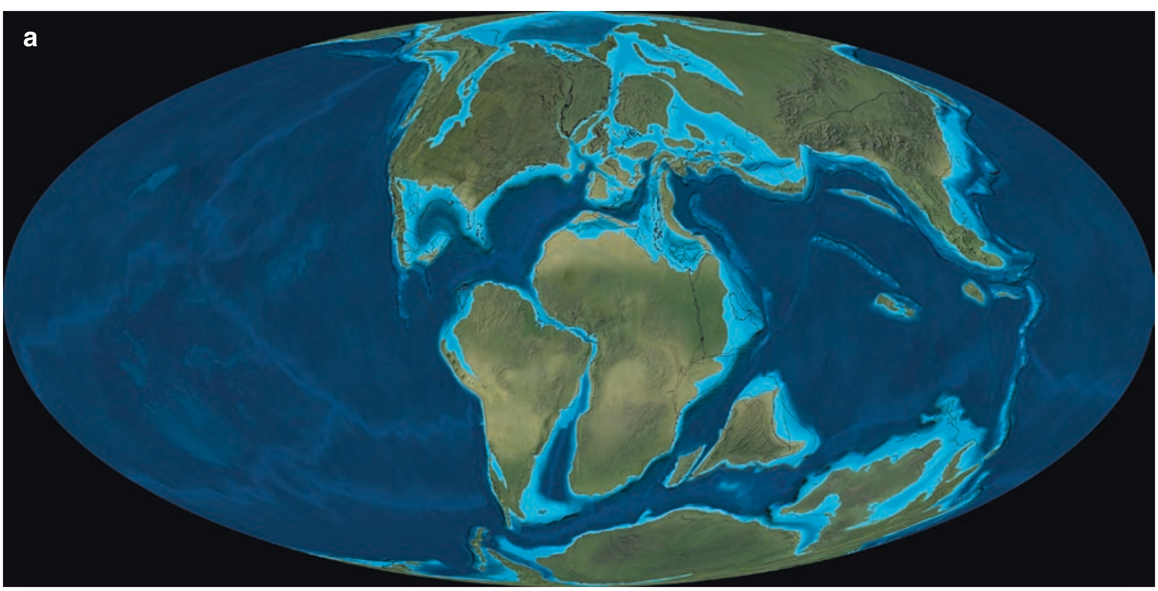


Fig. 8.1 Global paleogeography during Cretaceous showing expanding Atlantic Ocean and extremely long Cordilleran margin to the Americas that stretches from Asia and Alaska at the *top* to West Antarctica at the *bottom*. During these intervals, there was a direct relation between an expanding Atlantic and subducting East Pacific. (**a**) Early Cretaceous ca. 110 Ma. (**b**) Middle Cretaceous ca. 100 Ma. (**c**) Late Cretaceous ca. 80 Ma

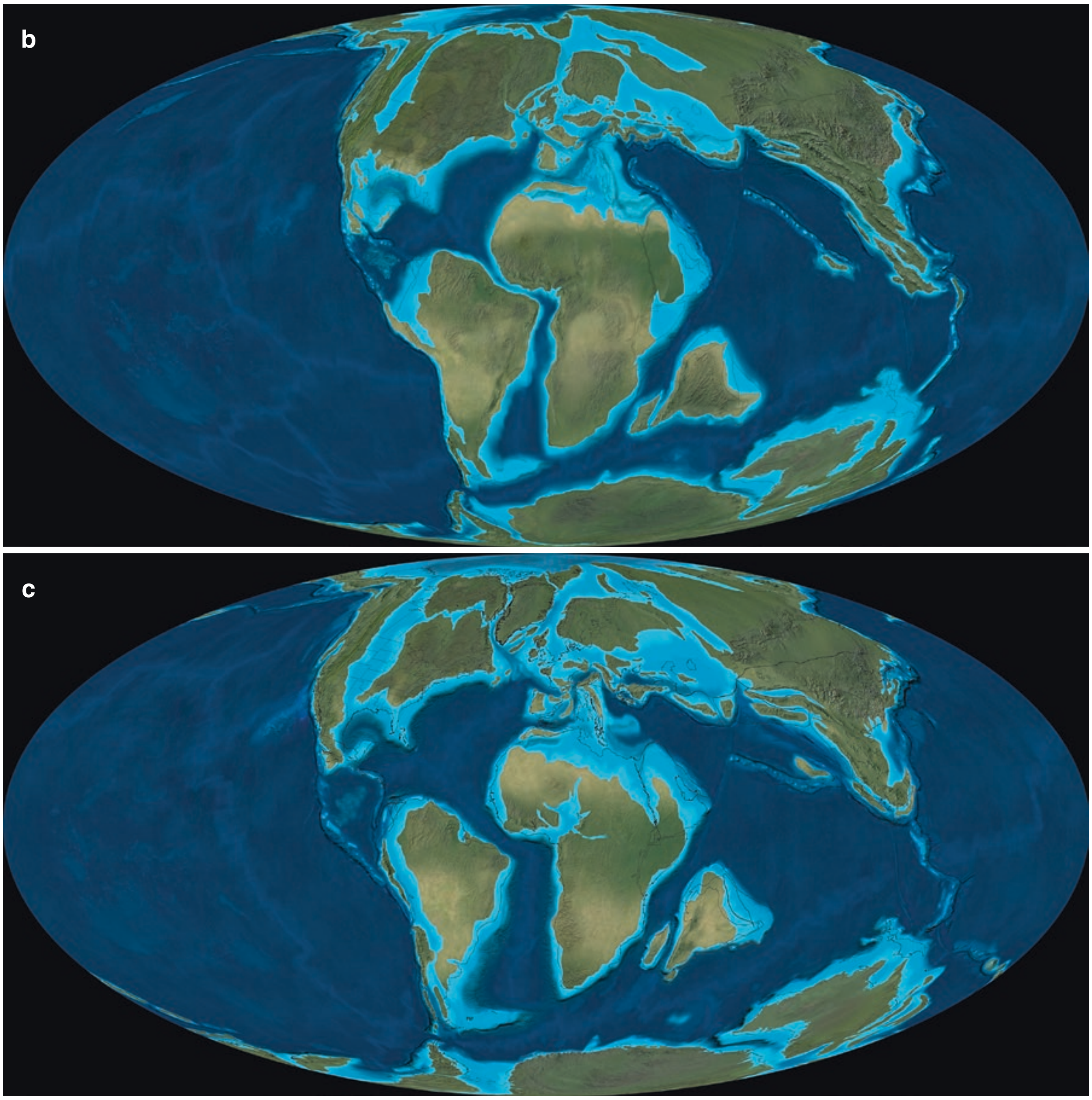


Fig. 8.1 (continued)

8.2 Wrangellia

Equivocal evidence suggests that Wrangellia docked in the vicinity of northern California, while superterrane Guerrero docked somewhere near southern California and northern Mexico (Fig. 8.2). Regardless of the precise docking location, both terranes arrived at North America riding on the Farallon plate. Wrangellia originally formed as an oceanic plateau in the Panthalassa Ocean, within 30° north or south of the equator during the Pennsylvanian to Jurassic periods. Although composed of many different rocks types, the Late Triassic flood basalts and capping white limestone is the defining mark of Wrangellia. The basalts were extruded onto the terrane during a 5-million-year period from about 232 to 227 Ma (Middle Triassic) and are capped by Late Triassic limestone that formed on the tropical reefs that grew on top of these volcanic rocks. Fantastic exposures of these white capping rocks on the black flood basalts are exposed in the Wrangell Mountains of Alaska.

While still plowing through the Panthalassa Ocean in the Pennsylvanian, Wrangellia collided and amalgamated with the Alexander Terrane, a "wayward' continental block originally part of Siberia or Baltica, that by the end of the Triassic had also collided with the Peninsular Terrane (now in southern Alaska). A subduction zone located west of Wrangellia smashed seafloor rocks against the west side of Wrangellia

Fig. 8.2 Paleogeography of SW North America in earliest Cretaceous (ca. 140 Ma). The Sevier thrust belt forms the prominent ridges from western Utah into Montana and a large foreland basin developed to the east. Early in the Cretaceous, rivers flowed parallel to the thrust belt northward across the Western Interior to join the seaway in northern Alberta. The Insular superterrane (aka Wrangellia) has accreted and forms the bulge in the coastline in the NW corner of the map; Guerrero is accreting along the SW margin. Opening of the Gulf of Mexico formed an elongate rift, the Chihuahua Trough along SW Texas, the Bisbee Basin in SW New Mexico and SE Arizona, and the McCoy Mountains Basin extending into SE California

and these rocks belong to the Chugach terrane. A complex fault system known as the Border Ranges Fault in Alaska is the modern expression of the suture zone between the Wrangellia and Chugach terranes. Over time, plate tectonics moved this superterrane to the northeast, crashing into the edge of North American during the Cretaceous. After docking, strike-slip displacement caused Wrangellia to travel first in a southerly direction, then shifting northward (Fig. 7.8). Complex is too tame a description for how these rocks may have been shuffled during the Cretaceous.

Table 8.2 Trench, forearc basin, and foreland basin deposits

Trench – Franciscan melange and related rocks:
One of the best studied subduction complexes on Earth – consists of the famous Franciscan Formation (or group) and related rocks across OR and WA and into BC; farther N, equivalent deposits comprise the Chugatch terrane, now present along SE AK
Trench deposits are extremely varied, complex, and of diverse origin. During much of Franciscan deposition, the trench system was part of an accretionary prism in which seafloor sediments, micro-terranes, and crustal irregularities were scraped off the subducting Farallon Plate and accreted or piled against the NA margin. Franciscan material that was scraped-off in the trench formed the accretionary prism whereas the material not scraped off was subducted and metamorphosed under high pressure, but relatively low temperature – a distinctive process called blue-schist metamorphism. The distinctive color was caused by blue minerals formed by high-pressure metamorphism
None of these trench deposits are ever in stratigraphic/depositional contact with either the forearc or arc to the east. The contact is always a fault, usually a transform or thrust. In some areas, the contact appears to be an extensional fault
Forearc basin deposits (Great Valley sequence or complex and related rocks):
Exposures range from Baja MX to SW OR with dismembered fragments present to N in SW BC
The Great Valley (and related rocks in SW CA) has deposits that range from marine shelf and rare continental environments through marine offshore into deep marine environments. Sandstone and mudstone are dominant rock types
Many units formed as turbidites. Nearly all sediment was derived from the adjacent arc
The forearc was well preserved in many areas – deposits are commonly flat lying to gently folded
Foreland basin and Western Interior Seaway:
The foreland basin (not to be confused with *forearc basin*) was deposited on the western NA craton
The foreland basin lay in a backarc setting (back or behind the arc from the trench) and is technically termed a retroarc foreland basin
From *ca.* 120 to 65 Ma it formed the axis of the Cretaceous Western Interior Seaway; for much of this interval, the seaway separated the landmass of NA in two – the sea extended from AK and NW Canada southward into the Gulf of Mexico
Within this seaway and its marginal deposits occur some of the greatest hydrocarbon- and dinosaur-bearing rocks on Earth. Fluvial deposits fed into the seaway, especially from the Sevier Mountains to the west and include proximal conglomerate to more distal sandstone and mudstone
Shoreline deposits are sandstone (*e.g.* Mesa Verde Group) that grades seaward into dark mudstone (*e.g.* Mancos and Pierre shales)
In marine areas protected from high sediment influx from land, limestone was deposited (*e.g.* Niobrara Ls). This limestone contains the richest concentration of Cretaceous marine “sea monsters” – plesiosaurs and mososaurs

8.3 An Accretionary Prism in the Cordilleran Trench: The Franciscan

Within the subduction trench offshore of western North America, a deep-water sequence of chert-rich and volcanic-rich sandstone and sandy mudstone with local basalt flows accumulated to form the *Franciscan assemblage* (Table 8.2; Fig. 8.3). Named for exposures on the San Francisco Peninsula, this dirty mixture of rock types, commonly classified as “greywacke” (*German* – grey earth rock) was initially deposited as trench axis and trench slope sediments. Specific depositional settings included material formed by gravity-slope, suspension, and turbidite processes. Following deposition, the sediments were subject to various processes associated with subduction (Fig. 8.4). Mélange formation and high-pressure metamorphism commonly altered the initial sedimentary package. Mélanges are fashioned by sedimentary and tectonic processes (inset boxes, Fig. 8.4). The term mélange refers to a large-scale brecciated rock that is characterized by a lack of continuous bedding and pervasive mud and sand matrix that encompasses rock fragments of all sizes. This type of rock is typical of subduction settings where sea floor mud and volcanic fragments are scrapped off the top of a descending plate and crunched up against the continent’s edge. In many cases, it is difficult to discriminate between tectonic and sedimentary processes. An analogy would be to take a small stem of thyme and pull it between pinched fingers. The leaves scrape off between the fingers forming a disarray of parallel stacked leaflets (the accretionary prism), while some of the leaves may not detach and are pulled between the fingers with the stem (the subducted fraction).

Metamorphism occurs when the original sedimentary deposits are dragged down the subduction zone and metamorphosed under high pressure but relatively low temperatures (Fig. 8.4). Much of the Franciscan assemblage is highly

Fig. 8.3 The Franciscan assemblage along the Central California Coast. (**a**) Cliff on Big Sur coast showing typical coastal exposure along this rugged coast. (**b**) Road cut on Highway 1, Big Sur Coast. This is an example of a tectonic melange with the bluish tint caused by high-pressure metamorphic minerals. (**c**) Coastal exposure along Highway 1 near Elephant Seal viewing area (cars in distance). *Bluish-green* rocks are fragments of the Jurassic Coast Range Ophiolite that slid into the Franciscan trench (olistostromes) and are encased within Franciscan deposits or eroded onto the beach. (**d**) Classic melange exposed on San Simeon State Beach north of Cambria. Highly fractured and jumbled bedding is typical of sedimentary melange – note green fragment of Coast Range ophiolite. (**e**) Lone blueschist outcrop in otherwise covered hillside south of Cambria along Highway 1. (**f**, **g**) The Franciscan contains several coherent large blocks of sedimentary rock called slabs. The two largest are exposed at Point San Luis west of San Luis Obispo and Moonstone Beach at Cambria (shown here). Bedding and other features suggest deposition on the floor of the Franciscan trench. The blocks were then encased in surrounding Franciscan melange. The blocks are up to 10 miles long by several miles wide and preserve evidence of Franciscan environments typically destroyed or altered elsewhere in the unit

Fig. 8.3 (continued)

Fig. 8.3 (continued)

Fig. 8.3 (continued)

faulted, deformed, and metamorphosed to blue schist (Fig. 8.3e). This created a unique suite of metamorphic rocks – the geologic indicators of subduction. Related and similar rocks in Oregon, Washington, British Columbia and Alaska were part of northward continuation of the trench system; in Alaska, this assemblage is known as the Chugach terrane.

Suggestions have been made that the Franciscan assemblage may be up to 16,000 m thick; however, the subsequent deformation makes it all but impossible to know for sure. These mostly metamorphic rocks make up the bulk of the Coast Ranges, from Douglas County Oregon in the north to Santa Barbara County California in the south; the submarine California Borderlands, which extend southward from Santa Barbara to off the coast of Mexico, are partially underlain by Franciscan rocks. Exposures occur on Catalina Island.

During the growth and dynamic accumulation of the Franciscan assemblage, an early iteration of the Pacific Coast Ranges was formed as scraped off material piled up east of the trench – the outer ridge shown on Fig. 8.4. A basin was formed between it and the high-standing continental arc (the Sierra Nevada). Basins formed in these settings are called *forearc basins*, since they sit forward (seaward) of the continental arc (Fig. 8.5). The Cordilleran forearc basin stretched from the Peninsular arc in Baja California to southwest Oregon. Later strike slip faulting caused some of the forearc deposits to be translated further north (today these dismembered sections are exposed in British Columbia along the Straights of Georgia).

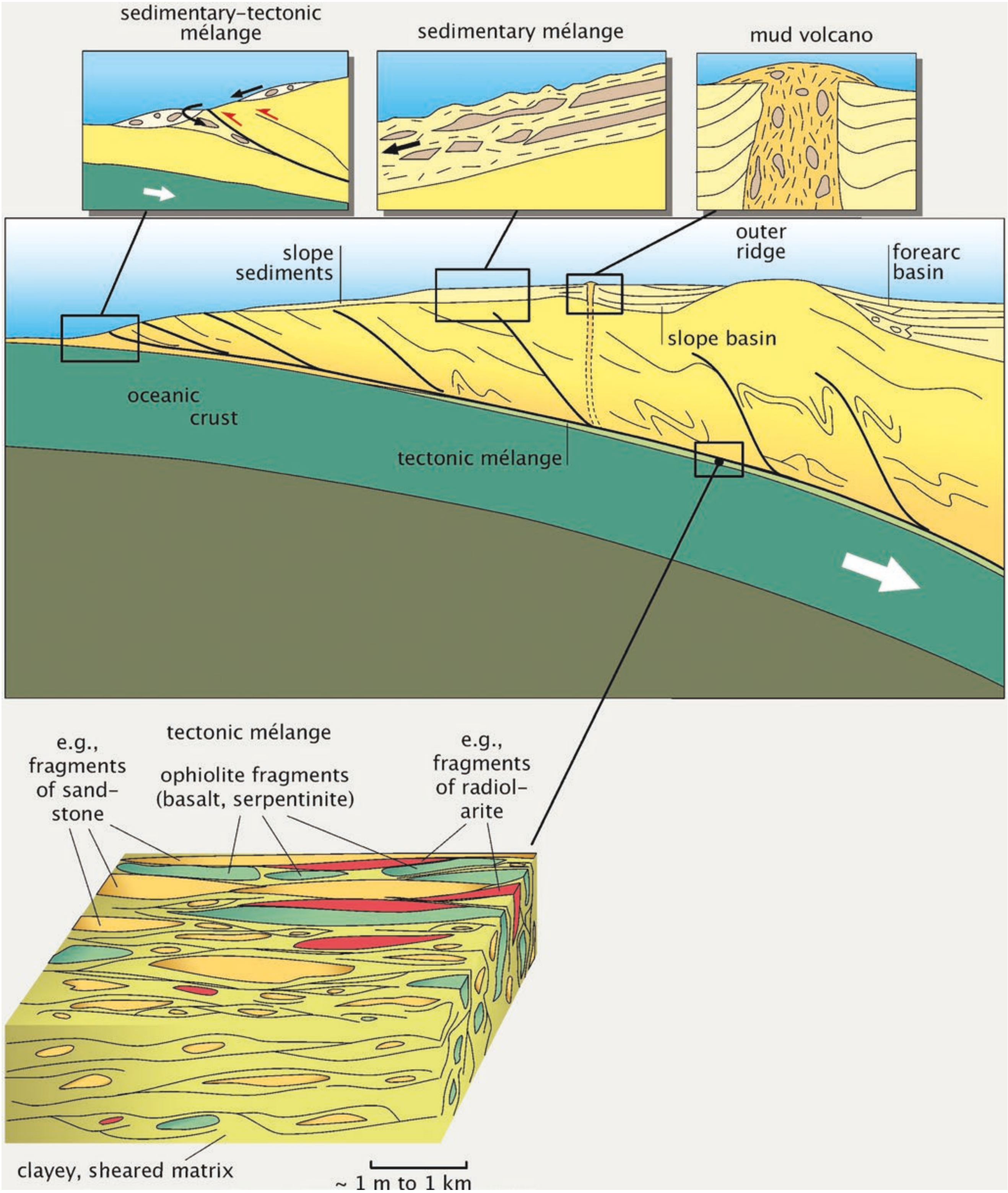
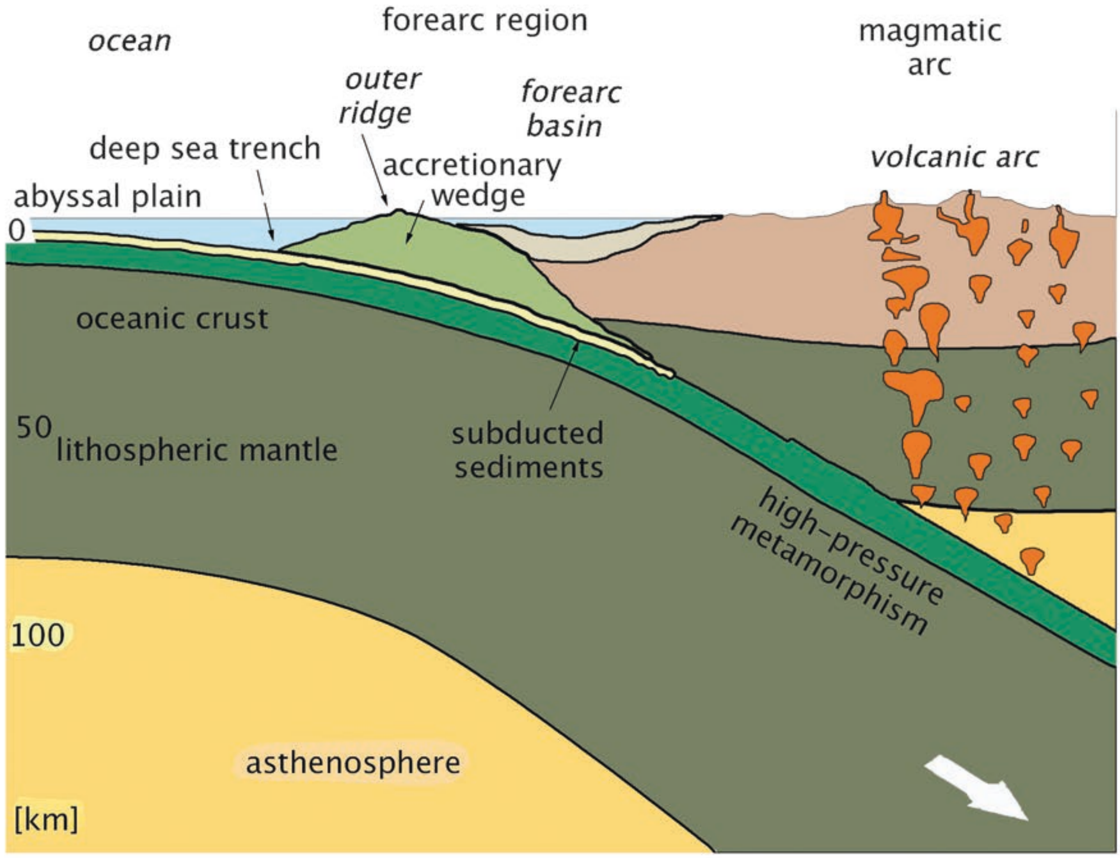


Fig. 8.4 Cross sections and block diagram showing characteristics of Franciscan sequence based on modern accretionary wedges. Sedimentary processes are dominant on upper surface of accretionary prism and include suspension, gravity, and turbidity deposits. These areas may be preserved and their sedimentary history readily interpreted (Fig. 8.3f, g). Tectonic processes dominate along the boundary between the wedge and subducting plate and in lower portions of the wedge. High-pressure metamorphism and tectonic rearrangement of initial sedimentary deposits forms the classic melange. Bluish high-pressure minerals such as glaucophane give parts of the Franciscan its characteristic color. Subsequent faulting and folding juxtapose disparate portions of the wedge into single outcrops making both local and regional correlation difficult (see examples in Fig. 8.3) (Modified after Frisch et al. 2011)



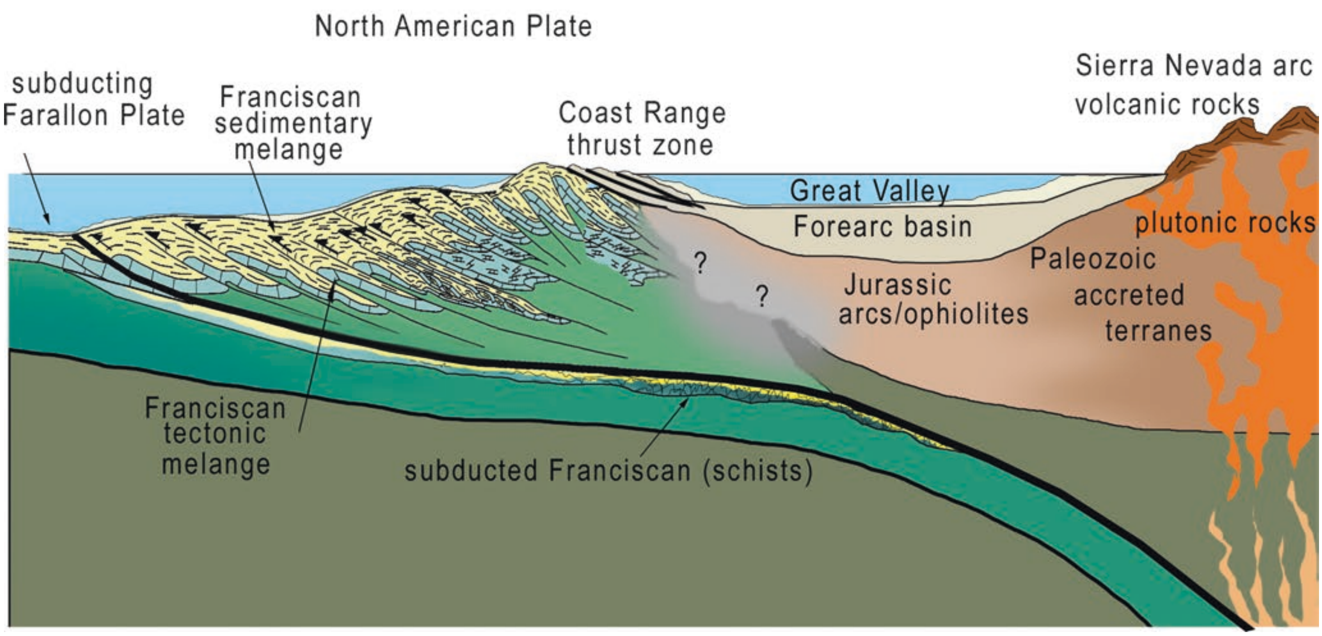


Fig. 8.5 Cross sections of the forearc region. *Upper*: general cross section of typical Cordilleran margin showing tectonic and sedimentary elements and geomorphic settings. *Lower*: details of forearc setting typical of the Late Jurassic through Paleocene of Central California showing tectonic and sedimentary setting of Franciscan and Great Valley sedimentary rocks. Light tan shows zones of active sedimentation. Note that most Franciscan deposits are bathyal to abyssal and that Great Valley deposits range from shoreline to abyssal. The contact between Franciscan and Great Valley rocks is everywhere tectonic – usually the Coast Range Fault zone. Queried areas have uncertain relations. Over long periods of geologic time, the entire forearc region became new continental crust added to western North America; Cenozoic sedimentary basins and associated volcanic rocks were developed across the forearc region during the ensuing compressional, transpressional, and transform tectonic regimes (Modified after Frisch et al. 2011)

8.4 Forearc Sedimentation: The Great Valley Sequence

It was in such a fore-arc setting that the *Great Valley Sequence* was deposited, an obvious name since its extent mimics the expanse of the Great Valley in central California. Although the Great Valley Sequence remains largely buried beneath younger sediments in the Central Valley, they are nearly 12,000 m thick. These rocks onlap the granite rocks of the Sierra arc to the east; however, *nowhere* are the forearc and trench deposits in depositional contact. Rather the contact is everywhere tectonic and in most places is bounded by the Coast Range Fault. The Great Valley Sequence is composed dominantly of deep marine shale and intercalated lenses of sandstone and conglomerate that originated as deep marine turbidites in submarine fans and canyons. Much of the material is derived from the volcanic and granitic debris that was shed off the adjacent Sierra arc. An apparent extension of the Great Valley, the Hornbrook basin east of the Klamath Mountains, contains similar sedimentary rocks.

Equivalent rocks are present both north and south of the Sierras (Fig. 8.6). Rocks in the Nanaimo Basin on the back side of Vancouver Island resemble the Great Valley Sequence although there is some debate as to whether this basin was a true forearc basin. Some of the best exposed forearc basin deposits in the world line the beaches of San Diego from La Jolla to Point Loma. Coastal exposures display Upper Cretaceous turbidite sequences bed for bed whereas more inland exposures are not as well exposed and show the forearc strata onlapping the arc sequence. Farther east along the I-10 corridor in Western Arizona and Eastern California, Cretaceous non-marine rocks are exposed in a probable western extension of the Bisbee Basin, the McCoy Basin (Fig. 8.6e). Thousands of meters of sandstone and mudstone formed in the rapidly subsiding basin.

Fig. 8.6 Cretaceous sedimemtary rocks of the forearc region and McCoy and Nanaimo basins. (**a**) Nanaimo Baisin exposed along Vancouver Island. The basin may be a continuation of the Great Valley Sequence or a backarc-interarc deposit. (**b–d**) Cretaceous forearc turbidite deposits along the San Diego Coast. See Fig. 2.8a for a model of the depositional setting. (**b**) Point Loma Formation mid-fan turbidites, Sunset Cliffs; (**c**) Cabrillo Formation fan-head conglomerate at Point Loma; (**d**) Point Loma Formation distal-fan turbidites at Point Loma; note angular unconformity below Pleistocene marine deposits. (**e**) McCoy Mountains Formation at McCoy Mountains near Blythe, California was deposited in a probable continuation of the Bisbee Basin

Fig. 8.6 (continued)

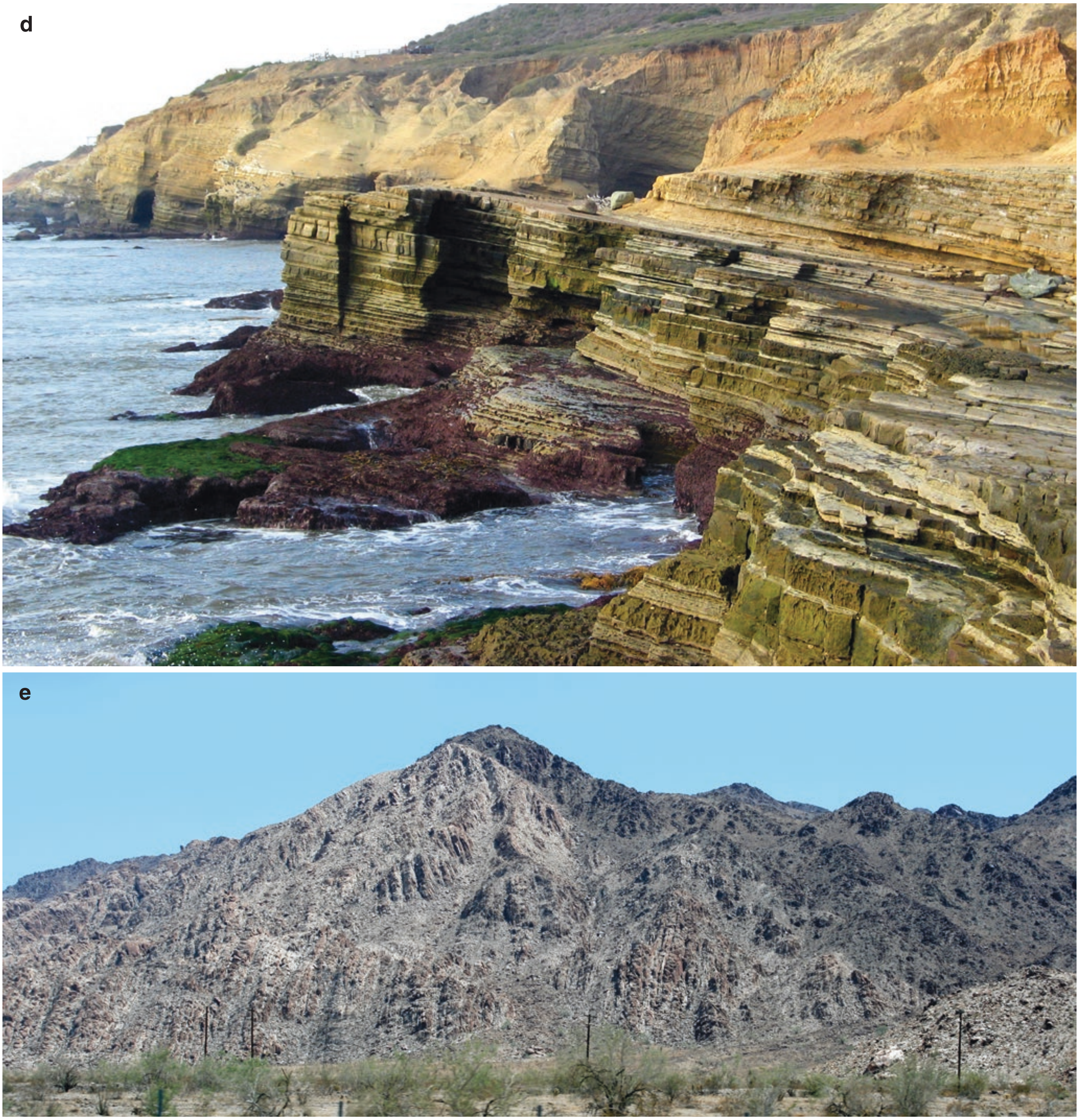


Fig. 8.6 (continued)

8.5 Expanding Arc and the Sevier Orogen

The on-going subduction throughout the Cretaceous resulted in the emplacement of more granite magma in the subsurface and explosive volcanic rocks on the surface. The volcanism produced the usual rhyolite, dacite and andesite rock types, while the granite intrusions carried gold mineral within the melt. This gold would eventually come to the surface but more on that later. The Cretaceous magmatic arc stretched from Baja California to southeast Alaska, and while much of the volcanic cover has been eroded, these areas today are underlain by massive granite plutons and batholiths – the cores of the arc volcanoes (Fig. 8.7). The granitic spine of Baja California and the Sierra Nevada Mountains in California, the Idaho Batholith, and the Coast Plutonic Complex in Canada and Alaska are the remnants of this once great arc.

Compression continued to dominate the central and eastern Cordillera and as more exotic terranes were attached to the continent, they squeezed and deformed the crust in an event known as the *Sevier orogeny*. This event began as early as 140 Ma and continued until about 55 Ma. Both compression and conductive heating elevated the crust along a broad margin of the continent uplifting the *Sevier Highlands*. Much of the deformation that occurred behind the continental arc (i.e. on the side of the arc away from the trench) was facilitated by folding and thrust faulting. These structures formed mountains in present day eastern Nevada and western Utah, Wyoming, Montana, and Idaho. The compressive forces took advantage of weak shale or mudstone as thin sheets of sedimentary rock cracked, broke and were shoved eastward one over the other (Fig. 8.8). During the Sevier orogeny, the crust was being thickened vertically and shortened horizontally in a process known to geologists as *thin-skinned deformation*.

Fig. 8.7 Rocks of the Cordilleran Cretaceous Arc. (**a**) Coast Plutonic Complex in Endicott Arm, a Pleistocene fjord with tidewater remnant glacier. (**b**) Granite monolith in Peninsular Ranges, Baja, Mexico. (**c**) Granite boulder, Peninsular Ranges near Lake Elsinore, California; boulders are forms created by weathering of fractures in otherwise massive granite. (**d**) Granite monolith in Yosemite National Park. (**e**) Coast Plutonic Complex along Inner Passage, British Columbia. The dark banded rocks towards the right, mostly gneisses, are part of the Coast Shear Zone. This is a band of onetime sedimentary rocks, the Gravina Belt, that formed in the narrowing ocean as Wrangellia collided with the Intermontane superterrane. The rocks were deformed and partly metamorphosed during the suturing, but the high-grade metamorphism occurred when the Coast Plutonic Complex was intruded into the suture zone. The plutons "stitched" Wrangellia with the superterrane and are called stitching plutons

Fig. 8.7 (continued)

Fig. 8.7 (continued)

Fig. 8.8 Thrust zones of the Sevier orogen. (**a**) The Charleston-Nebo thrust near Provo, Utah thrust the Oquirrh Group that comprises Mount Timpanogos over much thinner Triassic and Jurassic shelf deposits (hills in middle ground); shales and thin evaporate deposits in the Triassic and Jurassic facilitated the thrust. (**b**) Keystone Thrust near Las Vegas, Nevada thrust *thick*, *dark*, Cambrian dolomites over Jurassic sandstone. Several evaporate-bearing units along the sole of the thrust facilitated the fault

8.6 Foreland Basin and the Western Interior Seaway

A final landscape element of importance in the Cretaceous Cordillera was the development of a *foreland basin* to the east of the Sevier orogeny (note that the term foreland basin is a bit unfortunate since it sounds like and can be easily confused with a forearc basin). Foreland basins are downwarped sections of the crust formed by increased crustal thickening in the adjacent fold and thrust belt. Foreland basins therefore, are isostatic downwarps created when the weight of over-thickened crust in the thrust belt pushes the adjacent crust downward (like placing a heavy weight on a soft mattress). Foreland basins are often flooded with seawater if the downwarp is deep enough and a connection to the sea can be made.

Beginning about 120 million years ago, as the Sevier orogeny was thickening the crust through folding and thrusting, a foreland basin developed where the Colorado Plateau and Rocky Mountain sections of the Cordillera are located today (Fig. 8.9). This basin was ultimately flooded with seawater that came from both the north and south to bisect the entire continent from Alaska to the Gulf of Mexico. This formed the *Western Interior Seaway*, a body of water stretching from western Utah to Iowa (Fig. 8.10). Thick gray to black marine sediments were deposited in the depths of this seaway and are widely exposed on the Colorado Plateau, Rocky Mountains, and Great Plains (Fig. 8.11a).

As debris was shed from the Sevier Highlands toward the east and onto the floodplain (today's Colorado Plateau), it left a detailed record of the changing tectonics and environments. On the floodplain, great forests of tropical vegetation were compacted into coal beds, formed in the backwater swamps behind the Cretaceous shoreline. Increased magmatic activity in the arc resulted in increased folding and thrusting, which in turn uplifted the highlands, and shed more sediment into the basin to cause further downwarping. This dynamic setting resulted in a widely fluctuating shoreline that deposited sandstone along the shore as the sea transgressed and regressed across the Cordillera (Fig. 8.10). The cliffs and tablelands at Mesa Verde National Park in Colorado (Fig. 8.11b) and Chaco Canyon National Historic Park in New Mexico are examples of such ancient shoreline deposits. Many of these rocks are rich in dinosaur fossils from Alberta to Arizona and the spectacular finds are preserved in the Grand Staircase-Escalante National Monument (Utah) and the Dinosaur Provincial Park (Alberta).

Across the wide expanse of rocks laid down in the Western Interior Seaway are a plethora of names that reflect the complex stratigraphy of the interbedded sandstone and shale. Sandstone units include Mesa Verde, Wahweap, Frontier, Eagle, and Dunvegan; shale bodies include Tropic, Mancos, Cody, Pierre, and Wapiti. Cretaceous rocks are hydrocarbon-rich and are sites for oil and gas prospecting. Prodigious marine reptiles, sharks, and fish can be found in these marine deposits, reflecting the hot humid conditions that existed – no ice caps were present on planet Earth during the Cretaceous.

At 93 Ma (Table 8.3), the Western Interior Seaway was at its maximum extent and stretched as far west as the Wasatch Line in Arizona and Utah. For the next 15–20 million years, North America embodied three distinct land areas (but still part of a single North American tectonic plate), as global sea level had risen to one of its highest stands in the Phanerozoic (Fig. 8.1c). The worldwide sea level rise is attributed to increased volcanism in the western Pacific Ocean, which uplifted the bathymetry of the Pacific sea floor, displacing large volumes of sea water onto the fringes of all of Earth's continents. Furthermore, in the central Cordillera, continued thrusting in the Sevier orogenic belt overloaded the crust, causing even more subsidence in the foreland basin as the Interior Seaway flooded land from the westernmost Colorado Plateau to the Nebraska/Iowa border (Fig. 8.10). Ocean depths were likely between 150 and 200 m on portions of the mid-continent.

This was a time when the diversity of dinosaurs was at its maximum. Generally, Cretaceous dinosaurs were smaller but no less fierce than their Jurassic counterparts, including tyrannosaurs, hadrosaurs, ceratopsians, and velociraptor. In the Western Interior Seaway, giant (and small) plesiosaurs swam side by side with the great mosasaurs (New Mexico's state fossil). Turtles with shells 8 m in diameter have been found on the Great Plains of Kansas. Overhead, pteranadons and pterodactyls scavenged and hunted for fish, mollusks, crabs and insects. In southern Utah, a land dwelling therozinosaur managed to be preserved in marine sediments thought to have been deposited 90 km offshore – a specimen that likely died on land but was blown out to sea in a bloat and float scenario. The creature ultimately sank into the dark mud to escape scavenging (except for the skull that has never been found). This great diversity came to an end with a gigantic meteorite impact in the Yucatan region that created a sort of nuclear winter at 66 Ma.

Fig. 8.9 Paleogeography of most of North America at ca. 120 Ma (Early Cretaceous). The Western Interior Seaway continues to expand southward across northern Alberta

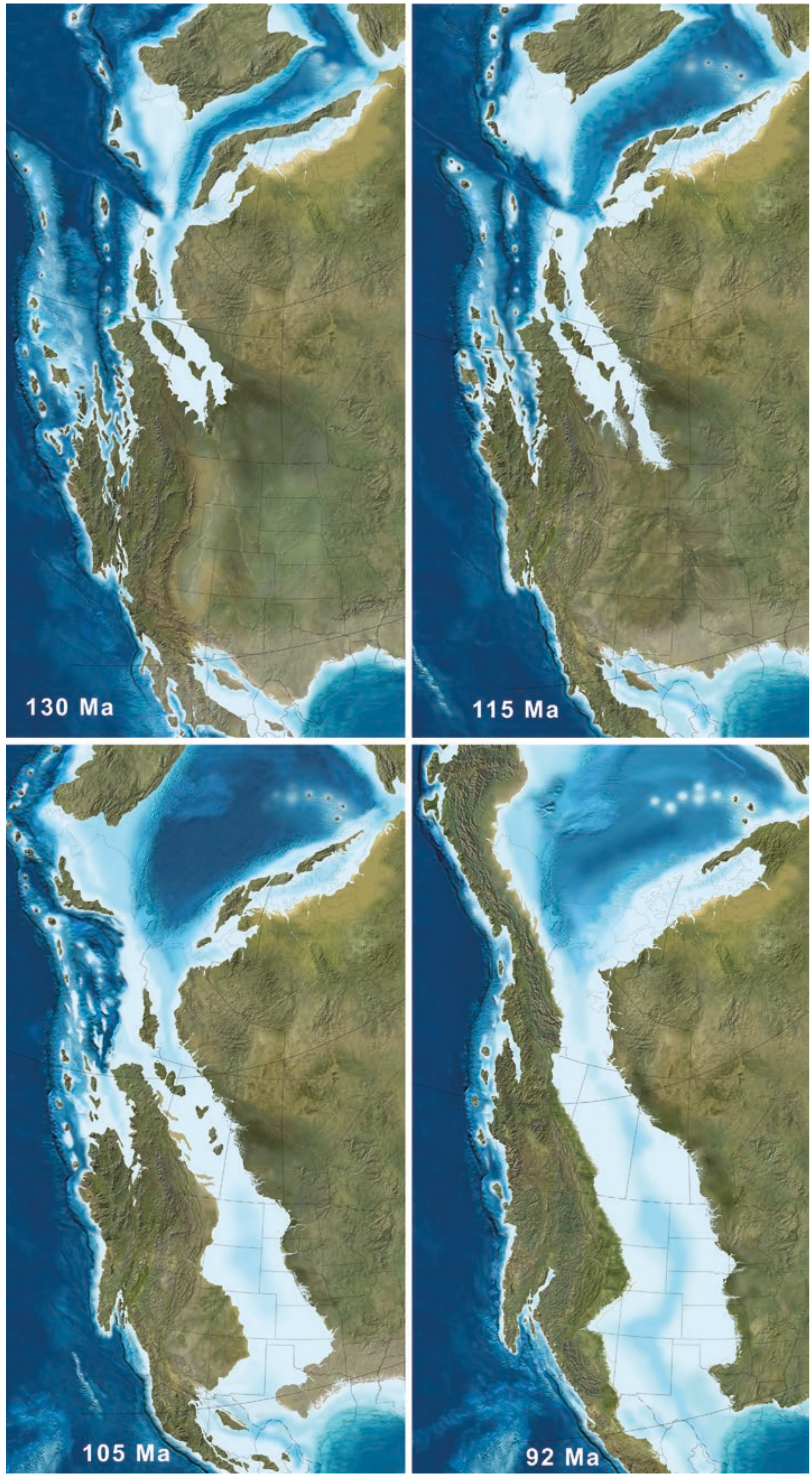
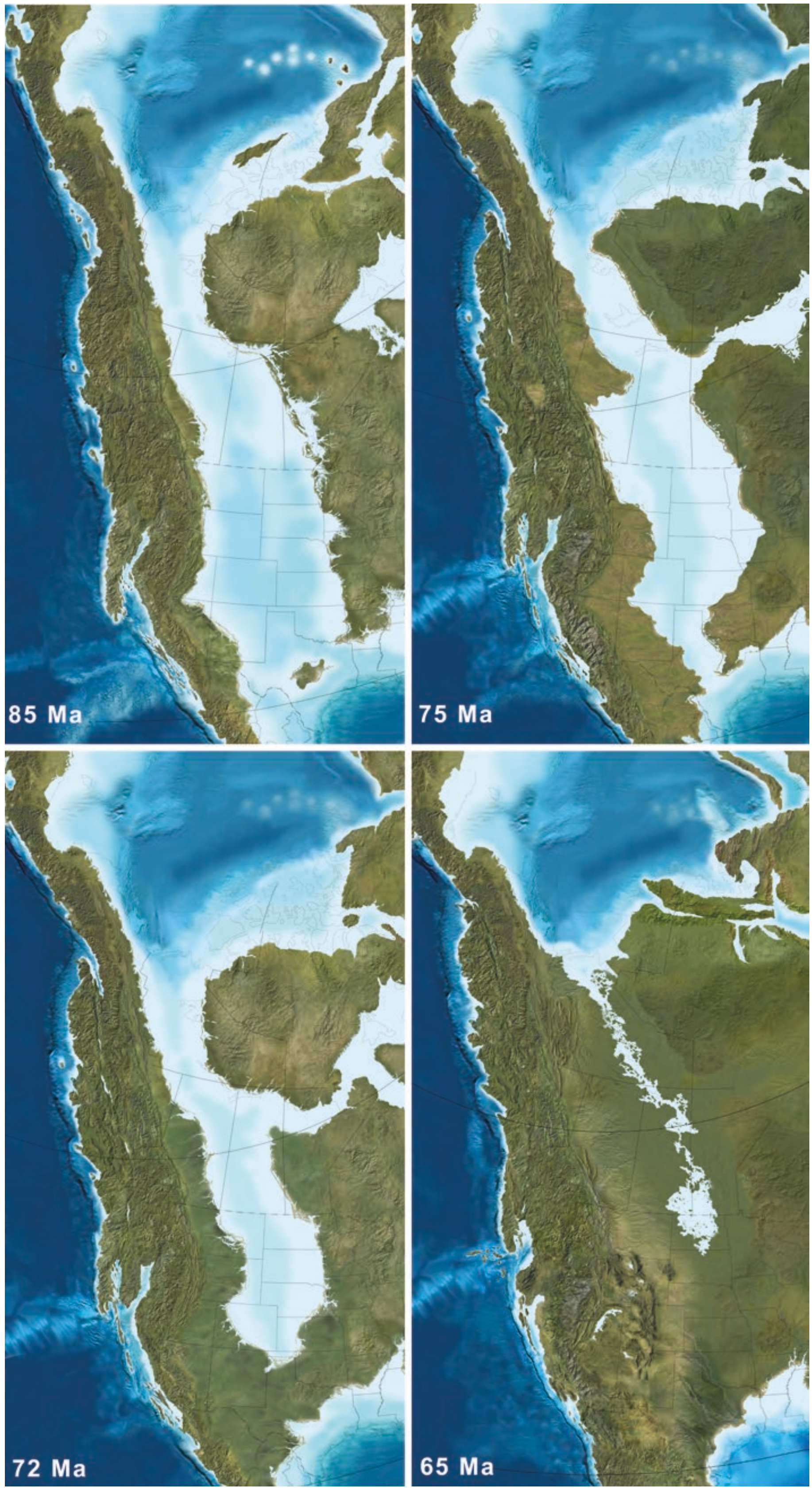


Fig. 8.10 Cretaceous geologic evolution of western North America shown by a series of paleogeographic maps. 130, 115 Ma Wrangellia (north) and Guerrero (south) have accreted; Nutzotin-Gravina Sea separates northern Wrangellia from Intermontane superterrane and the North American continent. Western Interior Seaway expands southward; Sevier orogen extends N-S length of North America. Canada (Arctic) Basin opens as Arctic Alaska rotates away from Northern Canada. 105, 92 Ma – Wrangellia closes Nutzotin-Gravina Sea and Western Interior Seaway splits NA into two landmasses; oceanic plateau approaches SW North America. 85, 75, 75 Ma – Oceanic plateau subducted and causes subduction angle to flatten; in response, sharp uplifts affect SW North America as subducted slab moves inboard under continent; mid-ocean ridge perpendicular to shore divides Farallon Plate with Kula Plate to north – northward migration of ridge drives Wrangellia northward along transform faults. Transgression-regressions of Western Interior Seaway driven by sedimentation rates, subsidence rates, and sea level changes. Major sediment influx from Mexico closes southern seaway. 65 Ma – Wrangellia moves northward to near present position and seamounts accrete below it to form core of Olympic Mountains. Western Interior Seaway retreats as sediment fills in basin and Rocky Mountains rise in its wake. The Western Interior Seaway was a dominant feature of Western NA for over 100 million years in the Jurassic and Cretaceous

Fig. 8.10 (continued)



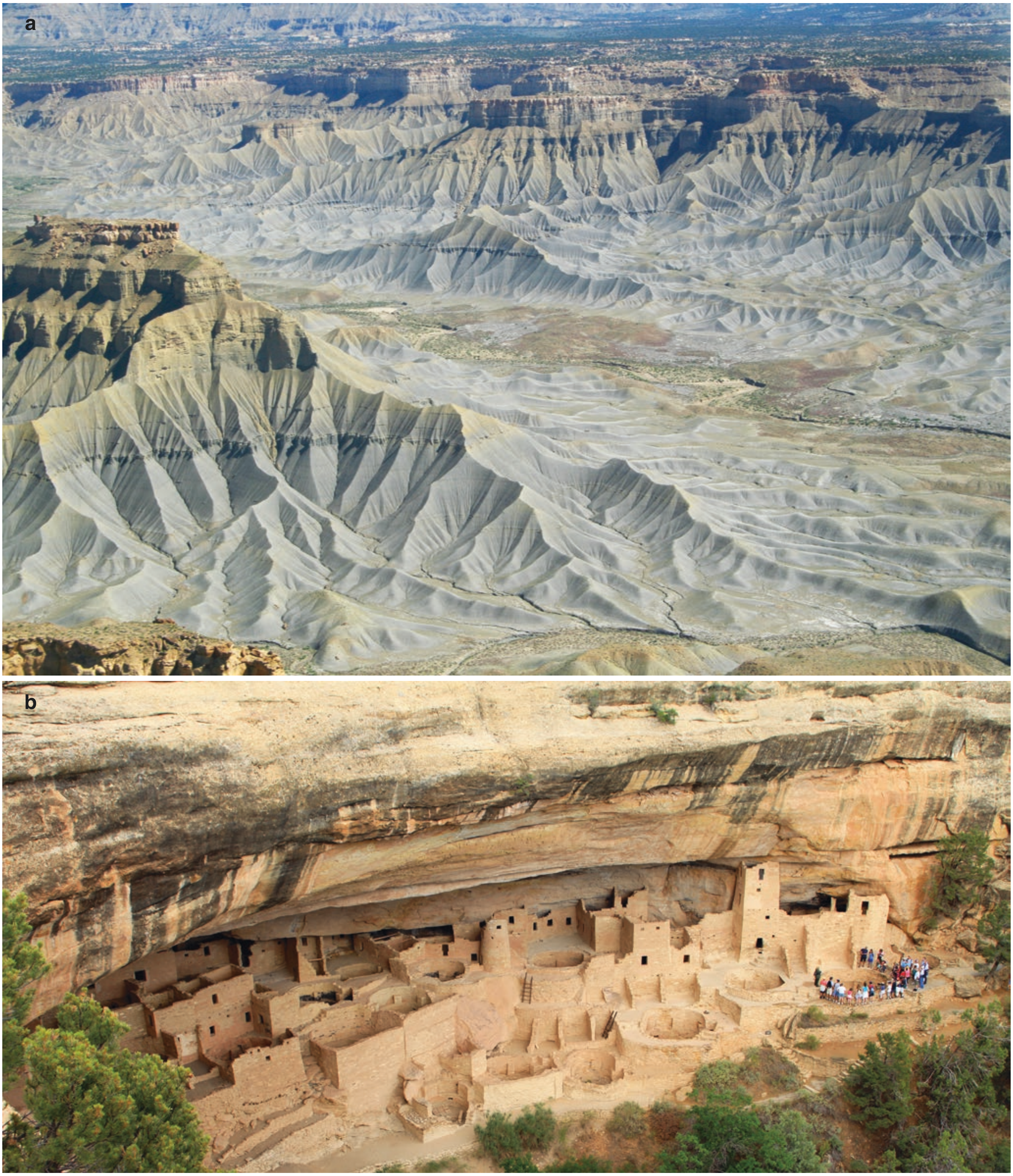


Fig. 8.11 Cretaceous shoreline and marine rocks, Western Interior. (**a**) Anatomy of a marine regression, Henry Basin, Utah. The gray mudstone of the Mancos Shale coarsens upward as the Mesa Verde Group sandstones signal the approaching land. (**b**) Shoreline sandstone overhang (Cliff House Sandstone of Mesa Verde Group) protects thirteenth century cliff dwellings in Mesa Verde National Park, Colorado

Table 8.3 Events 100–85 Ma

	Late Cretaceous I (*Ca.* 100 Ma – 85 Ma)
Time span	Arc magmatism and compression, Sevier orogen; Western Interior Seaway
Geologic – tectonic setting	Continued trends from Early Cretaceous; increase in spreading rate of Atlantic Ocean
	Expansion of Western Interior Seaway – Western NA lay across seaway from Eastern NA throughout much of Late Cretaceous
	Early Turonian (*ca.* 93 Ma) was one of highest global sea levels of all Phanerozoic time
Boundary of western North America	Wrangellia-Baja BC may have continued its southward transform drift motion throughout interval – how far south is highly debated
	Regardless of interpretation for Baja BC, Cordilleran trench formed plate boundary to Western NA from Mexico to Alaska and beyond
Terranes	Insular Superterrane accreted in scissors-like fashion, closing to north with final closure ca. 100 Ma
	Closure formed broad suture present from southern BC into Alaska (Gravina belt)
	Many smaller terranes of various origins accreted into Franciscan complex
Sedimentation patterns, trends	Continuation of most trends from Early Cretaceous (see Tables 8.1 and 8.2)
	High sea levels resulted in expanse of marine settings, especially in Western Interior Seaway
	From *ca.* 100 to 85 Ma Western Interior was part of a classic foreland basin that extended from E AK to S UT – subsidence was caused by stacking and loading of Sevier thrust sheets that depressed the adjacent craton and formed the foreland basin – the seaway occupied the basin
	Small to medium river systems fed into seaway from Sevier highlands building numerous deltas (*e.g.* Dunvegan (Alberta), Frontier (WY), Ferron (UT), and Gallup (NM) deltas)
	Organics trapped along the coastal plain generated extensive coal and hydrocarbon deposits
Igneous/metamorphic events	Massive generation of batholiths from AK to MX – Coast Plutonic Complex of BC and SE AK especially active
	Major metamorphic belts on either side of Coast Plutonic Complex
	Other metamorphic events follow trends from Early Cretaceous

8.7 Flat-Slab Subduction

Approximately 85 Ma (Table 8.4), Wrangellia began to change its drift direction as slivers were translated north along strike-slip faults (Fig. 7.8). The southern margin of the terrane drifted north to Vancouver Island and portions farther north ended in the Wrangell Mountains of Alaska. At 80 Ma, a large oceanic plateau approached the southwest corner of North America near southern California; it rode the back of the Farallon plate, and was subducted beneath the continent (Fig. 8.12). This submarine plateau may be the "missing half" of the Shatsky Rise, a modern oceanic plateau in the Western Pacific Basin offshore of Japan. Regardless of ultimate origin, a thickened slab of oceanic volcanic material plowed under the edge of the Cordillera, provided buoyancy to the Farallon plate, and caused its angle of descent to become less steep (less than 30°). This had the effect of causing arc magmatism to migrate to the east away from the Sierra-Baja Peninsular arc spine; because the depth at which the slab melted was pushed eastward, arc magmatism also migrated to the east. This change in the subduction angle and the consequent shift in magmatism to Arizona, New Mexico and Colorado (Fig. 8.13) also caused the axis of the Western Interior Seaway to migrate to the east. As a result, foreland basin deposition on the Colorado Plateau came to a halt and the marine environments shifted to the Great Plains. This shift ultimately would give way to the uplift the modern Rocky Mountains and the complete withdrawal of the Interior Seaway.

Slab flattening of the Farallon plate shifted the arc magmatism inland; the width of the shifted belt of arc magmatism was approximately the width of the zone of collision between the oceanic plateau and the western margin of the continent (Fig. 8.12). Normal arc magmatism continued along the Cordillera to the north in Idaho and Canada, and to the south in central Mexico. As the flat slab subducted, the Farallon plate split along a developing east/west-trending oceanic ridge – the Farallon plate maintained to the south while the new Kula plate formed to the north (Fig. 8.14). All the while, smaller terranes and other sea floor material entered the trench, which now extended from South America, through Central and North America, to Alaska and even eastern Asia. Rocks of the Franciscan assemblage continued to become jumbled as they were partially subducted and accreted to the coast in California.

The Cretaceous was a time of great upheaval in the Cordillera providing geologists with an excellent view of subduction related processes across half a continent. The preservation of these events is excellent, revealing a time when some aspects of the modern landscape began to emerge.

Table 8.4 Events 85–65 Ma

Time span	Late Cretaceous II (*Ca.* 85 Ma – 65 Ma) Subduction of thickened oceanic slab, flattened subduction, northward terrane migration, and fragmentation of Western Interior Seaway, late Sevier orogen and early Laramide orogen
Geologic – Tectonic setting	Continued rapid sea-floor spreading in Atlantic and rapid subduction in Cordillera
	At *ca.* 85 Ma large oceanic plateau (probably extinct oceanic ridge and associated seamounts) began to be subducted at present latitude of AZ and N MX
	Major changes developed where this thickened oceanic slab was subducted: (1) flattening of angle of subduction; (2) arc magmatism migrated inland to central CO and NM; (3) axis of Western Interior Seaway migrated NE across Great Plains; – subsidence pattern now controlled by flow patterns in mantle that resulted from flat-slab subduction
	Towards end of interval, Rocky Mountains were uplifted and the seaway withdrew
	Farallon plate separated by new mid-ocean ridge into Farallon Plate to south and Kula Plate to north – extensive group of seamounts developed along this plate boundary and were accreted to NA in Paleocene to form Olympic Mountains and Siletzia
	Huge meteorite impact occurred in Yucatan at *ca.* 65 Ma to mark end of Cretaceous and cause extensive mass extinctions
Boundary of western North America	Plate boundary remained at Cordilleran trench/subduction zone – part of global-scale feature that extended from South America northward to Eastern Asia
	Trench disrupted along southern margin of northward-migrating Wrangellia/Baja BC
Terranes	Insular Superterrane (Wrangellia/Baja BC) migrated northward along plate margin – distance and rate of migration strongly debated
	Smaller terranes and misc. seafloor material continued to accrete into Franciscan-Chugatch accretionary prisms
	As thickened oceanic slab subducted, the Franciscan trench/accretionary prism complex dismembered – later in Cenozoic, some of this material would become Nacimiento terrane and much of California Continental Borderland
	Portions of Franciscan complex that were subducted became metamorphosed to a distinctive schist that today is exposed widely across Central and Southern CA and Western AZ – these exposures mark areas of sharp, rapid Cenozoic uplifts that expose the Mesozoic Cordilleran subduction zone
Sedimentation patterns, trends	General patterns continue from previous Cretaceous intervals (see Tables 8.1, 8.2 and 8.3)
	Slowing subsidence rates and high sedimentation rates begin to close southern Western Interior Seaway at ca. 72 Ma – the seaway remained open to the north
	As the subducted slab migrated farther under the Southwest and propagated to the NE, the classic foreland basin was modified and the greatest area of subsidence shifted NE (E Mt. and NC WY)
	Great Valley and Franciscan trends continued much as before, although tectonism disrupted the Franciscan where the flat slab entered the SW US
	Beginning ca. 70 Ma, the Western Interior basin, which had previously been a continuous basin, became partitioned as Laramide (Rocky Mountain) uplifts developed
	Rapidly subsiding basins formed between Laramide uplifts; by 65 Ma the landscape had dramatically changed
Igneous/ metamorphic events	Much of US Cordilleran arc began to shut down 85 Ma as subduction flattened and arc magmatism migrated eastward into NM, Co, UT, and AZ
	Arc magmatism continued in the Coast Plutonic complex of Canada and in central Mexico and southward
	Metamorphism was widespread in Coast Plutonic Complex (Coast Shear Zone) where massive walls of gneiss were formed, originally at great crustal depths, now uplifted and exposed in glacial fjords
	Across the SW, the thickened flat slab was subducted and Franciscan material was partly subducted, metamorphosed and later uplifted to the surface where it is exposed in numerous mountain ranges (Rand-Pelonia-Orocopia-Catalina schists)

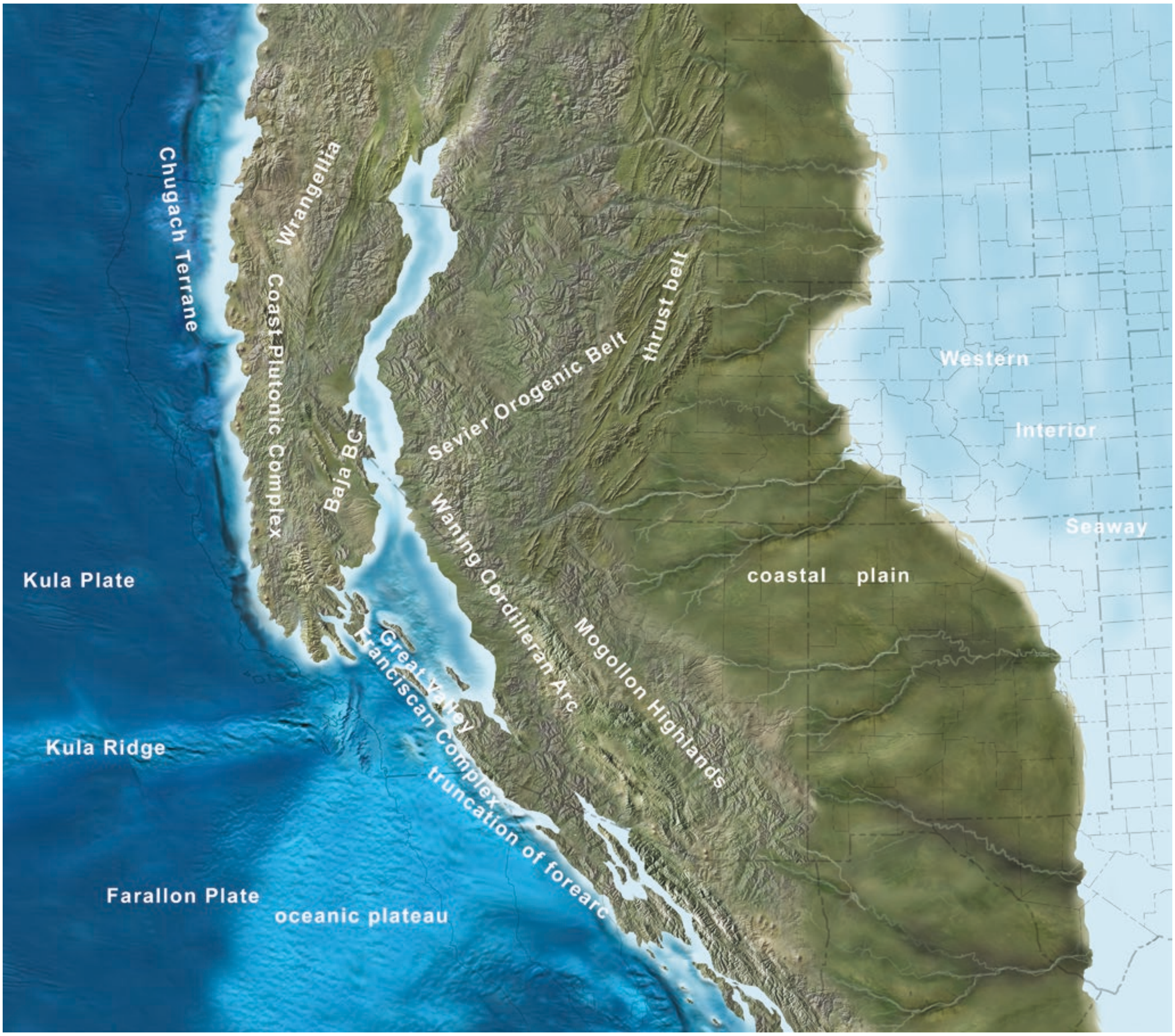


Fig. 8.12 Paleogeography of SW North America ca. 80 Ma showing tectonic elements and sedimentation trends; note oceanic plateau being subducted

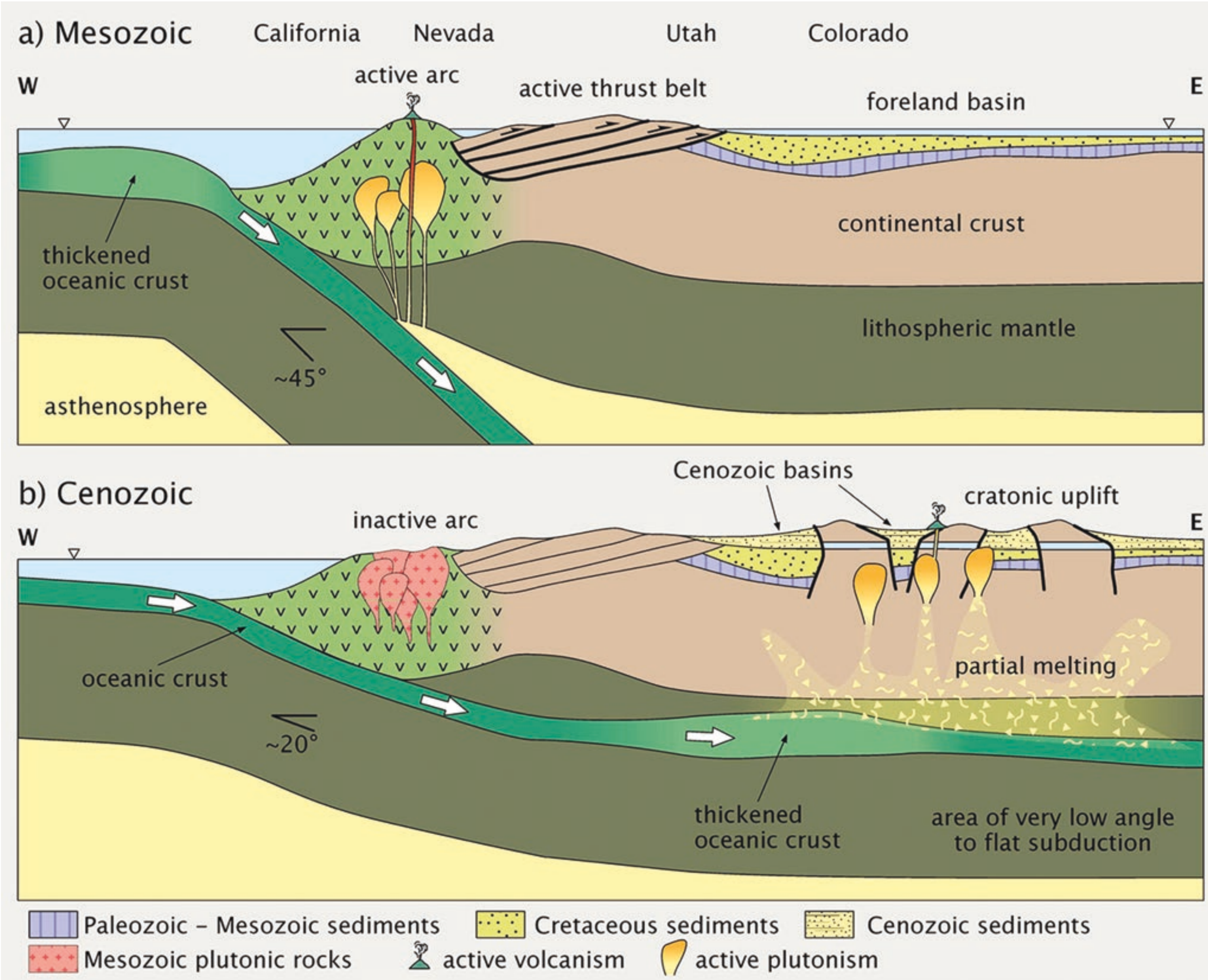


Fig. 8.13 Cordilleran Arc before and after flat-slab subduction. The arc shut down in the Late Cretaceous and the flat slab arrived under the Colorado Plateau by the Eocene (After Frisch et al. 2011)

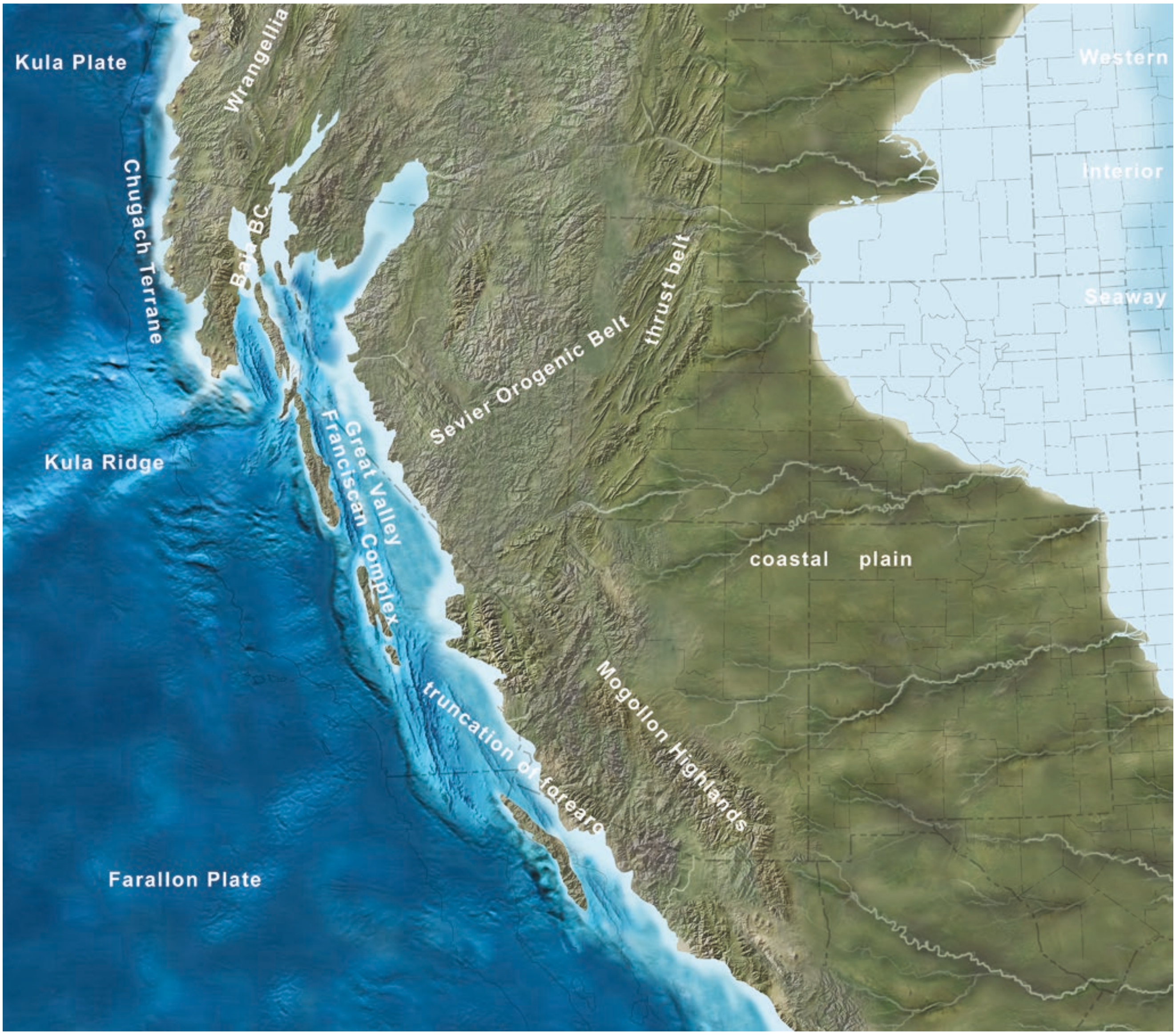


Fig. 8.14 Paleogeography of SW North America *ca*. 70 Ma. The Cordilleran arc between Northern Mexico and Central Nevada has completely shut down as the subducted slab migrates eastward in the subsurface. The Franciscan forearc zone is undergoing tectonic erosion and northward transport via transform faults (ridges in forearc). The axis of subsidence in the Western Interior Seaway has shifted well to the east. In 3–4 million years the seaway will be gone

9 Flat-Slab Subduction, the Laramide Orogeny, Uplift of the Colorado Plateau and Rocky Mountains: Paleocene and Eocene: Ca. 65–35 Ma

9.1 Dawn of the Cenozoic

The end of the Cretaceous gave way to the Paleogene Period, which includes the Paleocene, Eocene and Oligocene Epochs. At the dawn of the Paleogene (previously called the Early Tertiary), rapid sea floor spreading was occurring at the mid-Atlantic ridge, pushing fast-paced subduction at the western margin of the Cordillera (Fig. 9.1). Most of the continent was emergent during this interval with marine deposition limited only to the eastern seaboard, the Gulf of Mexico and the narrow fringes of the Pacific Borderland (Fig. 9.2). The accretionary prism of the Franciscan assemblage was still piling along the Coast Ranges but deposition of the Great Valley Sequence was superseded by several individual partitioned basins within the Central Valley. No large terranes arrived at the edge of North America during the Paleocene or Eocene Epochs.

We introduce the Cenozoic with a series of paleotectonic maps that range from 50 Ma to Present (Fig. 9.3). These maps will lead the reader through the rapidly evolving and varied tectonic settings that characterized the Cenozoic of western North America (Table 9.1). Words alone are difficult to describe these events so the maps should guide those interested in following this complex geologic history.

Fig. 9.2 North American Paleocene (ca. 60 Ma) paleogeography showing withdrawal of all epicontinental seas; note accretion of Olympic seamounts along southern edge of Wrangellia

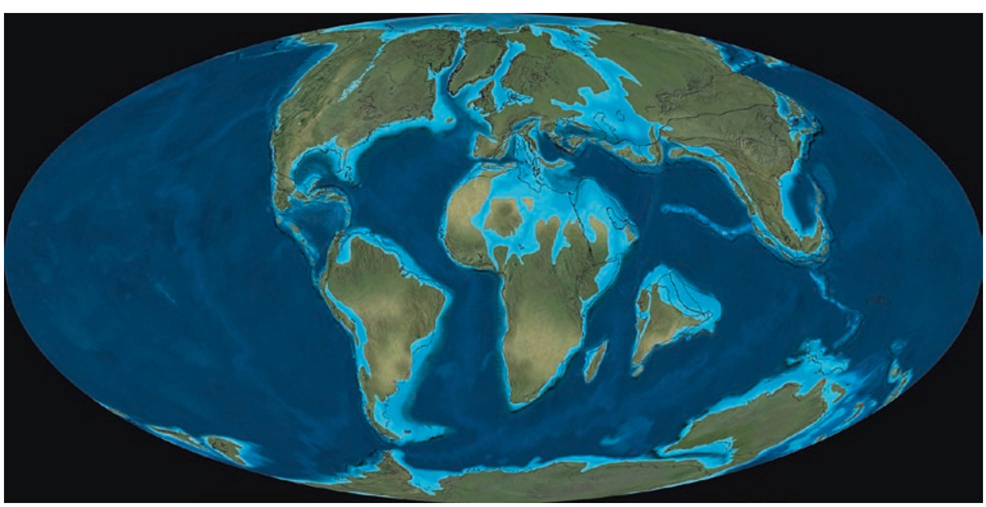


Fig. 9.1 Global paleogeography ca. 65 Ma near Cretaceous-Paleocene boundary. As the Atlantic and Indian oceans open, the modern shape of the continents begins to emerge. Note that the Cordilleran margin stretches from Alaska through South America

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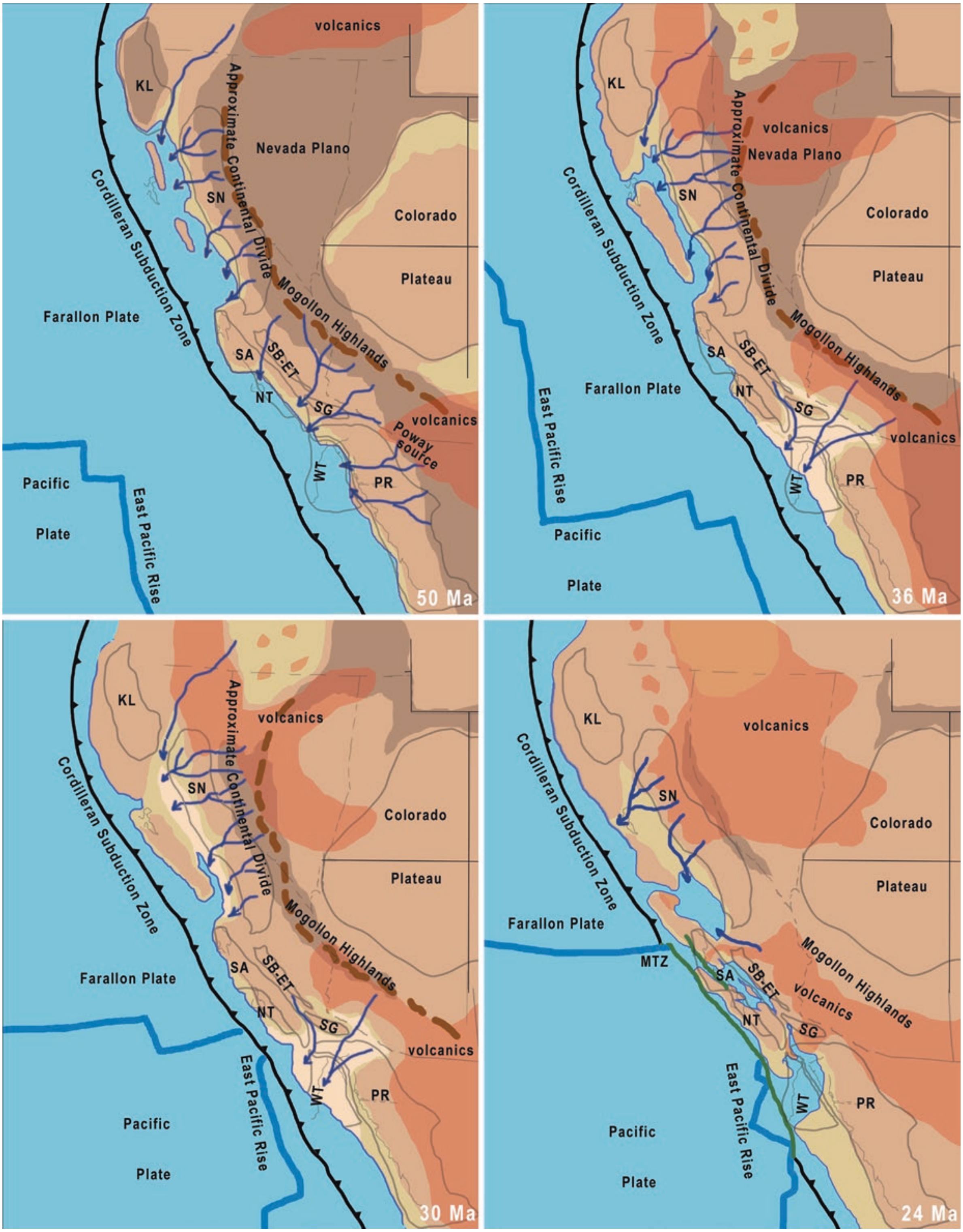


Fig. 9.3 A series of paleotectonic maps showing the Cenozoic evolution of SW North America. The Colorado Plateau remains fixed on all 14 maps, as Cordilleran elements to the west and south change in shape and location. (**1**) *50–24 Ma* showing the beginning of the evolution of a transform margin. (**2**) *18–12 Ma* showing the growth of the transform and northward migration of the Mendocino Triple Junction (*MTZ*). Note initial rotation of Transverse Ranges block and dynamic nature of the various sedimentary basins. (**3**) *10–4 Ma* showing rotation of transverse Ranges block, initial opening of Gulf of California, and initiation of the San Andreas Fault. (**4**) *2 Ma* present showing modern evolution of tectonic setting. Unlike the paleogeographic maps, the state borders and shorelines are warped in the older maps and gradually "unfold" to their modern configurations. This dramatizes the effects of extension and transform movements. *KL* Klamath Mountains, *NT* Nacimiento Terrane, *PR* Peninsular Ranges, *SA* Salinia, *SB-ET* San Bernidino-East Transverse Ranges block, *SG* San Gabriel block, *SN* Sierra Nevada, *WT* Western Transverse Ranges block

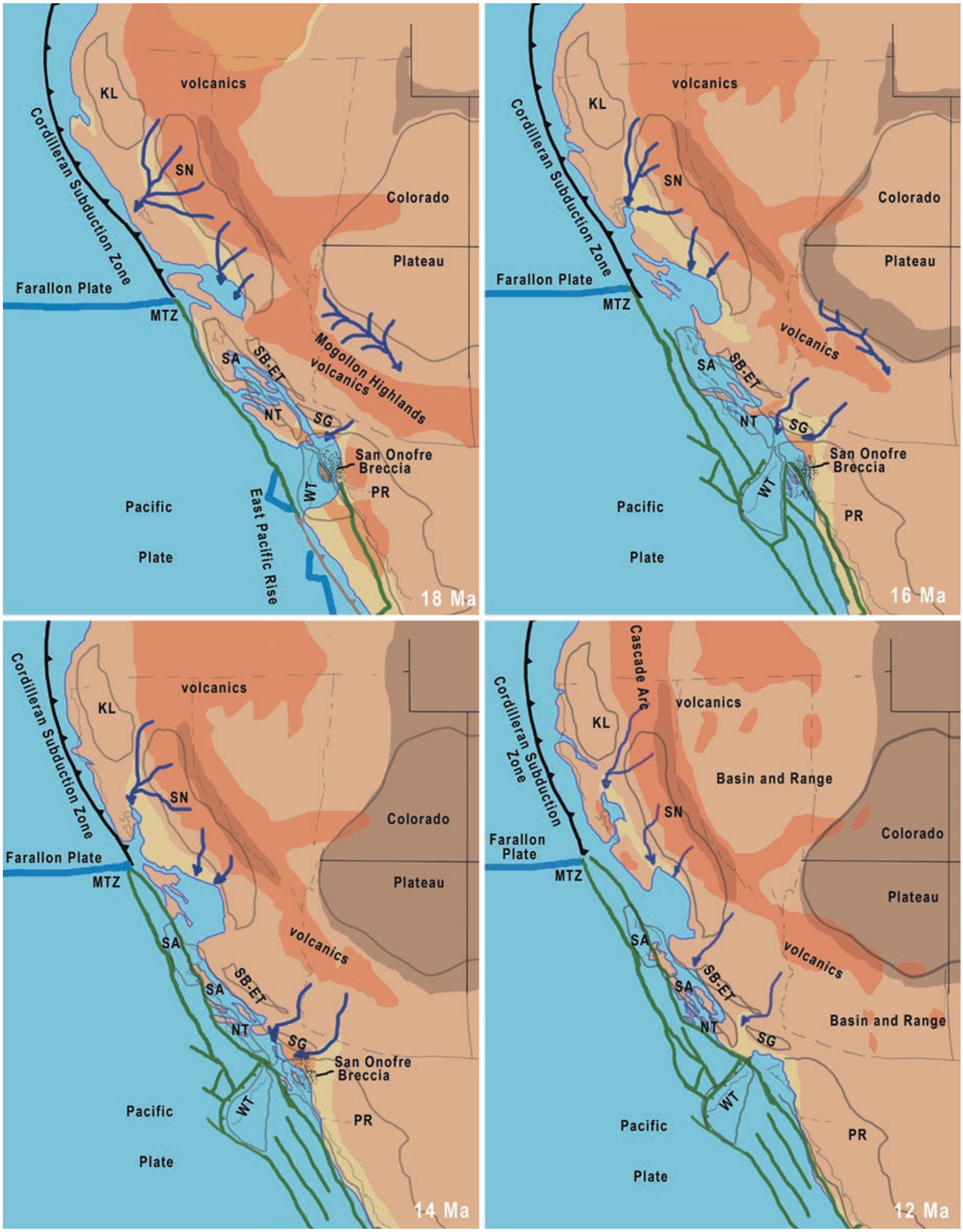
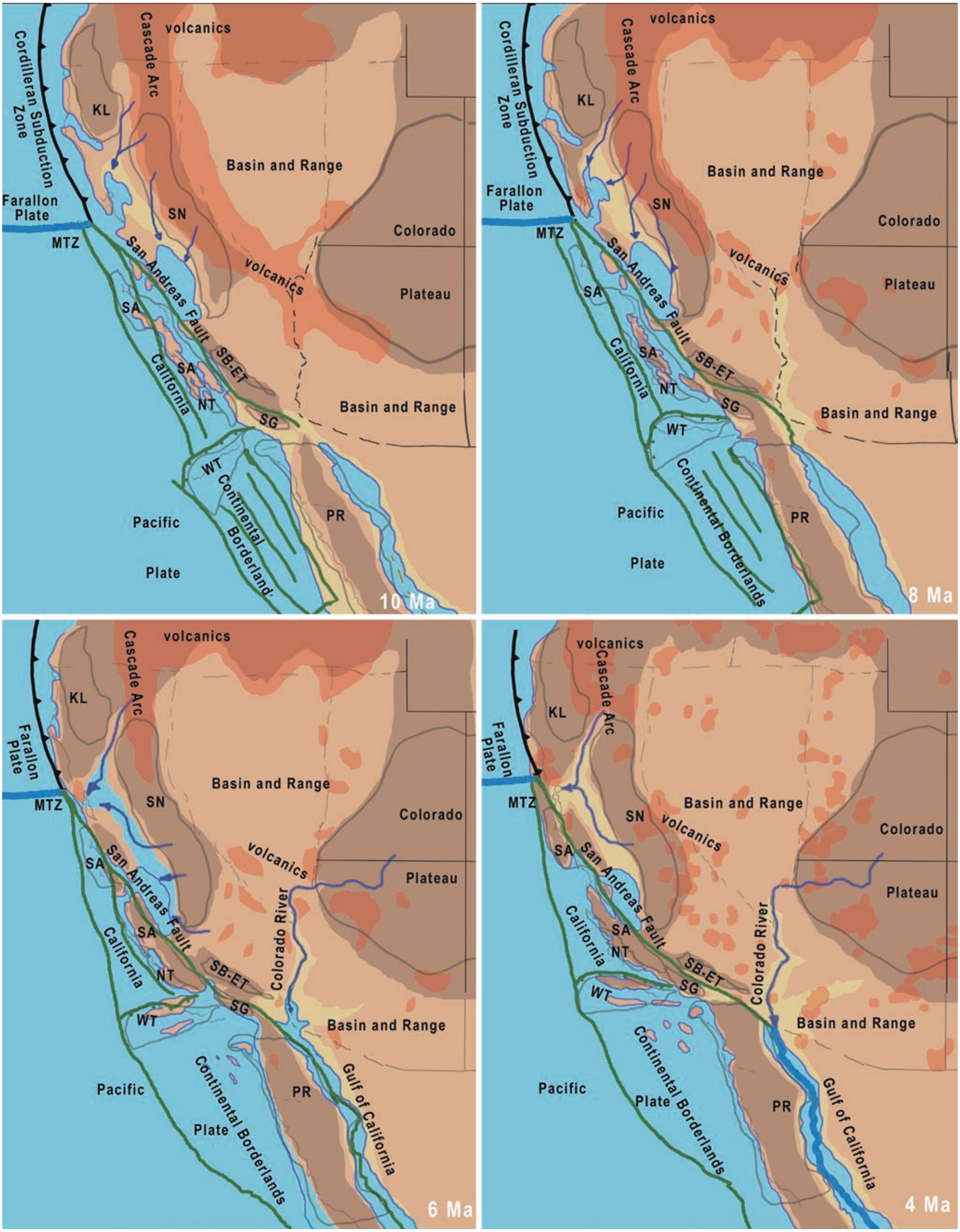


Fig. 9.3 (continued)



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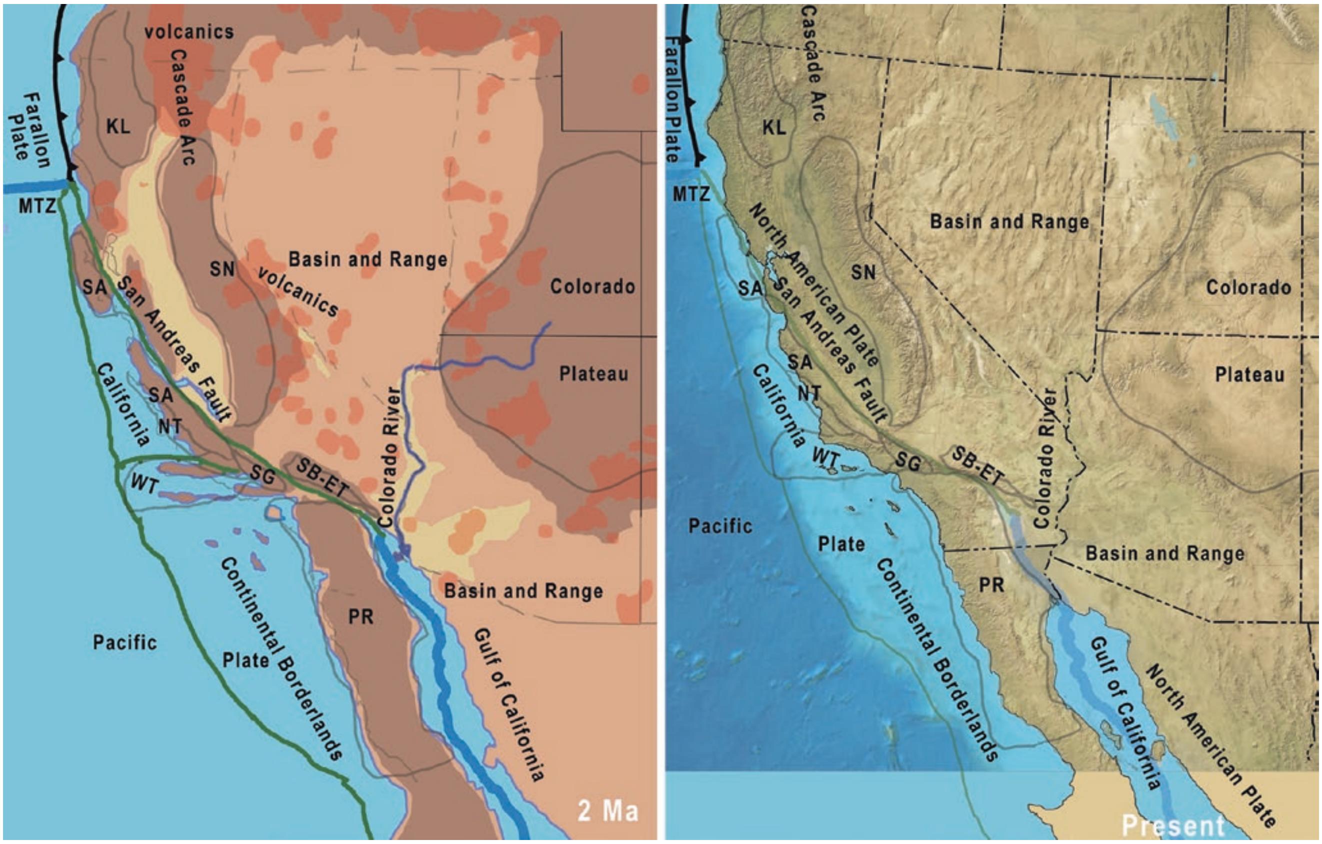


Fig. 9.3 (continued)

Table 9.1 Events 65–50 Ma

	Paleocene to early Eocene (*ca*. 65–50 Ma)
Time span	Flat-slab subduction, arc moves eastward onto craton, northward transport of fore arc – Laramide orogen
Geologic – tectonic setting	Continued rapid sea-floor spreading in Atlantic and rapid subduction in Cordillera
	Ca. 50 Ma, Gondwana was completely dismembered
	North America strongly emergent – marine deposition restricted to eastern seaboard, Gulf of Mexico shelf, and westernmost Cordilleran region
	By end of interval, most major accreted terranes (Insular, Intermontane) at or near present location
	Waning and final demise of both Franciscan and Great Valley sequences – however, shallow-angle subduction continued along Cordilleran trench; angle steepened throughout interval
	Arc magmatism developed as far east as Denver CO due to shallow/flat angle of subduction
	Strong uplift in Rocky Mountains (Laramide orogen) with major continental basins between uplifts
	Uplift of Colorado Plateau and formation of major monoclines
Boundary of western North America	Cordilleran subduction zone
Terranes	No significant new additions although some previously accreted terranes continued to migrate mostly northward along Cordilleran margin (e.g. Intermontane and Insular superterranes
	Significant dispersal of previous Franciscan material; most notably, the Nacimiento terrane was juxtaposed against Salinia; much of the former Franciscan material constructed the California Continental borderlands
	Parts of arc and forearc across S CA are missing and were likely subducted and/or displaced by transform faults (so-called tectonic erosion); some of this material was subducted and later uplifted and exposed in numerous mountain ranges across Central and Southern CA and Western AZ

(continued)

Table 9.1 (continued)

	Paleocene to early Eocene (*ca*. 65–50 Ma)
Time span	Flat-slab subduction, arc moves eastward onto craton, northward transport of fore arc – Laramide orogen
Sedimentation patterns, trends	Paleocene and Early Eocene sedimentary rocks, mostly sandstone, mudstone, and conglomerate, reflect diverse depositional and tectonic setting: fluvial and lacustrine deposits east of Sevier hinterland into the Rocky Mountains; marine, shoreline, and adjacent continental deposits along western Cordillera from Alaska to Mexico
	Along the West Coast, a series of diverse sedimentary basins were developed – many shoreline and shelf deposits abruptly grade west into deep marine deposits
	Following Late Cretaceous uplift and erosion, rapid Paleocene-Eocene transgression swept across Central and Southern California
	Several reconstructed depositional systems (e.g. Poway system of San Diego area) record complete transitions from fluvial conglomerates to east that grade westward into shoreline-deltaic environments and then deepwater submarine fan systems; distinctive pebbles in this system allow its reconstruction following dismemberment by late Cenozoic transform faulting – this reconstruction helps to quantify slip on the San Andreas Fault and rotation of the Transverse Ranges of Southern California
	Laramide (Rocky Mountain) basins contain extensive and locally very thick fluvial and lacustrine (lake) deposits – e.g. Green River Formation of UT, WY, and CO
Igneous/metamorphic events	Shallow subduction, following accretion and assimilation of the thick oceanic slab, caused arc magmatism to migrate NE – tracks of this pattern mark the Colorado Mineral Belt from Durango to Golden. Arc magmatism also shifted eastward across AZ into Western NM
	Extremely widespread and voluminous igneous events developed across Cordillera and onto craton
	During this interval, many important copper porphyry deposits of Sonora, Mx, AZ, and NM were formed as well as many other important metallic ore deposits across the greater Cordillera
	Franciscan high-pressure subduction and metamorphism continued

9.2 Nevadaplano

A postulated highland area located east of the Sierra arc in Nevada is called the *Nevadaplano* (Fig. 9.3a) and takes its name from a modern analog in South America, the Andean Altiplano. Geologists debate some aspects of its existence but it likely was a high, plateau-like feature uplifted out of the hinterland of the Sevier fold and thrust belt. A system of preserved drainage basins on the Nevadaplano and surrounding areas gives some of the best evidence for its existence. This system flowed from the postulated early Cenozoic continental divide, now located in west-central Nevada, eastward towards the large lakes on the Colorado Plateau, and to the west in a gentle descent across the Sierra Nevada region to the Pacific shore (Fig. 9.4). The drainage was established in the Paleogene and existed at least through the Eocene with evidence coming from Oligocene volcanic tuffs that overlie and preserve parts of the drainage system. As these Eocene rivers swept across the Sierra arc, they chiseled into the Sierra granite, which had emplaced lode-gold ore during the Nevadan orogeny. These Eocene rivers deposited fluvial sediments including eroded gold. These placer gold deposits from the Sierra foothills forever changed California and American history with their discovery in 1849. Evidence for the east-draining system is contained in a series of lake deposits across Nevada into central and Southern Utah. Geochemical and detrital zircon studies of these lakes prove the Nevadaplano connection.

Fig. 9.4 Paleogeography of SW North America at ca. 50 Ma (Early Eocene). Flat-slab subduction has generated arc volcanism far inland; note volcanoes in NW WY, C-SW CO, and in S NM and AZ. Along Pacific Coast, widespread Eocene deposition ranges from continental through deep marine. Nevadaplano, a high plateau centered over Sevier orogenic belt, marks a continental divide; numerous large and small lakes range across Western US. Newly raised Rocky Mountains shed sediment into basins between uplifts

9.3 Laramide Orogen

A period of uplift known as the *Laramide orogeny* was one of the seminal orogenic events to occur in the Cordillera (Fig. 9.2) and was a major result of the flat-slab subduction of the Farallon plate and the oceanic plateau riding on it. The Laramide orogeny is responsible for the initial uplift of the Colorado Plateau and the Rocky Mountains, and a rejuvenation of the Mogollon Highlands in southwest Arizona (recall these Highlands were first uplifted in the Triassic). The Laramide was named and first recognized for deposits that were shed into the Laramie Basin in southern Wyoming but many basin-fill deposits can be found in the northern Rockies area. It is the basement-cored uplifts however, that are the most recognizable features from the event.

These basement-cored vertical uplifts (Figs. 9.5 and 9.6) replaced the horizontally-directed thin-skin deformation prevalent during the Sevier orogeny. In the basement-cored style of deformation, older Precambrian and Phanerozoic faults and other zones of weakness were reactivated by compressive stresses to uplift discrete

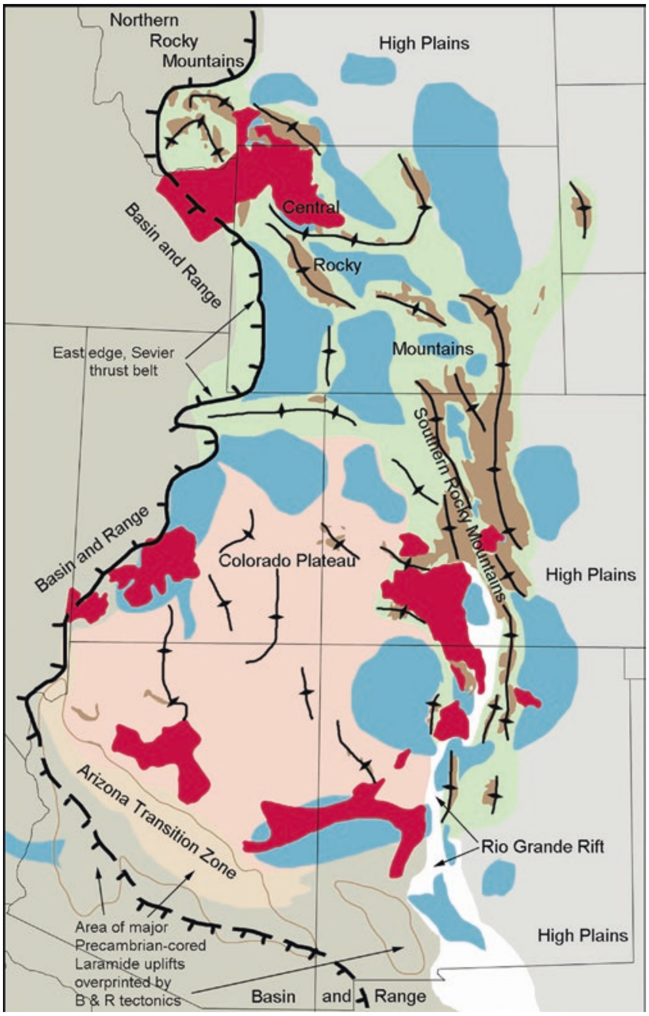


Fig. 9.5 Map showing distribution of major tectonic elements formed during Laramide orogen (80–40 Ma). *Blue* – Laramide basins; *green* – uplifts/arches; *tan* – basement-cored uplifts; *line with diamonds* – trend of uplifts; *red* – volcanic centers; other features as labeled

mountain cores. Adjacent to these basement-cored uplifts were down-faulted basins that received eroded material from the uplifts; interestingly, it is these basin deposits, not the uplifts, that first gave geologists clues to the Laramide orogeny. The deposits are composed of conglomerate, sandstone and mudstone, and contain zircons derived from the uplifted cores – grain size distribution and paleocurrent directions reveal sediment sources in the adjacent uplifts. In the Uintah basin of eastern Utah, zircons have shown that some of the material deposited there (the Colton Formation) originated from the eastern side of the magmatic arc in southeastern California, now part of the Mojave Desert, a phenomenal distance of travel across the Cordillera.

Although the uplift of the Colorado Plateau began in the Laramide, the precise amount is unknown relative to later periods of additional uplift. Nevertheless, the spectacular upwarps and monoclines seen on the Plateau today were formed in the Laramide. These upwarps typically have gently dipping western limbs and steep eastern limbs (the monoclines). Some of the upwarps might have had only subtle expressions on the Laramide surface, although sediments in the southern Uintah Basin were clearly derived from the adjacent San Rafael Swell. Numerous national parks and monuments preserve the scenery of these spectacular folds, including Grand Canyon National Park and Vermilion Cliffs and Grand Staircase-Escalante national monuments (East Kaibab monocline) and Capitol Reef National Park (Waterpocket monocline; Fig. 9.7). Note that many of the rocks seen today in the monoclines were deeply buried during their uplift in the Laramide and not exposed until the Neogene.

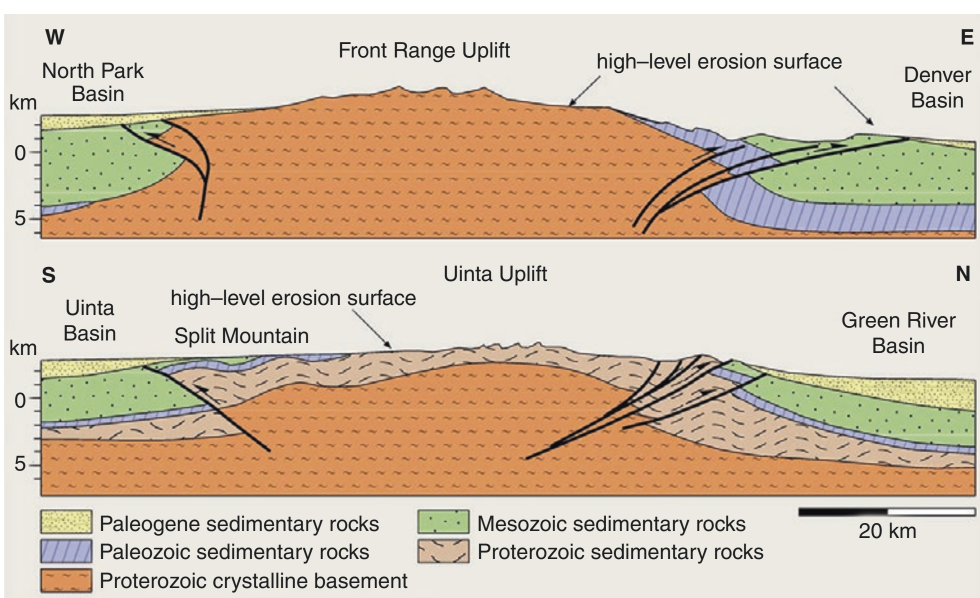


Fig. 9.6 Simplified panel cross sections of Front Range and Uinta uplifts, Southern and Central Rocky Mountains. Note the "flower pot" pattern exhibited by the faults as they fan out from the core uplift. Such structure documents that compressive forces generated the uplifts. The high-level erosion surfaces formed 40–30 million years ago and suggest that the Rockies were planed-off by erosion. Some combination of Late Cenozoic uplift and erosion exhumed the mountains from the relatively flat surface and Pleistocene glaciation shaped the present rugged landscape

Fig. 9.7 The Waterpocket Fold is a major Colorado Plateau monocline that runs the length of Capitol Reef National Park. This Laramide fold caused over a km of structural relief between the upthrown west block and downthrown east block. (**a**) Ground view; (**b**) arial view

9.4 Continental Sedimentation and Interior Lakes

In the Eocene, interior drained basins trapped freshwater to form huge lakes where the three states of Wyoming, Utah and Colorado intersect. The Green River Formation (Fig. 9.8) is the best known of these interior lake deposits and contains a detailed record for a 6 million-year period, yielding numerous fish fossils that proliferate rock shops across the west. Variably composed of sandstone, siltstone, limestone, coal, and evaporites, these deposits hold the world's largest reserve of oil shale. The hydrocarbons originated from the decay of microscopic cyanobacteria that lived in the lakes. Coeval and possibly separate lakes covered much of SW Utah where spectacular exposures in Bryce Canyon National Park (Fig. 9.8d) and Cedar Breaks National Monument allow detailed study of the lacustrine systems.

The Mogollon Highlands were the source area for drainage to the northeast and east of the magmatic arc. For a relatively short period of time, from 70 to 65 Ma, eroded sediment was carried from the Mogollon Highlands in Arizona and transported northeast across the Plateau and Rocky Mountain regions to the Great Plains and then southward to the Gulf of Mexico. This drainage system left scattered deposits on what is today the high-standing southern edge of the Colorado Plateau and their presence shows that the Mogollon Rim could not have existed during the early Cenozoic.

Laramide deposits also hold clues to the early evolution of mammals, the animals that occupied the ecological niches vacated with the demise of the dinosaurs. Within the first 5 million years of the Paleogene, mammals of all sizes had occupied all corners of the globe. Carnivores evolved very early in the Paleocene and the North American record for the evolution of horses is well documented, with species the size of small dogs appearing the Paleocene. A branch of carnivore that would become the great whales made the transition from land dwelling to marine dwelling by the Late Eocene. Proboscideans (elephants) appeared in the Paleocene in Africa but radiated to North America where their descendants would emerge as the mammoths and mastodons. Flowering plants, which made their first appearance in the Cretaceous, expanded greatly.

Fig. 9.8 Eocene lacustrine sedimentary rocks on the Colorado Plateau. (**a**) Mudstone-dominated Green River Formation, central Utah. (**b**) Fluvial-deltaic sandstone in Green River Formation north of Green River, Utah. (**c**) Oil shale in the Green River Formation near Grand Junction, Colorado. (**d**) Hoodoos carved in the Claron Formation, Bryce Canyon National Park, Utah

Fig. 9.8 (continued)

The climate cooled a bit immediately at the end of the Cretaceous but then warmed in the Eocene in a phase known as the Paleocene-Eocene Thermal Maximum (PETM). Sediment records indicate that a massive carbon injection into Earth's atmosphere occurred about 55.5 Ma, lasting no more than about 20,000 years but raising global temperatures between 5 and 8 °C (9 and 15 °F) for a period that may have lasted 200,000 years. This short term warming was part of a longer cycle of warming that lasted between 5 and 7 million years, from 57 to 50 Ma. The PETM event is used to quantify what might be possible in a modern warming event but the reasons for the spike in additional atmospheric carbon remain unclear. Change in ocean circulation patterns, dissolution of marine carbonate rocks, increased volcanic activity, volcanism that erupted through carbonate-rich sediments, orbital forcing, or perhaps the melting of submarine *methane clathrates* (frozen piles of methane) are the usual suspects. Most likely, there were feedback mechanisms that involved a combination of some, or all of these factors.

9.5 Laramide Magmatism

As magmatic activity shifted eastward in the Laramide across central and southern Arizona to southern New Mexico, it emplaced rich ores of copper in the crust. Today Arizona produces more than 50 % of the nation's copper; most of it originated in these magmatic events. The Colorado Mineral Belt, with its rich ores of silver and gold, traces the movement of the Farallon slab and its thickened oceanic plateau beneath the southern Cordillera from Durango to Silverton to Creede, and eastward to Golden, Colorado. Voluminous and widespread volcanism is evident across the Cordillera from southeast Alaska and British Columbia, to Montana, Idaho the southwest to Sonora Mexico. High-pressure, low-temperature metamorphism continued within the Franciscan assemblage as subduction continued off the coast of California.

In central Colorado west of Denver, an explosive volcanic field dammed a river resulting in the formation of a small lake 35–34 Ma. Fine-grained lake sediment preserved a rich fossil fauna that captures the essence of late Eocene ecosystem. Over 50,000 specimens representing 1700 different animals and plants have been collected since the 1870s, when gold-rush miners first encountered huge fossilized stumps of Redwood trees near the small town of Florissant. After decades of fossil removals, the area was preserved as Florissant Fossil Beds National Monument. A rich scientific environment now thrives in this former subtropical paradise as paleontologists uncover evidence for the many life forms that thrived in the late Eocene. The redwood stumps were preserved when a giant *lahar* (volcanic mudflow) swept through the valley, stripping the tree tops away but preserving the base of the trees in ash-laden sediment. Quieter intervals between eruptions preserved thousands of fossilized insects including ants, wasps, bees, caddis-flies, dragonflies, and midges. Cattails, water-lilies, elms, willow, maples and hickory also have been found at the site.

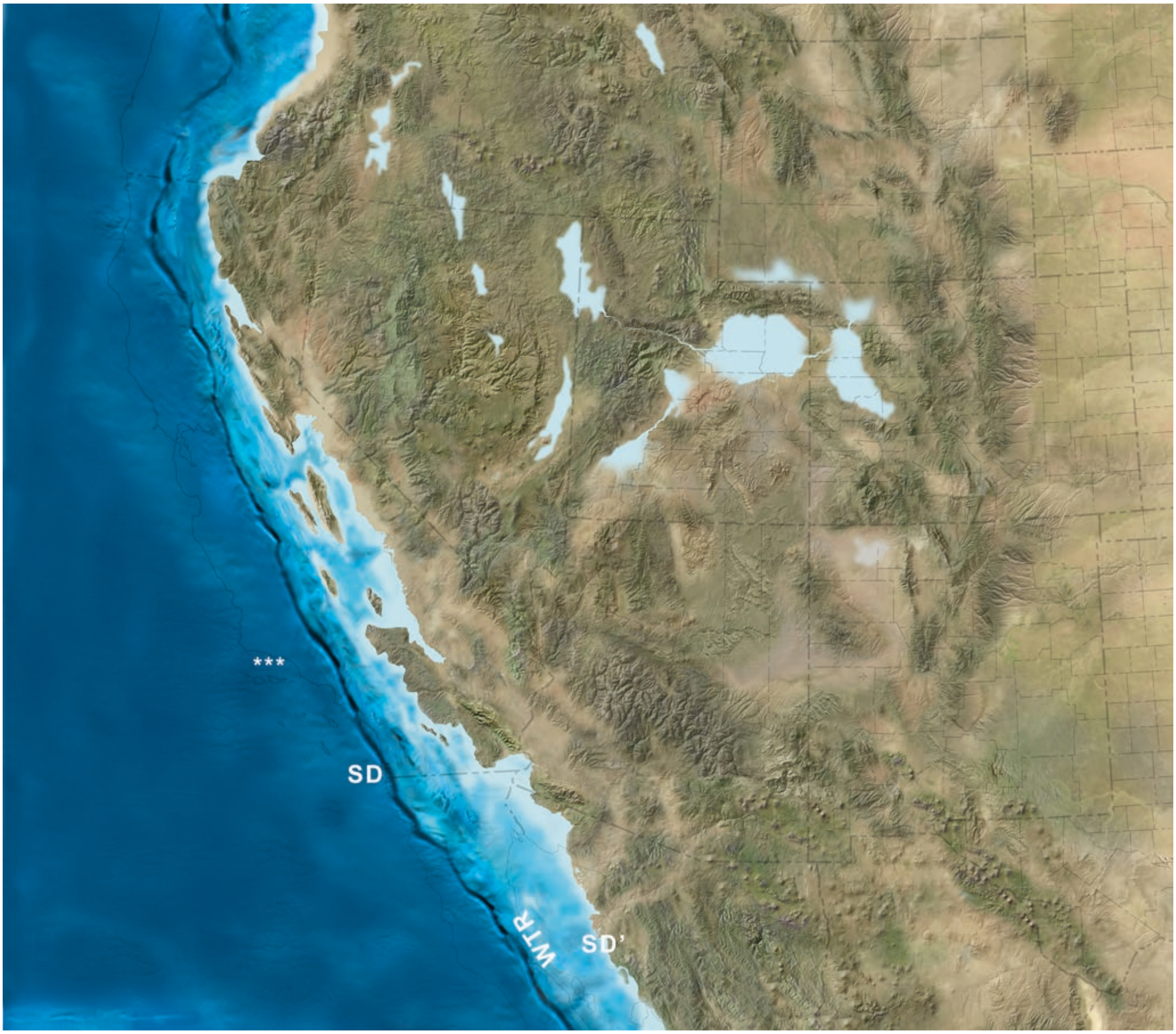


Fig. 9.9 Paleogeography of SW North America at ca. 45 Ma showing paleogeography following major Laramide and Sevier deformation but before extensive extension and transform margin tectonics. Note that the West Coast is closer to the stable Colorado Plateau than at present; elements now west of the San Andreas transform are much farther south on this map. As points of reference, the Western Transverse Ranges (*WTR*), shown here at the bottom of the map are at present located where the *** pattern is along the modern Santa Barbara Coast and *SD'* marks Eocene San Diego and *SD* marks present San Diego (note faint outlines of modern position of California). Note Poway fluvial-deltaic system at *SD'*. The Green River Formation (Fig. 9.8a–c) formed in the lakes in NE Utah, NW Colorado, and SW Wyoming and the Claron Formation formed in the lake in SW Utah

Beginning in the Middle Eocene and continuing into the Late Eocene (Fig. 9.9), the Farallon slab began to assume a steeper, more normal dip angle of about 45–60°. This may have been due to a gradual slowdown in the rate of sea floor spreading in the mid-Atlantic or a gradual cooling of the Farallon slab (Table 9.2). Whatever the cause, the steepened angle caused the axis of arc magmatism to swing back to the west. Radiometric dating of volcanism shows that the start of this swing back to the west began about 40 Ma, not coincidently when Laramide uplift begin to wane. As the magmatism swept west, it initiated the *Great Ignimbrite Flare-up* in Nevada and western Utah between 42 and 36 Ma (ignimbrite is a term for rocks formed in catastrophic rhyolitic eruptions). This flare-up was the source of much of the gold ore found in Nevada, one of the world's greatest gold-producing regions. The collapse of the Sevier Highlands and cessation of Laramide compression follow this magmatic event. With uplift reduced, an episode of regional erosion beveled parts of the Cordilleran surface to initiate the *Telluride erosion surface*, named for where it was first recognized in Colorado (Fig. 9.10).

Table 9.2 Events 50–35 Ma

Time span	Middle to late Eocene (Ca. 50–35 Ma)
	Subduction steepens and arc swings back (westward) towards Cordilleran margin, collapse of Sevier hinterland; East Pacific Rise intercepts western North America
Geologic – tectonic setting	Gradual slowing of Atlantic spreading rate; opening of North Atlantic
	Cordilleran subduction gradually steepens to normal angle; thus, the locus of arc magmatism sweeps westward across Colorado Plateau and Great Basin
	The Farallon Plate was the largest tectonic plate during much of the Mesozoic – its destruction in the Cordilleran subduction zone generated the huge volume of magmatic rocks that comprise the Cordilleran region
	As the Farallon Plate narrowed by subduction, the East Pacific Rise approached western North America – initial contact ca. 35 Ma
	Early extension across western North America caused gradual collapse and lowering of Sevier hinterland
	Late Eocene to Oligocene was a time of regional erosional planation of eastern Cordillera, especially across Rocky Mountain region (e.g. Telluride Erosion Surface) – this interval is marked by widespread unconformities across much of greater Cordilleran region
	Initiation of Great Ignimbrite Flare-up (ca. 38 Ma)
Boundary of western North America	Cordilleran subduction zone
Terranes	Continued juxtaposition along transform faults, especially in Canada and AK
	Continued accretion of oceanic crust in Western WA (seamounts, plateaus, extinct oceanic ridges – Olympic Mountains, Siletzia)
Sedimentation patterns, trends	Rapidly evolving conditions – numerous unconformities in many sections beginning in Late Eocene
	Forearc deposition mixed with volcanics as arc magmatism migrated westward – especially well- preserved deposits in western OR and WA
	Huge volumes of sediment from highland sources in N CA and ID filled forearc with thick deltaic and submarine fan deposits – e.g. Tyee Formation of WC OR
	Complex juxtaposition of uplifts and rapidly subsiding basins in forearc generated uneven distribution of preserved sedimentary rocks
Igneous/metamorphic events	Widespread and varied igneous activity as arc magmatism swung back towards normal position of Cordilleran arc
	Initiation of Cascade arc from Central CA into S BC
	Challis magmatic belt from NW WY to S ID and north into Canada
	Numerous magmatic events across UT, AZ, NV as arc migrated westward
	Large igneous province, Sierra Madre at ca. 38 Ma one of largest continental silisic igneous events in geologic record – stretched northward from Sierra Madre Mountains in MX to S CO, UT, and NV
	Renewed magmatism in Sierra Nevada

Fig. 9.10 The Late Eocene Telluride Surface exposed between *red* Pennsylvanian rocks below and Oligocene volcanics above. Though now greatly altered and eroded, the surface may have extended from eastern Nevada to Denver, Colorado and from Montana to central Arizona. The Rockies likely formed rounded highlands with relatively flat tops above lower-lying plains

9.6 Terranes Move Northward

Along the margins of Alaska and Canada, transform displacement was driving slivers of crust northward (Fig. 9.11) and terranes that now form the Olympic Mountains in Washington and the Siletzia terrane in Oregon arrived at their present location (Fig. 9.12). The Coast Plutonic Complex in Alaska and British Columbia continued as an active arc (Fig. 9.13). Relatively normal subduction appears to have been continuous along parts of the Alaskan and British Columbia coasts from Late Jurassic through Eocene.

Fig. 9.11 Mesozoic sedimentary and volcanic rocks now exposed near Juneau, Alaska were originally accreted hundreds of km farther south. As the Insular (Wrangellia) and Intermontain superterranes were driven north along major transform faults in the late Mesozoic and early Cenozoic, the rocks arrived at their final resting place

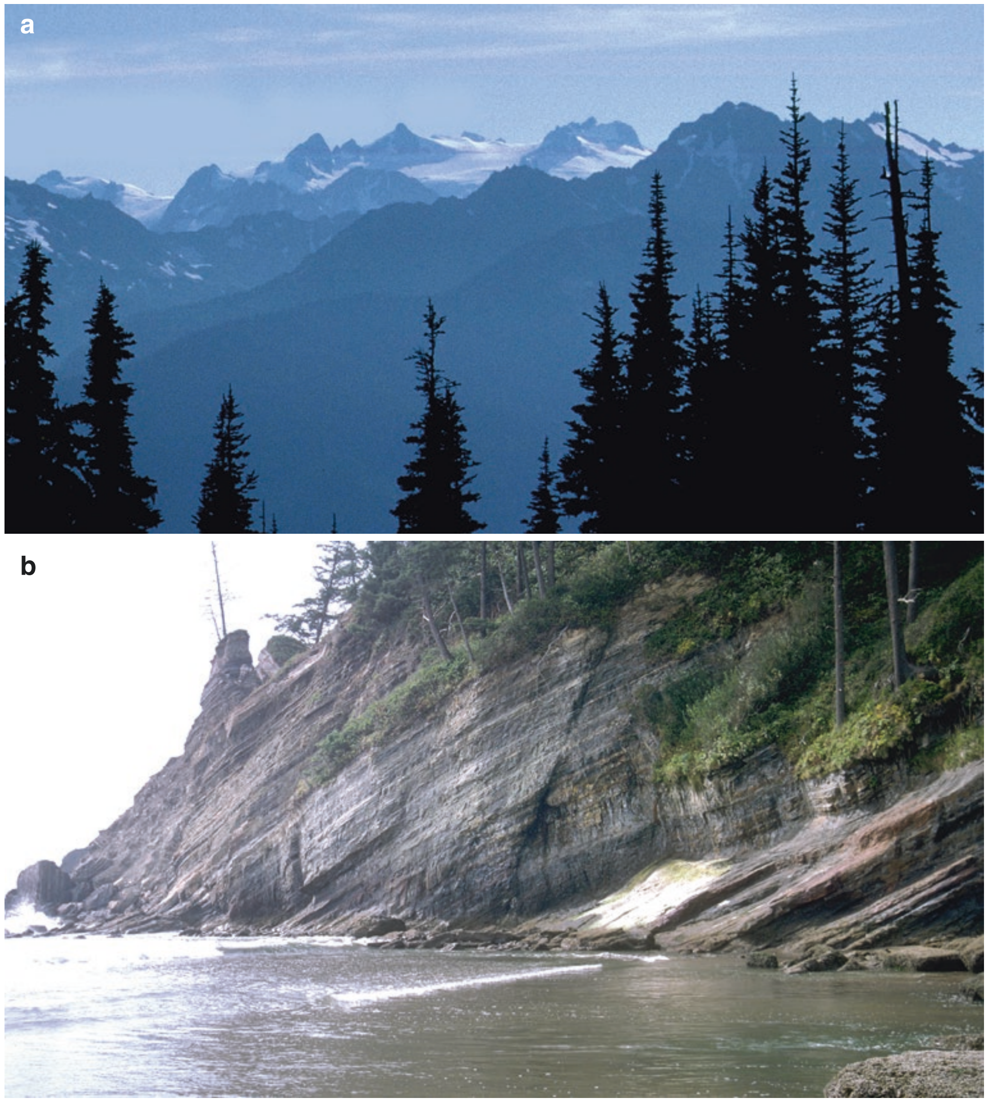


Fig. 9.12 Accreted terranes of the Pacific Northwest. (**a**) Olympic Mountains in W Washington accreted to North America as a series of seamounts and oceanic plateaus in the Eocene. (**b**) Turbidites in Siletzia formed as seamounts and plateaus accreted along W Oregon in the Eocene. Both terranes may have been generated by what is now the Yellowstone hotspot when it lay west of North America in the Pacific Ocean

Fig. 9.13 Granites in the Coast Plutonic Complex rise above a fjord near Petersburg, Alaska. Plutonism here continued into the Eocene

9.7 Paleogene Coastal Sedimentation

The early Cenozoic has well preserved records of sedimentation from Oregon southward to Baja. Some of these units have been well studied and add much to our knowledge of Cenozoic paleogeography. Across the Central Valley of California, especially in the San Joaquin Basin, a trough-like basin extended from north of Sacramento to south of Bakersfield. Huge fluvial systems draining the Nevadaplano formed large deltas, especially near Sacramento and Stockton. Large submarine fans developed down-axis from the deltas. The complex stratigraphic record is marked by rapid changes – deepwater deposits yield abruptly to shallow marine systems and then the opposite occurred; several unconformities mark the section, some suggesting sub-areal exposure and erosion. Great submarine canyons are preserved. These features indicate rapid changes in relative sea level, sediment supply, and possibly climate. The San Joaquin Basin persisted into the late Cenozoic, relatively undisturbed by tectonics, and today is a large, flat, lowland that separates mountains lying to the east and west.

The Pacific Coast from Oregon to Baja exposes parts of a complex group of early Cenozoic basins now more dispersed by large transform systems including the modern San Andreas Fault. The farthest north and one of the larger basins is the Tyee Basin of Western Oregon. The Tyee Basin was the forearc basin to the embryonic Cascade Arc. The basin, now exposed from north of Florence to south of Coos Bay and inland as much as 50 km, initiated as a deepwater basin that was filled from the southeast by rivers draining off the Klamath Mountains (Fig. 9.4, extreme NW corner of map). The prograding fan-delta-beach-fluvial system formed a classic regressive sequence across the basin.

Along the California Coast, early Cenozoic basins are present from north of San Francisco to south into Baja. When transform faults are restored, the northern basins (those on Salinia) were originally hundreds of km farther south. Most basins expose sedimentary rocks deposited in deepwater basin, submarine fan-slope, deltaic, and river systems (Fig. 9.14). Sedimentation was extremely heavy and subsidence rapid – even some thick sandstone sequences were deposited in deep water. Most sediment was from the east off the Sierras and Nevadaplano, but local highs along and between basins shed local coarse debris. Perhaps the most accurately reconstructed basin is exposed in San Diego and northward to the coast at Carlsbad. The Poway Basin as it is commonly called, exposes incised river canyons filled with fluvial conglomerate, the coastal plain-delta system, barrier bars, lagoons with abundant oyster faunas, offshore muds, and slope-fan systems to abyssal depths (Figs. 9.4 and 9.14). Transported within the system are distinctive "blood-red" pebbles and cobbles, the so-called Poway clasts. Some of the pebbles reached the submarine fans. This basin has been severely disrupted by Miocene to Recent tectonics. Restoration of horizontal slip and 120° of rotation provides strong evidence concerning the motion and displacement on the San Andreas and other fault systems. Such restoration as shown on Figs. 9.3, 9.4, and 9.9 in which features are restored to their previous locations for a given time slice are called *palinspastic reconstructions*.

Beginning approximately 35 Ma, big changes were on the horizon as the western edge of the Farallon plate approached the edge of the continent. Since the Late Triassic, subduction of the Farallon plate was the primary process in shaping the Cordillera but it was only a matter of time before its reign would end.

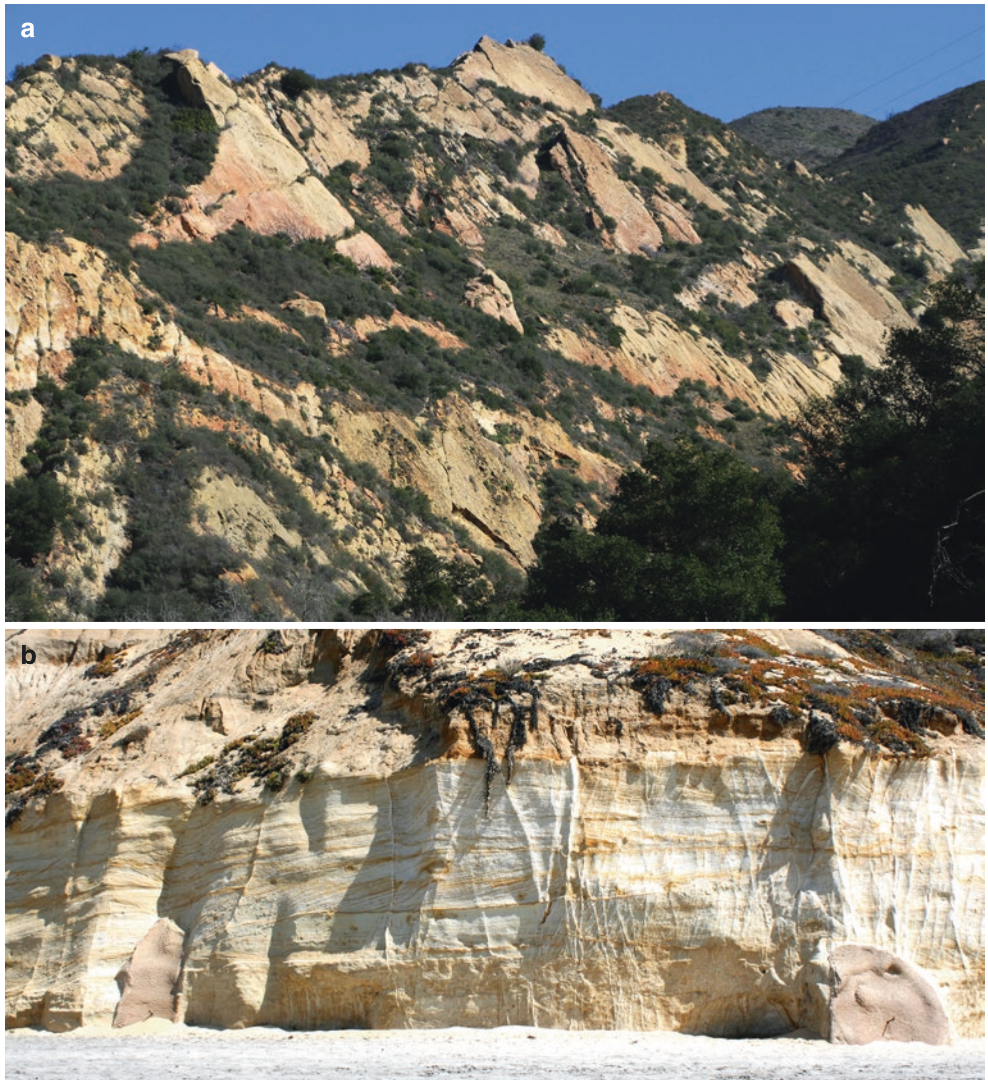
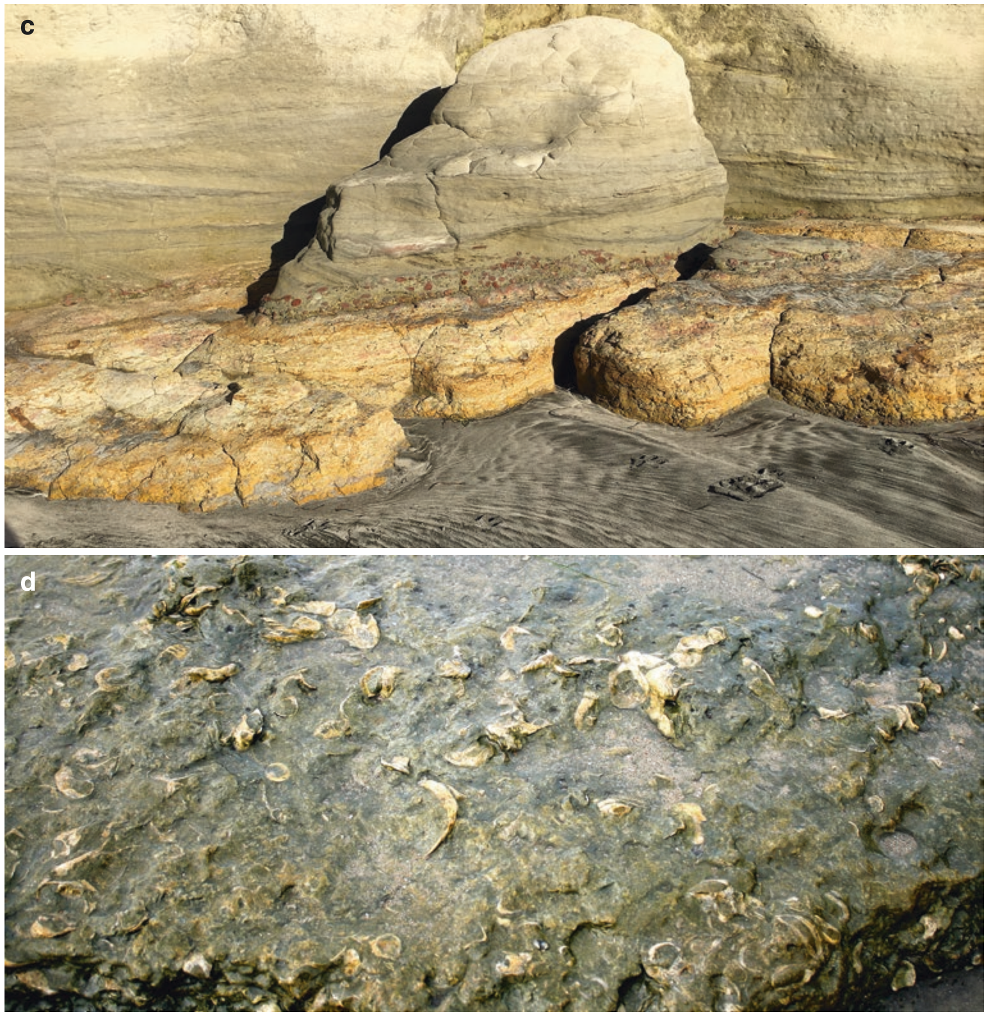


Fig. 9.14 Rocks in the Eocene basins of California. (**a**) Cretaceous and Eocene sandstones in the Santa Ynez Mountains west of Santa Barbara. The hogback ridges formed when the Transverse Ranges block rotated and collided with Salinia. (**b**–**d**) Sedimentary rocks in the Poway system near San Diego. (**b**) Barrier bar and beach sandstone of Torrey Sandstone, Solano Beach. (**c**) Del Mar formation sandy mudstone overlain by Torrey Sandstone, North Ponto Beach, Carlsbad-Encinitas. Barrier bar and beach sands transgressed over coastal lagoon deposits as the basin deepened. (**d**) Oyster fauna in the Del Mar Formation, a coastal lagoon complex at Del Mar

Fig. 9.14 (continued)



Changing Tectonics, Cooling Climates and the Dawn of Crustal Extension: Late Eocene to Early Miocene (ca. 35–20 Ma)

10

10.1 Birth of a Transform Margin

Subduction of the Farallon plate starting in the Late Triassic (225 Ma) was the single most important factor in shaping the Mesozoic and early Cenozoic landscapes of the Cordillera. Subduction shortened the crust laterally, thickened it vertically, gave rise to the development of a great magmatic arc, and brought numerous exotic terranes to the continent. The outcome of this subduction was that real estate was added to the continent. However, this nearly 200 million-year time interval of terrane accretion and compression started to change beginning around 35 Ma. This is when the East Pacific Rise and the Pacific plate first arrived at the North American margin and initiated a new set of processes that would alter the Cordilleran landscape in completely different ways (Fig. 10.1; Table 10.1).

The East Pacific Rise was a spreading center that was positioned between the Farallon and Pacific plates. As the East Pacific Rise contacted North America, the continent bordered the Pacific plate (Fig. 10.2). The subduction with the Farallon plate ended and a transform margin replaced it. The reason for this change is best seen by looking at maps. Examine the series of maps shown in Fig. 9.3(1). At 36 Ma, the subduction margin is intact. At the East Pacific Rise, the Pacific Plate is moving to the W (actually WNW) and the Farallon Plate is moving east to be subducted under North America. North America is moving slowly (relative to the Pacific Plate) to the WSW. Between 30 Ma and 24 Ma, the boundary of western North America adjacent to the Pacific Plate lengthened. The Pacific Plate is moving rapidly to the WNW and the North American Plate is moving slowly to the WSW. The Pacific Plate is pulling on (away from) North America at an oblique angle. Therefore, subduction is impossible where the two plates bound each other. The pull of the Pacific Plate causes North America to extend in a westerly direction. This extension is manifested by core complexes across S Arizona, that portion of North America adjacent to the Pacific Plate. This process continues and the length of the new transform margin grows as the Mendocino Triple Junction (MTZ) moves N relative to the Colorado Plateau (our fixed point on North America). The motion between North America and the Pacific Plate is transform – North America moves SW but the Pacific Plate moves NW and at a greater rate. Thus, to an observer straddling the transform, the Pacific Plate moves N while the North American Plate moves S. Such a motion defines a right-lateral or dextral strike-slip fault. The rapidly moving Pacific Plate tugs on the edge of North America and pulls blocks away from it. This

Fig. 10.1 Paleogeography of North America near the Eocene-Oligocene boundary (ca. 35 Ma). Note the approaching East Pacific Rise (Pacific Plate to left, Farallon Plate to right) along the West Coast of North America; it intercepted North America west of S Arizona

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Table 10.1 Events 35–20 Ma

Time span	Latest Eocene through Oligocene to early Miocene (ca. 35–20 Ma)
	Major change in Cordilleran tectonic patterns. Arc returns to previous position, great ignimbrite event, regional erosional planation. East Pacific Rise intercepts WNA in complex fashion
Geologic – tectonic setting	At ca. 35 Ma, East Pacific Rise intercepted Western NA at present latitude of S AZ
	Following initial contact, the zone of contact (plate boundary) lengthened and two triple junctions formed – Mendocino to N and Rivera to S. Through millions of years, the triple junctions moved farther apart and the Pacific-North American plate boundary became a linear transform. The Pacific Plate was moving rapidly to NW and the NA Plate was moving slowly to SW. The pull of the Pacific Plate on NA caused extension of Western NA. The Pacific Plate eventually "captured" portions of NA and pulled them (relatively) to NW. Thus was borne the right-lateral transform margin of SW NA
	Extension of NA continental crust is oldest (ca. 28 Ma) across S AZ; this was directly E of the initial contact of the East Pacific Rise
	The earliest phase of extension created series of core complexes – extension of the upper brittle crust literally pulled the crust apart and the lower crust rises to fill in the gap
	Over the past ca. 30 million years, these processes have completely reorganized the tectonic regime of Western NA. Subduction ceased at the transform margin because the Pacific Plate was moving away from NA whereas previously, the Farallon Plate moved towards and was subducted beneath NA
	As the crust and mantle responded to these changes, widespread and varied magmatism affected Western NA – but to the N and S of the migrating triple junctions, normal subduction continued. Thus, both extensional magmatism and subduction magmatism were occurring at the same time but in different places
Boundary of western North America	Following over 70 million years of Cordilleran subduction, the nature of the plate boundary changed. N and S of the triple junctions, the Cordilleran subduction zone remained active. Between the triple junctions, transform plate boundary expanded through the Cenozoic. The transform margin was very dynamic and jumped inland as fragments of NA were captured by the Pacific Plate. Where this occurred, the plate boundary lay within continental crust at the location on the transform. Much of this continental crust now lies below sea level and forms the California Continental Borderlands. The modern active transform is marked by the San Andreas Fault; at various times in the late Cenozoic, the boundary lay farther W along older transform margins
Terranes	Additional terrane juxtaposition and rotation took place along much of the Cordillera from Mexico to Alaska (see also, Table 10.2, The Salinian controversy)
Sedimentation patterns, trends	Oligocene and Early Miocene sedimentation was almost exclusively clastic sedimentation (carbonates are rare) along the entire length of the Cordillera
	Many areas of former marine deposition in the Eocene became non-marine in the Oligocene (e.g. Sespe Formation and related units)
	E-W trending non-marine basins of S CA mostly lay between the two migrating triple junction points. Sediment was mostly derived from regional uplift and denudation across much of western North America (e.g. Telluride erosional surface in Rocky Mountains)
	Submarine valley-fill in Sacramento Valley (upper Markley Fm)
	Marine deposition returned to the West Coast in the Early to Middle Miocene
Igneous/metamorphic events	Intense volcanism across Western Interior (e.g. San Juan Mtns, CO; Marysvale, UT, and from OR (John Day Volcanics) across NV, SE into AZ and Mexico (Sierra Madre volcanics)
	Expansion of Cascade arc to south
	Minor scattered volcanics along Pacific margin

process is called *plate capture* (see time slices 18–12 Ma on Fig. 9.3(2)). The process continues today and the modern transform – the strike slip boundary – is about 2,500 km long from Cape Mendocino, California at the north, to Puerto Vallarta, Mexico at the south.

At either end of the modern transform boundary are areas where three plates come together; such boundaries are called *triple junctions*. In the north is the Mendocino triple junction and to the south is the Rivera triple junction. To the north and south of these triple junctions, remnants of the Farallon plate still survive and have not yet been consumed. These fragments are called the Gorda, Juan de Fuca, and Explorer plates, located off the Pacific coast from northern California to southeast Alaska. In the south, the remnant is called the Cocos plate and is offshore of southern Mexico and Central America. Subduction still occurs between the oceanic and

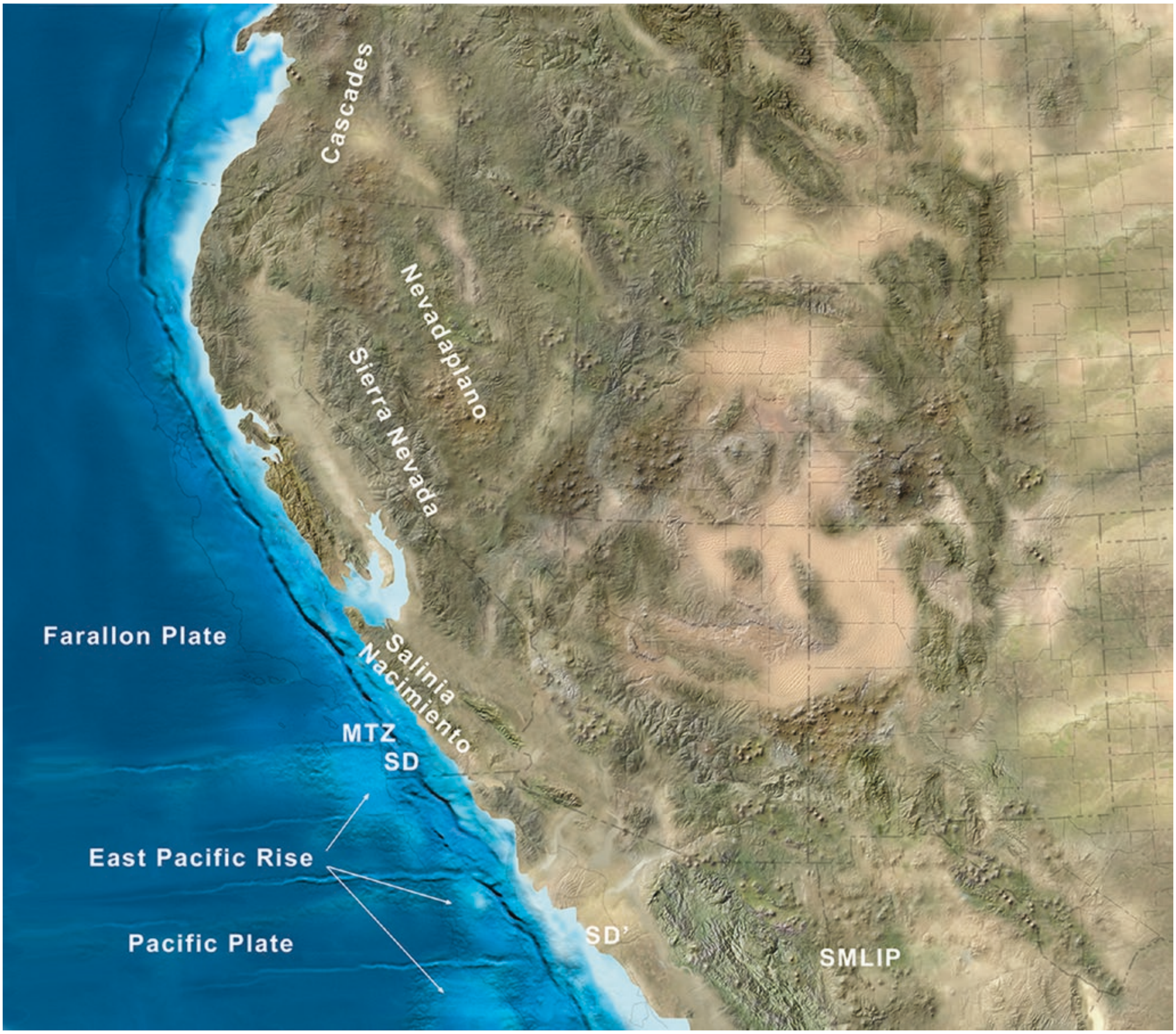

Fig. 10.2 Paleogeography of SW NA during Oligocene (ca. 30 Ma) showing immense area of volcanism as flat-slab subduction returns to normal and arcs swing back towards the West Coast. Northern belt swings down from Cascades in S Oregon across much of Nevada and adjacent Utah and E California. Southern belt comprises northern extension of Sierra Madre Large Igneous Provence (*SMLIP*), one of largest continental volcanic fields in geologic history – volcanism dominates from SW Colorado and expands southward into Mexico. This was time of widespread erosion across western North America as the Rockies, Nevadaplano, and Sierra regions were sites of regional, high-level erosion surfaces. Sand dunes covered the southern Colorado Plateau. Huge influxes of sedimemt into coastal regions caused major regression as former marine basins filled with sediment. Note East Pacific Rise against North America west of S Arizona. *SD* Modern Dan Diego, *SD'* Eocene San Diego, *MTZ* Mendocino triple junction

Table 10.2 The Salinian controversy

The Salinian controversy: as recently as 25 years ago, there was considerable controversy regarding the origin of Salinia – that portion of CA west of the San Andreas Fault and north of the Transverse Ranges – approximately the coastal region northward from Ventura to Cape Mendocino
Hypothesis 1 – Salinia and some of the areas south of it including the San Gabriel Mountains were exotic to NA – perhaps a fragment from Andean South America that had drifted northward, was accreted to NA in the middle Cenozoic, and then moved farther northward along the San Andreas Fault. This hypothesis was based chiefly on paleomagnetic evidence that suggested an equatorial position as late as the Cretaceous – SW California was ~35° N at that time. Such a discrepancy demanded that Salinia had to be exotic to NA
Hypothesis 2 – Salinia is a continuation of the Sierra Nevada and was an extension of the Peninsular Ranges of SW CA and Baja MX that formed the western portion of the Mojave area. The terrane was obliquely severed by the San Andreas and similar older Miocene faults and transported northwest (right-lateral) along the transforms. The Mojave was dismembered and extended as the Pacific Plate pulled Salinia away from its previous position. This hypothesis suggests that Salinia is not exotic to NA but rather an integral part of the Cordilleran arc-trench system. The western portion of Salinia is also a controversial block, the Nacimiento (*aka.* Sur-Obispo) terrane. According to the second hypothesis, this terrane represents displaced Franciscan trench-forarc accretionary rocks that docked with Salinia before its NW journey along the San Andreas. Recent detrital zircon studies along with detailed geologic mapping and interpretation have substantiated the second hypothesis and resolved one of California's greatest geologic controversies

continental plates, with associated arc volcanism located inland (the Cascade arc in the north and the Mexican and Central American arcs to the south).

The initial transform boundary was positioned father west than the modern San Andreas Fault but these zones are now less active as the transform boundary has jumped to the east (see time slices 18 Ma to Present on Fig. 9.3). The Pacific Plate has been relentless in its process of stealing terranes from North America! If this process continues, these blocks including most of Southern California, will eventually be adjacent to SE Alaska.

10.2 Salinia

As slivers of previously accreted terranes and arc rocks were translated north along various transform faults, a block named after the Salinas Valley near modern-day Monterey, California, called *Salinia*, was transported northward. The Sierra Nevada batholith was once continuous with, and linked to the Peninsular Range batholith in Baja California. Presently, they are separated by a "magmatic gap" in this once continuous granitic spine. The gap, now marked by isolated granite outcrops in the highly dismembered Mojave Desert, stretches between the San Gabriel Mountains and the southern Sierra. When restored (50–30 Ma, Fig. 9.3), Salinia fills this gap. Results from detrital zircon studies and other types of geologic analyses have bolstered this interpretation (Table 10.2). A second exotic terrane outboard of Salinia is Nacimiento (also known as Sur-Obispo) and it may represent a part of the Franciscan assemblage that was also displaced northwest to become juxtaposed next to and probably thrust under Salinia. Bounded on the east by the San Andreas Fault and on the west by the Nacimiento Fault, Salinia contains granite rocks which differ markedly from adjacent rocks (Fig. 10.3). Exposures can be seen at Bodega Head, Point Reyes, Point Lobos, and the northern Big Sur. Its southern margin is a fault zone against which the Transverse Ranges have been emplaced. Offshore, Salinia is exposed on the Farallon Islands; these islands, ironically, are where the Farallon plate takes its name but that plate has already been subducted and consumed here and the islands are part of Salinia.

Fig. 10.3 Salinia and Nacimiento. (**a**) The dark brooding cliffs at Ragged Point, S Big Sur Coast reflect the Franciscan-dominated Nacimiento terrane. Note spectacular marine terraces in background. (**b**) Lighter cliffs along the N Big Sur Coast near Bixby Bridge are east of the Sur-Nacimiento Fault and reflect the granites and metamorphic rocks of Salinia. (**c**) Salinian Hobnail Granite at famous lone cypress tree, Monterey Peninsula. Both terranes have migrated northward at least several hundred km, mostly along the San Andreas Fault. Salinia restores to S of the Sierras and W of the Mojave (Fig. 10.2)

10.3 Metamorphic Core Complexes

Meanwhile, farther into the interior of Sonora and Arizona, stretching of the Earth's crust led to the development of unique features known as m*etamorphic core complexes*. These features were first recognized in the late 1960s, having escaped detection previously when these low-angle displacements were mapped and interpreted as thrust faults. Detailed mapping and regional synthesis revealed that they are low-angle normal faults, known as detachment faults – or simply detachments. When the Earth's crust was stretched during the Oligocene, it thinned along these sub-horizontal faults as slices of crust were pulled away at low-angles. The removal of the overlying mass caused the heated rocks deeper in the crust to rise upwards buoyantly. As these uplifts formed, they caused increased slippage on the detachments in a runaway feedback loop. The rocks that rose upward were shaped as dome-like masses composed of metamorphic rock, giving the name to these features. The carapace rocks that slid from the domes traveled a dozen km or more, often to the northeast or southwest in the direction of the extensional stress. As the blocks slid away, they also rotated backwards into the low-angle fault plane (Fig. 10.4).

Some of the best examples of these core complexes are located near the metropolitan areas of Phoenix, and Tucson, Arizona (Fig. 10.5). Near Phoenix, the South Mountains core complex is home to the largest municipal park in the United States, the South Mountain Park and Preserve at over 16,000 acres. Its rounded summit traces a line of *mylonite* textures on the slip plane of the fault (mylonite is a metamorphic texture where crystals are deformed in the ductile environment). The upper plate rocks that were once located on top of the South Mountain core complex are now those at famous Camelback Mountain, located about 18 km to the northeast. As the block that contains Camelback Mountain was gradually pulled off the South Mountain core complex, eroded material was deposited as course conglomerate in nearby depressions. These sedimentary rocks also took a ride on the back of the detached block. Near Tucson, the dome-shaped Santa Catalina Mountains are also a core complex, along with the nearby Rincon, Tortolita, and Graham mountains. The upper plate or carapace rocks that slid off to the southwest of the Santa Catalina Mountain core complex are the Tucson Mountains, preserved in Saguaro National Park West. About 25 metamorphic core complexes have been mapped in the intermountain west from British Columbia to Sonora Mexico.

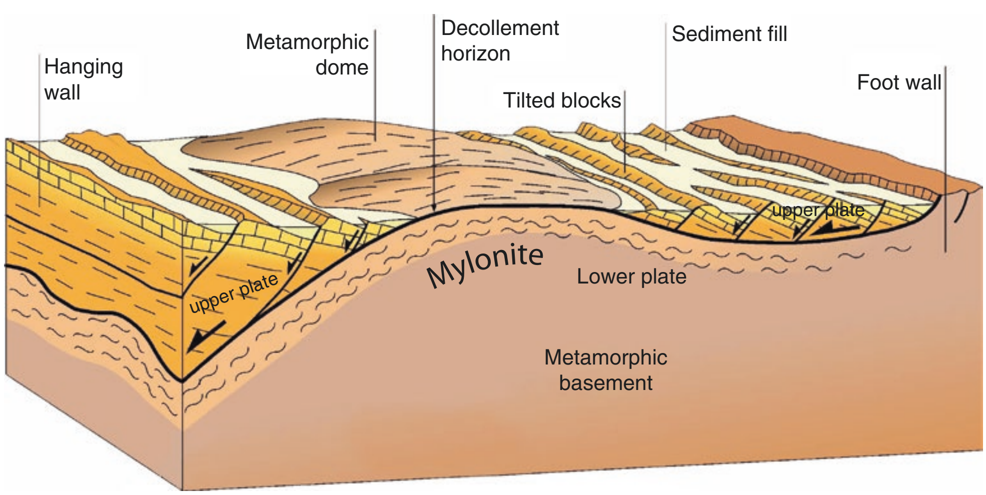

Fig. 10.4 Block diagram showing major components of a metamorphic core complex. These elements are present across regions that have undergone extreme crustal extension. The domed lower plate exposes deeper crustal levels. Across areas underlain by Precambrian basement, the lower plate consists of high-temperature/high-pressure granite-gneisses that formed at mid- to lower-crustal levels (15–25 km deep). Across the western Cordillera, especially on the California Continental Borderlands and in various ranges across Salinia and the Mojave, the lower plate consists of metamorphosed Franciscan rocks that were once part of the subducted Farallon Plate later uplifted and exposed by extreme crustal extension (From Frisch et al. 2011)

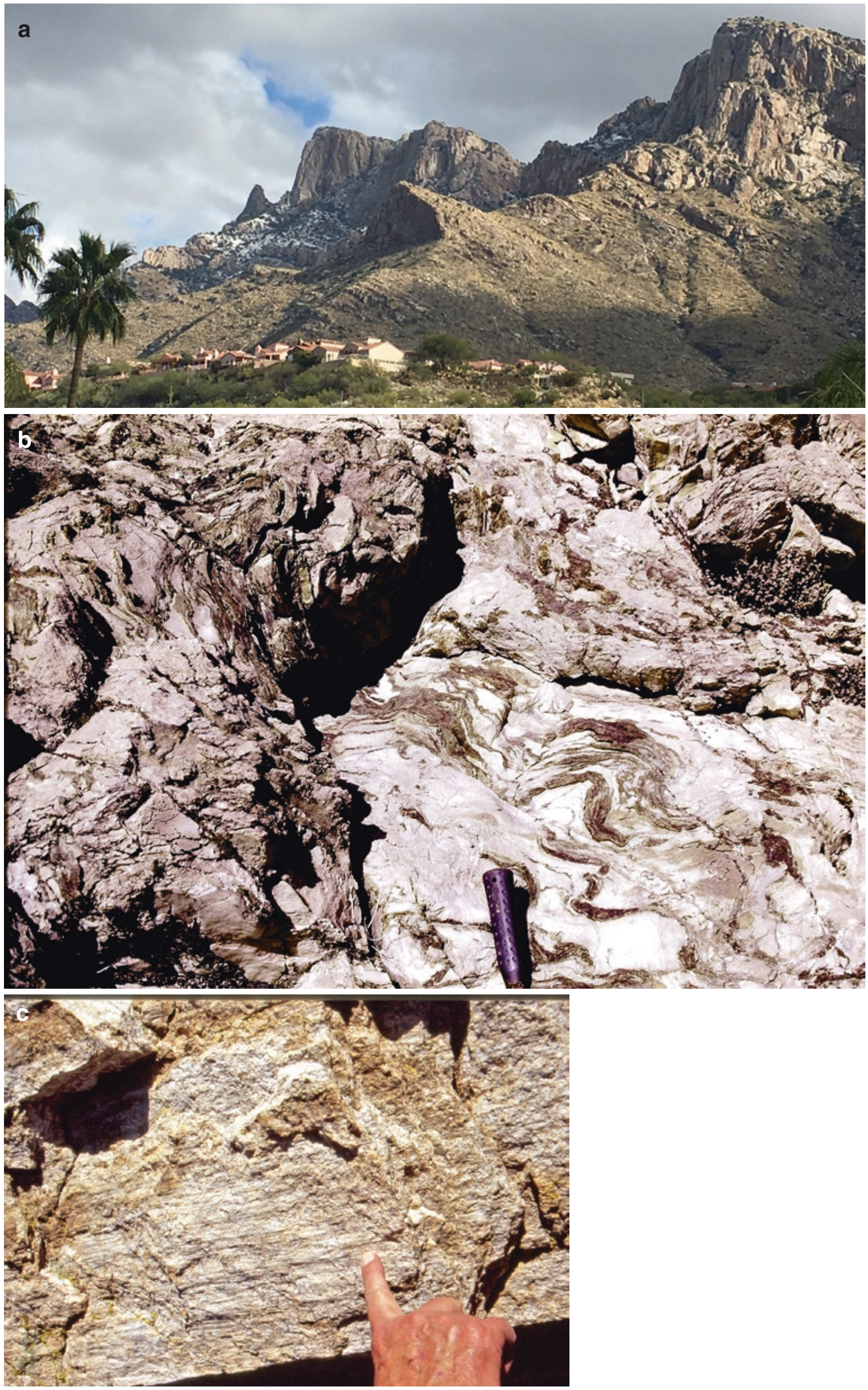

Fig. 10.5 Metamorphic core complexes in Arizona. (**a**) Catalina Mountains from N of Tucson. The top of the cliffs defines the eroded dome of the lower plate and exposes the Catalina Gneiss. (**b**) Strongly metamorphosed and attenuated Permian Kaibab Limestone in the lower plate of the Harquahala Mountains, SW Arizona. The Kaibab has been attenuated to several meters thick from its normal thickness of 150 m. (**c**) Mylonite fabric in the lower plate, Catalina Mountains, near Tucson. Mylonites are extreme high P-T metamorphic rocks with granite-like texture (but without true melting) and are typical of core complexes

10.4 Continental Sedimentation and Climate Change

Throughout the North American Cordillera from Oligocene through the early Miocene, clastic sedimentation dominates the setting – carbonate rocks are rare. Examples include the Sespe and Vasquez Formations (Fig. 10.6) located in Ventura and Los Angeles counties in southern California. These coarse-grained conglomerate and sandstone units were laid down in fluvial, floodplain, and nearshore environments and like many continental-derived rocks, are often rusty brown or red in color due to the oxidation of iron in the sediment. Keep in mind that rocks above and below this dominantly continental sequence are mostly deep marine rocks. The clasts originated when erosion wore down the surrounding uplands: there is widespread evidence of regional uplift across much of California during the Oligocene explaining the shift from marine to continental deposition as basins filled rapidly with sediment and shallowed. Other Oligocene continental rocks include the Titus Canyon Formation in Death Valley and the Mogollon Rim Formation in central Arizona.

From the Sespe Formation a variety of animal faunas are known including an early type of rhinoceros (*Amynodontopsis*), a rodent (*Simimys*), and an ancient insectivore (*Sespedectes*). Famous specimens from the Titus Canyon Formation near Death Valley California are the Titanotheres (or Brontotheres), huge mammals that resemble and are closely related to rhinoceroses, horses and tapirs. Some Titanotheres from the late Oligocene stood over 2.5 m tall. These grazing animals suggest expansive grassland or savanna habitat, marking a substantial change from the previous subtropical conditions that existed during the Paleocene-Eocene Thermal Maximum (55.5 Ma) and show a climate that was gradually cooling.

One of the biggest influences affecting global cooling around 33.5 Ma was the opening of the great Southern Ocean, which served to isolate the Antarctic continent as it drifted over the South Pole (Fig. 10.7). Open, circumpolar

Fig. 10.6 Vasquez Sandstone (Oligocene-Miocene) in the San Gabriel Mountains, California. The Vasquez is one of several sandstones of this age that formed when former marine basins filled rapidly and received non-marine sediment. The nearby Vasquez rocks are some of the most photographed rocks in Southern California and are seen in many movie and commercial backdrops

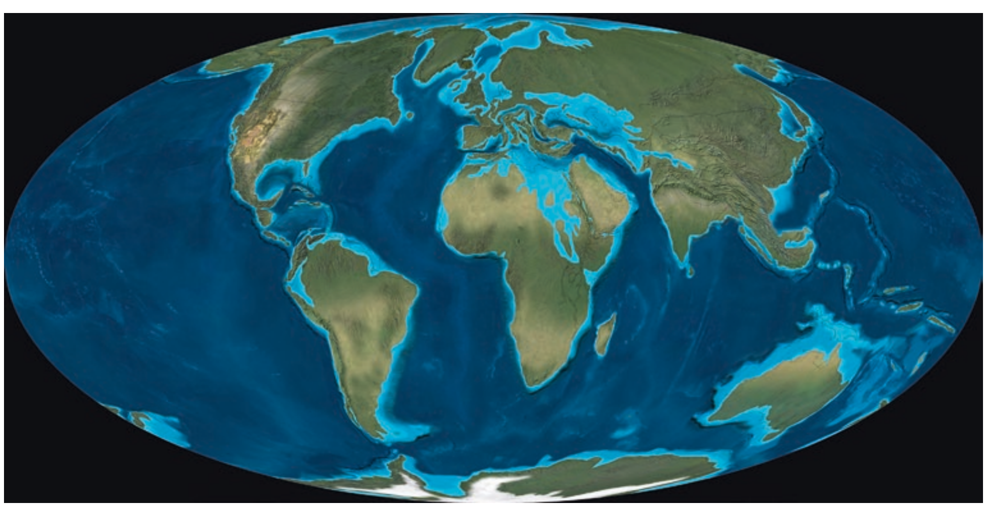

Fig. 10.7 Global paleogeography in the Oligocene at ca. 30 Ma. The Southern Ocean (S Atlantic and Indian) has opened causing much change in global atmospheric circulation and climate. The Antarctic ice sheet has recently appeared and India is slamming into S Asia. This was a busy time in global tectonics and Earth history and set the stage for global climate change towards much cooler temperatures

circulation in the Southern Ocean precluded the dispersal of warm tropical and temperate water toward Antarctica and caused it to descend into a deep freeze. This may have been the most important factor to initiate the cooling, although a well-known, large meteorite impact centered over Chesapeake Bay may also have played a significant role in the change. A result of the cooling was the diversification of the grasses and the expansion of the grassland ecosystem. Grasses did not evolve until the Miocene, so Oligocene grazers fed on woody shrubs and ferns. The expansion of the grasses and grasslands in the Miocene was a major innovation in the development of modern ecosystems.

10.5 Widespread Oligocene-Early Miocene Volcanism

Coincident with the changing climate was increased volcanic activity in certain parts of the Cordillera (Fig. 10.8). Beginning 35 Ma and continuing until about 27 Ma, the San Juan Volcanic Field erupted in southwestern Colorado and buried the widespread Telluride erosion surface. These explosive rhyolitic and dacitic eruptions emplaced much of the gold and silver mined in the San Juan Mountains in the nineteenth and twentieth centuries. The Marysvale volcanics in southern Utah and the Sierra Madre volcanics in northwest Mexico flared up as well. Ultimately, the great system of canyons in the Sierra Madre, including the famous Barranca del Cobre in Chihuahua, would be carved into these layered volcanic rocks.

Across the Colorado Plateau, the Navajo volcanic field and several of the laccolithic mountains were formed during the Oligocene and Early Miocene (Fig. 10.8d–f). A surface possibly correlative to the Telluride surface covered much of Arizona and New Mexico. Because of extensive recent erosion, only parts are preserved. In the Chuska Mountains along the Arizona-New Mexico border, the Oligocene-Miocene Chuska Sandstone, which overlies the surface, is preserved beneath Miocene volcanic rocks (Fig. 10.9).

In Central California, a chain of igneous-cored buttes extend from Islay Hill near San Luis Obispo to Morro Rock on the Pacific Ocean (Fig. 10.10). These stocks fed volcanoes now long eroded and apparently follow a linear weakness in the crust, possibly a fault.

Fig. 10.8 Volcanic activity of the Western Interior. (**a**) The Marysvale volcanic center was part of a huge Oligocene complex that stretched across S Nevada and SW Utah, here seen along the Sevier River near Marysvale, Utah. (**b**) The Needles Range along the California-Arizona border near Needles, California comprises sharp peaks carved from Oligocene-Miocene volcanics. (**c**) Oligocene and Miocene volcanics line parts of both I–40 and I–10 in W Arizona and E California, seen here along I–40 in California. (**d**) The Navajo volcanic field ranges across the Navajo Reservation in Arizona, New Mexico, and Utah; Church Rock and Aglatha Peak (background) are Oligocene volcanic necks on the edge of Monument Valley. (**e**, **f**) The Henry Mountains of Utah are the archetypical laccoliths, defined by G. K. Gilbert over 100 years ago. The earliest radiometric dates suggested Eocene ages; however, more recent dates are Oligocene (23–31 Ma). The dark igneous rocks in the photos have intruded and domed-up the colorful Jurassic sedimentary rocks

Fig. 10.8 (continued)

Fig. 10.9 The Chuska and Lukachukai Mountains along the Arizona-New Mexico border expose part of a widespread Oligocene erosion surface and overlying eolian sandstone. (**a**) Here, Triassic sedimentary rocks are cut by the surface which is overlain by the Oligocene Chuska Sandstone and capped by lavas ca. 25 Ma. This is one of the rare, datable exposures of this widespread erosion surface. (**b**) Outcrop of Chuska Sandstone, an eolian deposit now exposed near the top of the mountains (ca. 2900 m elevation), but obviously deposited on a broad, flat surface at least slightly depressed from surrounding terrain. Such inversed topography indicates complex patterns of uplift and erosion through the middle and late Cenozoic. The surface clearly truncates the nearby Laramide Defiance Monocline, thus providing a minimum age for Laramide deformation on the Colorado Plateau; inset – close-up of eolian bedding

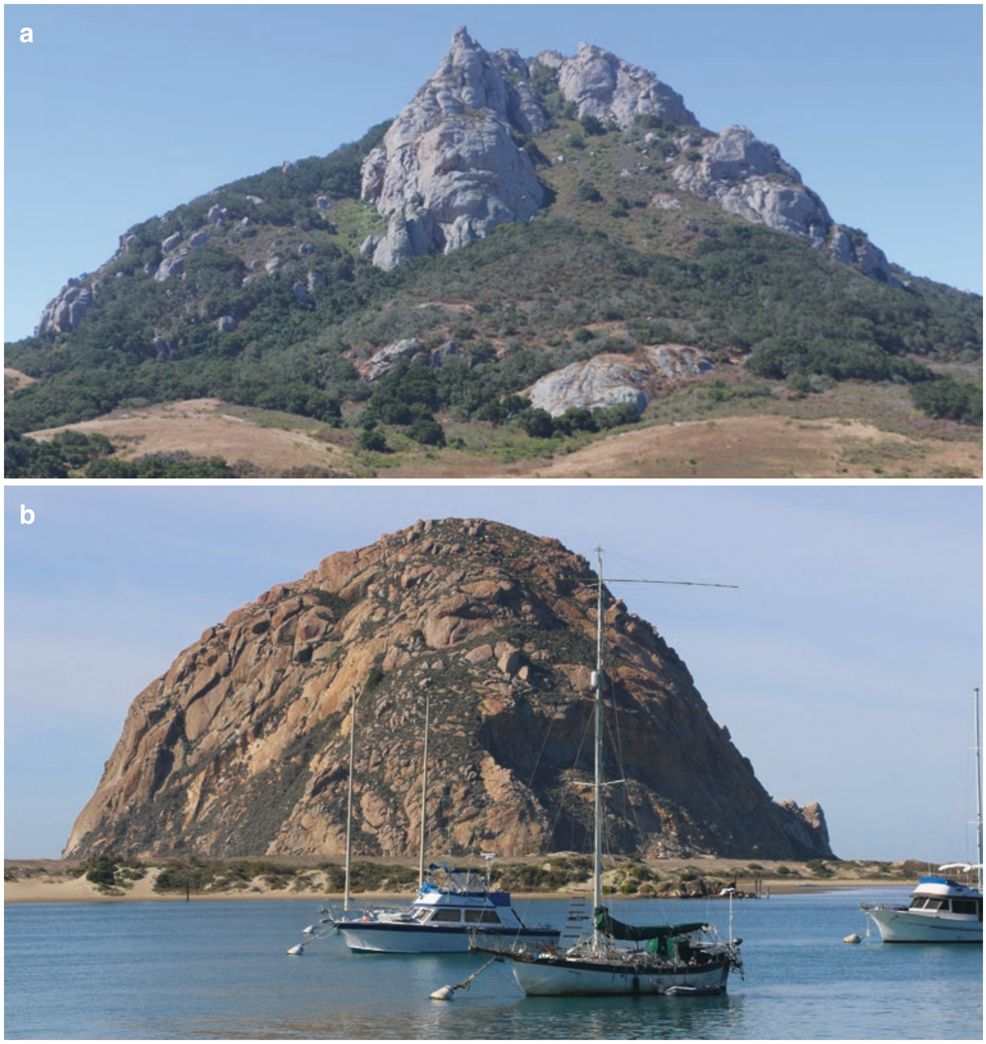

Fig. 10.10 A string of nine volcanic necks, plugs, and domes stretches 29 km from Islay Hill near San Luis Obispo to Morro Rock on the Pacific shore; composed of dacite 23–27 Ma, clasts of the rocks are now exposed in the Pliocene Pismo Formation at Point Sur, 145–160 km farther N, documenting minimum offset on the San Gregorio-San Simeon-Hosgri Fault. (**a**) Hollister Peak and (**b**) Morro Rock are the two most famous buttes in the chain. Morro Rock is the namesake for morro (*Sp.* – nose; *aka.* moro), a common name applied to dome-shaped rocks

The John Day volcanics in north central Oregon were also erupted during the Oligocene and Early Miocene and are beautifully exposed in the John Day Fossil Beds National Monument (Fig. 10.11). They range in age from about 39 to 18 Ma and formed from both the volcanic ash erupted from nearby volcanoes and weathered soils that developed between eruptions. Because of the presence of datable zircons in the volcanic rocks, age controls for the John Day Formation are robust: the Big Basin Member (including the Bridge Creek Beds) are between 35 and 32 Ma, the Turtle Cove Member is 30–28 Ma, the Picture Gorge Ignimbrite (28.7 Ma), the Kimberly Member (28–25 Ma), and the Haystack Member (25–18 Ma). Fossils recovered from the John Day strata include over 60 plant species and nearly 100 mammal species. Plants such as sumac, hawthorn, serviceberry, hydrangea and raspberry grew across the landscape, while trees consisted of walnut, laurel, chestnut, pecan, cashew, elm, mulberry and pines. One plant fossil of note is *Metà sequoia* or dawn redwood, a genus once believed to be extinct until it was found growing in the Sichuan and Hebei provinces in China in 1941. Of the mammals, species include various carnivores and grazers including dogs, cats (*Smilodon,* the famous saber-toothed cat), oreodonts (a sheep-like mammal), horses, camels, large pigs, and rodents, turtles, and opossums. It was a rich pageantry of life forms in the Oligocene of the Pacific Northwest. However, the great changes that were initiated then just mark the beginning of events to follow.

Fig. 10.11 Volcanic and volcanic-rich sedimentary rocks in the John Day Formation, Sheep Rock, John Day Fossil Beds National Monument, OR. Strata in this photo range from 39 to 18 Ma. The Picture Gorge Ignimbrite, a welded tuff, forms the dark ledge half-way up the butte. John Day River in foreground

11 The End of Cordilleran Subduction and the Formation of the Basin and Range: Early and Middle Miocene: Ca. 20–10 Ma

11.1 Basin and Range Beginnings

With continued encroachment of the Pacific plate at the edge of North America, extensional stress was brought to the heart of the Cordillera and areas of the crust that had been previously compressed and vertically thickened began to be thinned and pulled apart (Fig. 11.1; Table 11.1). As some segments of the North American plate were pulled apart, Salinia continued its northwest march, as well as other parts of southern California. For example, the future San Gabriel Mountains were located much farther south in the Early Miocene, near San Diego and northern Baja California (Fig. 11.2). As the crust pulled apart this block rotated nearly 180° in a clockwise motion as it moved northwest. The San Gabriel's remain among planet Earth's fastest growing mountain ranges as the rocks are shoved to the south along great thrust faults as the block is shoved up against the San Andreas Fault to the north (Fig. 9.3).

Forces that created the metamorphic core complexes soon gave way to a different kind of extension around 17 Ma. The former Sevier and Mogollon highlands, areas that had been uplifted by compression in the Mesozoic and early Cenozoic, were now subjected to extension that occurred along brittle, high-angle normal faults (Fig. 11.3a). These faults ripped through the landscape, first in central and southern Arizona and southeastern California, then progressing north into Nevada and western Utah, and southeast into Sonora Mexico, New Mexico and west Texas. Through time, the forces of extension became elongated to the north and southeast. Perhaps nowhere is the extensional phase of the Cordillera's history better displayed than in central Nevada where the Basin and Range was first described by G. K. Gilbert in the 1870s (Fig. 11.3b).

The western edge of this extensional belt is located at the foot of the Sierra Nevada in the Owens Valley of eastern California, where faulting has created one of the planet's most spectacular escarpments, the Eastern Sierra wall (Fig. 11.3c). Opposing this grand façade far to the east is the Wasatch Front, where the Salt Lake and Provo valleys have been dropped along the Wasatch Fault. The Basin and Range has been stretched nearly 100% from its Middle Miocene dimension and the straight-line distance between the Sierra and the Wasatch Front is currently 700 km. This suggests that the Sierra arc was once perhaps only 350 km west of the Wasatch Front and the Colorado Plateau. To the south, the eastern boundary of the Basin and Range is the Rio Grande rift and the distance between it and the San Andreas Fault is nearly 900 km, approximately twice what it was in the Middle Miocene. The birth of the Basin and Range Province was no small event in the history of the Cordillera.

Fig. 11.1 Paleogeography of North America at *ca.* 20 Ma, Early Miocene, as East Pacific Rise intercepts NW and SW coasts. This was a time of major extension across S Arizona and into the Mojave region and progressively northward into the Basin and Range. The Pacific Plate begins to capture parts of SW North America. Canada and parts of N US drained NE into a huge river system that emptied into the Labrador Sea. Remainder of continent E of the Rockies drained into Gulf of Mexico or Atlantic. Western Rockies, Colorado Plateau, and Basin and Range area had internal drainage and ponded. From the Sierras west, streams drained into the Pacific

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Table 11.1 Events 20–10 Ma

Time span	Early and Middle Miocene (*Ca.* 20–10 Ma)
	Subduction of East Pacific rise; complex, rapidly evolving marine basins respond to transform stresses; birth of modern San Andreas Fault; regional extension and core-complex generation
Geologic – tectonic setting	Continued transition from subduction margin to transform margin along SW NA as triple junctions moved farther apart
	The Pacific Plate exerted tensional forces along the transform and began to capture portions of NA and transfer them to the Pacific Plate – at *ca.* 17 Ma, these captured blocks began drifting NW; this initiated the right-lateral movement of blocks or terranes that were formerly part of NA (note that the San Andreas Fault had not yet formed) including Salinia, S CA, and Baja, MX
	As tensional forces increased, SW NA underwent extreme E-W extension
	Extension produced crustal thinning and faulting and folding of brittle upper crust
	The Basin and Range was formed due to these extensional processes
	The Southern margin of the Colorado Plateau, the Mogollon Rim, was formed by 20 Ma as Central and Southern AZ were pulled away from the Plateau
	Extension occurred as far east as the Rio Grande Rift
	Widespread volcanism accompanied extensional events as deep extensional fractures provided conduits for basaltic lavas
Boundary of western North America	Complex transform margin between two migrating triple junctions
	Subduction margin to north and south
	Transform margin from BC to SE AK
Terranes	No significant terrane additions
	As transform margin expands, terranes shuffled by transform processes
Sedimentation patterns, trends	Clastic sediments dominate length of Cordillera
	Persistent tectonic movements constantly reshape basins creating numerous unconformities and sharp changes in sedimentation patterns
	Numerous examples of deepwater facies adjacent to shelf, shoreline, and continental deposits
	Deepwater deposits such as Monterey Formation typified by diverse suites of chert, sand and mud turbidites, and siliceous limestone
	Coarse conglomerates with westerly sources (San Onofre) shed from uplifts on California Borderlands
	Clastics and evaporites fill basins across Basin and Range
	Many clastic sequences interbedded with volcanic deposits across entire Western NA
Igneous/ metamorphic events	Extremely voluminous, widespread, and locally thick volcanics, varied in composition but dominantly basaltic, throughout entire Cordillera and especially across the Basin and Range, Snake River Plain, and Columbia Plateau
	Cascade arc magmatism continues
	Large Volcanic centers surround Colorado Plateau

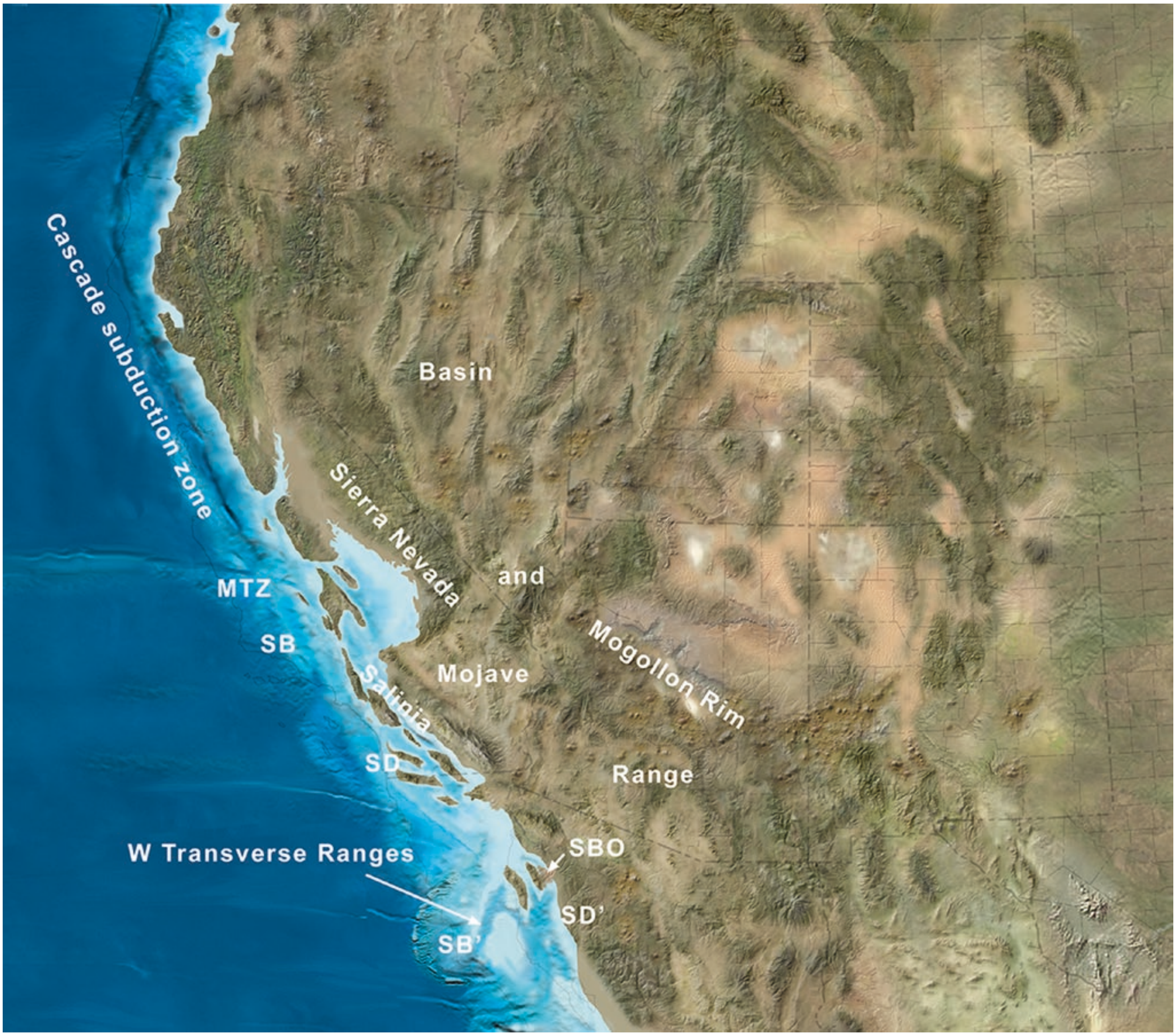

Fig. 11.2 Paleogeography of SW North America at *ca.* 15 Ma, Early to Middle Miocene. This was a time of widespread and intense volcanism from the S Rockies across New Mexico and Arizona into Mojave region, the Sierras, Cascades, and much of C and S California. The Cascades-Sierra events reflect the return of the Cordilleran arc to a more normal position, but exclusively N of Mendocino triple junction (MTZ). Most of the remaining volcanism was in response to rapid extension on W North America S of MTZ. Note rotation of Western Transverse Ranges away from S California (both well south of present locations). San Onofre Breccia (SOB) is shed off blocks of exposed Catalina Schist to west. Note numerous islands and adjacent basins in which Monterey and similar formations were deposited. SB, SD – Present locations of Santa Barbara and San Diego, respectively; SB', SD' Early Miocene locations

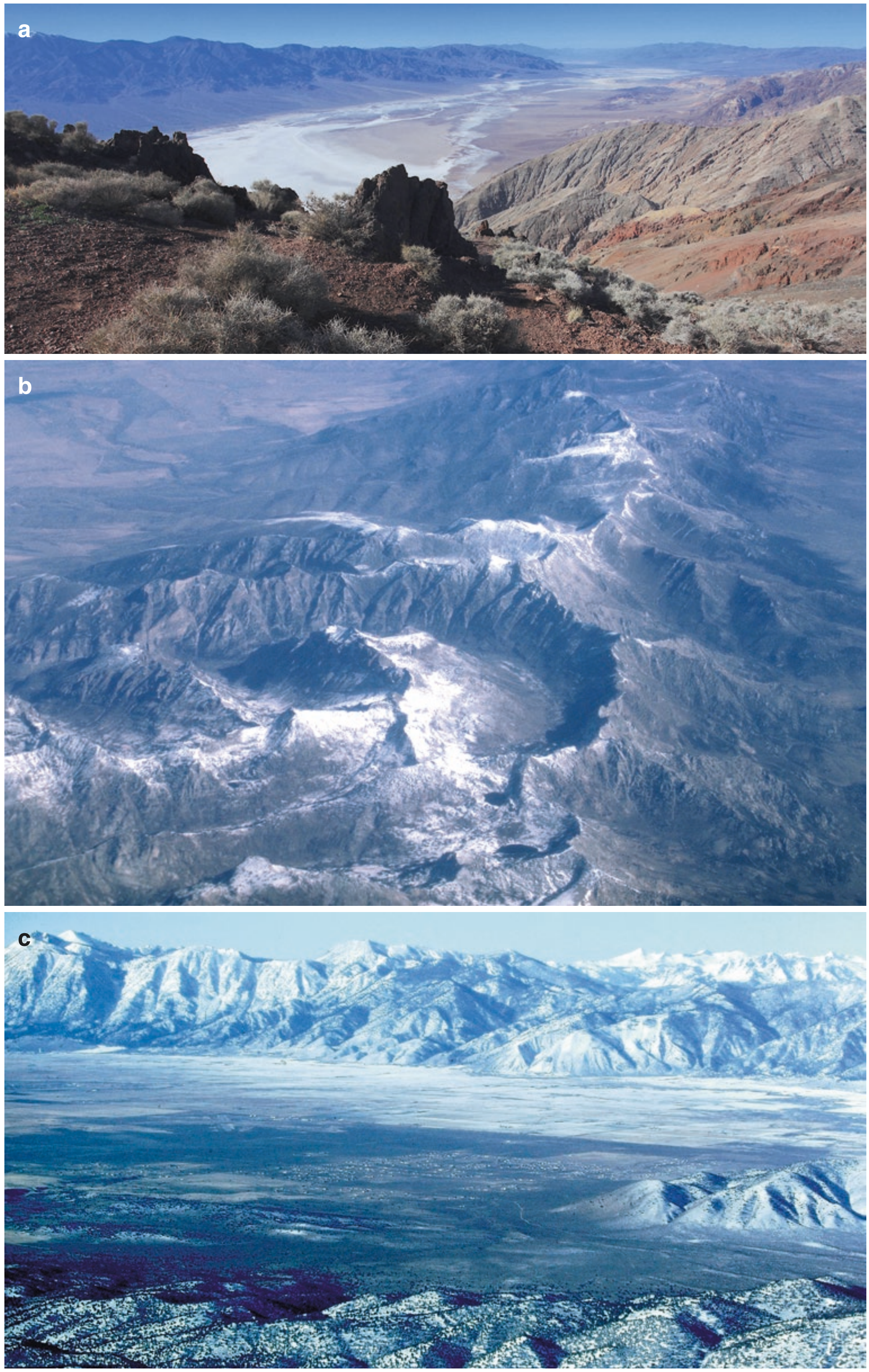

Fig. 11.3 Modern aspects of Basin and Range. At 15 Ma, the Basin and Range looked somewhat different than it does today. Most ranges were much broader and the basins were narrower or not yet evolved. (**a**) Basin and Range at one of its extreme landscapes, Death Valley, California. The Panamint Mountains in the background have peaks over 3000 m and Badwater in the valley is almost 80 m below sea level. (**b**) The Ruby Mountains in NE Nevada expose thick Paleozoic sedimentary rocks deposited near the continental margin, later incorporated into the Sevier thrust belt, then faulted during the Basin and Range orogen. (**c**) The sharp eastern scarp of the Sierra Nevada marks the western margin of the Basin and Range. Seen here with Owens Valley below, this relief was formed in the Neogene, but the time of uplift of the Sierras remains controversial

11.2 Transform Faults and the San Andreas Fault System

The San Andreas Fault came to the world's attention in 1906 after an estimated 7.8 magnitude earthquake was triggered by right-lateral movement along the previously unrecognized fault. About 80% of the city of San Francisco was destroyed by this earthquake and over 3000 people lost their lives. The 1906 rupture propagated north to south for about 450 km but the whole length of the fault is over 1200 km. Precursors to the San Andreas were active between 28 and 30 Ma but movement accelerated *ca.* 24 Ma when the Pacific plate and the North American plate shared an extended boundary (Fig. 9.3). However, other parallel lines of weakness, mostly west of the present San Andreas Fault (Fig. 11.4), took up this earlier displacement and the San Andreas Fault (*sensu stricto*, as opposed to San Andreas System) has had most of its motion occur in the last 6–8 million years. The reasons for the generation of a transform system of faults and plate boundary were discussed in the last chapter; here we will focus more on the geologic results of this system. By their very nature, the amount of movement on transform faults can be difficult to assess. Unless a specific geologic marker such as a distinctive volcanic rock or distinctive pebbles shed from a known source can be identified and shown to be completely older than the fault system, offset can only be estimated. The length of the fault does not directly correlate with its amount of offset. Also, transform faults jump or shift from one location to another, sometimes over short periods of time, additionally complicating estimation of amount of fault offset.

Transform systems tend to constantly alter the locations of source areas and sedimentary basins. As rocks of different resistances to erosion interact, source areas pop up and down; basins open and close or widen and narrow or deepen or shallow as faults move, change locations, or change rate of motion. No wonder the Miocene rocks of the Coast Ranges have such variability, commonly over short distances.

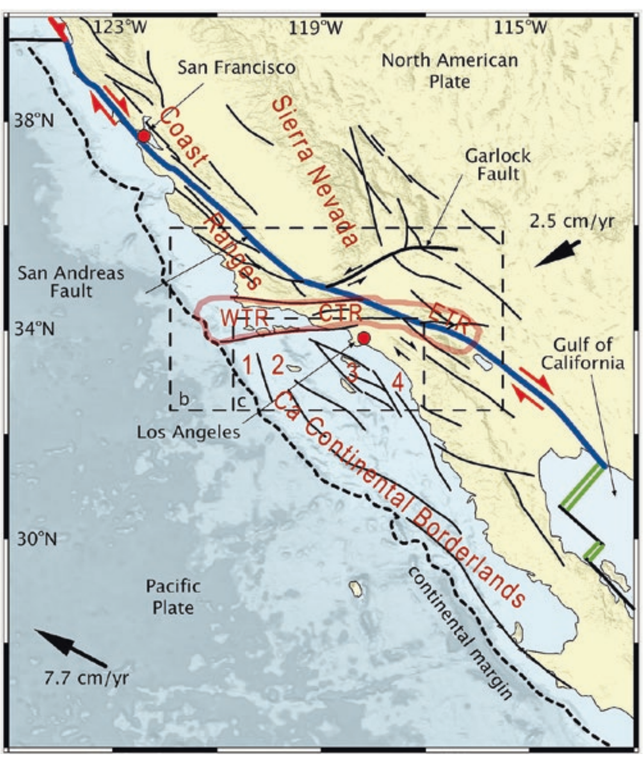

Fig. 11.4 Modern and recent tectonic elements of Southern California. The San Andreas Fault marks boundary between Pacific and North American Plates. *WTR* Western Transverse Ranges, *CTR* Central Transverse Ranges, *ETR* Eastern Transverse Ranges. Also labeled is the Continental crust underlying Continental Borderlands: *1* Franciscan (Mz subduction zone); *2* Great Valley forearc; *3* window into Farallon Plate (tectonic melange of Franciscan); *4* Peninsular Ranges batholith. Boxes *b* and *c* outline areas of intense deformation (Modified from Frisch et al. 2011)

11.3 Late Cenozoic Basins: The Monterey Formation

As the transform system propagated and terranes were pushed northward, certain areas underlain by resistant rocks (or thick, buoyant crust) tended to remain as uplands – sedimentary source areas. Examples include the Gabilan Range, Sierra de Salinas, and Santa Lucia Range. Conversely, areas such as the Ventura, Santa Maria, San Joaquin, Los Angeles, and Salinas basins subsided rapidly and were filled with large volumes of sediment. The Ventura Basin contains over 7 km of Neogene sedimentary rocks.

Most Neogene sedimentary basins in the Coast Ranges were directly connected to the cool waters of the Pacific and subject to persistent westerly winds. These conditions, in part brought on by the global cooling that began in the Oligocene, generated coastal upwelling. In a broad sense, these conditions persist today. The rich influx of organics generated by these currents resulted in organic-rich, fine-grained, deepwater sedimentary deposits. Best known of these rock units is the Monterey Formation and related rocks – in recent years, the Monterey Formation has been divided into several formations. Complicated by adjacent upland source areas that supplied sediment, commonly as turbidity currents, Monterey-type sedimentary rocks dominated many basins (Fig. 11.5). Much like the Franciscan (but not to confuse the two), Monterey rocks vary greatly in lithology, bedding characteristics, and color, commonly in adjacent outcrops. Much of the formation is siliceous, the result of the accumulation of vast numbers of diatoms (single-celled algae with cell walls made of silica). The original organic opaline silica has been recrystallized to various forms of quartz and the change in crystal structure and texture has greatly altered such rocks. Mud-rich turbidites are another dominant rock type.

In off-shore California, transform faults led to the formation of about 20 individual basins in the *Continental Borderland Province* of California. The basins are separated by intervening ridges such as the Palos Verde Peninsula, Catalina Island and the Channel Islands. Beginning about 17 Ma these basins began to accumulate marine sediments (Fig. 11.6); as basins towards the continent filled with sediment, younger sediment by-passed them to fill in more outboard basins – the process continues today. The Los Angeles basin is an example of one of these Neogene basins formed by the San Andreas Fault and its parallel strands. It was filled towards the end of the Pliocene and now the Los Angeles and Santa Ana Rivers carry sediment into basins submerged by the Pacific.

This variably thick sequence of mostly bio-siliceous rock provided an exquisitely perfect environment for the production and subsequent preservation of hydrocarbons; indeed, for its size the Los Angeles basin holds the richest oil deposits anywhere. The marine plankton (diatoms and radiolarians) provided the organic matter that readily migrated into adjacent sandstone units as the basins subsided.

Fig. 11.5 The Monterey Formation was deposited in numerous deep-water basins mostly near the transform margin of North America. Its modern extent ranges from N Salinia to the Baja coast and from modern offshore basins to the San Joaquin Basin. In many areas, the formation has been renamed as more accurate stratigraphic correlations have been published. (**a**) Classic Monterey outcrop at Gaviota State Beach near Santa Barbara. These rocks were deposited west of San Diego and rotated and transported north to the present flank of the Santa Ynez Mountains. (**b**, **c**) *Monterey* outcrops (now mapped as Pismo Formation) at Montana del Oro State Park near Morro Bay. (**d**) Monterey (Pismo) porcellanite outcrop at Avila Beach near San Luis Obispo. The original opaline texture from billions of diatoms has been recrystallized to chert although the original bedding is still visible. (**e**) Chert-rich beds of probable turbidite sequence at Crystal Cove State Park N of Laguna Beach

Fig. 11.5 (continued)

Fig. 11.5 (continued)

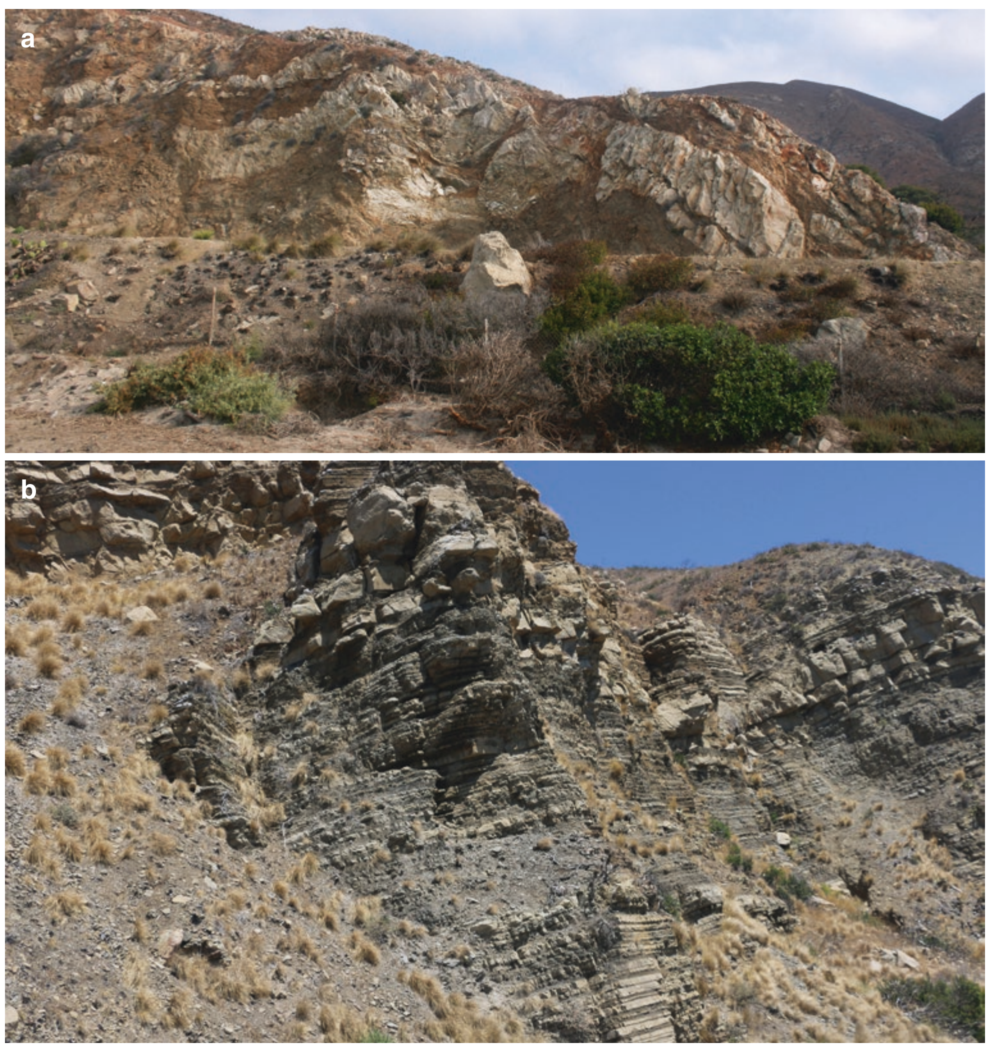

Fig. 11.6 The Miocene Topanga Formation is widely exposed in the Santa Monica Mountains. Originally part of the Santa Monica Basin on the NW flank of the Peninsular Ranges block, the rocks were uplifted in the Pasadenan orogen when several blocks converged along the San Andreas Fault. (**a**) Crumpled sandstone and mudstone beds in the Topanga Formation at Point Mugu on the Malibu Coast. Interbedded Conejo Volcanics hold up the ridges in the background. (**b**) Topanga turbidite deposits near Malibu. These unstable cliffs have brought down more than one mansion, especially at Pacific Palisades to the N

11.4 The Strange Odyssey of the Transverse Ranges

Odd as it may seem, an observer in a boat 20 Ma who was situated over what is today Santa Barbara (then submerged) and was looking east, would see the shoreline of San Diego (then, as now, above sea level). Today, when one looks east from Santa Barbara, the view is along the longest stretch of east-to-west coast in southern California, parallel to the Santa Ynez Mountains. San Diego is over 200 km to the southeast and the Channel Islands block its view across the Santa Barbara Channel. During those 20 million years ago, Santa Barbara and the Santa Ynez Mountains, the Channel Islands, and several other pieces of California were transformed by the activity of the San Andreas Fault system. The best way to follow this complicated journey is to look at the maps in Fig. 9.3. At 24 Ma, note that the Western Transverse Ranges (WT) are mostly under water, firmly against the Peninsular Ranges (PR) where San Diego, on dry land, lies directly east. Beginning ca. 16 Ma, the Pacific Plate with its tug on North America begins to dislodge the Western Transverse Ranges. More importantly, the Western Transverse Ranges begin to rotate clockwise. Follow the remaining time slices and watch as the California Continental Borderlands expands behind the lead of the Western Transverse Ranges. But there were more consequences.

The path taken by the Western Transverse Ranges was only made possible if extension of the crust occurred in symphony with the rotation and northward movement. Much of this extension was accomplished by sub-horizontal extension along detachment faults. Remembering what happened when extension took place in the core complexes of Arizona makes the next step easier to follow. The subducted Farallon Plate was (and still is) under the Continental Borderlands. As extension took place, the lower plate – the Franciscan rocks of the Farallon Plate – buoyed upwards along several transform faults (remember everything on the Pacific Plate is moving northwest). At 17 Ma, these uplifted blocks on the Continental Borderlands shed sediment into the adjacent marine basins. One of these blocks was large enough to shed sediment eastward towards the continental shore (Fig. 11.7). Boulders as much as 3 m in diameter along with cobbles, pebbles, and sand were shed into the basin that lay between the uplifted block and

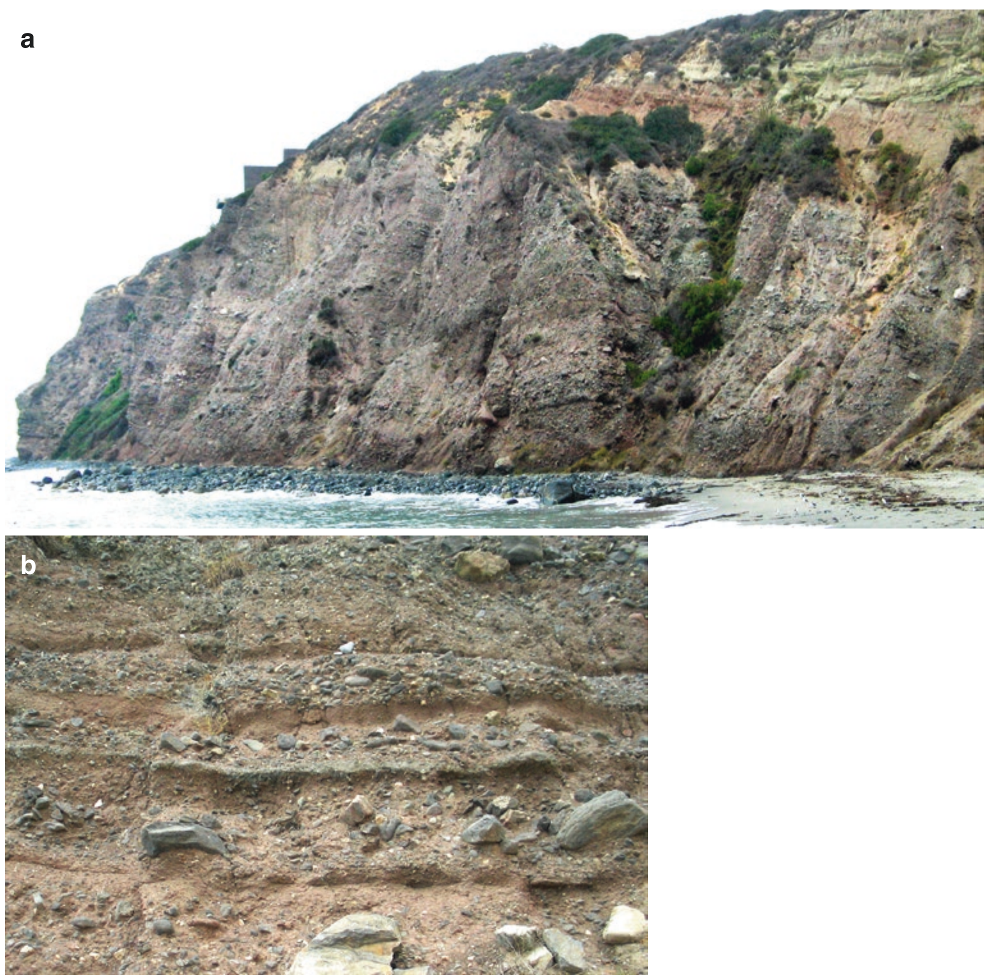

Fig. 11.7 Miocene breccia and sandstone in Orange County. The San Onofre Breccia is an unusual unit, not only because of its large grain size, but also due to it being clearly sourced to the west – offshore California. (**a**) Overview of cliff exposure at Dana Point. Even from a distance the large boulders are visible. (**b**, **c**) Closer views of bedding and large grains, Dana Point. (**d**) Catalina Schist fragment eroded from breccia at Dana Point. An uplifted block of Catalina Schist was the source of the coarse grains in the San Onofre. (**e**) Coarse-grained sandstone, locally pebbly (not visible in photo) at Main Beach, Laguna Beach, California. These deposits are considerably finer than the breccia at Dana Point 10 km S; equivalent rocks a few kms NE of here are deep marine muddy turbidites of the Monterey and Topanga formations

Fig. 11.7 (continued)

the shoreline. Sedimentation was so rapid that parts of the basin were filled and the coarse wave of sediment spewed onto land. Thus, was formed the San Onofre Formation, often referred to as breccia because the blocks of material shed off the uplift are quite angular. The most dramatic exposures occur above the harbor at Dana Point (Fig.11.7a–c). The San Onofre is exposed widely across southwest Orange County, especially from Dana Point northward along Laguna Beach and southward through the brown hills along I-5 on Camp Pendelton. As you may have guessed, the clasts in the San Onofre are mostly pieces of the Catalina Schist (Fig. 11.7d), named for Catalina Island where it is exposed. Catalina Island is interpreted to be a faulted dome of once-buried Franciscan Formation; the dome has exhumed the partially subducted Farallon Plate and the tectonic melange that is carried downward with it. Similar tectonic setting are also exposed on land in various mountain ranges in Western Arizona and Southern California.

It is hard to imagine a more unusual scenario for the Neogene history of Southern California. Is there additional evidence to support this or are there other hypotheses to explain it? There are several other independent lines of evidence to support the above; one was discussed in conjunction with the Eocene Poway fan. The distal fan is missing off the San Diego coast – likely truncated by a fault. Part of this missing fan is exposed on the Channel Islands south of Santa Barbara. When rotated and moved southward with the other Western Transverse Ranges, the missing piece fits up against the San Diego area. Paleomagnetic data confirms the 120° rotation. Geochemical, detrital zircon, and structural studies strongly support the uplift and exposure of the subducted Farallon Plate.

The Transverse Ranges extend from the Western Santa Ynez Mountains at Point Conception eastward across Southern California to the Chocolate Mountains near Desert Center. The Central Transverse Ranges consist of the northern blocks of the Peninsular Ranges that jammed into the North American Plate as the San Andreas Fault moved them northward – the Santa Monica, San Gabriel, and San Jacinto-Santa Rosa Mountains. The Eastern Transverse Ranges lie across the fault and include the San Bernardino, Little San Bernardino, and Chocolate Mountains. Their E-W trend, though not as perfect as the Western Transverse Ranges, resulted from the bend in the San Andreas Fault and the compression that resulted from it (Fig. 2.12). On Fig. 9.3, follow the San Gabriel block from SW Arizona to its present position as the Peninsular block moved NW.

11.5 Volcanism Reigns in the Pacific Northwest

Farther north and coincident with the crustal stretching were voluminous eruptions of lava in the Cordillera. Cascade arc volcanism was active but volcanism of another kind took center stage, initiating profound changes in the interior Pacific Northwest. Beginning around 16.6 Ma and lasting until 15 Ma, the thickest portion of the well-known Columbia River basalts began to erupt in huge quantities from a few shield volcanoes and linear fissures. Over 163,000 km^2 in northeast Oregon, southeast Washington and west-central Idaho were buried in these gigantic continental flood basalts (Fig. 11.8). Earth had previously experienced similar events producing expansive flood basalt such as the Siberian Traps (251 Ma), the Karoo basalt (183 Ma) in South Africa, and the Deccan Traps (66 Ma) in India.

The earliest Columbia River basalts are exposed on Steens Mountain in south-central Oregon where 40 distinct lava flows have been mapped in the walls of deeply dissected can-

Fig. 11.8 Coastal exposures of the Columbia River basalts. (**a**) Pillow lavas below lighthouse in SW Washington along the Columbia River mouth document subaqueous flows under the sea. (**b**) Brooding cliffs near Tillamook, Oregon expose several basalt flows. Some of these flows originated many tens to a hundred-or-more kms to the east

yons. Following these early shield-producing flows were eruptions from fissures, some with lengths up to 37 km. The fissures trend to the northwest hinting at a possible relationship to Basin and Range faulting. Other studies show that heat associated with the Yellowstone hot spot might be responsible for the great outpouring of lava. Still others invoke a meteorite impact in southeastern Oregon to initiate these flows. Chemical analysis of the lavas suggests a connection to the hot spot and the eruptions may have taken advantage of the faults to reach the surface.

Nearly everything about the Columbia River basalt is impressive. They are composed of over 300 individual lava flows located between the Cascades and the Rocky Mountains. In some places the lava measures more than 4000 m thick or more than twice the depth of the Grand Canyon. The eruptions filled depressions on the landscape first, then flowed downhill to the west along the course of the Columbia River, some all the way into the Pacific. The Pomona flow issued from a fissure located in west-central Idaho and traveled 600 km to the sea, making it the longest known lava flow on the planet. The total volume of lava erupted equals several hundred thousand cubic kms – enough lava to fill the Grand Canyon 42 times over. For comparison, the volume of material erupted from Mt. St. Helens on May 18, 1980 was only several cubic kms. The Grande Ronde Basalt contains 120 individual flows holding about 85% of the volume of the entire volcanic field, enough lava to bury the continental United States in 12 m of hardened rock. Much of this occurred within a period of less than one-and-half million years! Many of the picturesque sea stacks along Oregon's northern coast are the wave-cut remnants of Columbia River basalt.

With such voluminous eruptions, some geologists have postulated that the Columbia River basalts may have played a role in the development of the Miocene Climatic Optimum (MCO), a gradual warming trend in an otherwise cooling phase that had been underway since the end of the PETM at 55.5 Ma. The cause for the warming, lasting from 17 to 15 Ma, is inconclusive to date but the usual suspects – changes in ocean circulation patterns, mountain uplift, an increase in CO_2 levels (ironically to levels equally measured in 2015), and volcanism – are invoked. Any inputs from volcanism must include the widespread Columbia River basalts. The MCO saw temperatures rise about 7–9 ° F (3–4 °C) compared to today, resulting in a smaller Antarctic Ice Sheet and sea levels nearly 20 m higher than at present.

Plant fossils from this time show warm temperate conditions. During the height of the MCO, species such as swamp-cypress, Metasequoia, and alder were growing adjacent to lakes in the Basin and Range. On higher ground oak, sycamore, maple, and ginkgo fossil leaves are found. Animal species include peccaries, rhinoceros, and seven genera of horse (today there is one). Elephants also thrived in the open grasslands or shrub environments and a species known as *Zygolophodon* rooted for food using an elongated jaw and protruding lower teeth in a shovel-like fashion. The Basin and Range in the Miocene was a much different place that the dry desert basins and isolated mountain ranges of today.

11.6 Colorado Plateau and Basin and Range Provinces Differentiate

This is the time when the Colorado Plateau and the Basin and Range were separated into distinct provinces (although the prior physiography of the region might also serve to differentiate them). This topographic inversion resulted in a drainage reversal on the southern Cordillera. Uplift and volcanism in the arc in the Mesozoic created drainage away from the arc crest to the east and northeast, at least until about 33 Ma. After this date, evidence for flow direction disappears for a lack of deposits and are not "seen" again until about 16 Ma. Drainage between 33 and 16 Ma on the future Colorado Plateau becomes disrupted, obscure, confused, ponded, dry, rerouted, or reversed. There simply is not much information for this time.

However, in north-central Arizona, erosion formed the Mogollon Rim no later than about 20 Ma. Its formation was facilitated by down-dip retreat of northeast-dipping strata away from the Mogollon Highlands located to the southwest. This northeast dip was imparted to the bedrock strata during Laramide uplift when the highlands were rejuvenated and raised higher relative to the Colorado Plateau. As post-Laramide erosion incised into the tilted, softer strata (such as the Permian Hermit Formation), the overlying harder rocks (Coconino Sandstone and Kaibab Limestone) were undercut,

Fig. 11.9 Bright, colorful cliffs of Permian rocks define the Mogollon Rim, the SW edge of the Colorado Plateau near Sedona, Arizona

resulting in the formation of an elongated escarpment that became the Mogollon Rim (Fig. 11.9). As the valley beneath the Rim developed, drainage became redirected from its former northeast flow onto the Plateau surface to the southeast (recall the Rim gravel deposited during the Laramide on top of the Plateau). Paleogeographic indicators within the deposits suggest a southwest source area that brought material to the base of the Rim (evidence from clast composition types); drainage then deflected to the southeast as the Rim blocked its flow (evidence from clast imbrication directions). The deposits may indicate the time when drainage reversal began across the southern Colorado Plateau. The change in landscape was dramatic. Pre-Late Oligocene aggrading rivers flowed across a broad northeast-dipping pediment onto the Colorado Plateau and dumped their sediment load in the Baca Basin along the Arizona-New Mexico border. As the streams became degrading, they encountered resistant rock that formed ridges with a NW-SE strike. The streams deflected to the SE, probably following a strike valley. When downcutting streams encountered the nonresistant Hermit Formation, broad, deepening valleys resulted. The soft Hermit undercut more resistant units like the Coconino Sandstone and the Mogollon Rim evolved. Detailed studies near Sedona, Arizona have shown that over 20 million years the Rim has retreated 10 km, not a particularly rapid rate.

The upper Colorado River was likely in place at Grand Mesa Colorado (near Grand Junction), as sediment from the river has been found preserved at 3000 m beneath an 11 Ma lava flow. This means that the upper Colorado River was in place flowing to the west prior to 11 Ma. Where the river might have gone downstream from here will be discussed in the next section. At *ca.* 10 Ma, many of the features on the modern landscape had begun to appear. The Basin and Range was developing and differentiating from the Colorado Plateau.

Many of the volcanic rocks from this interval are well exposed across the modern Cordilleran surface. The Arizona Transition Zone, that area between the Colorado Plateau and Basin and Range in central Arizona, had widespread basaltic volcanism and several periods of violent eruption (Fig. 11.10). NE of Phoenix, the Apache Leap Tuff (18.7 Ma) blanketed a large area in a single eruption. Similarly, the Peach Springs Tuff across much of west-central Arizona also resulted from a single, violent eruption. And as the Basin and Range lowered and spread from the western margin of the Colorado Plateau, a large N-S trough developed, the Colorado River trough, and filled with over 1000 m of volcanics and sediment. Hoover Dam is nestled in a deep canyon carved by the Colorado through the volcanics (Fig. 11.11).

It is difficult to imagine a more diverse and more important interval in Cordilleran geologic history that the Early and Middle Miocene. Only a few finishing touches are left to flesh out the “painting” of the Cordilleran landscape – not the least of which is the relentless movement of the San Andreas Fault and associated violent young orogeny and the carving of Grand Canyon and other landscapes on the Colorado Plateau.

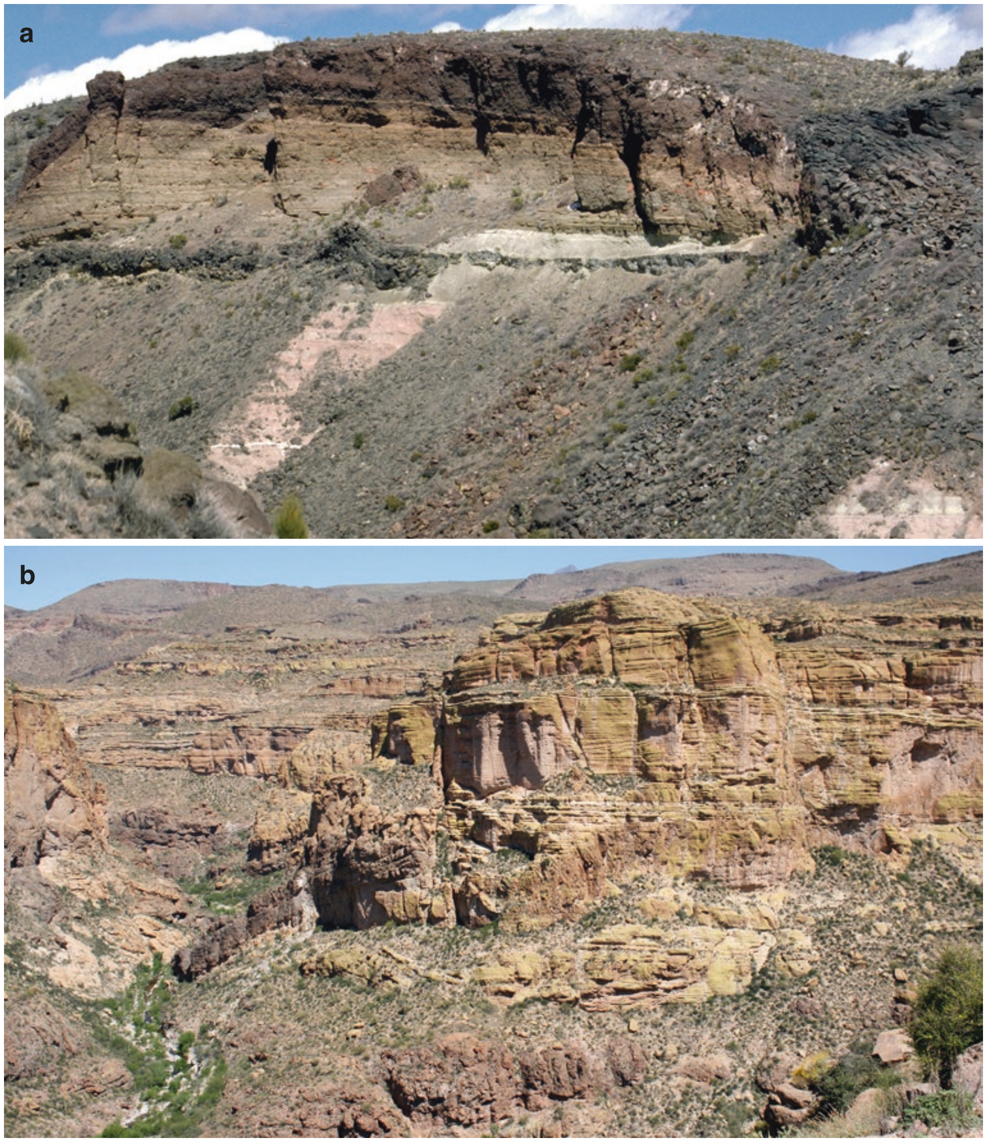

Fig. 11.10 Volcanic rocks in the Arizona Transition Zone. (**a**) Hickey Formation along I-17 in C Arizona is part of a well-preserved volcanic field 15–10 Ma. Various light-colored ash beds and a thin lava flow are capped by volcaniclastic sediments and a *dark-colored* basalt flow. (**b**) General view of Superstition volcanic field east of Mesa; numerous rhyolite flows and ashflow tuffs are visible. (**c**) The Apache Leap tuff represents a single eruption that spread hot ash over much of central Arizona. Legend has it that Apache warriors jumped to their death rather than surrender to the US Calvary in the late nineteenth century. (**d**) The Peach Springs tuff near Kingman is also the product of a single eruption; both it and the Apache Leap are 18.7 Ma, though their sources are distinctly different

Fig. 11.10 (continued)

Fig. 11.11 The Colorado River Trough is a Miocene extensional basin west of the Colorado Plateau. The rapidly subsiding basin filled with coarse-grained sediment and volcanics. (**a**) General view across the Colorado River north of Bullhead City, Arizona. (**b**) Hoover Dam is securely fashioned to Miocene volcanics in the Colorado River Trough. View is downstream from the dam

12 Interior Basins, Drainage Integration and Deep Incision: Late Miocene to Pliocene: Ca. 10–2.6 Ma

12.1 The Beginning of the End

As the story of the North American Cordillera approaches its current scene, the intervals of time that are segregated from one another become much shorter. Generally, this is due to more closely spaced data points highlighting the changing tectonic and sedimentary environments. However, some aspects of the Cordillera's recent history are no better understood than events that happened hundreds of millions of years ago. After all, a thick sequence of marine limestone spanning tens of millions of years reveals quite clearly the environments that could not have existed for that long span of time. It might seem counterintuitive at first glance that older events could be as well, or even better known, than more recent ones. But knowing that the recent history of the Cordillera involves many periods of uplift, faulting, volcanism, erosion, and drainage reorganization shows why this is so. A wide variety of processes have been active in the recent past and the interplay between them explains why significant uncertainties remain about the Cordillera's recent past.

Basin and Range faulting was still ongoing at 10 Ma and began to spread from southern and central Nevada northward into northern Nevada, Oregon and Idaho (Fig. 12.1; Table 12.1). In the eastern Rocky Mountains, the Teton Range began its uplift from a planar landscape 9 Ma. Within the core of this much-admired mountain range are Neo-Archean and Paleo-Proterozoic crystalline rocks that impart a classic Alpine appearance (Fig. 1.14a). The crystalline core is what most comes to mind when viewing the range from its spectacular eastern front. However, an early and middle Paleozoic sedimentary cover is exposed on the more gently tilted western side near Driggs in eastern Idaho. Recall that this cover represents quiet, shallow marine deposition on the continental shelf during the early and middle Paleozoic. In the adjacent mountains southwest of the Tetons, Sevier-age thrust faults reveals how this cover was telescoped and tectonically shortened during the Mesozoic. Late Miocene faulting that lifted the Tetons above Jackson Hole (with 8,000 m of gravel deposited in the adjacent basin) is just the latest in a long series of wide ranging events that helped create this iconic landscape.

Given the distance between the Teton uplift and the San Andreas Fault (the primary factor driving Basin and Range extension), it is perhaps too large a stretch to consider the San Andreas as the ultimate cause for Teton uplift. Looking north, one sees the steam-laden Yellowstone country (Fig. 12.2) with its gigantic calderas hidden beneath a blanket of green lodgepole pines. Perhaps it was the evacuation of immense volumes of magma from beneath Yellowstone that could explain differential uplift of the Teton Range.

12.2 Relentless Volcanism Continues

The Yellowstone hot spot is a plume of hot rock that has left a line of explosive volcanism from southeastern Oregon through Idaho to northwest Wyoming. Numerous calderas, ash-flow tuffs, and lava flows record the progression of the North American continent over this relatively stationary hot spot. Chemical analysis of the lavas in the Steens Mountain area of southeast Oregon suggest that at 16 Ma the area was sitting over the Yellowstone hot spot. Through time, as the North American plate drifted west by southwest, sequentially younger eruptions originating from the hot spot erupted and appeared gradually further east through time. Consequently, some geologists propose that the Tetons were raised by the differential collapse of the crust after magma evacuation from beneath Yellowstone and environs.

Further west, Idaho's Snake River Plain is an arcuate-shaped feature that occupies one-fourth of the state of Idaho, stretching nearly 600 km from the Oregon to Wyoming borders. It is divided into three sections, western, central and eastern. The western section is a classic *graben* structure that began to form about 12 Ma (graben is a German word for "grave" and its meaning geologically refers to a fault-bounded

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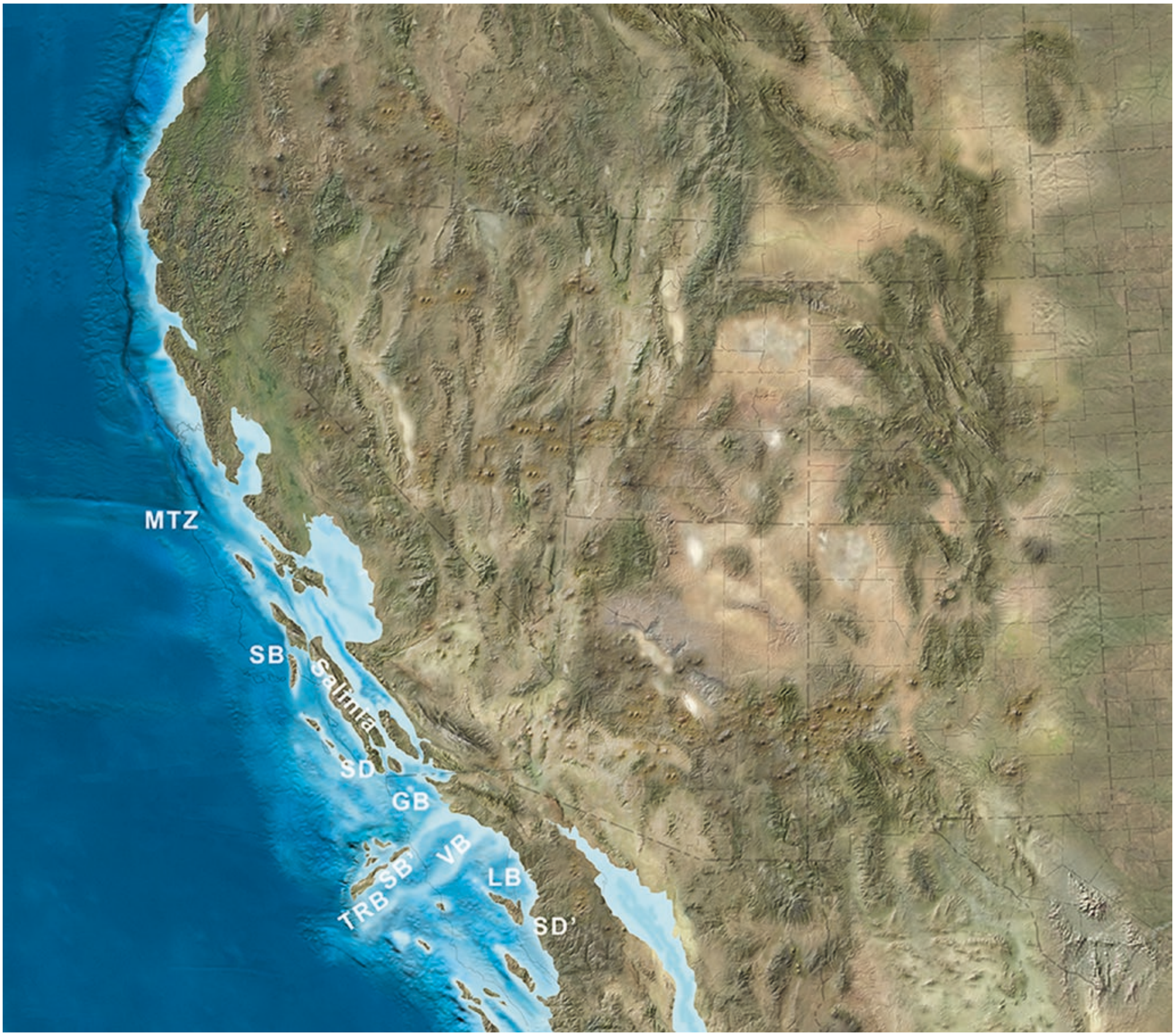

Fig. 12.1 Paleogeography of SW NA at *ca.* 10 Ma, Late Miocene. Widespread volcanism continues as extension across the Central Basin and Range continues. The early San Andreas Fault stretches from the Mendocino triple junction (*MTZ*) SE to east margin of Peninsular Ranges. The Western Transverse Ranges (*TRB*) rotate and the Los Angeles Basin (*LB*) and the Ventura Basin (*VB*) open in its wake and the Guadalupe Basin (*GB*) forms to the NW. These basins contain some of the thickest Late Miocene and Pliocene rocks in the world. The Miocene Monterey Formation, one of the most prolific petroleum producers on Earth, was deposited in the myriad of basins across C and S California. Marine waters were present in the future Gulf of California but the ocean basin had not opened yet. SB, SD – Present locations of Santa Barbara and San Diego, respectively; SB', SD' Late Miocene locations

Table 12.1 Events 10–2.6 Ma

	Late Miocene through Pliocene (*Ca.* 10–2.6 Ma)
Time span	San Andreas transform and Basin and Range extension, Coast Range orogen
Geologic – tectonic setting	Transform margin expands – San Andreas Fault has rapid right-lateral offset
	Continued extension promotes widespread volcanism
	Voluminous outpouring of basalts across Columbia Plateau
	Basin and Range expands northward into N NV and SW OR
	Incredible subsidence-sedimentation rates in basins across S and C CA (e.g. Ventura and Los Angeles basins)
	Sharp, local uplifts especially adjacent to rapidly subsiding basins – many Miocene rocks deformed by Pliocene-Pleistocene events – Pasadena orogen
	Sea of Cortez (Gulf of California) opens at 6 Ma as Baja CA extends away from Sonora MX – young oceanic crust formed in rift
Boundary of western North America	Expansion of transform margin as triple junctions separate at accelerating rates
	Subduction continues N and S of triple junctions
	Transform margin off BC and AK also expands
Terranes	Complex shuffling of terranes as transform faults create large strike-slip offsets (*e.g.* Salinia – see Table 10.2)
	No significant new terrane accretion
Sedimentation patterns, trends	Late Miocene and Pliocene basins developed incredible subsidence rates (tens of kms/several million years – Santa Maria-Guadalupe, Ventura, Los Angeles – mostly clastic sedimentation – deepwater muds and sand/mud turbidites dominate marine basins (Pismo, Monterey, Capistrano fms. and related rocks
	Thick Late Miocene and Pliocene sedimentation along S and E margins of Colorado Plateau
	Extensive clastic and evaporitic sedimentation in Basin and Range
	At *ca.* 6 Ma, Colorado River carves Grand Canyon and reaches Sea of Cortez. Huge volumes of sediment transported from Rocky Mountains-Colorado Plateau into newly formed Gulf of California
Igneous/ metamorphic events	Basaltic volcanism expands NE onto Colorado Plateau
	Continued volcanism across Basin and Range
	Southern margin Cascade arc retreats northwards as triple junction migrates northward
	Snake River Plain/Columbia Plateau basalts blanket much of Pacific Northwest

Fig. 12.2 Old Faithful in Yellowstone National Park marks the present location of the Yellowstone hotspot. Its location farther west in the Miocene may have controlled volcanism on the Columbia Plateau and Snake River Plain

basin dropped between two uplifted shoulders). The graben trends perpendicular to the trace of the Yellowstone hot spot and like the Tetons, it too may have collapsed by the removal of magma during earlier hot spot eruptions. The eastern part of the province, running parallel to the hot spot track, is underlain by ash-flow tuffs, ignimbrite, and overlying shield volcanoes; it likely formed during *bi-modal volcanism* when both basaltic and rhyolitic compositions were erupted.

The central part of the Snake River Plain resembles the eastern part but in addition contains the Glenn's Ferry Formation, a sequence of fluvial, lacustrine and interbedded volcanic rocks. These show that wetland, riparian and lake environments existed alongside the occasional volcanic outbursts about 3.8 Ma. One of the earliest modern horse fossils (*Equus simplicidens*) and an extinct camel (*Camelops*) have been found in these beds. These genera originated and evolved in North America during the Middle Eocene, then migrated across the Bering land bridge to establish populations in Asia, before their extinction here at the end of the last Ice Age. Their disappearance here was likely caused by human hunting pressure rather than climate change, although the debate is far from over.

The Cascade Range produced huge strato-volcanoes that continue to be active today. Gentle lava flows alternate with more explosive events to produce the steep-sided peaks (Fig. 12.3a). Some explosive volcanism was catastrophic – Mount Mazama exploded violently 7700 years ago (an event marked on Native American totem poles) to form the deepest lake in North America, Crater Lake (Fig. 12.3b). The Cascades owe their existence to continuing Cordilleran subduction.

Fig. 12.3 Some of the strato volcanoes in the Cascades were formed in the Late Miocene and Pliocene. (**a**) Mt. Rainier. (**b**) Crater Lake marks the location of Mt. Mazama which exploded 7700 years ago

12.3 Uplift of the Sierra Nevada

The Sierras are one of the highest mountain ranges in the lower 48 states (Figs. 7.6b, 11.3c), rivaling the peaks of the Colorado Rockies. During the Mesozoic and Paleogene, the Sierra Nevada formed the western flank of the Nevadaplano and river systems flowed west across the region to the Pacific. During the Eocene and Oligocene, canyons were carved into Sierra bedrock and filled with thick conglomerates and lava flows. Both suggest the area was uplands. There is no question that relief along the east flank of the Sierras originated during the Middle and Late Miocene as the Basin and Range pulled away and sunk relative to the Sierra Nevada. But when was the Sierran block uplifted to its present elevation (being careful to differentiate between elevation and relief)? The debate rages with one school suggesting that the Sierra crest was near its present *elevation* in the late Mesozoic or Paleogene. The other school argues that the Sierra Nevada was a relatively low upland until Miocene and Pliocene uplift – as the Basin and Range sunk, the Sierras rose. There is much evidence that both schools cite for their arguments; much of this is complex and beyond the scope of this book. Our maps clearly show uplands throughout the Cenozoic and the strong *relief* is apparent and clearly originated in the Miocene (Fig. 12.1), but we stop short of suggesting absolute values of elevation during the Cenozoic. Let the debate continue.

12.4 Growing Transform Margin and Coastal Sedimentary Basins

Although no terranes were added to the continent during this interval of time, the San Andreas Fault actively displaced terranes in Southern California and slivers of crust were shuffled to the northwest along the strike-slip faults as far north as southeast Alaska. This right-lateral motion further accelerated basin development and sedimentation rates in the Santa Maria-Guadalupe, Ventura and Los Angeles basins. Marine sedimentation was rapid during Middle Miocene to Early Pliocene in the middle and upper Monterey Formation (although much of this interval has been reassigned to the Pismo Formation). Some of the thickest Late Miocene and Pliocene deposits on Earth are present in the Ventura Basin. Amazingly, sedimentation, subsidence, and uplift were all going on at the same time over a relatively small area. Angular unconformities mark the section documenting subsidence and sedimentation, immediately followed by uplift and erosion, and then succeeded by sedimentation again. It is not unusual to see Late Miocene and Pliocene deposits strongly tilted and beveled and overlain by Late Pliocene and Pleistocene deposits (Fig. 12.4). What is even more astounding, the entire Pliocene is just 2.8 million years in length; a lot of wallop was packed into this short interval.

These sediment and organic-rich traps further augmented the future hydrocarbon wealth of southern California's basins. As the rich hydrocarbons oozed toward the surface, their volatile components escaped and tar pits developed in some parts of the Los Angeles basin. Ice Age animals would later wander too close and succumb to these tarry traps and become a rich trove of fossils in the La Brea tar pits.

Another spectacular depositional event is recorded in the sea cliffs at Dana Point and San Clemente in Orange County, California (Fig. 12.5). The Late Miocene and Pliocene Capistrano Formation is an offshore, relatively deep water deposit of mud and sandy mud that forms low, unstable sea cliffs – an unremarkable unit. However, above the Dana Point Harbor and at San Clemente State Park are two remarkable deposits that represent a submarine canyon fill. Sediment funneled off the highlands of the Peninsular Ranges block to the east, rushed downstream towards the Pacific, and entered the Capistrano Basin through two submarine canyons. The dynamics displayed in the two outcrops are indescribable. Chaotic channel-fill and slope deposits are preserved in unorderly fashion with bodies of pure clean sand adjacent to pebble conglomerates. These two outcrops go down in the geologic literature as some of the finest examples of submarine canyon sedimentation on Earth.

Coeval with events of sedimentation, erosion, and mountain building was the constant raising and lowering of base level – sea level in the case of coastal regions. Global sea level fluctuated relatively moderately during the interval but events in the Cordillera suggest local (apparent) sea level fluctuated hugely. Such events demand local control – uplift and subsidence in alternating fashion are those controls. The Pasadenan orogen, a relatively new term, was coined for the dramatic uplift of the San Gabriel Mountains near Pasadena but has been expanded to cover more widespread events as well (Fig. 12.6). The entire Coast Range suffered dramatic late Neogene and Quaternary orogeny and some would argue that this was a time of significant uplift of the Sierra Nevada, Colorado Plateau, and Rocky Mountains, not to mention Basin and Range events.

12.5 Sedimentation, Drainage Development, and the Birth of the Modern Landscape

Sedimentation was underway as well in the interior basins of the Basin and Range and the southern Colorado Plateau – now well enough differentiated to be called by their present-day names. In the Basin and Range, clastic and evaporative sequences filled the deepening fault-bounded troughs. Some basins contain impressive amounts of fill at the foot of the tilted ranges. Conglomerates were deposited on fans and in canyons while sand and mud formed on fan toes and on flat basin floors, commonly co-mingled with evaporites. There are many examples of sediments from one range burying adjacent ranges (Fig. 12.7). Volcanic ashes and flows intercalate with the sediments.

The Muddy Creek Formation occupies numerous distinct basins in the Lake Mead region and its easternmost basin at the base of the Grand Wash Cliffs provides possible age constraints on the age of the Colorado River at this locality. Deposition began about 13 Ma here when faulting separated the Grand Wash Cliffs from the Grand Wash basin. The Grand Wash Fault is a listric normal fault, meaning that the fault plane flattens at depth. These types of faults are common in the Basin and Range for this time interval. Displacement up to 5000 m deepened the basin and provided accommodation space for the deposition of the Muddy Creek Formation (Fig. 12.8).

All well and good – except none of the sediment appears to have been derived from the Grand Canyon or the Colorado Plateau immediately to the east of the basin. Instead the clastic deposits were shed from sources to the west with the sequence ultimately capped by the late Miocene Hualapai Limestone (5.9 Ma). This gives a maximum age for the Colorado River here, often rounded to 6 Ma. A basalt flow dated at 4.4 Ma at Sandy Point on Lake Mead a short distance downstream, caps unequivocal Colorado River sediment that gives a minimum age for the river at this location. Another basin on the opposite side of the Grand Canyon, the Bidahochi basin, is now minimized by geologists in the importance it bears in deciphering the history of the river but ironically, this newer interpretation for the Bidahochi

Fig. 12.4 Tight folding and rapid uplift of Late Miocene and Pliocene deepwater sedimentary rocks is on display in Montana del Oro State Park a few kms north of Morro Bay. (**a**–**c**) Latest Plicene to Peistocene beach and fluvial deposits overlie the Pismo Formation (previously assigned to Monterey Formation). The Pismo was deposited in a deep marine basin as recently as Middle Pliocene and has subsequently been folded and uplifted, truncated, and overlain by sediment deposited at or near the surface, all evidence for the geologically recent Pasadenan orogen

Fig. 12.5 More evidence for Miocene-Pliocene dynamics is present along the Capistrano Coast from San Clemente to Dana Point. The present coastline lay near the Late Miocene-Pliocene shelf edge with sharp uplifts feeding river systems to the E and the subsiding Capistrano Basin on the California Continental Borderlands to the W. Two rivers carved deep submarine canyons as they carried sediment load into the ocean. Spectacular channel fill and channel-mouth fans are exposed at San Clemente State Beach (**a**, **b**) and Dana Point (**d**). Deepwater Capistrano Formation sandy muds are exposed along Capistrano Beach (**c**) S of the San Clemente pier. The transition between the fan-channel complex and the deepwater sediments is exposed along the beach N of the State Park. The thin sand body in (**c**) pinches out a few hundred meters N as one moves progressively away from the fan

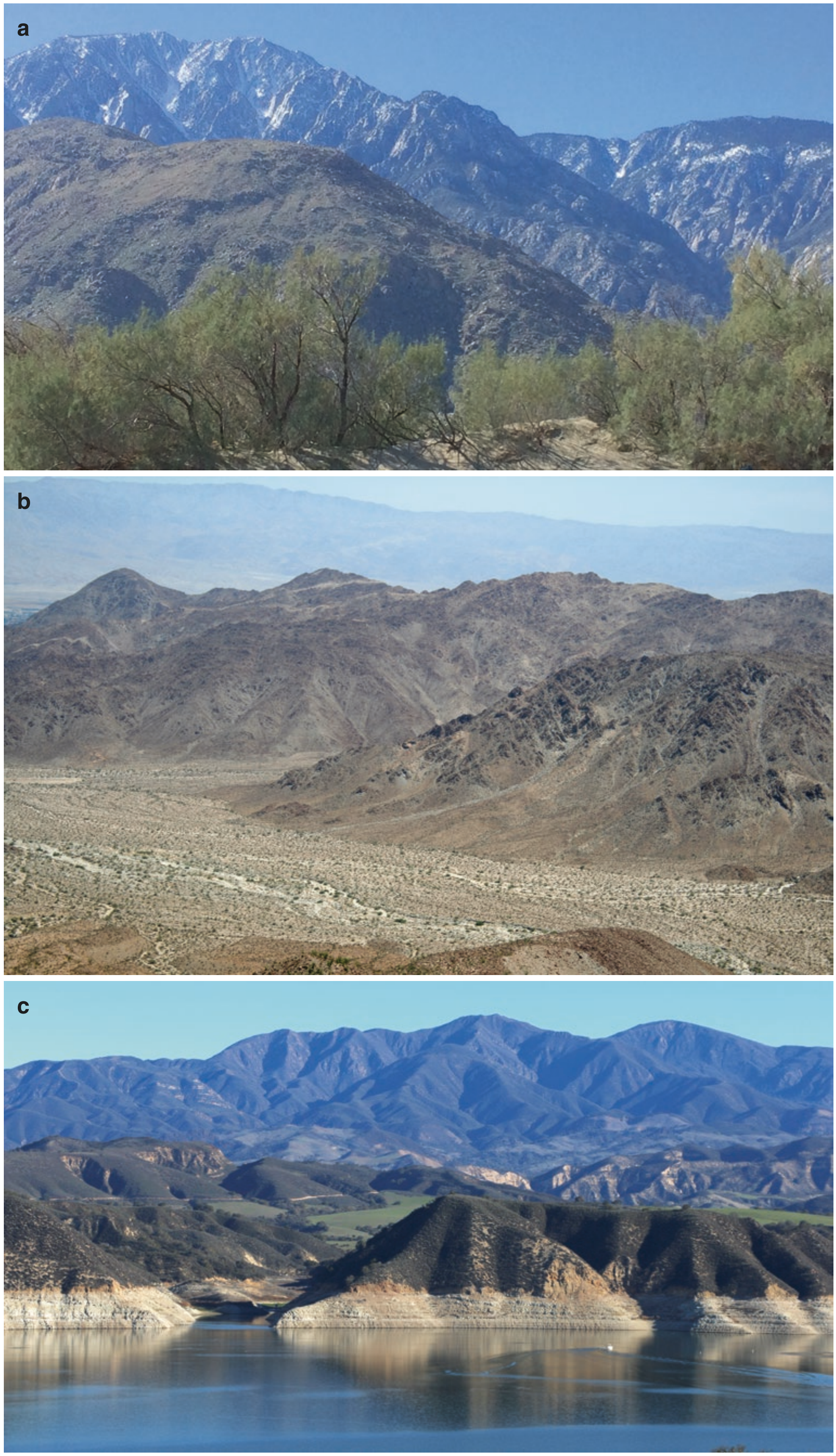

Fig. 12.6 The type area for the Pasadenan orogen is in the Transverse Ranges adjacent to Pasadena. Some of the greatest Pliocene uplift rates on Earth are documented in the San Gabriel, San Bernardino, San Jacinto, and Santa Rosa Mountains where the Peninsular Ranges block has slammed into the North American Plate along the San Andreas transform system. (**a**) Mt. San Jacinto (3302 m) rises above San Gorgonio Pass west of Palm Springs, directly opposite Mt. San Gorgonio (3506 m – not shown here), the highest peak in Southern California. The two peaks are separated by the San Andreas Fault. (**b**) View from the Santa Rosa Mountains SE across Coachella Valley (in haze) to the Little San Bernardino Mountain (distant skyline). The San Andreas Fault runs down the valley. (**c**) The Santa Ynez Mountains N of Santa Barbara were folded and uplifted when the Transverse Ranges block rotated and collided with southern Salinia in the Late Pliocene and Pleistocene

Fig. 12.7 The Basin and Range normal faulting is the hallmark of the Basin and Range orogen and generally progresses NW from SE Arizona to NW Nevada. (**a**) The Gila Bend Mountains near their namesake town in SW Arizona are part of the older Basin and Ranges. Note lower ranges in the background that appear to be in the process of being buried. Faulting is inactive in this region so erosion rules. (**b**) Spectacular exposure of dissected alluvial fan in north-central Phoenix; the schist and vein quartz cobbles and pebbles can be directly traced to the bedrock of the Phoenix Mountains a km to the N

Fig. 12.8 The point in time when the Colorado River found its way off the Colorado Plateau into the Gulf of California ushered in profound changes across the entire Southwest. Plateau rivers were bottled up 2000–3000 m above sea level before the break occurred. The most profound changes occurred on the Plateau with the incredible dissection of thick, colorful sedimentary rocks and at the rivers' new mouth as it spewed sediment into the Gulf. This aerial view shows the upper Lake Mead region at the mouth of Grand Canyon. The Miocene Muddy Creek Formation underlies the lighter patches in the foreground and center of the photo. The Muddy Creek and Hualapai Limestone were not derived from the Colorado River; therefore, the river here is younger than these sedimentary rocks (*ca.* 6 Ma)

Formation raises more questions than it answers. The Bidahochi at one time was considerd a major sink for the Colorado River before Grand Canyon allowed passage to the west. However, there is just not enough sediment in the Bidahochi, especially the easily recognized Colorado River gravels, to support such a hypothesis.

To illustrate, the foregoing discussions show that the Colorado River can be no older than 6 Ma at the Grand Wash Cliffs but is nearly twice as old at 11 Ma at Grand Mesa near Grand Junction Colorado. This leaves the question, "Where was the Colorado River between 11 Ma and 6 Ma between these two localities?" An outlet to the Snake or Columbia rivers to the northwest is not out of the question, while a depositional basin in the Canyonlands region (modern Lake Powell area) may have been a possible sink. No deposits for either scenario have been found to date and so the debate goes on.

However, the origin of the Lower Colorado River is coming into clearer focus. Below Grand Canyon, the river occupies the *Colorado River extensional corridor*, (a Basin and Range feature) and likely owes its placement to this deep structure. The processes that placed it here are quite different. Beginning in the Las Vegas basin and moving downstream sequentially through no less than four other basins, geologists have shown that the relatively rapid arrival of river water from an unknown source upstream, sequentially filled each basin with water and sediment. A sequence of deposits from bottom to top in each basin begins with (followed by interpretation in parentheses) (1) alluvium derived only from the enclosing mountains (local sediment source), (2) younger debris that originated exclusively from the narrow divides that separated each basin (initial spillover from basin above), (3) capped with lacustrine limestone and marl (sedimentation in enclosed, dammed body of water), (4) topped with Colorado River sediment (upstream dam breached allowing influx of Colorado River). The sequence offers a startling conclusion – basin fill and subsequent spillover created a course for the lower Colorado River. As more water arrived at each basin, it filled to a point where the bedrock divides were over-topped, breached, and eroded forming lakes downstream, eventually to the Gulf of California. Age constraints from enclosed tuffs show that the top-down series of basins formed between 5.6 Ma in the Cottonwood basin and 4.1–3.3 Ma in the Blythe basin. Debate is on-going regarding the extent of marine incursion into the Blythe basin, but current equivocal interpretation suggests that the Blythe basin was lacustrine in the north and perhaps marine to the south. Interestingly, the fossil and geochemical evidence contradict each other.

So what might have caused the relatively rapid arrival of Colorado River water into these basins? Was it headward erosion up through the Kaibab upwarp that captured some segment of the upper river? Or was it basin-spillover from some impounded body of water upstream from the Grand Canyon? Could karst processes and subsequent collapse of strata in the eastern Grand Canyon have connected the upper and lower portions of the river? Any of these three models, or a combination of the three, could explain how the upper river delivered water to and integrated the upper basins with the lower basins; and just as importantly, carved the incredible landscapes of the Colorado Plateau (Fig. 12.9). Dates from 5.6 to 4.1 Ma seems to indicate when much of this occurred.

The origin of the integrated Colorado River is not just a local problem; the reasons and effects are a broader Cordilleran problem. During the reign of Cordilleran subduction, sediments reached the West Coast from as far away as the Colorado Plateau (even before it was a plateau). Jurassic through Eocene-Oligocene rocks in the Coast Ranges have detrital zircons that were derived from the Plateau and uplands in Idaho and Montana. However, with the development of the transform margin, uplift of the Coast Ranges, Sierras, and other highlands blocked sediment from

Fig. 12.9 The Colorado Plateau is marked by profound dissection. (**a**) The Colorado River enters the Plateau a few kms above Grand Junction. Downstream, the river encountered the buried late Paleozoic Uncompahgre Uplift and carved into Proterozoic basement. Triassic and Jurassic rocks overlie the buried uplift, shown here in Westwater Canyon in eastern Utah. (**b**) The San Juan River is a major tributary to the Colorado system. Incised meanders are carved into Pennsylvanian rocks at Goosenecks of the San Juan in SE Utah. (**c**) Brilliant Triassic and Jurassic sedimentary rocks are intensely carved by aptly named Red Canyon near upper Glen Canyon in SE Utah. (**d**) The most famous canyon on Earth, Grand Canyon, is the region of penultimate carving by the Colorado River and attending mass wasting along canyon walls. The mile-deep (1500 m) crevice occurs where the river cuts across the Laramide Kaibab Uplift

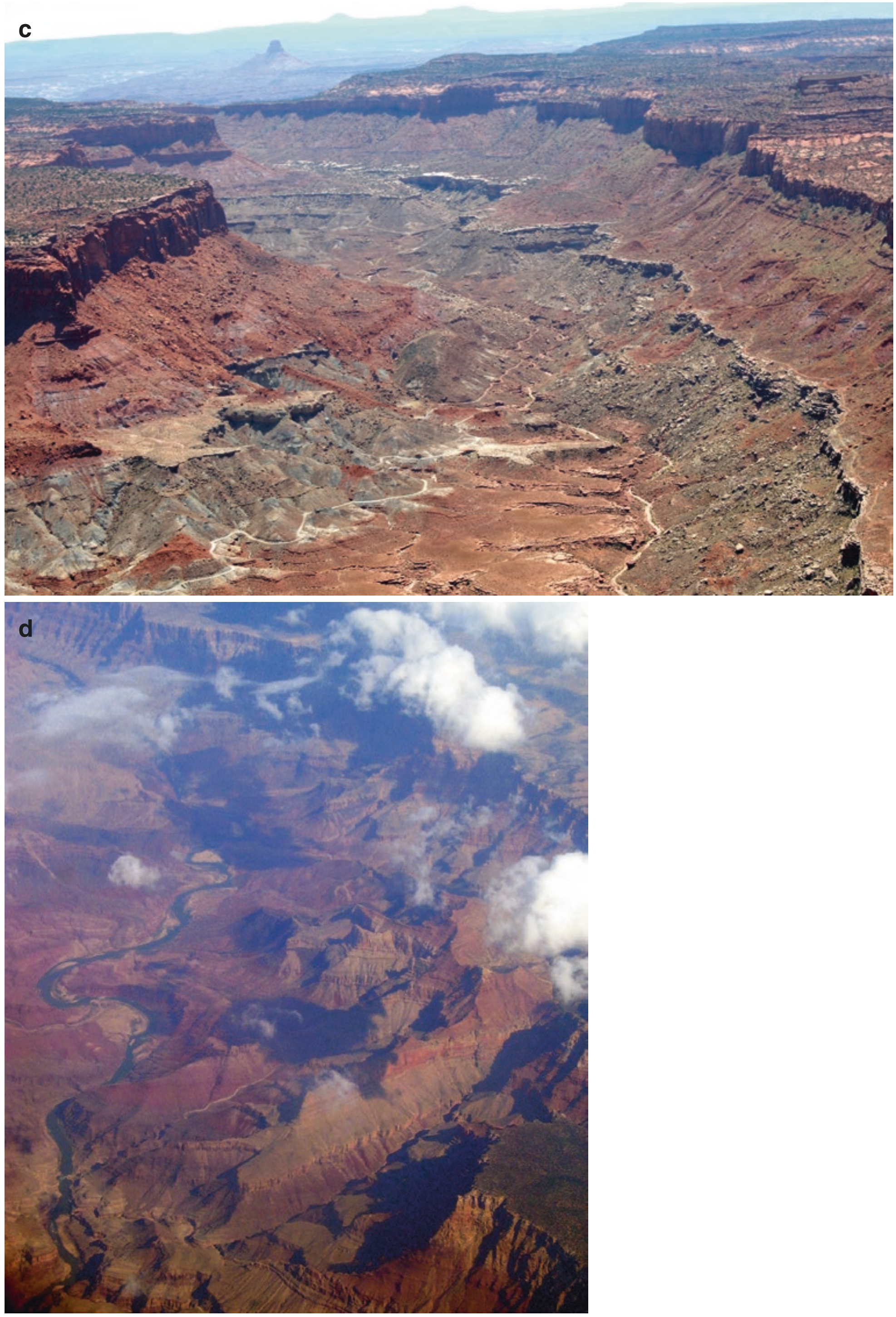

Fig. 12.9 (continued)

eastern sources and the detrital zircon record does a rapid flip towards locally derived sedimentary sources. Furthermore, during most of the Miocene, sediments from the Colorado Plateau and adjacent Rocky Mountains had no outlet; eastern portions of the Central and Southern Rockies were drained into the Gulf of Mexico and areas farther north drained across Canada into the Labrador Sea. Finally, the plug was pulled – by whichever above model you prefer – and huge volumes of sediment drained this former pent up area and rushed into the Gulf of California. Why? At *ca.* 6 Ma, the San Andreas system linked with fractures in W Mexico and the Gulf opened. Sea level extended as far north as Yuma, Arizona and possibly Blythe, California and the extreme potential gradient between the 2000 and 3000 m elevation of the Colorado Plateau, only several hundred kms to the north-east, was tapped by sea level (Fig. 12.10). Why didn't the

Fig. 12.10 Paleogeography of SW NA *ca.* 5 Ma, Pliocene. Continued extension has moved the West Coast to nearly its present position. The Gulf of California (*GoC*) has flooded with marine waters and the Colorado River empties into it through the Grand Canyon (*GC*). Other abbreviations as in Fig. 12.1. Salinia southward to the Peninsular Ranges have moved northward along the San Andreas Fault and the Western Transverse Ranges have rotated to nearly E–W. The Los Angeles and Ventura Basins continue to fill with several kms of sediment. The Mendocino *TZ* has migrated N of San Francisco. SB, SD – Present locations of Santa Barbara and San Diego, respectively; SB', SD' Pliocene locations

Plateau find a drainage to the west? The San Andreas system produced NNW-trending mountains and valleys, not an easy path for rivers from the east to navigate. Today, the Transverse Ranges from a significant drainage divide between the Mojave River and others draining northeast to die in the Basin and Range and the Los Angeles, Santa Ana, and other rivers draining into the Pacific.

As the Miocene gave way to the Pliocene Epoch at 5.3 Ma, a gradual cooling prevailed worldwide; interestingly, the mid-Pliocene (3.3–3.0 Ma) saw temperatures rise to about to 5°F (2°C) warmer than today, with sea level about 25 m higher (water expands with warmer temperatures). After 3.0 Ma, the Greenland ice sheet began to expand and the increased surface area of the ice reflected solar radiation back into space, possibly initiating the *Ice Age*. This cold phase in Earth history is known formally as the Quaternary Period and its beginning is now set at 2.588 Ma (or rounded to 2.6 Ma – but previously placed at 1.8 Ma).

During the latest Pliocene as the climate cooled, tropical species retreated to low latitudes while grasslands expanded into drier and cooler temperate regions. In North America rodents expanded in diversity and range, as well as mastondons and gompotheres (two types of elephants), but the North American rhinoceros and oreodont became extinct. Around 3.5 Ma, the Isthmus of Panama developed by volcanic activity as the Caribbean plate moved to the east. This newly established land bridge brought the arrival of the giant sloth, glyptodont, armadillo, porcupine and opossum to North America, while species such as dogs, cats, bears, and horses moved south, contributing to the decline and extinction of some native South American forms. In Africa, the cooling climate caused woodlands to become less dense and our early hominid ancestors such as *Australopithecus* came out of the trees and adjusted gradually to life on the grasslands. This brought challenges and opportunities but obviously, the opportunities allowed us to expand our range from our initial roots in Africa to the larger world.

13 The North American Cordillera Today: Pleistocene, Holocene and the Anthropocene: Ca. 2.6 Ma to Present

13.1 Continuing Tectonic and Volcanic Processes

At the dawn of the Pleistocene, the western Cordillera was largely shaped in its present form. All terranes that had amalgamated to North American from Alaska to Mexico, through a span of over 350 million years, formed a significant fraction of the landscape. Although these terranes were highly deformed and often covered by younger rocks or thick vegetation, geologists working in the field noticed their anomalous origin and so these exotic terranes were ultimately identified. To think of a time before these terranes were known and understood is to think of Cordilleran geology in its infancy.

For the most part, tectonic and volcanic events in the Quaternary were a continuation of those of the Pliocene (Figs. 13.1 and 13.2; Table 13.1). In the north, Cascade volcanoes were erupting ash and lava to create the modern edifices of Rainier, St. Helens, Hood and Shasta. The Columbia River was slicing through the Columbia River Basalts. To the south, the Monterey Formation had been uplifted in part along the Pacific margin and was exposed in the Coast Ranges or in basins in southern and central California. The Sierra Nevada was uplifted and Baja California was rifted from mainland Mexico along the right-lateral transform faults that had opened the Gulf of California. A result of the rifting was that the Colorado River found an outlet to the sea and was busy carving the Grand Canyon. The San Andreas Fault still tugged at the long-traveled and rotated blocks of the Transverse Ranges but the process was far enough along to make them fully recognizable to any would be Pleistocene traveler.

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Fig. 13.1 SW North America during the Early Pleistocene (*ca.*) 2 Ma. Terranes west of the San Andreas Fault are approaching their present positions. Many of the modern landforms across the map can be discerned although the Los Angeles (LAB), Ventura (VB) and Guadalupe (GB) basins are still underwater. Salinia forms the prominent NW trending peninsula along S California

Fig. 13.2 Pleistocene and Recent tectonic and volcanic features. (**a**) The dormant volcanic crater on top of Mt. Rainier is clearly visible from the air. (**b**) Tilted Pliocene strata along the Central California coast document recent tectonic activity. (**c**) The San Andreas Fault in Coachella Valley separates the Peninsular Ranges on the Pacific Plate (foreground) from the San Bernardino Mountains on the North American Plate (in distant haze). The San Andreas system is the dominant tectonic element of the late Cenozoic in California. (**d**) The Sur-Nacimiento Fault, one of many transform faults in Southern California separates the Nacimiento Terrane on the *left* from the Salinian Terrane on the *right* near Point Sur. (**e**) Many of the faults in the southern and central Basin and Range are no longer active but their offset is still apparent as here along the Catalina Mountains north of Tucson, Arizona

Fig. 13.2 (continued)

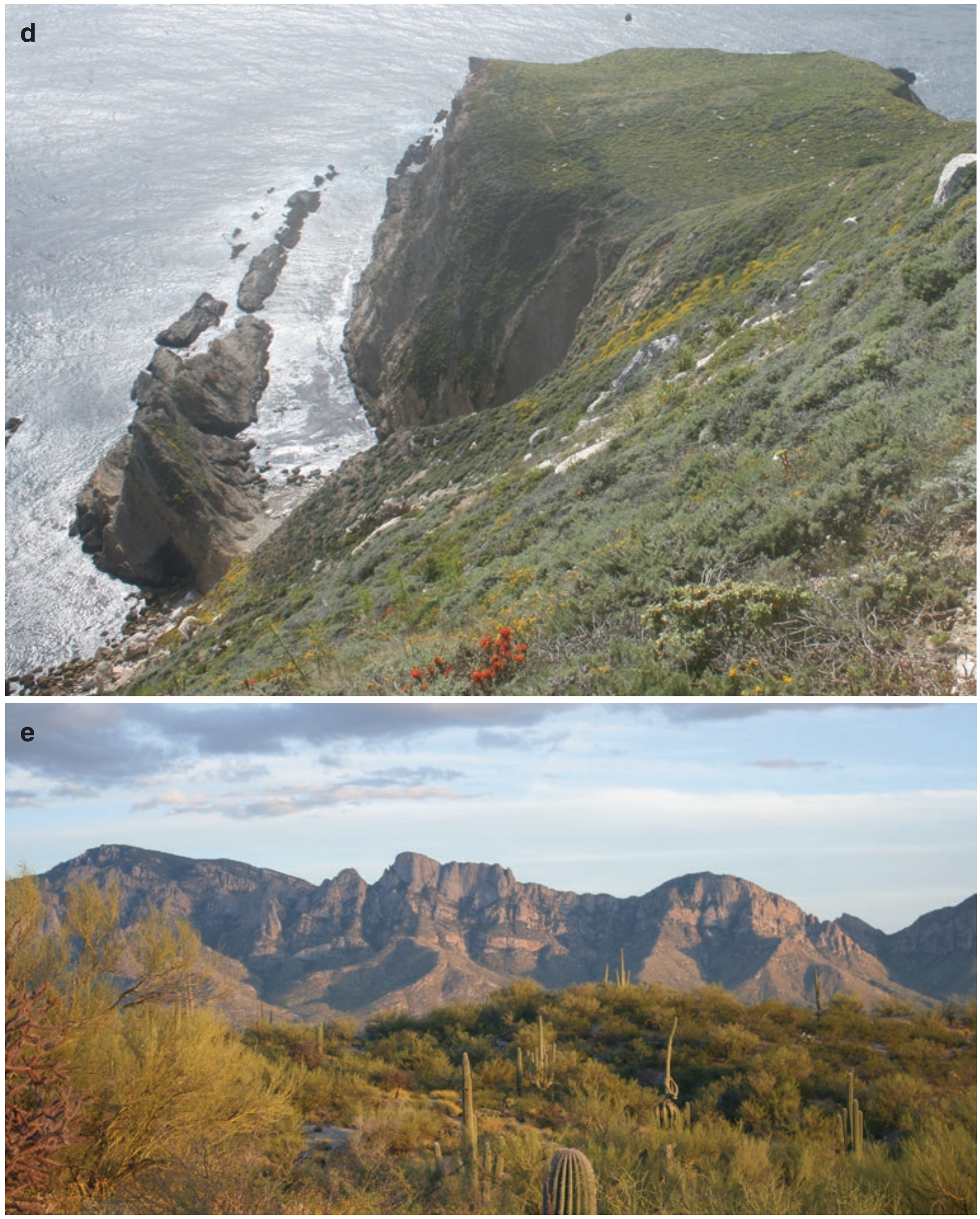

Table 13.1 Events 2.6 Ma to present

Time span	Quaternary (*Ca.* 2.6 Ma – Present): Pleistocene; Holocene (Anthropocene); Coast Range/Pasadenan orogen; Pleistocene glaciation; humans as geological agents
Geologic – tectonic setting	Pleistocene glaciation – now known to consist of 13 glacial-interglacial cycles
	Rapid separation of triple junctions generates rapid transform offset on San Andreas Fault
	Widespread orogeny and uplift across Cordilleran region – strong uplift of Transverse Ranges referred to as Pasadenan orogen; Coast Range orogen affected much of Cordilleran coast; Pleistocene to Recent uplift substantial in many regions
	Erosional processes dominate as modern landscape evolves – extreme canyon cutting across uplands and plateaus
	Episodic uplifts produced numerous marine terraces along coast
	Volcanism expands farther onto Colorado Plateau
	Glaciation of highlands and formation of large glacial lakes in lowland basins
Boundary of western North America	Continued expansion of transform margin
	Subduction continues N and S of transform margin
	Significant capture and NW movement of former NA continent west of San Andreas Fault
	Recent studies suggest that the Pacific-North American plate boundary is presently shifting eastward into Death Valley-Owens Valley
	The western boundary of North America depends on whether one is considering the *plate boundary* or the *continental margin*: the boundary of the North American Continent includes all continental crust east of the oceanic crust of the Pacific Ocean and thus comprises not only the North American Plate, but also continental material now part of the Pacific Plate
Terranes	No new terranes were added – rather, there was complex juxtaposition of blocks along the San Andreas and related faults
Sedimentation patterns, trends	Local sedimentation in basins, continental to east (Basin and Range) and marine to west – strong partitioning of basins by complex tectonic/topographic patterns
	Most drainages sub-regional except for major rivers like Colorado, Columbia, and Frazier that cross complex tectonic boundaries and flow into ocean basins from continental interior
	Glacial deposits widespread
Igneous/metamorphic events	Continued widespread volcanism – migration continued NE across S Colorado Plateau
	Cascade arc shrunk from south as triple junction migrated northward

13.2 Winter Is Coming

One aspect of the Cordilleran story however, had yet to be placed as a final flair on the western landscape – the Pleistocene glaciations and associated *pluvial* environments (pluvial refers to periods of increased precipitation and lessened evaporation). A combination of factors including a change in ocean circulation patterns, perhaps brought on by the appearance of the Panamanian land bridge, changes in the suns' solar output or orbital variations, uplift of the Tibetan Plateau, feedback mechanisms from an increased albedo effect of Arctic sea ice, and/or volcanic activity, all united to produce one of the planet's most pronounced Ice Ages (Fig. 13.3). High-standing mountains like the Rockies, the Sierra Nevada, the Cascades, received snow that did not melt during the summer, allowing for increased accumulations in subsequent winters that formed the great glaciers (Fig. 13.4). These glaciers helped to shape the modern landforms by scraping the bedrock into the many characteristic glacial forms such as horns, cirques, artêtes, U-shaped valleys, and moraines (Fig. 13.5). Some areas here have glacial features as obvious as any in the Alps where the initial evidence for the Pleistocene glaciations was first observed.

One of the best places to see the complete 'source-to-sink' aspects of a modern glacial environment is from the Juneau ice field to the Mendenhall Glacier where it enters the sea (Fig. 13.6). Here one can see glacial dynamics and appreciate the erosive power of moving sheets of ice. Another characteristic of coastal mountains that have been glaciated are fjords; some of those in Alaska and British Columbia are 50 km long or even more (Fig. 13.7). Some fjords contain glaciers that reach the sea (tidewater glaciers), some hang far above modern sea level having shrunk over recent times, and some have little evidence of the glaciers that once carved them.

Glacial ice deposits consist of *till* – unsorted, mostly unstratified chaotic masses of sediment with grains of all sizes commonly present (Fig. 13.8). Shaped, rounded mounds of till that accumulate at the margins of glaciers are called moraines. These deposits are widespread across much of the higher or more northerly Cordillera and allow geologists to reconstruct Pleistocene glaciers. Figure 13.4 shows southwest North America during the pinnacle of Pleistocene glaciation. The map attempts to show every known mountain glacier and every glacial lake – it should be pointed out that not every glacier or lake was at maximum extent at the same time.

Fig. 13.3 North America during the Late Pleistocene glacial maxima *ca.* 20,000 years ago. As sea level was nearly 120 m lower than it is today, land extended farther seaward. Note the ice-free corridor between the Cordilleran and Laurentian ice sheets, at times wider, that allowed the First Americans to migrate into North America from Asia

Lowland areas devoid of ice did not escape the consequences of a colder Pleistocene climate. Increased rainfall at lower elevations together with a decrease in evaporation caused basins to become filled with freshwater. Huge lakes dominated the valleys in the Basin and Range, with Lake Bonneville filling depressions in western Utah and eastern Nevada, and Lake Lahontan occupying valleys in western Nevada and easternmost California (i.e. Owens, Death, and Amaragosa valleys). Lake Lahontan in some places was 175 m deep and occupied 22,000 km^2. Along the shores of these lakes, the open water and cold Ice Age wind facilitated the scouring of numerous wave-cut terraces across mountain fronts, including the well-known benches of the Wasatch Front near Salt Lake City and Provo Utah. The discovery of these features, first observed by G. K. Gilbert in the 1870s, helped prove the existence of a former worldwide Ice Age, then a still new and unconventional idea to science.

Vegetative communities in the Pleistocene were similar to those seen today but were found about 400 m lower in elevation because of the decrease in temperature and increase in precipitation. Much of the evidence comes from *middens*, the nests of pack rats (or wood rats of the genus *Neotoma*) composed of woody vegetation that was collected within maximum of 200–80 m of the nest. As the nests become cemented with feces and urine, they survive undisturbed in caves or cavities in the rocks for thousands of years. Pieces of the cemented material, called *amberat*, can be collected and taken to a lab where the species of woody material can be identified. The organic matter can be radiocarbon dated, giving an age for the nest and revealing what was growing adjacent to the nest at that time. The middens are sometimes as old as the maximum limit of the radiocarbon technique (55,000–60,000 years) and serve as a proxy for the lack of written records from the Ice Age.

Ice Age animals also roamed the Cordilleran landscape such as mammoths, giant Shasta ground sloths, camels, horses, and other extinct animals. Colder climates tended to result in larger individuals to conserve warmth and energy (smaller forms tend to dominate in tropical warm environments). The La Brea tar pits in downtown Los Angeles are one of the best repositories for Ice Age fauna, at least as it concerns Cordilleran coastal environments. Pluvial lake deposits in the Basin and Range are rich in avian, insect, invertebrate, and vertebrate fossils. Many of the above species went extinct at the end of the Pleistocene but some of their relatives kept their genetic links alive after moving across the land bridges to other continents, for example camels and horses in Asia, and tapirs and llamas in South America.

Another important migration during the late Pleistocene was the arrival of man into the New World between about 14,000 and 15,000 years ago. Most genetic studies show that up to 96% of modern Native populations in the two America's trace their lineage to people who migrated from eastern Siberia, either along a coastal route or an ice-free corridor from Alaska along the eastern front of the Rocky Mountains. Whether the coastal or the ice-free corridor route is invoked, humans radiated quickly once they arrived in these previously unpopulated landscapes. In southern Arizona, the Lehner Mammoth-Kill Site shows a close association between humans and mammoths. It was discovered in 1952 when a rancher found spear points embedded in mammoth remains. Other species later excavated at the site include horse, tapir, bear, bison, and rabbits. At Tule Springs National Monument northwest of Las Vegas, fire hearths have been found that led to a major archaeological dig showing that people were in this area 10,000 years ago. Within the chalky soils of the site, mammoth, extinct bison, saber-toothed cats, wolves, and giant sloths have been found. It was during the waning stages of the Pleistocene that man arrived and saw the Cordilleran landscape for the first time. It's amazing to think of the first time a person laid eyes on Mt. Rainier, the Tetons, or the Grand Canyon.

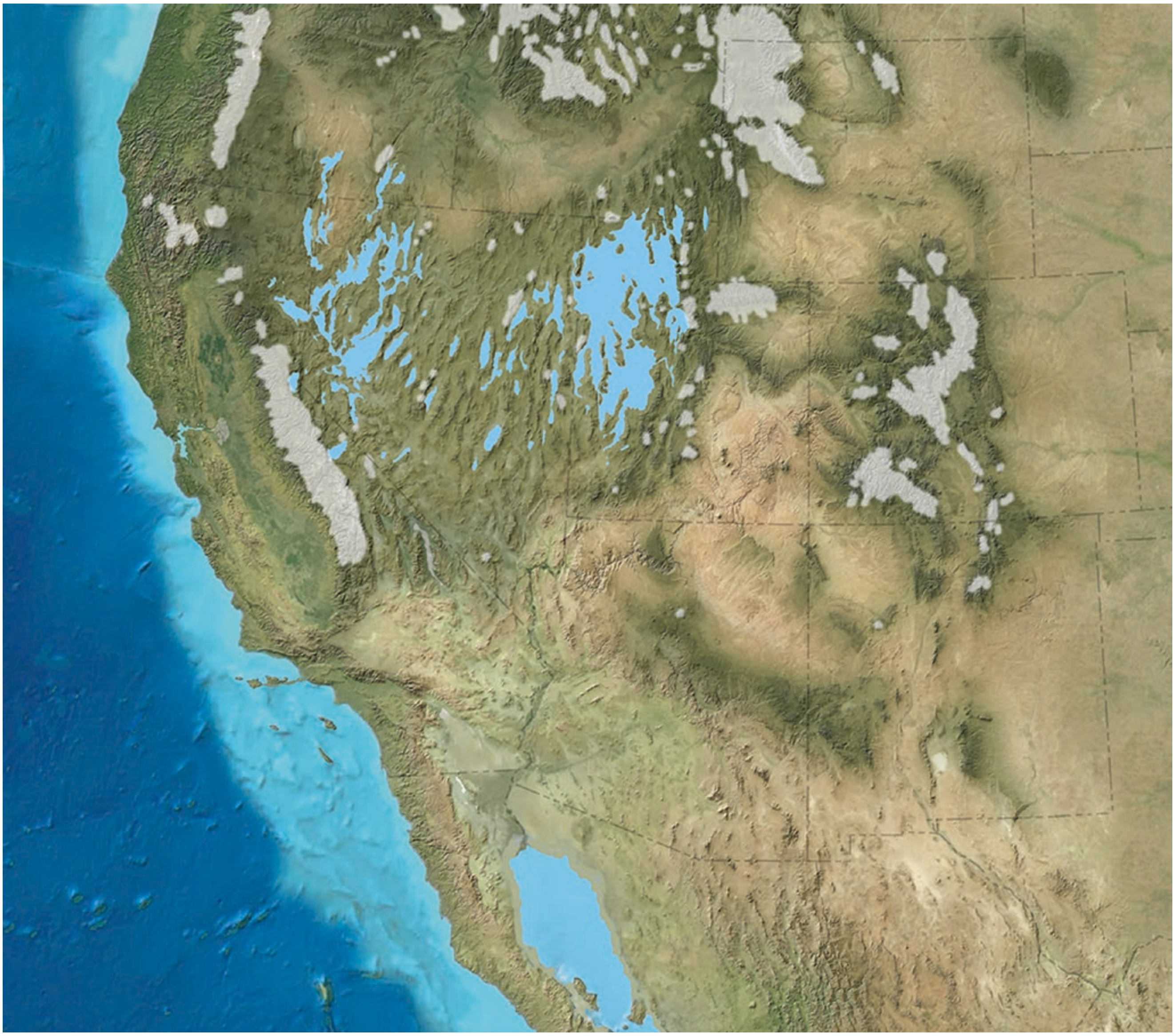

Fig. 13.4 SW North America during maximum Pleistocene glaciation. Individual mountain glaciers and Great Basin lakes are shown. Lake Bonneville in W Utah and E Nevada was the largest of the Great Basin lakes. Note that the eastern end of the Channel Islands are almost attached to the mainland – this allowed dwarf mammoths to migrate to and live on the islands

Fig. 13.5 Various glacial features such as aretes, cirques, and horns are clearly visible in this aerial view of the Canadian Rockies

Fig. 13.6 The Juneau ice field and Mendenhall Glacier show the nature of glacial regions from source to sink. (**a**) In the Juneau ice field, only the highest peaks stand above the broad glacial areas. (**b**) As the glacier moves down valley, the *dark stripes* are medial moraines that mark where glaciers have merged up valley. (**c**) The valley widens and the glaciers are full of moraines and crevasses as the ice flows down valley. Lakes and streams occur along the glacial surface. (**d**) The Mendenhall glacier is a tidewater glacier that flows into the sea. Note the icebergs near the center of the photo. The ridge in the center foreground is a moraine formed when the ice extended farther down valley. The bare areas above the present ice show the level of the ice several hundred years ago

Fig. 13.6 (continued)

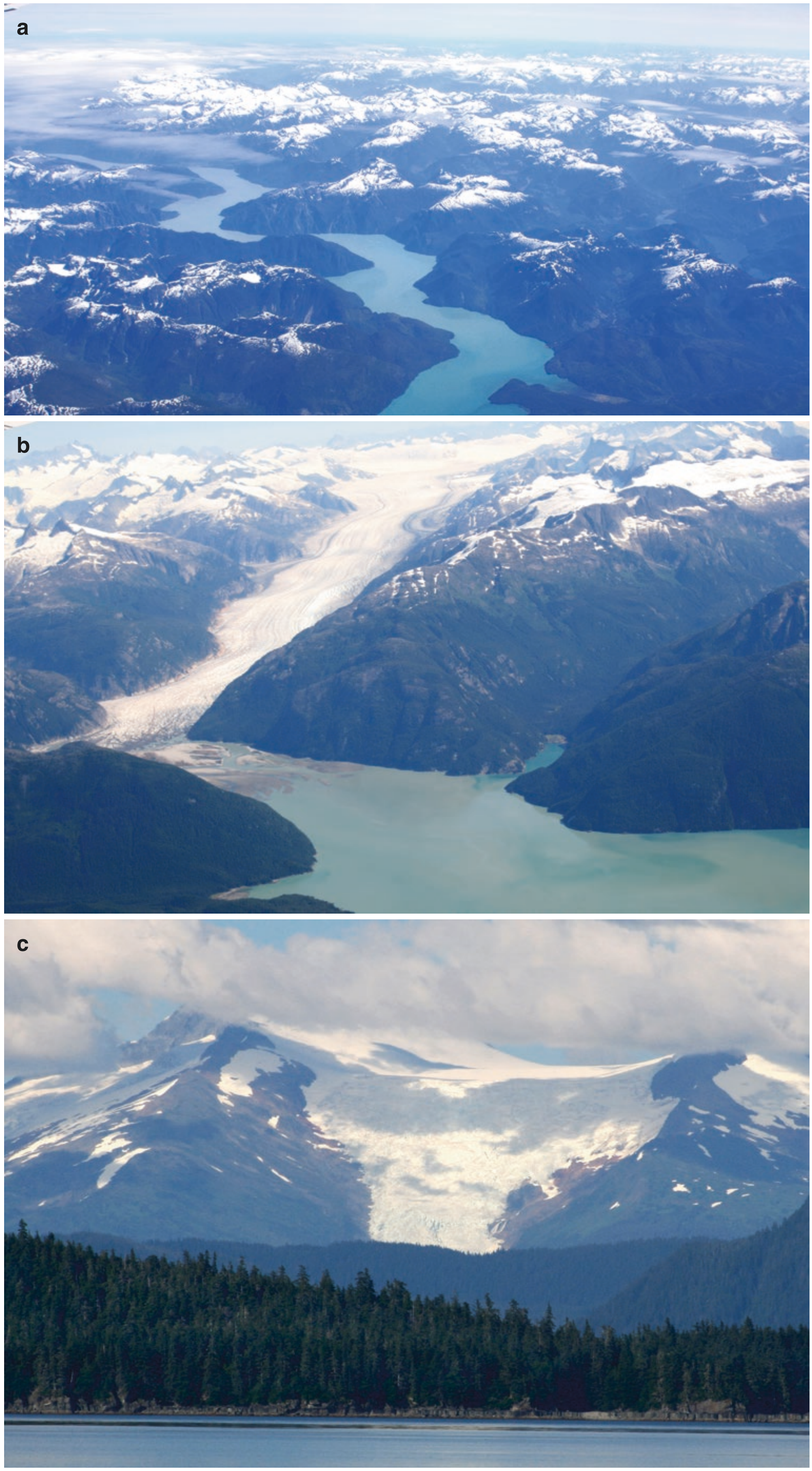

Fig. 13.7 Fjords are valleys filled with seawater that mark the location of previous glaciers. (**a**) A fjord extends for more the 50 km below its glacial source along the central British Columbia Coast. (**b**) A tidewater glacier steeply enters a fjord in central British Columbia. (**c**) A glacier in SE Alaska near Petersburg hangs far above its fjord (hidden by ridge)

Fig. 13.8 (**a**) Till is the material deposited directly by glacial ice. This till near Durango, Colorado shows the characteristic poor sorting, wide range of grain size, and non-stratified nature. (**b**) Moraines are the ridges of till deposited at glacial margins. The lumpy hills in the foreground represent several generations of moraines at the foot of the Sierra Nevada in E California. (**c**) Glaciated peaks of the Sierra Nevada rise above moraines adjacent to Mono Lake

13.3 Lakes and Ice Dams

As the ice sheets spread southward from southern British Columbia and Alberta, they flowed toward and temporarily blocked drainages such as the Clark Fork of the Columbia River in western Montana. Ice dams up to 600 m high, impounded water of the Clark Fork, forming glacial *Lake Missoula*, a body of water covering 7800 km^2 and containing half the volume of modern Lake Michigan. Between 15,000 and 13,000 years ago, the ice dam was breached, releasing torrents of water downstream to create the Channeled Scablands in eastern Washington. Up to 40 cycles of damming and breaching have been reported, making an average life-span of a lake and consequent outburst flood of about every 50 years. The earliest Siber-Americans may have witnessed the fury of these gigantic glacial floods.

Other remarkable Ice Age floods are known to have occurred in the Cordillera as well. As pluvial Lake Bonneville received increasing amounts of water, lake levels ultimately reached their lowest rim and spilled into an adjacent basin. In this way, basin after basin was inundated with freshwater, such that ancient Lake Bonneville was composed of a series of interconnected, elongate arms. With each subsequent spillover, overall lake level would adjust accordingly and eventually the lake reached an elevation of 1591 m by about 15,500 years ago. This high-stand created the wave-cut Bonneville Bench along the Wasatch Front.

Lake levels remained constant until about 14,500 years ago when a low rim located at Red Rock Pass in present-day southern Idaho began to spill water from the gigantic lake. As the water flowed over the pass, it cut deeper into the rim and released ever increasing amounts of water. Erosion was swift and the lake catastrophically released thousands of cubic kms of water in the first few weeks, lowering its level by about 100 m within 1 year. As the water moved downstream it created a huge mega-flood that formed Shoshone Falls on the Snake River, incising into an old, Yellowstone hot spot lava flow. After the catastrophic release, the lake level stabilized to form the Provo Bench at an elevation of 1475 m along the Wasatch Front. The changing climate at the end of the Pleistocene caused the lake to dry out and today the Great Salt Lake is the final remnant of former Lake Bonneville at ±1280 m.

Not all Pleistocene events involve pluvials or ice. In western Grand Canyon two normal faults with down-to-the-west displacement suggest increasing encroachment of Basin and Range stress onto the Colorado Plateau. The Hurricane and Toroweap/Sevier faults have a combined displacement of 600 m and caused basaltic volcanism to flow to the surface in the Uinkaret Volcanic Field around 830,000 years ago. Most of the vents erupted on the north side of the Grand Canyon but some flows and vents were located within the canyon, already cut to near present depths. On at least 13 different occasions, lava dams were built across the channel of the river and dams as high as 700 m have been documented. One individual flow traveled no less than 125 km down the river corridor. Some dams may have been unstable to start but in at least five instances, cataclysmic outburst floods were released when the dams failed catastrophically, releasing huge volumes of water downstream, with deposits as much as 175 m above the river channel containing clasts up to 30 m in diameter.

13.4 The Pleistocene Along the Coast

Pleistocene features dominate coastal regions, even great distances from the nearest glacial deposit or ice-age lake. Two aspects stand out along the Coast Ranges from Washington to Baja – marine terraces and reddish-brown Pleistocene deposits, both marine and nonmarine (Fig. 13.9). There are several steps in forming marine terraces, although not all steps are always preserved. (1) Bedrock is planed off by wave erosion as coastal cliffs retreat. (2) Any combination of marine and nonmarine sediment forms and is dispersed across the bench. (3) The terrace is uplifted or sea level falls (or both) to form the elevated terrace and its deposits. In some cases, the sediment was never deposited or was eroded after the terrace was uplifted. In many cases, two or more terraces are present in the same stretch of coast. Perhaps the record is held by the 13 terraces on the Palos Verdes Peninsula southwest of Los Angeles – terraces are spaced between from 20 to 80 m apart. It should be an easy matter to use terraces to document previous sea level or times of uplift but this is not the case. In some cases, the elevation of a given terrace changes along the strike of the coast (warping of the terrace during uplift or topography formed when the terrace was created). Gaps between terraces along the coast may produce interesting results; for example, one terrace along a given stretch gives way to two or more terraces farther along the coast. How do they correlate and why is there one here and then two or more there? Careful studies can sometimes answer these questions by using preserved faunas (certain planktonic foraminifera evolved rapidly during the Pleistocene), radiometric dating, grain mineralogy, and other methods. One of the biggest hurdles is to separate tectonic changes in elevation from sea level changes. And, of course, younger terrace formation can obliterate older terraces.

Sea level changes can create other coastal features, among them elongate lagoons perpendicular to the coast (Fig. 13.10). Some of the best examples are in San Diego County between the La Jolla Peninsula and Oceanside. Pleistocene rivers were larger, carried more sediment, and were graded to positions offshore both farther west and at lower elevations than modern

Fig. 13.9 Marine terraces of the California coast. (**a**) A prominent terrace along the Big Sur Coast near Bixby Bridge. (**b**) Marine terrace at Point Loma clearly shows the various phases of formation. The sharp lower boundary on Cretaceous turbidites marks the original wave-cut bench. Cobbles and boulders mark initial Pleistocene deposits and are overlain by the typical fine-grained *red* Pleistocene deposits. The terrace surface is at the top. (**c**) Typical weathering of Pleistocene terrace deposit at Point Loma. (**d**) Pleistocene marine deposits bear clams and oysters in this exposure at N Ponto Beach at Carlsbad. The upper fluted deposits are probably nonmarine

Fig. 13.9 (continued)

rivers. The Pleistocene rivers, during a sea level low-stand, carved deep valleys through relatively soft Eocene rocks. When glaciers melted and sea level rose, the valleys flooded to form the lagoons. Modern sediment is now filling in the lagoons but many extend 5 km inland. Other coastal features formed by Pleistocene and Recent events include massive slumps and landslides, coastal tar seeps from petroleum-rich rocks, propagation of large sand shoals that protect coastal regions and form natural harbors (now commonly modified) such as the magnificent San Diego Harbor, and the incessant coastal erosion that is modifying the landscape as you read this, much of this through human carelessness (Fig. 13.11).

Members of the Lewis and Clark Expedition in the early nineteenth century were the first American citizens to visit the western Cordillera. Earlier Native and Spanish inhabitants pre-dated the Age of Enlightenment and so the first scientific impressions of the region can be known. In 1858, John Strong Newberry, was the first geologist to lay eyes on the Grand Canyon and his siren call about the nature of the great gorge beckoned even more of them. Soon, geologists were traversing the river, making surveys across the landscape and writing government reports about the riches and the beauty of the western Cordillera. Since their day, the stream of admirers has never stopped and likely never will.

Fig. 13.10 Batiquitos Lagoon at Carlsbad is the best studied coastal lagoon along the San Diego County coast. The valley that contains the lagoon was carved during a Pleistocene low stand and flooded when sea level rose. Sediments are currently filling the lagoon

Fig. 13.11 Pleistocene and Recent features along the California coast. (**a**) A massive landslide and slump at La Conchita near Santa Barbara has closed US 101 several times in recent years. The slide in 1995 destroyed several homes and several residents were killed. (**b**) Tar issues from a vent along the beach at Carpenteria near Santa Barbara. The petroleum is sourced from the organic-rich Monterey Formation. (**c**) San Diego Harbor, one of the world's great natural harbors (now "engineered") is created by a large mass of sand that forms a spit behind Point Loma, the peninsula in the foreground. (**d**, **e**) Coastal erosion above North Ponto Beach at Carlsbad. In December 2016, two houses at the point to the left of the smoke stack almost went into the Pacific during rain and high waves

Fig. 13.11 (continued)

Erratum to: Ancient Landscapes of Western North America

Erratum to:
R.C. Blakey, W.D. Ranney. (eds.), ***Ancient Landscapes of Western North America,***
https://doi.org/10.1007/978-3-319-59636-5

This book was inadvertently published with wrong spelling for name of the "Mt. Rainier" in caption of Fig. 12.3 of Chapter 12 and Fig. 13.2 of Chapter 13.

The wrong spelling used in the older version of the book: Mt. Ranier

The correct name for the mountain is: Mt. Rainier.

The error has been corrected and is reflected in both print and electronic versions.

The online version of the original chapters can be found under
http://dx.doi.org/10.1007/978-3-319-59636-5_12
http://dx.doi.org/10.1007/978-3-319-59636-5_13

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Epilogue

The North American Cordillera has evolved through an incredible amount of time. Most people are satisfied to appreciate the beauty that can be seen, touched and enjoyed today, lacking any desire to pursue its many and varied pasts. However, those who choose to see and experience it through geologic time have innumerable iconic landscapes to enjoy. Scenery as varied as equatorial seas, mountain chains, shorelines, Sahara-like deserts, rivers surrounded by tropical jungles with dinosaurs munching on leaves (or each other) – all of these happened and are recorded in rocks. Through time, more mountains, more rivers, more lakes, evolving drainages, the list goes on. For nearly 3.5 billion years, the Cordilleran landscape has been in the works and amazingly, the story is not yet complete. The plates still move and shift like a deck of cards shuffled over and over again. Our sun may have used only half of its fuel since its beginning and so many billions of years of Earth history still await future earth scientists.

Apparently, none of this history has been to known to any animal except the human species. We alone invented the tools that facilitated our evolution, transforming us from limb-swinging, leaf-eating tree dwellers, to the keepers of the fires on the ground, to hunters who cooked meat, and gatherers who planted seeds and settled down to water crops. Moving forward to probe the Earth's depths for carbon-based fuels like coal, oil and gas, allowed us to move faster, farther, higher, and deeper that any other creature had before. Along the way we stumbled quite unknowingly onto the fact that our planet holds evidence for its long and varied history. It is largely the lure of economic gain that has propelled this desire to understand Earth history. But as we were busy with developing markets and making profits, some were drawn to this story simply in awe of the changes it recorded. Who among us isn't amazed to learn of a tropical limestone (Wrangellia) poking out from an Alaskan glacier? Who isn't impressed by the impressions of palm fronds found in a Wyoming sandstone or the saber-toothed cats and Wooly mammoths pulled for the bottom of an urban tar pit? If you have made it this far in the book then you too are likely someone who has been touched by the story of Earth history.

Man is a voracious animal who has learned to dominate every environment found on the planet. At first, we did it to survive the hunger of the lion and then it was to provide some sense of predictability to our needs and wants. How ironic then that most of the uncertainty we still must contend with comes from the natural forces that have always been here shaping the landscape, and ourselves, in the process – explosive volcanism, unpredictable earthquakes, roaring tsunamis, and climatic changes that often resulted in extinction events. In the end, the only lesson possible is that we are a momentary backdrop to the long pageantry of Earth history. For sure, a noticeable and forceful backdrop, but one that nevertheless must simply get in line behind the list of species who have called this place home. Some of them are survivors, the vast majority are not.

Not everything need necessarily be doom and gloom for the human race. Our intelligence gives us the power to know the Earth through time, to see its varied pasts and know what may be our possible future. As we look backwards, we see where certain species became too specialized to survive a changing world and were brought face to face with their own extinction. Others were adaptable, lucky perhaps in an amenable environment, but survivors nonetheless.

What will become of the human species? Will we use our relatively newfound intelligence to better comprehend the past so that we can at least have a say in charting our future? Or will we simply rely on the old and simple coping mechanisms that brought us to this moment in time? Only time will tell. No matter how the human experiment with intelligence turns out, we can be assured that the ever evolving tectonic story of our planet will march on as if we were never here. For some of us this will be a bit unsettling. For others it comes as comforting.

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Glossary

Accommodation space Space in which sediment is deposited and preserved; created by some combination of subsidence and rise in base level (usually sea level).

Acidic Magma and magmatic rock with more than 65 weight-% SiO_2.

Active continental margin Continental margin with a subduction zone dipping beneath – destructive plate boundary.

Aeolian, eolian Environment or process of the wind, depositional setting of wind-blown dunes.

Alkali-feldspar Mineral, potassium-sodium feldspar; typically light colored.

Alkaline Term for magma or magmatic rock rich in alkalis (Na_2O, K_2O) with reference to the content of silica (SiO_2) or alumina (Al_2O_3).

Alkaline basalt Basalt with high content of alkalis (Na, K) and lower content of silica as compared to tholeiitic (oceanic) basalt; typically occurring in graben structures and above hot spots.

Alluvial (alluvium) General term applied to all deposits (but mostly rivers) formed by running water.

Alluvial fan Lobe-shaped landform and deposit at point where steep-gradient (mountain) streams become shallow gradient and deposit sediment.

Amphibole Mineral group similar to pyroxene but containing hydroxyl ions. An important member of this mineral group is hornblende.

Amphibolite Rock derived from basalt or gabbro by regional metamorphism; main mineral constituents are amphibole and plagioclase.

Amphibolite facies Medium- to high-grade regional metamorphism.

Anatexis Melting of rocks in continental crust during high-grade regional metamorphism.

Andesite Volcanic rock, typically formed above subduction zones; intermediate in composition.

Arch, upwarp, uplift Area that is uplifted relative to surrounding areas of subsidence; *cf.* basin.

Argillite Lithified or possibly slightly metamorphosed claystone or other fine-grained rock.

Arkose Sandstone rich in feldspar; commonly shed from granitic masses.

Asthenophere Shell of the upper mantle directly below the base of the lithosphere, mostly at depths between 100 and 250 km; contains low amounts of melt rock.

Basin and Range Geologic province west of Colorado Plateau and east of Sierra Nevada that was subjected to Tertiary faulting and consists of alternating mountain ranges and intervening basins.

Basalt Volcanic rock, very common on the ocean floor and in flood basalts on the continents. Basaltic magma evolves by partial melting of peridotite in the mantle.

Basement Metamorphic and igneous base on which a younger sedimentary cover sequence was deposited. The basement of Laurentia is Precambrian; the basement of the central and western Cordillera is Jurassic and Cretaceous.

Basic Magma and magmatic rock with 45–53 weight% SiO_2.

Batholith Large body of plutonic rock mainly composed of granodiorite and granite, typically occurring in the magmatic belt above subduction zones.

Blueschist High-pressure metamorphic rock formed in subduction zones. Contains glaucophane.

Blueschist facies Low-grade, high-pressure metamorphism.

Breccia Rock mainly composed of angular rock fragments. May evolve tectonically (fault breccia) or by sedimentary processes.

Brittle Rigid behavior of rock with fracturing during deformation (as opposed to ductile).

Calc-alkaline Magmas and magmatic rocks mainly formed above subduction zones.

Calc-alkaline basalt Basalt with substantial contents of calcium, alkalis, and aluminum. Typically formed above subduction zones.

Calcite Mineral, calcium carbonate. Main constituent of limestone and chalk.

California continental borderlands Unusual continental shelf off Southern California and Baja that averages 250 kms wide. Bedrock consists of major rock units of the California coast including areas of highly extended crust that formed when the Transverse Ranges rotated from Baja and drifted northward on the Pacific Plate; the partially subducted Farallon Plate forms the bedrock in extended areas.

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Carbonate (rock or sediment) Collective term for any rock or sediment composed of $CaCO_3$ or [Ca, Mg]CO_3; includes limestone and dolomite.

Chlorite Greenish mineral similar to mica.

Clastic sediment Sediment formed by transportation and deposition of mineral and rock fragments; most common rock types are sandstone, conglomerate, and mudstone (shale).

Claystone Clastic sedimentary rock composed of quartz and clay minerals with grain-sizes below 0.06 mm.

Coast range(s) Series of variable mountains ranges along US and Canadian coasts that range in widths from 10's to 100's of kms and heights from 100's to thousands of meters. Most were uplifted in late Cenozoic.

Collision General term for amalgamation or accretion of two or more rigid plates.

Conglomerate Sedimentary rock mainly composed of pebbles.

Contact metamorphism Metamorphism generated by the thermal aureole of intrusions.

Continental crust Outermost shell of the solid Earth, ca. 35 km thick in average and forming the continents and shelf areas. Average composition is andesitic with about 60 % SiO_2. Beneath mountain ranges thickness increases up to ca. 70 km.

Continental margin Zone at margin of continent; may be active or passive.

Core Innermost zone of the Earth below *ca.* 2,900 km depth, mainly composed of iron and nickel. The outer core is liquid, the inner core (below *ca.* 5,100 km) is solid.

Correlation (of rock units) Determination of age relations (time-rock stratigraphic) of rocks from place to place.

Craton (*Gr.* = strength) a large, stable block of the earth's crust that forms the nucleus of a continent.

Crust Outer, brittle layer of Earth; two major types --continental crust and oceanic crust.

Dacite Volcanic rock equivalent of granodiorite, hence, intermediate in composition between granite and diorite; typically formed above subduction zones.

Deep earthquake Earthquake with focus between 350 and 700 km depth.

Deep sea trench Depression at the margins of oceans with water depths up to 11 km. Indicates a convergent plate boundary where a subducting plate plunges down into the mantle.

Destructive plate boundary A plate boundary in which crust is destroyed – a subduction zone.

Diagenesis Compaction and alteration of sediments at temperatures below 200 °C (pre-stage to metamorphism).

Diapir Rising, mostly tube-shaped rock body of highly variable diameter. The ascent is a result of density inversion (less dense body under more dense body, In Cordilleran regions, a common diaper forms when serpentinite beneath oceanic crust rises.

Diatoms Siliceous algae.

Dike Magmatic rock body forming a mostly sub-vertical sheet, typically several decimeters or meters thick. Often feeder channel under a volcanic edifice.

Diorite Plutonic rock typically formed in the magmatic belt above subduction zones. Intermediate in composition and equivalent to andesite.

Dolomite *Mineral*, calcium-magnesium carbonate. *Rock,* carbonate rock composed of the mineral dolomite.

Ductile Plastic behavior of rock without fracturing during deformation.

Dune Large (> 30 cm high) sandy bedforms created by wind and running water.

Dunite Peridotite formed in the uppermost mantle directly below the oceanic crust.

Environment (depositional) Site where sediment is deposited; sum of all physical, chemical, and biologic processes at the site that act on sediment and produce sediment's characteristics.

Facies *Sedimentary facies* is the sum of characteristics of a sediment determined by its place and conditions of formation (e. g., marine facies, deep-water facies, sandy facies). *Metamorphic facies* reflects the pressure and temperature conditions during metamorphism.

Ephemeral Active only part of the time, usually applied to streams that flow infrequently.

Epicontinental sea Sea upon the continent, especially interior seas; Hudson Bay and North Sea are modern examples.

Erg Large areas of wind-blown sand (Arabic); sand seas.

Estuarine Of or pertaining to wide river mouths where marine processes penetrate into river mouth; used to describe setting, processes, and products.

Eustacy Of or pertaining to global sea level; changes in sea level of global, rather than local effect.

Evaporite Salt deposits formed by evaporation; gypsum, halite, and potash are common examples.

Extension Tectonic setting in which crust is being pulled apart.

Fault Displacement of two blocks along a fracture. *Normal fault*: Inclined fault plane with the hanging-wall block (block above the fault plane) moving downwards relative to the footwall block (expression of horizontal extension). *Reverse fault*: Hanging-wall block moving upwards relative to the footwall block (expression of horizontal compression). *Thrust fault*: reverse fault with a shallow-dipping fault plane (expression of strong horizontal contraction). *Strike-slip fault*: Horizontal movement of two blocks past each other along a steep-dipping fault; may be *dextral* (right-lateral) or *sinistral* (left-lateral).

Feldspar Most common mineral in the Earth's crust. Plagioclase (Na-Ca feldspar) and alkali-feldspar (K-Na feldspar) represent two different mineral sub-groups.

Flood basalt Huge sheets of flat-lying basalts formed above a hot spot. Horizontal layers of lava and vertical fissures cause a staircase-like morphology; also *termed trap* basalt (trappa, *Swedish* stairs). May cover areas more than 1,000,000 km^2.

Fluvial sediments Terrestrial sediments formed as river deposits.

Foraminifera Large group of protozoans.

Foliation Pattern in metamorphic rocks whereby minerals align parallel to each other; allows geologists to infer direction of forces that produced metamorphism.

Foreland basin (foredeep) Basin formed adjacent to stacked thrust sheets; thrust sheets bend adjacent crust downwards causing subsidence.

Formation Formal rock-stratigraphic term; any mappable rock body that can be separated from any adjacent rock body; in areas where formal rock stratigraphy has been established, all rocks must be assigned to one or more formations.

Gabbro Plutonic rock, coarse grained equivalent to basalt. Most abundant rock in oceanic crust.

Garnet Mineral group widely occurring in metamorphic rocks. The exact composition of garnet is indicative of pressure and temperature conditions during metamorphism.

Geothermal gradient Increase of temperature with depth. In continental crust, normally *ca.* 30 °C/km.

Glass/volcanic glass Fine-grained, non-crystalline material that cools rapidly after ejection from volcano.

Glaucophane bluish-violet mineral of the → amphibole group formed under → high-pressure metamorphic conditions; yields color to blueschists.

Gneiss High-grade metamorphic rock rich in quartz, feldspar, and mica, derived from either sedimentary or magmatic (mostly granitic) rocks.

Graben, graben structure Elongate low-lying, surficial structure characterized by a central downthrown block along its axis and uplifted shoulders. Forms by crustal extension. Synonym: *Rift.*

Graded bedding Sedimentary layer with decreasing grain size towards the top. Forms from waning flows; thick, repetitive sequences of graded bedding characterize turbidity deposits.

Granite Most common plutonic rock, coarse-grained equivalent to rhyolite.

Granodiorite Plutonic rock similar to granite but with less quartz content; most abundant rock type in most batholiths.

Granulite facies high-grade regional metamorphism (without melting).

Graywacke Sandstone containing substantial amounts of feldspar and rock fragments along with quartz; commonly with mud-rich matrix.

Greenschist Rock formed in low-grade regional metamorphism from basalt and gabbro; green mineral chlorite provides the color.

Greenschist facies Low-grade regional metamorphism.

Heat flow Amount of heat passing through a boundary layer, (e.g., the Earth's surface); unit of heat per square meter.

Hingeline Linear zone that marks sharp change in subsidence rate of sedimentary basin; separates thin strata from thick strata.

High-alumina basalt Basalt rich in aluminum (Al_2O_3 >16 weight-%), and typical of subduction zones (same as calc-alkaline basalt).

High-pressure metamorphism Metamorphism typical of subduction zones in which material on the subducted plate is subjected to high pressure but low temperatures.

Horst Elevated block between two grabens; typified by *ranges* in Basin and Range.

Hot spot Zone on the surface of Earth under which a mantle diapir rises; heat from diaper causes volcanism at the surface *e.g.* Hawaii.

Hydrothermal activity Hot water circulating in cracks and pores of rocks.

Intermediate composition Magma and magmatic rock with 53–65 weight-% SiO_2; diorite and andesite are intermediate rocks.

Intertonguing (of rock layers) Alternation of contrasting lithologies where one lithology pinches out into contrasting lithology; caused by shifting back and forth of depositional settings with contrasting lithology.

Intrusion Magma penetrates older rocks and crystallizes at depth – stocks (small) and batholiths (large) are examples.

Island arc Arcuate (in map view) chain of volcanic islands above subduction zones; applied to this tectonic setting whether arcuate or not.

Laccolith Pancake-like igneous intrusion that domes up or pushes apart sedimentary rocks that it intrudes; usually fed by central plug or stock.

Lacustrine General term referring to lakes and their deposits.

Lava molten magma that reaches surface (and commonly spreads) before solidifying.

Limestone Sedimentary rock mainly composed of calcite and mainly formed by the accumulation of shells and skeletal particles of organisms.

Lithified Cemented; to become a rock; hardened.

Lithology literally rock type; common field term include sandstone, limestone, mudstone, granite, schist, etc.

Lithosphere Outer solid shell of rock that comprises the plates; encompasses the *crust* (continental or oceanic) and the *lithospheric mantle*. Thickness ranges between 70 and 150 km; locally up to 200 km beneath mountain ranges.

Magma Rock melt.

Magmatic rock Plutonic and volcanic rock formed by cooling from a melt.

Mantle Shell of the Earth between crust and core. The boundary between upper and lower mantle is at a depth of *ca.* 660 km.

Marine sediment Sediment deposited in the ocean or sea (with normal marine salinity: – 3.5 %).

Mélange *(Fr* = mixture, to mix) Mixture of different rocks formed by sedimentary or tectonic processes. Characterized by a block-in-matrix structure: more rigid rock types form blocks in a matrix of softer and strongly deformed rock. The blocks can range in size to kilometers. Most melanges from in subduction zones.

Metamorphic core complex/metamorphic dome Dome-shaped bulge of highly metamorphosed rocks (exposed lower plate) formed by substantial crustal extension.

Metamorphism The process of change in rocks caused by heat and/or pressure; texture and/or mineralogy are changed from original rock.

Microcontinent General term applied to small block or part of a plate that consists of continental crust; a continental block of small proportions.

Mid-ocean ridge Elongate ridges in ocean crust where new oceanic lithosphere is formed; Constructive plate boundary.

Moho Boundary layer between crust and mantle.

Monocline Fold typical of Colorado Plateau with a single steep limb; in theory a steplike bend that separates uplifted and down-dropped horizontal strata, but more commonly the steep flank of an asymmetrical anticline-syncline pair.

Monsoon Climate pattern in which summer months generate more precipitation than winter months; SE Asia is typical example.

Mud A general sediment term for any mixture of *silt and clay* (all particles finer than *sand*).

Mylonite Strongly deformed and recrystallized rock formed in a shear zone; deformation occurs in a ductile (plastic) manner.

Obduction Opposite to process to subduction. Material scraped off subducted plate onto overriding plate; typical of how ophiolites are formed.

Oceanic crust Outermost shell of the solid Earth forming the ocean floors. Average thickness 6–8 km. The composition of the oceanic crust is basaltic/gabbroic (*ca.* 50 % SiO_2).

Oceanic plateau Submarine plateaus with thickened oceanic crust standing above the abyssal plains. Common origins: hotspots, inactive mid-ocean ridges, inactive arcs, small rifted continental blocks.

Ophiolite Rock association of the oceanic lithosphere tectonically emplaced on continents by *obduction* or suturing between colliding continental blocks.

Orogen Mountain range – *the product* – formed by tectonic processes associated with active plate margins.

Orogen/orogenesis The *processes* of forming an orogen.

Paleocurrent Some indicator in sedimentary rock such as cross bedding that yields ancient flow direction.

Paleogeograhy Literally “ancient geography”; refers to how Earth looked in the past.

Palinspastic (restoration) A technique used to progressively undeform a geological map or cross section in an attempt to reconstruct the position of various blocks to a state before a given tectonic event(s); an interpretation (model) is used to build the restoration – an attempt to reconstruct the geometry of earlier stages of the geological development of an area. The maps in this book use reconstructions suggested in the geologic literature – thus, the maps are palinspasticly restored.

Pangaea Supercontinent present in the Late Paleozoic and Early Mesozoic (*ca.* 300–170 Ma).

Panthalassa Large ocean opposing Pangaea.

Passive continental margin Continental margin inwhich the continental crust is connected to the adjacent oceanic crust. *Does not represent a plate boundary*.

Pelagic sediment Sediment formed in the open ocean without much/any continental sediment input.

Peridotite Major rock type in Earth’s mantle; mainly composed of olivine and pyroxene (ultrabasic rock).

Period Formal subdivision of geologic time, usually with a duration from 30–60 million years. Most widely used division of geologic time; *cf.* system.

Pillow lava Basaltic lava with bulbous (pillow-like) structures formed during interaction of lava and seawater (subaqueous lava).

Plagioclase Sodium-calcium feldspar.

Plate Part of the rigid outer shell of the solid Earth, consisting of crust (oceanic and/or continental) and the lithospheric mantle. Plates move as a unit and interact with other plates at active plate boundaries; most present plates contain both continental and ocean crust in various proportions.

Plate boundary types *Constructive* (divergent) plate boundary – plate boundary along which new oceanic lithosphere is formed at mid-oceanic ridge. *Destructive* (convergent) plate boundary – plate boundary along which one plate subducts beneath the other at subduction zone. *Conservative* plate boundary: Plate boundary along which plates slide past each other at transform fault.

Pluton/plutonic rock Body of intrusive igneous rock, usually coarse-grained due to slow cooling; solidified magma chamber.

Protolith Parent rock – used in context of metamorphic rocks and refers to what rock-type was before metamorphism.

Quartzite Metamorphic rock derived from sandstone, mainly composed of quartz.

Radiometric age determination Dating of minerals and rocks using the decay of radioactive isotopes *(e. g.,* uranium-lead method).

Regional metamorphism Metamorphism affecting large crustal bodies; formed in the magmatic belt above subduction zones and/or during mountain building processes.

Regression Seaward shift of the coastline due to sea-level drop or uplift of the shelf area.

Rhyolite Volcanic rock rich in silica (SiO_2). Equivalent to granite.

Rift/rifting splitting or pulling apart of continents or ocean basins so that extension of crust occurs; usually accompanied by normal faulting and graben formation; extensive rifting results in new plate formation – a rift separates one plate into two.

Rodinia Supercontinent present in Late Precambrian that contained most all continental material of the time.

Salt *Sedimentary rock* formed by evaporation of saline water; *mineral* formed by evaporation.

Sandstone Clastic sedimentary rock originating from sand (grain size 0.06–2 mm). Quartz is typically the predominat constituent.

Sea-floor spreading As new crust forms and cools at mid-ocean ridge, older cooled crust spreads apart.

Seamount Submarine volcano, commonly arranged in chains that formed above hot spots.

Sedimentary basin A low area where sediments accumulate and are preserved; because basins subside through geologic time, they are characterized by thick sedimentary deposits relative to surrounding regions.

Serpentine Metamorphic *mineral* transformed from olivine or pyroxene by absorption of water; commonly associated with subduction zones.

Serpentinite Metamorphic *rock* mainly composed of serpentine.

Shelf, platform A broad low area generally at or slightly below sea level; the site of broad, thin (compared to basins) sedimentary deposits of marine and shoreline origin.

Sial Acronym (silicium and aluminum) coined by Alfred Wegener to characterize continental crust.

Siliciclastic (rock or sediment) A clastic deposit (grains can be any size) containing silica-bearing minerals, most commonly quartz, feldspar, or clays; *cf.* carbonate.

Sill Magmatic rock body forming a subhorizontal sheet that follows bedding plane; typically several decimeters or meters thick and at shallow depth.

Siltstone Fine-grained sedimentary rock with grain size between 0.002 and 0.06 mm. Main constituents are quartz and clay minerals.

Sima Acronym (silica and magnesium) coined by Alfred Wegener to characterize oceanic crust and mantle.

Slab breakoff Breakaway of the subducted oceanic part of a lithospheric plate after continent-continent or arc-continent collision. Process causes isostatic uplift of a mountain range in response to loss of part of lithosphere.

Stratigraphic (stratigraphy) Of or pertaining to the study and classification of stratified rocks.

Stratovolcano Volcano with steep slopes (up to 40° inclination) and alternating layers of lava and volcanic ash.

Strike-slip fault See transform fault.

Subduction Process in which oceanic lithospheric plates sink into the depths of the upper mantle at convergent plate boundaries.

Subduction zone The sum of features that characterize convergent plate boundaries; major components are trench, forearc, and magmatic arc.

Subsidence Sinking of an area through geologic time; opposite of uplift or mountain building, although the two commonly occur together.

Suspension Sedimentary process in which particles settle out of water (or air in volcanic eruptions), largest particles first. *Graded bedding* results if there is a range in original grain size. Common as upper portion of individual turbidity flow; *pure or hemi-pelagic* suspension occurs when mud (from shore) or dust (from wind) settles into quiet water. Most suspension deposits are *mud-rich*.

Supercontinent Assembly of several continents by collisional orogenic events; commonly contain all or most of continents at given time. Pangaea and Rodinia are examples.

Suture, suture zone Elongate belt along which colliding continents and/or terranes were welded together during collision/accretion; zones are typically marked by highly deformed rock, metamorphic zones, plutons, and ophiolites.

System (time-rock) Time-rock equivalent of period; system is used when referring to rocks of a given time whereas period is used when only time is being discussed. Time occurred whether or not rocks were formed to record geologic history, hence, the reason to differentiate the two terms.

Tectonics Of or pertaining to large-scale structures of the lithosphere; as stress acts on rock bodies, they reaction by movement and deformation (strain). Deformation can be ductile or brittle and acts in all dimensions from sub-microscopic scale to plate scale (*plate tectonics*); especially applied to study of large-scale structures through geologic time.

Terrane A substantial block of rock – a crustal block – that is bounded by faults and usually contrasts with surrounding rock bodies. Terranes can be far-traveled blocks accreted to a continent – commonly called exotic terranes; or terranes can be displaced to another portion of the same continent.

Terrestrial sediment Sediment deposited on land. Major terrestrial settings are *fluvial* (river), *lacustrine* (lake), and *eolian* (wind deposits).

Terrigenous sediment *Clastic* sediment composed of fragments derived from a continent or island (land) and generally transported into the ocean or large lake by rivers or wind. *Chemical* and *biological* processes occur within the ocean or lake and are the *opposite* of terrigenous.

Thrust A fault in which one block of rock is pushed over another at a low angle. Usually older rocks are pushed over younger rocks. Thrust faults are indicative of compressive forces.

Thrust belt A large area dominated by thrusting (and folding), commonly continental in length and several hundred kms wide.

Tilted block Block usually associated with *normal faulting*. Because normal faults tend to progress from near vertical at the surface to inclined or even flat at depth, blocks commonly rotate (slide down and tilt backwards as the fault changes dip). Some tilted blocks have significant horizontal displacement. Such large dis tilted by normal displacement along the → fault.

Time An interval or episode in which something occurs; deep time refers to geologic time scales to differentiate from human concepts/lengths of time.

Time transgressive Refers to geologic process that requires amounts of geologic time to move across a region; mountain building (orogeny) and transgression-regression are examples.

Traction Sedimentary processes in which the flow of the current (shear stress) moves particles that are mostly in contact with the bed (bottom). Usually produces ripple bedding, cross bedding, or distinctive horizontal bedding – traction affects san- and gravel-sized particles.

Transform (strike-slip) fault A vertical fault in which there is significant horizontal movement – the blocks or plates slide past each other horizontally. A transform boundary is *a conservative plate boundar*y. The largest transform faults connect offsets in mid-ocean ridges and are commonly over a thousand kms in length; such faults commonly continue into continents and cause major horizontal displacement (measured in hundreds of kms. *e. g*. San Andreas Fault).

Transgression Continent-ward shift of the coastline due to sea-level rise or subsidence of the coastal area; opposite *regression*.

Trap(p) basalt Large-scale flood basalt; commonly covering hundreds of thousands $kms^{2.}$

Turbidity current Suspension of sediment caused when a denser body laden with sediment enters a less dense body of water; the generated *tubidity current* moves sediment laterally by complex processes of *suspension* and *traction*, commonly into deep water typically gliding down a submarine slope. Common at continental margins of all types. The deposited layer typically shows *graded bedding* and can form deposits hundreds of kms in length and thousands of meters thick. One of the more common sedimentary deposits (*turbidite*) in the North American Cordillera.

Tuff Deposit of volcanic ash (mostly *dust-sized* particles); *Welded tuff* forms when hot volcanic ash fuses to form rock.

Ultrabasic Refers to magma and magmatic rock with less than 45 weight-% SiO_2.

Unconformity A surface or bedding plain in layered rocks that represents significant geologic time without a rock-sediment record.

Uniformitarianism A geologic doctrine that states that processes and physical laws have a consistency or uniformity over large amounts of time; sometimes misused to state that conditions remain the same through geologic time, which is incorrect. Geologists paraphrase uniformitarianism as "the present is the key to the past". Although uniformitarianism is widely upheld by modern geologist, we also know that the doctrine must be applied with restraint!

Viscosity A measurement of the ease at which a fluid flows; low viscosity yields large area of dispersal with respect to volume whereas a viscous flow is less dispersed. With respect to magmas, basaltic flows have low viscosity and acidic magmas have high viscosity.

Volcanic arc A magmatic zone that tends to be linear and arcuate; parallel to and generated by *subduction zones*; the arc is always on the *upper plate* of the subduction zone.

Volcanic glass Rock that is composed of non-crystalline material; formed from a melt by rapid chilling (often in contact with water). The atoms are not arranged in a lattice as are crystals.

Volcanic rock Magmatic rock composed of lava, lapilli (cinders – 2-64 mm in diameter), and/or tuff <2 mm) that formed at the Earth's surface (subaerial or submarine).

Western interior General region of Western North America inland from the coast that usually includes the Rocky Mountains (US and Canada), Colorado Plateau (US), part or all of the Basin and Range (US and Mexico), and westernmost High Plains (US and Canada).

Window (*sensu* tectonic) An exposure, framed by the upper plate and usually caused by erosion, in which the lower plate is visible at the surface (often referred to as *fenster*, the *German* equivalent). Windows provide important views of rocks otherwise covered by a younger plate.

Zircon Mineral, zirconium silicate. Zircon is an extremely durable mineral and maintains its age of crystallization through repeated cycles of erosion and metamorphism. Forms the basis of the important field of study detrital zircon analysis. The sedimentary rock that contains the detrital zircon can be no older than the enclosed zircon.

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Index

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