22.1 THE NORTH AMERICAN CORDILLERA—An essay by Elizabeth L. Miller[1]

22.1.1 Introduction

The broad mountainous region of western North America is known as the **"Cordillera,"**[2] an orogenic belt that extends from South America (the Andean Cordillera) into Canada (Canadian Cordillera) and Alaska (Figure 22.1.1). The youthful topography of this impressive mountain belt is closely related to ongoing crustal deformation, as indicated by the distribution of seismicity across the width of the orogenic belt (Figure 22.1). The present plate tectonic setting and the dominant style of deformation vary along strike of the orogen: folding and faulting above an active subduction zone in the Pacific Northwest of the United States and Alaska; strike-slip or transform motion along the Queen Charlotte Fault (Canada) and San Andreas Fault (California); and extension and rifting in the Basin and Range Province of the western United States and Mexico's Gulf of California. Variations in structural style are also apparent across the orogen; for example, crustal shortening and strike-slip faulting in coastal California are concurrent with crustal extension and basaltic volcanism in the adjacent, and inboard, Basin and Range Province. This diversity in plate tectonic setting and structural style of the Cordillera along and across strike, likely characterized the past history of the orogenic belt, which has been shaped primarily by Pacific–North America plate interactions. The continuity of such interactions since the Late Precambrian makes it the longest-lived orogenic belt known on Earth.

The Cordillera provides an excellent natural laboratory for studying the evolution of a long-lived active margin and the effects of subduction and plate boundary processes on the evolution of continental crust. However, the exact nature of the relationship between plate motions and continental deformation, whether mountain building or crustal extension, remains a complex question for the following reasons. The theory of plate tectonics treats the Earth's lithosphere as a series of rigid plates that move with respect to one another along relatively discrete boundaries. This simplification applies well to oceanic lithosphere, which is dense and strong and thus capable of transmitting stresses across great distances without undergoing significant internal deformation. However, it does not apply well to continents, whose more quartzo-feldspathic composition and greater radiogenic heat flow make them inherently weaker. Displacements or strain within continental crust can accumulate at plate tectonic rates (1–15 cm/y) within narrow zones of deformation, or can take place more slowly (millimeters to centimeters per year) across broad zones of distributed deformation. Thus continents can accumulate large strains, thickening over broad distances during crustal shortening, and thinning during extension. Evidence for these strain histories are at least partially preserved in the geologic record because the inherent buoyancy of continental material prevents it from being subducted into the mantle. Mantle-derived magmatism can lead to greater strain accumulation within continental crust by increasing temperatures and thus rheologically weakening the crust, allowing it to deform in a semicontinuous fashion. Because of these considerations regarding the thermal structure, composition, thickness, and rheology of continental crust, the response of the overriding continental plate to changes in subducting plate motion or to changes in the nature of plate interactions along a margin may be sluggish and may vary with time and depth in a complex fashion.

Thus, orogenic belts like the Cordillera may be at best imperfect recorders of past plate motions. Our understanding of the link between plate tectonics and continental deformation is evolving as more detailed geologic and geochronologic studies are carried out,

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[2]Spanish for mountain or mountain chain.

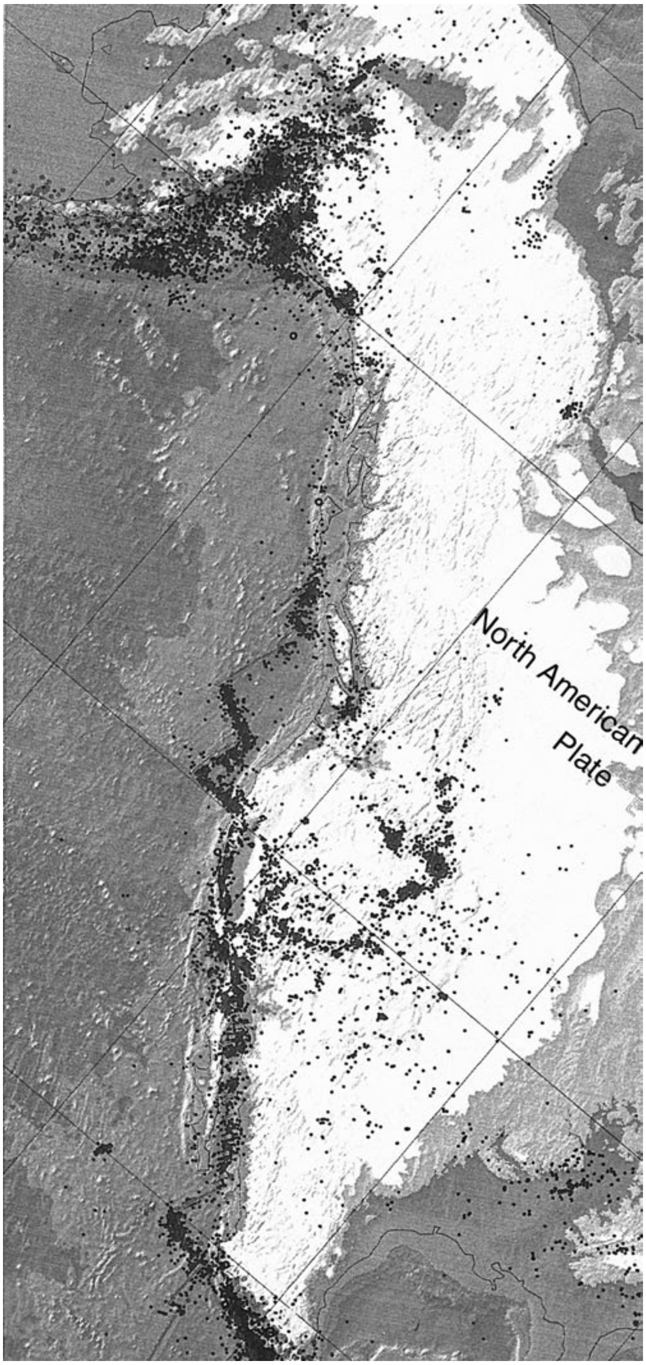


FIGURE 22.1.1 Digital topography, plate tectonic setting and seismicity map of the North American Cordillera.

providing quantitative information on the timescale of events and the rates of geologic processes, and increasing our ability to compare the timing of events from one part of the belt to the next. Geophysical and petrologic studies remain key tools that help us to understand how physical processes in the deeper crust and mantle are coupled to more easily studied deformation at shallower levels of the crust.

22.1.2 Precambrian and Paleozoic History

Studies of modern active plate margins have played an important role in interpreting the more fragmentary geologic record of analogous events in the North American Cordillera (Figure 22.1.2). Based on these comparisons, it appears that all plate tectonic styles and structural regimes known on earth, with the exception of continent-continent collision (like the Himalaya), played a part in the creation and evolution of the North American Cordillera. The initial formation of the Cordilleran margin dates back to the latest Precambrian. The Windemere Supergroup is a thick succession of shelf-facies clastic rocks deposited between about 730 Ma and 550 Ma, its facies and isopachs define the newly rifted margin of western North America after the breakup of the Rodinia supercontinent. The Windemere Supergroup forms the lower part of a 15-km thick, dominantly carbonate shelf succession whose isopachs and facies boundaries closely parallel the trend of the Cordillera and are remarkably similar along the length of the Cordillera from Mexico to Alaska. This shelf sequence (including the older and more localized Belt-Purcell Supergroup) is now spectacularly exposed in the eastern Cordilleran fold-and-thrust belt, whose overall geometry and structure are controlled by the facies and thickness of this succession.

The Paleozoic history of the Cordillera has generally been described as one of continued passive margin sedimentation and little active tectonism. However, embedded in the western Cordillera are a multitude of tectonic fragments of island arcs and backarc basin sequences that range in age from Cambrian to Triassic (Figure 22.1.2). The common conception that these represent a collage of far-traveled terranes exotic to the Cordillera ("suspect terranes") is being reevaluated as a result of numerous studies that indicate many of these sequences developed adjacent to, but offshore of, the western edge of the continental margin. Although these "exotic" fragments are likely displaced from their site of origin by rifting, thrusting, and strike-slip faulting, their presence nonetheless argues convincingly for a long history of subduction of paleo-Pacific crust beneath the western edge of the North American plate. Study of these accreted fragments suggests that during the Paleozoic, western North America looked much like the Southwest Pacific today, with its fringing arcs separated from the main Australasian continental shelves by backarc basins. During the Paleozoic, the North American shelf itself experienced episodes of regional subsidence and uplift, but no sig-

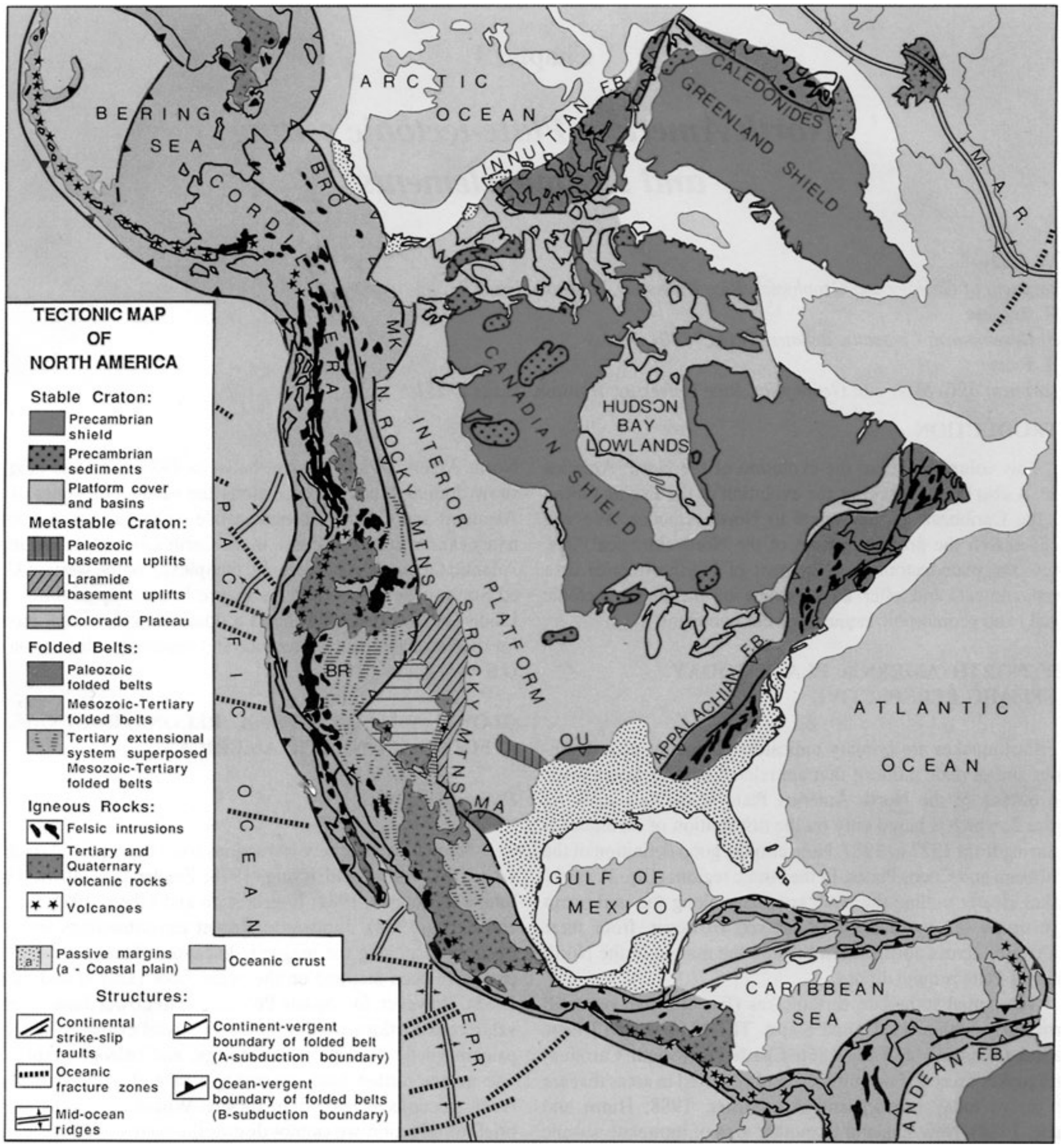


FIGURE 22.1.2 Simplified geologic/tectonic features map of North America. BR = Basin and Range Province; BRO = Brooks Range, MK = Mackenzie Mountains, MA = Marathon Uplift, OU = Ouachita Mountains, M.A.R. = Mid-Atlantic Ridge, E.P.R. = East Pacific Rise; F.B. = fold belt.

nificant deformation. Exceptions include deformation and intrusion of latest Proterozoic to Late Devonian granites along parts of the margin in Alaska and southern British Columbia, and the closure of deep-water, backarc basins by thrusting onto the shelf during the earliest Mississippian Antler Orogeny (Roberts Mountains Thrust) and during the Permo-Triassic Sonoma Orogeny (Golconda Thrust) in the western U.S. part of the Cordillera.

22.1.3 Mesozoic History

Magmatic belts related to eastward subduction beneath western North America are much better developed beginning in the Mesozoic (Figure 22.1.2). Arc magmatism of Triassic and Early Jurassic age (230–180Ma) is recorded by thick sequences of mafic to intermediate volcanic rock erupted in an island arc (Alaska, Canada, and the northern part of the U.S.) or continental arc (southwestern U.S.) setting. Tectonism accompanying subduction during this time-span was generally extensional in nature, leading to rifting and subsidence of parts of the arc and continental margin. The Middle to Late Jurassic brought a dramatic change in the nature of active tectonism along the entire length of the Cordilleran margin. This time-span is characterized by increased plutonism during the interval 180–150 Ma and many hundreds of kilometers of crustal shortening. This shortening closed intra-arc and backarc basins, accreted arc systems to the North

American continent, and fundamentally changed the paleogeography of the Cordillera from a southwest Pacific–style margin to an Andean-style margin, a tectonic framework that persisted throughout most of the latest Mesozoic and Cenozoic. The preferred explanation for this orogeny is that it is linked to rapid westward motion of North America with respect to a fixed hot-spot reference frame (Figure 22.1.3). This westward motion occurred as the North Atlantic began to open and, in effect, caused the western margin of the continent to collide with its own arc(s) and subduction zone(s) and then to deform internally. Deformation associated with Middle Jurassic orogenesis (sometimes referred to as the Columbian Orogeny) began first in the region of elevated heat flow within and behind the arc, and migrated eastward with time towards the continental interior.

In the Cretaceous, we have a better record of the nature of Pacific Plate motions with respect to North America (in large part from magnetic anomalies on the ocean floor) and it is possible to draw some inferences about the link between orogenic and magmatic events and the history of subduction beneath the active margin. There is a general lull in deformation and a lack of evidence for significant magmatism during the time interval 150–120 Ma, which possibly corresponds to a time of dominantly strike-slip motion along the Cordilleran margin (Figure 22.1.3). Particularly rapid rates of orthogonal subduction of the Farallon and Kula Plates occurred in the later part of the Cretaceous and Early Tertiary, resulting in the emplacement of major batholiths inboard of continental margin subduction zone complexes. Depending on the configuration of subducting oceanic plates, large components of margin-parallel strike-slip faulting are also implied. How much, where, and along what faults this motion was accomplished are still controversial questions. In the western United States, the emplacement of the composite Cretaceous Sierra Nevada batholith occurred (Figure 22.1.2). On the western (forearc) side of the batholith, depressed geotherms caused by the rapidly subducting slab led to high pressure–low temperature (blueschist) metamorphism within rocks now represented by the Franciscan Complex. The intervening Great Valley Basin underwent a similar history of "refrigeration" during rapid subduction. Sediments deposited in this basin were buried as deep as 10 km, but the section reached temperatures of only about 100°C, suggesting thermal gradients of 10°C/km or less. In contrast, heat flow in the arc and backarc region to the east was high and accompanied by major shortening; the latter migrated eastward with time and resulted in the well-known Sevier foreland fold-and-thrust belt (Figure 22.1.4). At any given latitude, there are typically a series of major thrusts that displace stratified Paleozoic-Mesozoic shelf sediments eastward, with a minimum total displacement of 100–200 km. Along most of its length, the eastern front of the thrust belt closely follows the transition from thin cratonic to thicker shelf sequences, indicating important stratigraphic influence on the structures produced. Deeper parts of the crust between the thrust belt and the magmatic arc were hot and mobile and underwent thickening by folding and ductile flow (Figure 22.1.4). Crustal thickening in turn precipitated crustal melting, now represented by a belt of unusual muscovite-bearing granites that lie just west of the main thrust belt (Figure 22.1.4). Because the orogen at this latitude was later reworked by Cenozoic extension and its crust thinned, the amount of crustal thickening during the Mesozoic is still controversial. Was the western United States, at the end of the Cretaceous like the Tibetan Plateau or Andean Altiplano, underlain by 70–80-km thick crust? Or was crustal thickening more modest as evidenced by the ~50 km thick crustal root beneath the unextended Canadian Cordillera today?

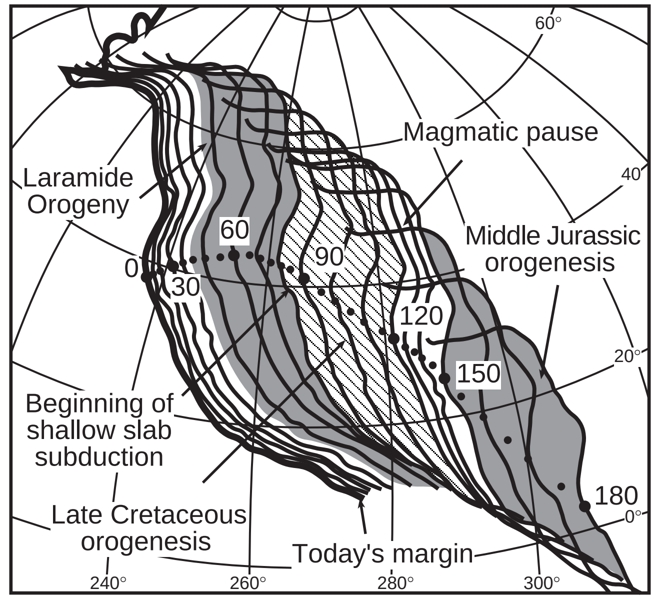
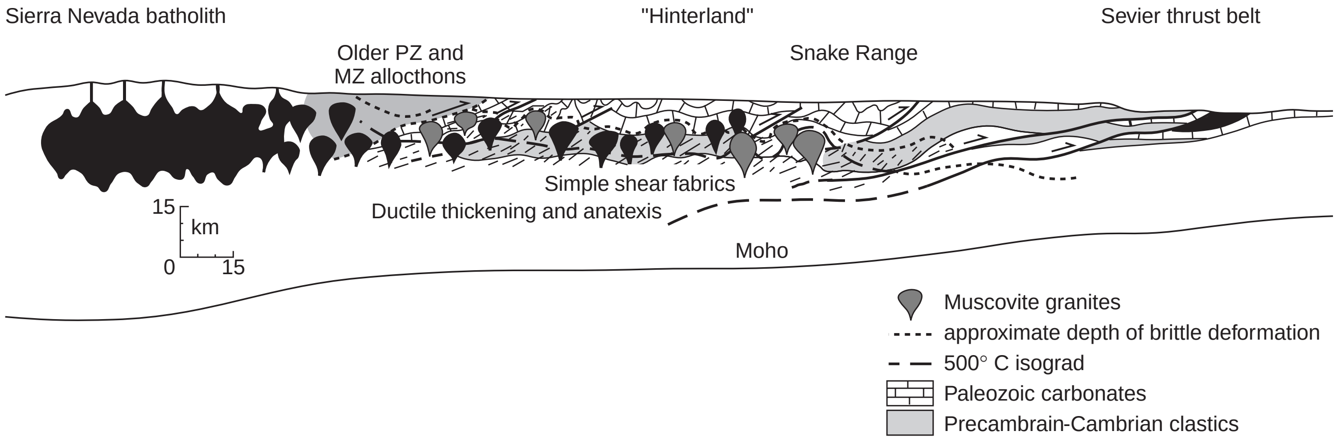


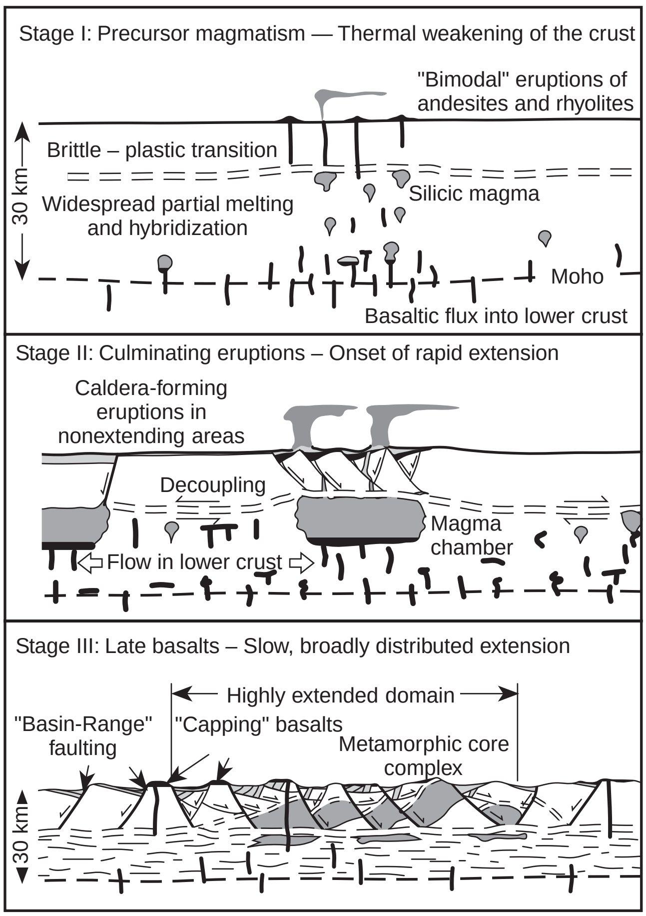
FIGURE 22.1.3 Correlation of deformational events and motion of the west coast of North America with respect to hot spots from the Late Jurassic to the Cenozoic.

22.1.4 Cenozoic History

After the latest Cretaceous, the history of the western U.S. segment of the Cordillera differs substantially from its neighboring segments to the north and south, where subduction driven arc magmatism and crustal



(a)



(b)

FIGURE 22.1.4 (a) Schematic crustal cross section of the western United States at the end of Mesozoic subduction-related arc magmatism and backarc crustal thickening. (b) Schematic sequence of superimposed Cenozoic Basin and Range extension-related events leading to the present (mostly young) crustal structure of the orogenic belt.

shortening continued uninterrupted into the Early to Middle Tertiary (Figure 22.1.5b). Magmatism in the western U.S. portion of the belt shut off abruptly at about 80 Ma, although subduction continued and, in fact, accelerated, achieving convergence rates of ~15cm/y. These north-to-south differences have been attributed to segmentation of the subducting slab, in which there was an extremely shallow angle of subduction beneath the U.S. portion of the belt. This hypothesis is supported by evidence for rapid cooling of the Sierra Nevada batholith as it moved into a forearc position. As the crust of the arc and backarc was “refrigerated,” it regained its rheologic strength and was thus able to transmit stresses for greater distances. During this time, deformation stepped far inboard to Utah, Colorado, and Wyoming, where crustal-penetrating reverse faults caused uplift of the Rocky Mountains during the latest Cretaceous to Eocene Laramide Orogeny (Figure 22.1.5b). Their uplift was contemporaneous with continued shortening in the foreland thrust belt in Arizona and Mexico to the south, and in Montana and British Columbia to the north (Figure 21.1.5b).

Plate motions between the oceanic Kula and Farallon Plates and North America changed again at the end of the Paleocene, and the component of orthogonal convergence diminished rapidly (Figure 22.1.3). In the western United States, it is hypothesized that the shallowly dipping slab either fell away into the mantle or gradually “decomposed” due to conductive heating. Decompression melting of upwelling asthenospheric mantle into the previous region of the slab generated basalts that heated the base of the thickened continental crust, a process that caused extensive assimilation and melting of crustal rocks. This magma mixing ultimately led to eruption of large volumes of intermediate to silicic volcanic rocks (Figure 22.1.5c). Volcanism migrated progressively into the area of previously

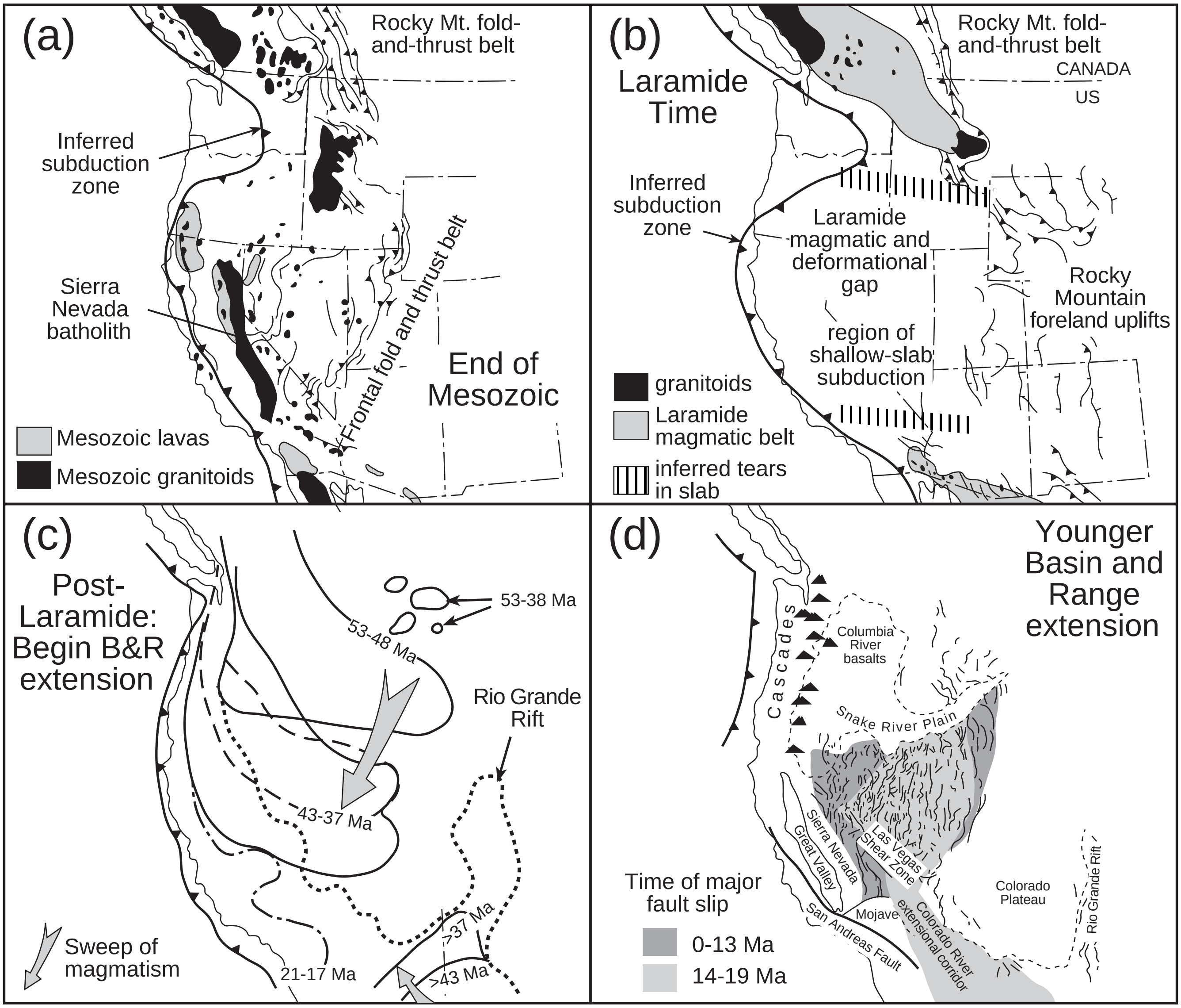


FIGURE 22.1.5 Summary of events leading up to the formation of the Basin and Range Province of the western United States.

flat slab subduction, both southeastwards from the Pacific northwest and northwards from Mexico. The large input of heat into the thick crust rheologically weakened it, and by Miocene time (about 21 Ma), when the slab finally fell away, this heat input triggered wholesale extensional collapse of much of the western United States, resulting in the formation of the present Basin and Range Province (Figure 22.1.5d). This broad zone of continental extension wraps around the southern end of the unextended but (thermally) elevated Colorado Plateau and projects as a finger northwards along the Rio Grande Rift on the eastern side of the plateau. To the west of the Basin and Range Province lies the unextended Sierra Nevada crustal block, with its thicker crustal root, and the virtually undeformed Great Valley sequence, underlain in part by oceanic crust refrigerated during the Mesozoic (Figure 22.1.5d). Volcanism and seismicity are diffuse across this broad zone of continental extension, and thermal springs abound. One of the most impressive physiographic features related to young volcanism is the depression of the Snake River plain, which is believed to represent the Miocene to Recent track of a mantle hot spot that now resides beneath Yellowstone National Park. The present Basin and Range Province, together with associated extension in the Rio Grande Rift and north of the Snake River plain, reflects ~200–300 km of east-west extension that began in the Early to Middle Tertiary and continues today. The modern, regularly spaced basin-and-range physiogeography that lends

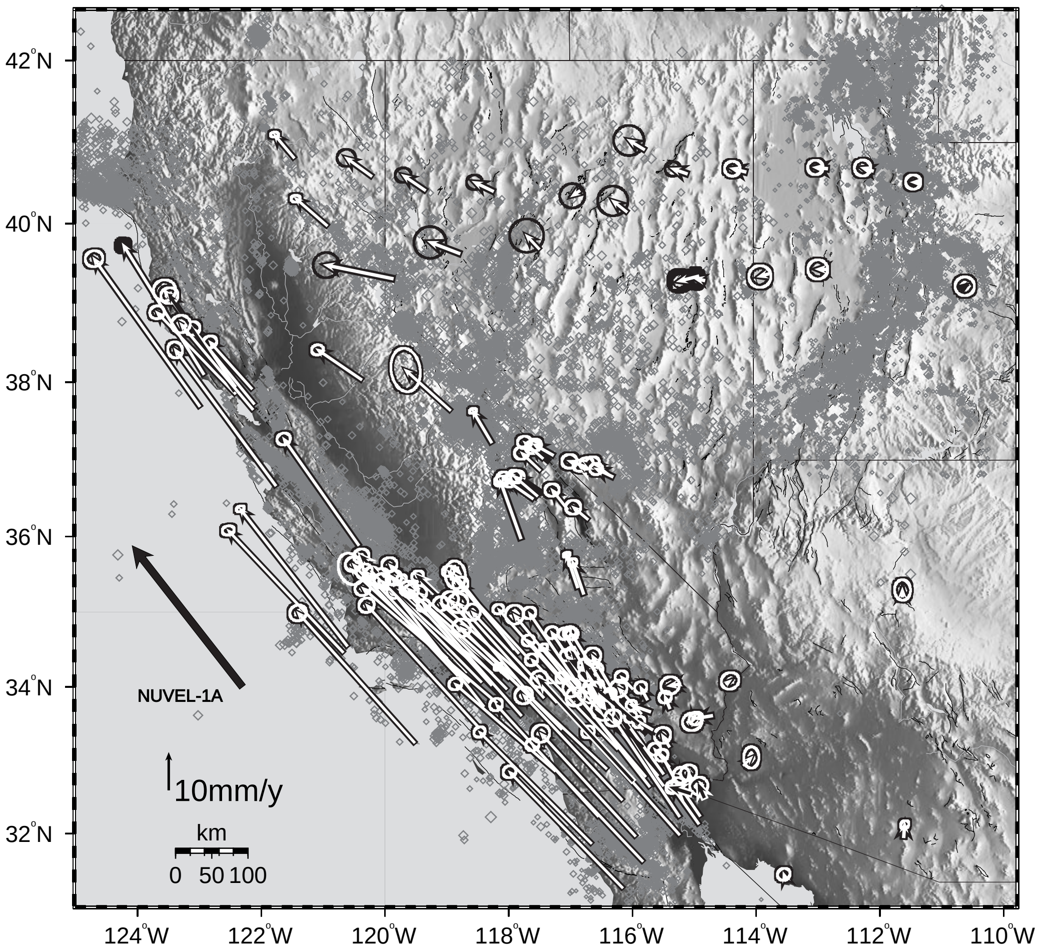


FIGURE 22.1.6 Motion vectors of various sites in the western United States relative to stable North America and NUVEL reference displacement. Site motions show strike-slip along the San Andreas fault system. Extension occurs in the Basin and Range Province north of about 36°E and changes smoothly into the strike-slip motion across a well-defined transition zone. South of 36°E, the San Andreas system accommodates most of the plate motion, and little deformation occurs in the Basin and Range.

the province its name is the surficial manifestation of the youngest system of major normal faults bounding large, tilted, upper crustal blocks (Figure 22.1.5d). Global positioning system (GPS) studies show the partitioning of strain across the western part of the U.S. Cordillera, with some strike-slip motion related to Pacific–North American plate motions taking place in the western part of the Basin and Range Province, between the relatively cold and thick crust of the Sierra Nevada and the hot and thin crust of the Basin and Range (Figure 22.1.6).

Given the long history of ocean-continent plate interaction along the western margin of North America, it may seem surprising that the actual limits and present topography of parts of the Cordillera are dictated mostly by the youngest events to affect the belt (Figure 22.1.1). For example, the Basin and Range Province includes all or parts of the Mesozoic magmatic arc, backarc, and thrust belt, as well as older Paleozoic allochthons and sutures; it is also underlain by the Precambrian rifted western margin of North America. Despite the diversity of tectonic elements across the Basin and Range, the crust is uniformly 25–30 km thick and much of it stands >1 km above sea level, reflecting an anomalously thin and hot mantle lithosphere. The flatness of the Moho across this broad (600 km) extensional province implies that the lower crust was capable of undergoing large-scale flow during extensional deformation (Figure 22.1.4). Thus, it seems clear that the present-day structure of most of the crust and perhaps the entire lithosphere across this region reflects only the youngest event to affect this long-lived orogenic belt. This would imply that if the upper 5–10 km of the crust were removed by erosion, we would probably see very little evidence for the previous 600-m.y. history of this orogenic belt. Convergence presently occurs beneath the Alaskan-Aleutian portion of the margin and beneath the Pacific Northwest, and transform boundaries separate the North American and the Pacific Plates along most of the rest of the margin. In Alaska, shortening and associated diffuse seismicity occur in the overriding North American continent across a broad distance (1000 km). Large-magnitude subduction-zone earthquakes have occurred as recently as 1964 (beneath Anchorage) and uplift by reverse faulting has generated some of the most spectacular and rapidly rising mountains of the Cordillera, including Denali (~6,000 m) in the Alaska Range. Active shortening-related deformation extends northward to the Arctic margin of Alaska. Shortening dies out westward and is replaced by north–south extension in the Bering Strait region, where the mighty Cordillera finally ends. In the Pacific Northwest, folding and thrusting are active in the surficial part of the crust above the Cascadia subduction zone and, as predicted, a subduction-zone earthquake occurred beneath Seattle in early 2001. Detailed studies of contemporary deformation, paleoseismicity studies, and Native oral tradition suggest recurrence intervals of 300 years for such earthquakes, and raise the specter of very large (M>8.0), devastating earthquakes in the future beneath cities such as Portland and Seattle.

In California, the relative motion between the Pacific and North American Plates is partitioned into strike-slip displacement along the San Andreas Fault, and into folding and thrusting related to shortening perpendicular to the San Andreas transform plate boundary (reflected by the recent Loma Prieta and Northridge earthquakes). The exact physical explanation for the observed strain partitioning and how deformation at the surface is coupled with strain at depth in the earth's crust in such zones of continental deformation remain exciting and challenging problems for structural geologists and geophysicists.

22.1.5 Closing Remarks

This brief essay on the geologic and tectonic evolution of the North American Cordillera permit us to make several generalizations about the evolution of such orogenic belts.

- Mountain building (i.e., thickening of continental crust) is not necessarily the result of subduction and collision of allochthonous crustal fragments (terranes) along an active continental margin. Subduction occurred for long spans of time during the history of the Cordilleran margin, but, as in the southwestern Pacific, led mostly to rifting and backarc basin development. True mountain building in the Cordillera appears to have occurred during finite time intervals of rapid convergence and increased absolute westward motion of North America, and was accompanied by magmatic activity.
- The North American Cordillera has long been cited as a classic example of continental growth by the lateral accretion of allochthonous terranes. However, this mechanism is probably not the most fundamental or important process of crustal growth, unless it involves the addition of mature island arcs. Rifting, with formation of rift basins on existing continental shelves, along continental slopes, and within island arcs, and the subsequent filling of these basins by thick prisms of sediment have contributed significantly to the formation of many terranes now incorporated in the Cordillera. Extensional thinning and reworking of continental crust or previously thickened orogenic crust, especially when accompanied by magmatic additions from the mantle, can serve to redistribute and remobilize crust across great portions of an orogen, and the results of these processes often equal or exceed estimates of crustal shortening within the same belts. The best example of this is the reworking and shape-changing of the continent during Cenozoic extension in the western United States.
- Magmatism is a process that is closely linked to deformation in mountain belts. The Cordillera provides excellent examples to illustrate that magmatism is intricately tied to deformation, in that heating causes rheologic weakening of the crust. The rise of magmas transports heat to higher levels of the crust, permitting continents to undergo large-scale deformation, whether by shortening or stretching. This is evidenced by the increasingly better documented eastward migration of magmatism and deformation of the Cordillera in the Mesozoic, as well as by the space-time relation between magmatism and extensional tectonism of the western United States in the Cenozoic.
- Many intriguing questions remain about the evolution of mountain belts such as the Cordillera. Because it is actively deforming, the Cordillera also presents us with a wonderful opportunity to study some of these questions. One of these is how strain-partitioning occurs, that is, where a particular motion vector between two plates or two parts of a continent is partitioned into different styles of deformation in different parts of the orogen (e.g.,

folding and thrusting in the Coast Ranges and strike-slip faulting along the San Andreas Fault in California). Other questions are understanding how seemingly incompatible strains take place within an orogen (e.g., east-west shortening in the Coast Ranges of California and east-west extension in the Basin and Range Province) and what are the driving forces for such strains. The need to answer such questions is a good reason to study contemporary deformations at the scale of the entire orogen. GPS studies measuring contemporary motion across the Cordillera (Figure 22.1.6) are an excellent way to characterize deformations at this scale.

ADDITIONAL READING

The information and ideas in this essay have been distilled from the author's own works and views, and those of many others, as represented in the various chapters of the books, *The Cordilleran Orogen: Conterminous U.S.* and *The Geology of the Cordilleran Orogen in Canada*, two of the volumes of the Geological Society of America's *Decade of North American Geology Series.* A particularly helpful review of the evolution of the western United States is given in Burchfiel et al. (see the following bibliography).

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