North America: Central Cordillera☆

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Introduction

The Spanish term "cordillera" refers to a series of parallel ranges or chains of mountains. The word was first applied in the western hemisphere to the mountain ranges of western South America, i.e., Las Cordilleras de los Andes. In the western United States, the Rocky Mountains and Coast Ranges and mountains between are collectively called the Cordillera. The focus of this article is on the central part of the western North America Cordillera, and includes the mountain belt from ~49°N to ~31°N, an area that extends ~2000 km. The North American Cordillera is part of a semi-coherent mountain belt that extends from Patagonia to Alaska.

Diverse physiographic provinces are included in the "Central Cordillera." Where crossed by the 39th parallel, it includes from east-to-west, the Rocky Mountains, Basin and Range Province, Sierra Nevada, Great Valley, and Coast Ranges (Fig. 1). Farther south, the Colorado Plateau is a prominent physiographic province between the Rocky Mountains and Basin and Range Province; whereas in the northwestern United States the Cenozoic volcanic provinces (Snake River Plain, Columbia Plateau, and Cascade Ranges) are prominent. These physiographic provinces are directly related to the tectonic components of the orogenic system (Fig. 2). An important topographic feature in the Central Cordillera is the tract of high elevation that constitutes the Rocky Mountains and adjacent Colorado Plateau and Great Plains. Most of the 14,000-ft or greater mountain peaks in the conterminous United States are within the Southern Rocky Mountains, with the exception of Mt. Whitney (14,494 ft.; ~4421 m) in the Sierra Nevada and Mt. Shasta (14,162 ft.; ~4319 m) and Mt. Rainier (14,410 ft.; ~4395 m) in the Cascade Range.

Crustal thickness in the Central Cordillera is strikingly variable. The Colorado Rocky Mountains and Sierra Nevada both exceed 50 km in thickness. The thinnest continental crust is in the northern Basin and Range Province (~25–20 km), around the northern part of the Gulf of California (Salton Trough), and in southeastern California and southwestern Arizona where the crust has been extended.

Precambrian Framework

The nucleus of North America is the Precambrian craton commonly referred to as "Laurentia." This Precambrian craton consists of seven or more Archaean microcontinents welded together along Paleoproterozoic collisional orogenic belts. The western margin of Laurentia became a rifted continental margin during the Neoproterozoic and Early Cambrian breakup of the early Neoproterozoic (1.1–0.9 Ga) supercontinent "Rodinia."

The Archaean Wyoming province is exposed in basement-involved, Laramide (Late Cretaceous and early Paleogene) uplifts of the Rocky Mountain foreland. The province is divided into three subprovinces (oldest to youngest): Montana metasedimentary subprovince, Beartooth-Bighorn magmatic zone, and Southern accreted terranes (Houston et al., 1993; Mueller and Frost, 2006). The Montana sedimentary subprovince and Beartooth-Bighorn magmatic zone are characterized by great antiquity, including rocks as old as 3.5 Ga as well as detrital zircons with ages up to ~4.0 Ga and Nd model ages exceeding 4.0 Ga. Terrane accretion and continental-arc magmatism along the southern margin of the province occurred at 2.68–2.50 Ga. The Wyoming province is bordered by Proterozoic orogenic belts on all its margins (Fig. 3, after Mueller et al., 2011).

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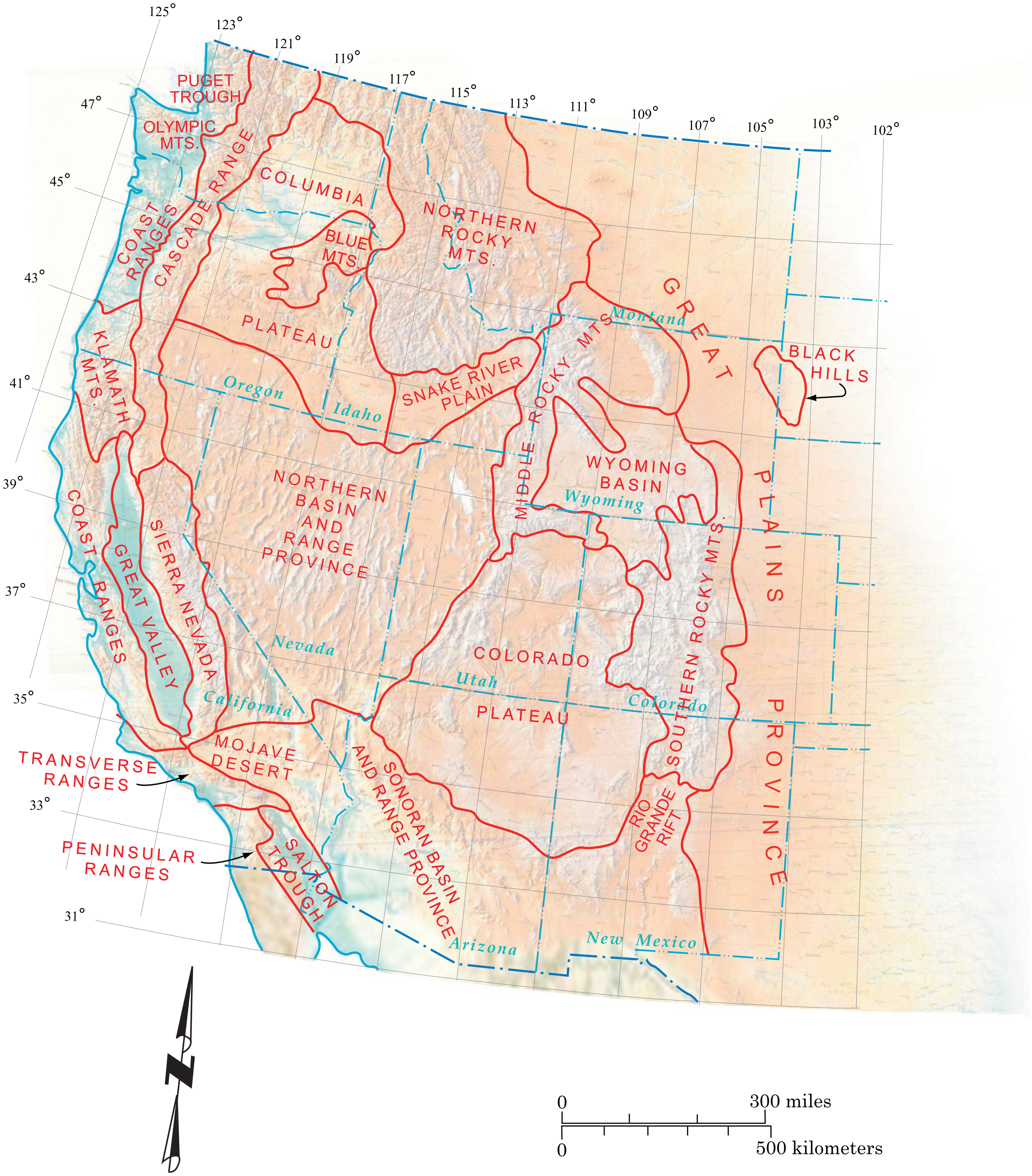

Fig. 1 Major physiographic provinces of the United States. Base map © 1992 Raven Maps and Images.

Along the southern margin of the Wyoming province, a Paleoproterozoic geosuture (Cheyenne belt) is well exposed in the Medicine Bow Mountains of southeastern Wyoming (Fig. 3). This tectonic boundary is interpreted as a Paleoproterozoic collisional zone between a rifted continental margin (Archaean Wyoming province and overlying Paleoproterozoic rocks) and a Paleoproterozoic oceanic supra-subduction complex (Karlstrom and Houston, 1984; Jones et al., 2010). This collisional orogenic event, the Medicine Bow orogeny, developed during the interval 1.78–1.75 Ga. It was apparently the harbinger of a series of Paleoproterozoic accretion events, which continued until ~1.60 Ga. This long history of lateral accretion of chiefly juvenile Paleoproterozoic crust yielded a zone of accretion at least 1300-km wide, now extensively exposed in parts of Colorado, New Mexico, and Arizona. In the southwestern United States, these accretion events have been traditionally referred to as the Yavapai and Mazatzal orogenies (Fig. 3). An alternative interpretation suggests that pre-existing continental crust, part of the 1900–1800-Ma Trans-Hudson-Penokean

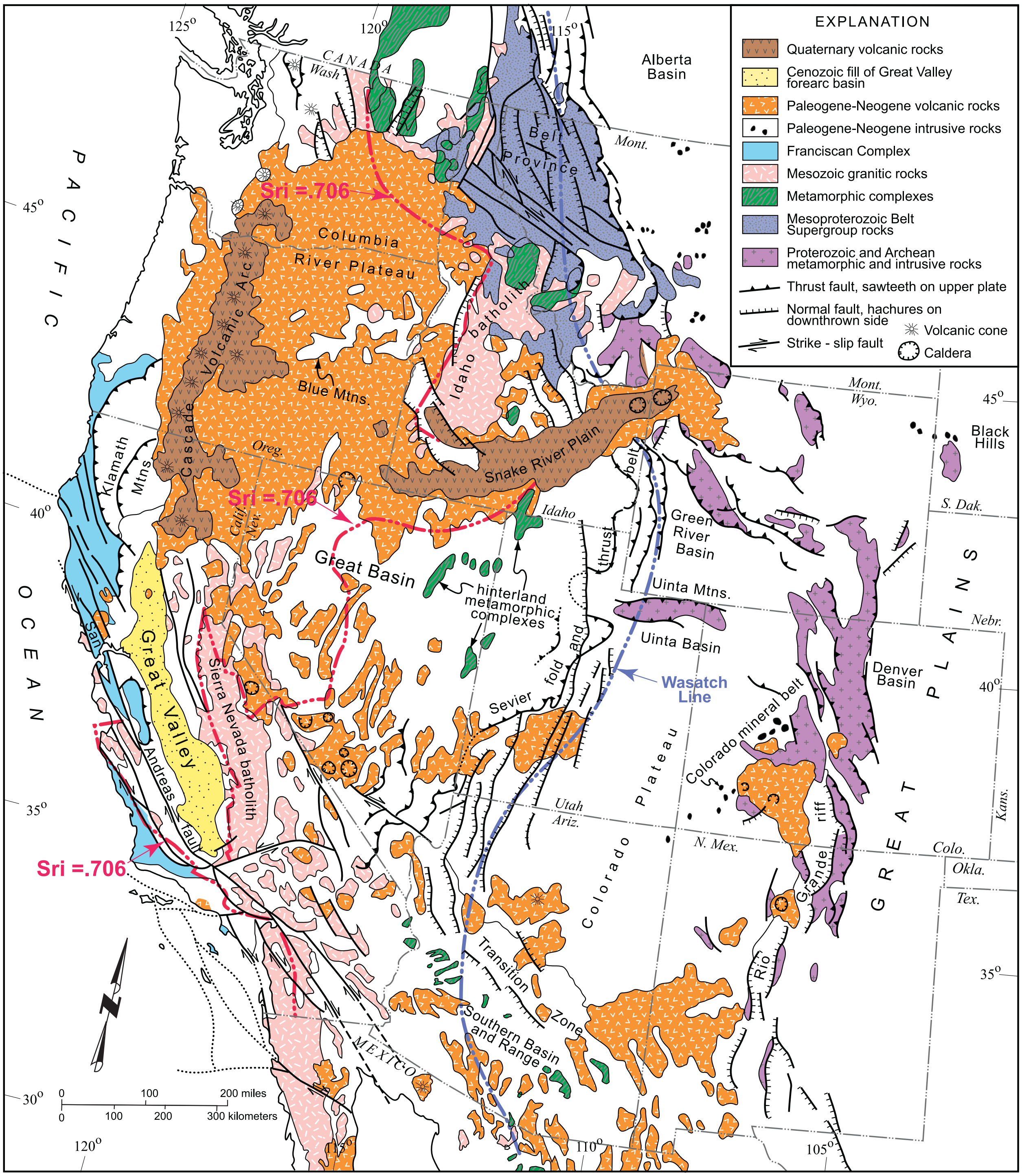

Fig. 2 A tectonic map of the U. S. Cordillera showing selected geologic/tectonic features.

orogen with Archean enclaves, were part of the collage of Paleoproterozoic rocks accreted south of the Cheyenne belt (Bickford and Hill, 2007). In this model, tholeiitic basalt derived from the mantle was emplaced into pre-existing continental crust of Trans-Hudson-Penokean age during crustal extension. These magmas were the heat source to cause melting of the continental crust to yield the rhyolite component characteristic of the bimodal volcanic successions of the Colorado Paleoproterozoic accretionary belt.

By ~1.6 Ga, a supercontinent (i.e., "Nuna" after P. F. Hoffman) had been assembled that included Laurentia and other ancient elements that are now part of the Greenland and Baltic shields. This supercontinent experienced multiple magmatic and tectonic events in the next 500 million years. During the first one, a broad belt of Mesoproterozoic magmatism and associated tectonism

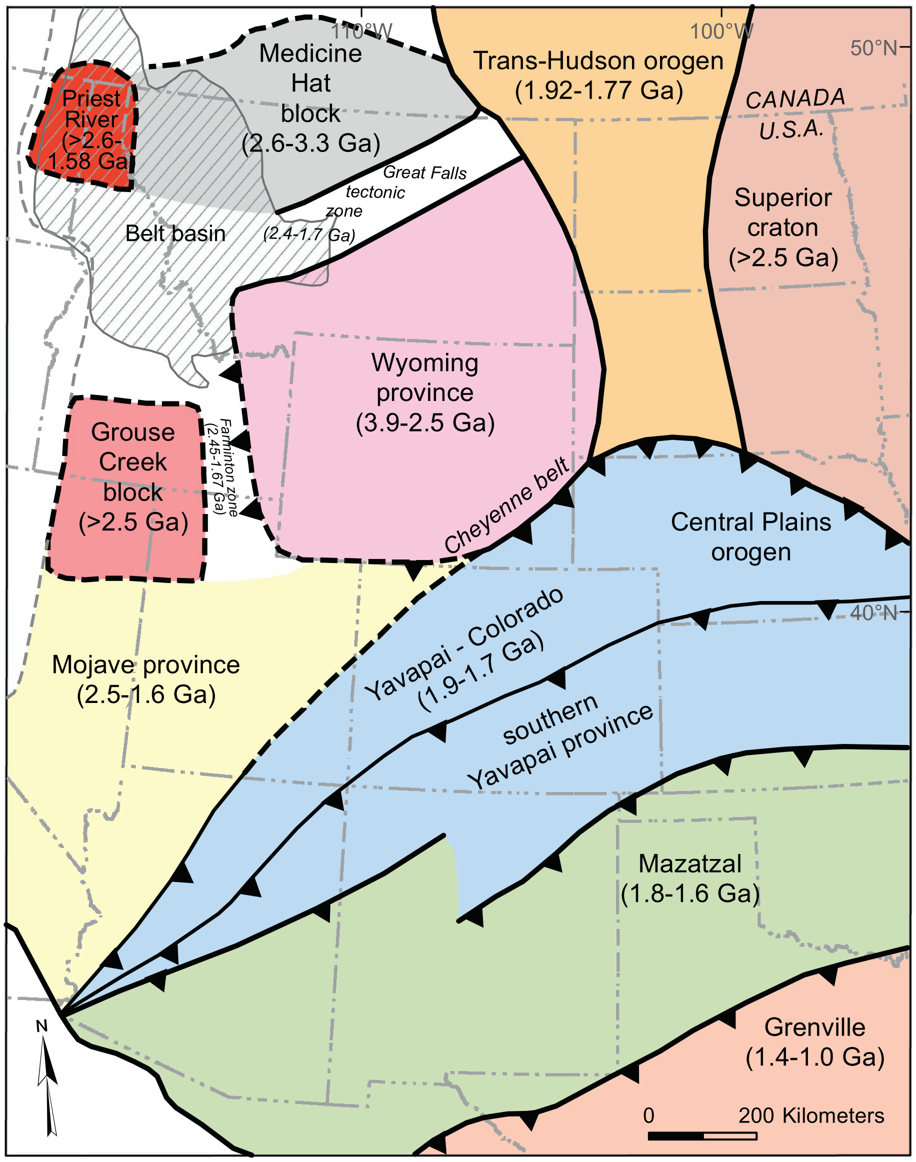

Fig. 3 A generalized map of the major Precambrian provinces of southwestern Laurentia. The age ranges are derived from U-Pb radiometric ages and isotopic model ages. Phanerozoic cover rocks have been removed. The intracratonic, Mesoproterozoic Belt basin accumulated an enormous stratigraphic section (~15 km) of siltite, argillite, quartzite, carbonate rocks, and locally mafic igneous rocks (i.e., Belt Supergroup), chiefly exposed in western Montana and northern Idaho (MacLean and Sears, 2016). Modified from Mueller, P. A., Wooden, J. L., Mogk, D. W. and Foster, D. A. (2011). Paleoproterozoic evolution of the Farmington zone: Implications for terrane accretion in southwestern Laurentia. *Lithosphere* 3, 401–408, Fig. 1A with permission from The Geological Society of America.

developed across much of the supercontinent. In the Rocky Mountains, this magmatism is well represented by ~1.4-billion-year-old plutonic complexes that are widespread south of the Cheyenne belt. Plutons of similar age are common in the Basin and Range Province of Arizona, in the Mojave Desert of southeastern California, and in the subsurface of west Texas and eastern New Mexico. Near the end of the Mesoproterozoic, the North American craton experienced both rifting (manifested by the mid-continent rift system) and severe contraction, a product of the collisional Grenville orogeny (~1.1–0.9 Ga). That orogeny culminated in assembly of the early Neoproterozoic supercontinent Rodinia whose reconstruction remains controversial.

Breakup of Rodinia and Neoproterozoic to Mid-Paleozoic Sedimentation

The breakup of Rodinia was followed by development of a thick wedge of Neoproterozoic through mid-Paleozoic continental shelf deposits along the Cordilleran and Appalachian margins. In what is now the Canadian Cordillera, rifting began at ~750 Ma and evolved into a Neoproterozoic passive margin where the Windermere Supergroup was deposited. In the Central Cordillera, initial rifting was from ~720–660 Ma. This rifting was incomplete, and only during a second rifting event (~570–520 Ma) was the rift-to-drift transition achieved with the deposition of immature siliciclastic strata (Yonkee et al., 2014). Regional subsidence followed with the deposition of Middle Cambrian to Upper Devonian carbonate-rich strata.

Neoproterozoic clastic deposits, including glacial diamictite, can be traced from the Mackenzie Mountains in the Canadian Cordillera to the Death Valley region, southern California. The Neoproterozoic rocks in the Central Cordillera are considered rift deposits that accumulated in isolated basins, but by Early Cambrian a continuous, Atlantic-type, passive margin existed virtually the length of the western North American Cordillera. The east-west-trending Uinta Mountains, Utah, expose a 4–7-km-thick siliciclastic succession of an intra-Rodinian rift basin that developed in the Neoproterozoic (~770–740 Ma). The Uinta Mountain Group correlates with other Neoproterozoic rift basin deposits in the Central Cordillera such as: the Pahrump Group (Death Valley, California), Chuar Group (Arizona), and Big Cottonwood Formation (Wasatch Mountains, Utah) (Dehler et al., 2010).

The Neoproterozoic deposits were the initial stratigraphic units of an enormous wedge of chiefly clastic and carbonate rocks that accumulated along the rifted, western margin of the Central Cordillera through Late Devonian time. This wedge of continental margin deposits is sometimes referred to as the "Cordilleran miogeocline," and this passive-margin sequence reached ~10,000 m in total thickness. The miogeocline is separated from a partially equivalent, but considerably thinner, cratonic sequence by the "Wasatch line," interpreted as a hinge line in the depositional framework of the Central Cordillera (Fig. 2). The Phanerozoic cratonic sedimentary sequence is characterized by disconformities and in some cases complete periods are unrepresented (e.g., the Silurian over most of Wyoming). This fundamental boundary is also interpreted as the eastern limit of Neoproterozoic, syndepositional faulting related to initial rifting of Rodinia in the Central Cordillera. Subsequently, the Wasatch line represents an important boundary during Pennsylvanian-Permian basin development (Oquirrh basin).

Another fundamental boundary in the southern Cordillera is the $Sr_i = 0.706$ line, a boundary based on the initial $^{87}Sr/^{86}Sr$ ratio in Mesozoic and Cenozoic igneous rocks (Kistler and Peterman, 1978; Chapman et al., 2017). This isotopic boundary has commonly been interpreted as the western extent of Precambrian basement rocks (Fig. 2); and therefore, also roughly correlates with the western extent of passive-margin sedimentary rocks. Precambrian basement provinces have been delineated by Nd-depleted mantle model ages (Bennett and DePaolo, 1987). The Archean Wyoming province yields ages >2.7 Ga. Mojavia, a Precambrian province that extends from southeastern California to central Utah (Fig. 3), is characterized by model ages of 2.0–2.3 Ga. Provinces south of the Cheyenne belt yield progressively younger Nd model ages of 1.8–2.0, 1.7–1.8, and <1.4 Ga (Bennett and DePaolo, 1987). These data support the concept of progressive outward crustal growth from the Archean Wyoming province along the southern margin of Laurentia (Fig. 3).

Paleozoic Orogenies

Passive margin sedimentation ended in Late Devonian time when Cambrian through Devonian oceanic rocks of the Roberts Mountains allochthon were thrust onto the continental shelf during the Antler orogeny, best documented in north-central Nevada. Slope-and-rise sedimentary rocks and seafloor mafic volcanic rocks were thrust upon coeval, shallow-water shelf strata along a regional thrust fault (Roberts Mountains thrust). Detailed paleontological and stratigraphic studies have shown that the Roberts Mountains allochthon consists of fault-bounded packets of oceanic-facies rocks imbricated into a tectonic wedge. A great clastic wedge (Antler flysch) was shed eastward from the resulting highlands into a broad foredeep that included much of eastern Nevada and extended into Utah. Upper Pennsylvanian and Permian limestone and clastic rocks unconformably overlie the Roberts Mountains allochthon. Similar relationships occur to the northeast in the Pioneer Mountains of central Idaho and to the southwest in roof pendants in the Sierra Nevada batholith. Various plate-tectonic models have been suggested for the Antler orogeny and considerable debate has focused on the Antler magmatic arc that plays a role in virtually all of them. Some have argued that the Antler arc subsided after collision with the western North American continental margin and was subsequently buried by younger rocks of later orogenic cycles. Others have stated that Devonian oceanic-arc rocks in the eastern Klamath Mountains and northern Sierra Nevada are the magmatic arc elements involved in the Antler orogeny; however, there is debate about the facing direction of the arc. One hypothesis is that the arc faced and migrated southeastward during progressive rollback of the subducted slab. Still another model suggests that the arc faced westward, and the emplacement of the Roberts Mountain allochthon was related to the collapse of a back-arc basin.

Near the Permian-Triassic transition a tectonic event similar to the Late Devonian-Early Mississippian Antler orogeny occurred in the Central Cordillera. The field relationships for this event are known best in northwestern Nevada. The deep-water chert-argillite-limestone-greenstone of the Havallah sequence was thrust eastward onto autochthonous, shallow-water upper Paleozoic strata along the Golconda thrust. This Golconda allochthon is composed of numerous fault-bounded slices of rock like the Roberts Mountains allochthon. This contractional orogeny is referred to as the Sonoma orogeny, and again there is debate over the facing direction of the oceanic arc involved in this orogenic event. One school of thought interprets the tectonic setting for the Sonoma orogeny as an oceanic arc-continental margin collision involving incipient subduction of continental crust beneath an east-facing oceanic arc (i.e., subduction directed westward). Others view the Sonoma orogeny as another example of the collapse of a back-arc basin developed behind a west-facing oceanic arc (i.e., subduction directed eastward), remnants of which are preserved in the northern Sierra Nevada and eastern Klamath Mountains. An anomaly of the Sonoma orogeny, unexplained by any model, is the fact that it did not create an extensive foreland basin. There is also debate about the final age of emplacement of the Golconda allochthon, which some workers argue was post-Triassic, probably of Jurassic or Cretaceous age.

Far to the east of the Antler and Sonoma orogenies, and approximately between them in time of origin, are structural and sedimentological effects related to the amagmatic, Pennsylvanian-Permian, intraplate Ancestral Rocky Mountains orogeny. Manifestations of the late Paleozoic Ancestral Rockies are best demonstrated in the present-day Colorado Rocky Mountains and environs, but structural and sedimentological effects related to the Ancestral Rockies orogeny can be traced from southern Oklahoma to northern Nevada. The uplifts supplied salmon pink to red arkosic sandstones, which grade into marine strata; these deposits are important components of the late Paleozoic stratigraphic section of the Southern Rocky Mountains. The Ancestral Rockies orogeny is commonly interpreted as an intraplate orogeny related to the late Paleozoic collision of the South American-African plates of Gondwana with the southern margin of Laurentia during the development of the supercontinent Pangea. Orogenic effects of this continent-continent collision are manifested in the Marathon-Ouachita orogeny in the south-central United States and are part of an extensive late Paleozoic orogenic system that can be traced from west Texas to central Europe.

Truncation of the Cordilleran Miogeocline and Pre-Cenozoic Strike-Slip Faulting Along the Southwestern Margin of the Cordillera

In a 1969 synthesis of the plate-tectonic evolution of California and environs, Warren Hamilton noted the apparent truncation of the southwest-striking Cordilleran miogeocline in southern California and northwestern Mexico. Although Hamilton (1969) favored late Paleozoic to Triassic truncation, subsequent studies have demonstrated that in Early to Middle Pennsylvanian time the depositional framework in the Death Valley region experienced a fundamental change in orientation from northeast-southwest to northwest-southeast. This important change in orientation of late Paleozoic depositional facies in southeastern California is interpreted as the result of a sinistral transform fault zone that was initiated during the Early or Middle Pennsylvanian and continued to be active into the early Mesozoic. In Late Triassic time (Norian) this northwest-southeast strike was maintained during the initiation of the Cordilleran continental-margin magmatic arc that can be traced from southern Arizona into the eastern Sierra Nevada. Late Paleozoic magmatism is recognized in eastern Mexico where it invades Gondwanan crust, whereas scarce Late Permian plutonic rocks occur in the western Mojave Desert and environs. How these igneous rocks relate to the development of the continental-margin magmatic arc is uncertain, but the occurrences in the Mojave Desert area suggest magmatism shortly after the establishment of a newly formed continental margin bounded by a transform-fault system (i.e., sinistral California-Coahuila transform; Dickinson, 2008).

Another widely cited tectonic hypothesis concerning major strike-slip displacement along the southwestern margin of the Central Cordillera postulates a major Late Jurassic, sinistral, transform-fault boundary designated the "Mojave-Sonora megashear." This regional fault zone has been considered to be significant in the translation of part of northern Mexico (e.g., "Caborca block") into its present position in the Central Cordillera after the initial rifting and breakup of Pangaea and during the development of the Gulf of Mexico. However, the recognition that Paleozoic depositional and structural trends were initially truncated in the Central Cordillera in late Paleozoic time has dramatically reduced the potential significance of the Mojave-Sonora megashear in reshaping the southwestern margin of the Central Cordillera.

Possibly significant Early Cretaceous, dextral strike-slip faulting has been suggested in the wall rocks of the Sierra Nevada batholith; and younger, right-slip, crystal-plastic shear zones are known from the Sierra Nevada batholith. In one speculative model, a large-scale, Early Cretaceous dextral strike-slip fault system is hypothesized to have extended from the Mojave Desert region to the western margin of the Idaho batholith, suggesting significant northward translation of a large tract of the accreted terranes of the western Cordillera (Schweickert and Lahren, 1990; Wyld and Wright, 2001). The region inferred to have been displaced northward following its accretion to western North America includes the Blue Mountains (northeastern Oregon), Klamath Mountains (southwestern Oregon and northwestern California), and northern Sierra Nevada (Fig. 1).

Late Paleozoic to Early Mesozoic Continental to Oceanic Magmatic Arc

The Middle Pennsylvanian-middle Early Triassic oblique truncation of the continental margin of the Central Cordillera was subsequently overprinted by the development of a northwest-southeast-trending magmatic arc. It can be traced from southern Arizona where it is built on continental (sialic) crust to the eastern Klamath Mountains where it is built on oceanic (ultramafic to mafic) crust. The transition from continental to oceanic arc is inferred to occur at about 39° N latitude in the Sierra Nevada. This early Mesozoic magmatic arc is thought to have been west-facing with an eastward-dipping subduction zone (Barth et al., 2011). Late Triassic (~220 Ma) blueschist-facies metamorphic rocks in the northern Sierra Nevada, Klamath Mountains, and near Mitchell, Oregon (inlier of the Blue Mountains Province) are interpreted as the innermost subducted rocks of an accretionary complex that developed seaward of the magmatic arc. Its development initiated a long-lived convergent plate-boundary zone along the Central Cordillera. This west-facing magmatic arc served as the "backstop" for the accretion of numerous tectonostratigraphic terranes that were added to the western North American continental margin from mid-Jurassic through early Paleogene time.

Accreted Terranes

The "terrane concept" was conceived and initially applied by W. Porter Irwin (United States Geological Survey, 1972) to explain complex geologic relationships in the southeastern Klamath Mountains of California. Subsequently, the concept has been utilized throughout the western North American Cordillera (Coney et al., 1980) as well as in other orogens (e.g., Appalachians and Caribbean region). A tectonostratigraphic (or lithotectonic) terrane is an allochthonous, fault-bounded assemblage of rocks with a different geologic history than that of adjacent rock units. Tectonostratigraphic terranes can consist of continental-margin features such as a displaced continental margin or part of an original fringing island arc and/or its subduction complex. Oceanic features such as plateaus, seamounts, or even back-arc basins may occur as discrete terranes in accretionary orogens. The tectonostratigraphic terranes in the western North American Cordillera are tectonic slices of such crustal elements and are not lithospheric or even crustal sections. The juxtaposition and amalgamation of such slices produced the Cordilleran "collage" of terranes that characterizes the western part of the orogen.

In the Central Cordillera, Phanerozoic tectonostratigraphic terranes are the basic "building-blocks" of continental accretion west of the $Sr_i = 0.706$ line (i.e., the inferred western margin of Laurentia in the Central Cordillera). Beginning in the late 1970s and extending to the present, many geologic studies have focused on determining the affinity of various tectonostratigraphic terranes that are part of the Cordilleran orogen. Clearly some of these terranes are "pericratonic," having originated near the western margin of Laurentia, whereas other terranes are truly "exotic" to the Cordillera. These far-traveled terranes represent major additions to western North America.

Ophiolites, sometimes dismembered, are an important component of some of the accreted, tectonostratigraphic terranes of the Central Cordillera. In the Klamath Mountains of northwestern California and southwestern Oregon, well-preserved ophiolitic sequences range in age from early Paleozoic through Late Jurassic. The oldest are in the eastern parts of the Klamath Mountains and younger sequences are to the west. Some examples are the Trinity subterrane, North Fork, Rattlesnake Creek, and Western Klamath terranes (Fig. 4, after Snoke and Barnes, 2006). The Josephine ophiolite of the Smith River subterrane (part of the Western Klamath terrane) is the best-studied ophiolite sequence in western North America. To the northeast in the Blue Mountains of northeast Oregon, the Baker terrane includes important ophiolitic sequences (e.g., Canyon Mountain complex). In east-central California, ophiolitic sequences commonly occur as tectonic slices along the Foothills fault system of the western Sierra Nevada metamorphic belt. The Late Jurassic Coast Range ophiolite occurs along the boundary between the Great Valley forearc basin and Franciscan accretionary complex. Many, if not all, of these Cordilleran ophiolites developed in supra-subduction-zone settings, which indicate origins by rifting and spreading within oceanic arcs. This intra-arc extension may have been a result of oblique subduction and broad-scale transtension within the arc similar to the present rifting and spreading in the Andaman Sea north of Sumatra. In contrast, the rifting and spreading may have been more orthogonal such as the ongoing propagating rift and spreading center related to the opening of the Lau Basin behind the Tofua (Tonga) arc in the southwestern Pacific. This supra-subduction interpretation of Cordilleran ophiolites implies proximity to, and temporal overlap with oceanic-arc deposits, and has been demonstrated throughout the Cordillera by detailed geologic mapping coupled with geochemical and geochronological studies. A particularly well-documented example of this relationship is the deposition of the Upper Jurassic Rogue and Galice formations and development of the Late Jurassic Josephine ophiolite—all within the Western Klamath terrane. The Galice Formation, consisting of slaty metashales and metagraywackes with subordinate metaconglomerate and metavolcanic rocks, lies depositionally on both the Rogue Formation and Josephine ophiolite. This situation suggests a close proximity in space and time between an oceanic arc (Rogue Formation), its adjacent sedimentary apron (Galice Formation), and the development of a complete ophiolite sequence (i.e., Josephine ophiolite).

Another type of tectonostratigraphic terrane common in the western North American Cordillera is the accretionary complex terrane. Some of these terranes include ophiolitic components (e.g., the Baker terrane in northeastern Oregon) but most are either chert-rich or clastic-rich and characterized by tectonic mélange, broken formation, and/or olistostromal deposits. Fossiliferous rocks in some accretionary complex terranes provide some of the most reliable paleogeographic data obtainable from tectonostratigraphic terranes. In the Cordillera, limestone blocks (of tectonic or olistostromal origin) yield fossils long recognized as "exotic" to the western North American Cordillera. For example, Permian Tethyan fossils have been discovered in the Klamath and Blue Mountain provinces (North Fork, Rattlesnake Creek, and Baker terranes) and are especially characteristic of the Cache Creek terrane of British Columbia, Canada. The significance of the Tethyan fauna in the Cordillera is still debated by paleontologists. However, the association of these exotic limestones with blueschist-facies blocks strongly suggests that these terranes represent accretionary complexes that incorporated various rock types during the subduction of Pacific Ocean crust along the margin of western North America. The polarity of the original magmatic arcs related to these accretionary complexes is commonly controversial. Some accretionary complexes in the Central Cordillera may be composites produced by collision of oppositely facing arcs. A possible example is the Baker terrane (northeast Oregon) that apparently developed during late Paleozoic through early Mesozoic time between the partly coeval Olds Ferry and Wallowa arcs. Such a situation is analogous to the arc-arc collision presently ongoing in the Molucca Sea between the oppositely facing Sangihe and Halmahera island-arc systems.

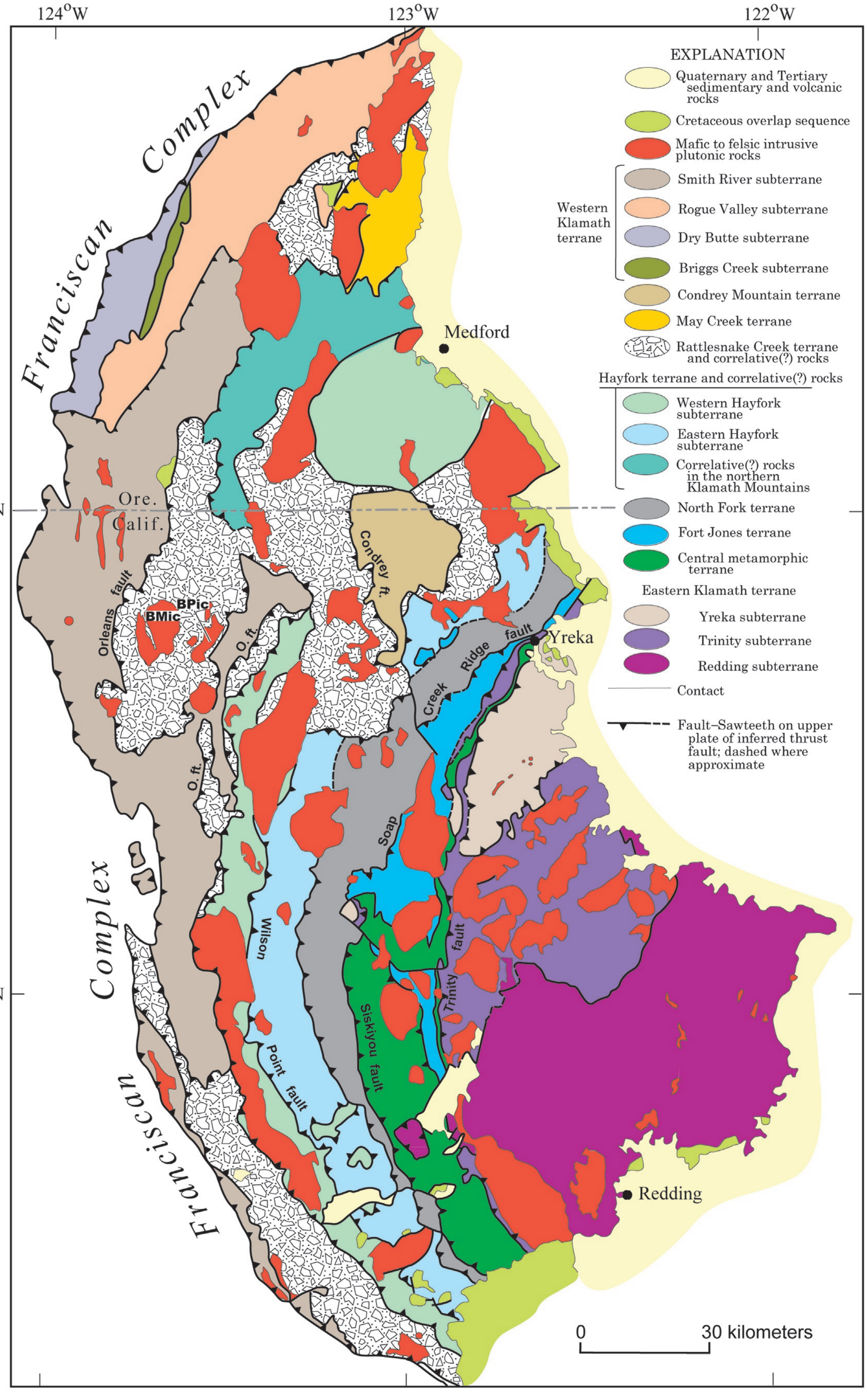

Fig. 4 Geologic map of the tectonostratigraphic terranes of the Klamath Mountains, northwestern California-southwestern Oregon. From Snoke, A. W., and Barnes, C. G. (2006). The development of tectonic concepts for the Klamath Mountains province, California and Oregon. In Snoke, A. W. and Barnes, C. G. (eds.) *Geological studies in the Klamath Mountains province, California and Oregon: A volume in honor of William P. Irwin. Geological Society of America Special Paper 410*, pp 1–29. Boulder, Colorado: The Geological Society of America, Fig. 3, with permission from The Geological Society of America.

Jurassic Magmatic and Tectonic Events

The Jurassic history of the western North American Cordillera is particularly complex and includes various events along the continental margin as well as orogenic effects within the interior of the continent. How these Jurassic orogenic processes interrelate is a major unresolved problem in Cordilleran tectonics. A classic Late Jurassic orogeny of the continental margin is the Nevadan orogeny. Various studies have suggested that the age of this orogeny can be tightly bracketed in the Klamath Mountains at ~150 Ma.

However, in light of the plate-tectonic paradigm coupled with recognition that terrane accretion is commonly progressive along a continental margin, the regional significance of a tightly defined orogenic event has been questioned. The classic definition of the Nevadan orogeny is based on rock relationships in the western Sierra Nevada of California and Klamath Mountains of northwestern California-southwestern Oregon in comparison to the California Coast Ranges. These include folds and associated cleavage in Kimmeridgian-Oxfordian (Upper Jurassic) metasedimentary rocks of Mariposa and Galice formations and the nearby association of relatively undeformed Tithonian (uppermost Jurassic stage) sedimentary rocks of the Knoxville Formation in the Coast Ranges. This classic definition was re-enforced with the recognition that Early Cretaceous granitic plutons cut these structural features in the Sierra Nevada.

The plate-tectonic setting of the Late Jurassic Nevadan orogeny is especially controversial with respect to the inferred geologic evolution of the western Sierra Nevada as compared to that of the Klamath Mountains. Many tectonicists have favored a collision between a west-facing early Mesozoic arc (i.e., an eastern arc) and an exotic, east-facing oceanic arc (i.e., a western arc) to explain the geologic relations manifested in the western Sierra Nevada metamorphic belt. The accreted western arc would be separated from the eastern arc by a composite accretionary complex, in part manifested by the Paleozoic and Triassic Calaveras complex east of the Sonora fault. In the Klamath Mountains, structural relationships involving west-directed regional thrusting preclude the accretion of an exotic east-facing oceanic arc. In this light, the most widely accepted tectonic model for the Nevadan orogeny in the Klamath Mountains is the collapse of a back-arc basin behind a west-facing oceanic arc (Rogue-Chetco arc) (Harper and Wright 1984). In this model, collapse could be related to increased coupling across the subduction system (i.e., the arc became contractional after an earlier extensional history). Resolution of these two contrasting tectonic scenarios has not been completely achieved, although some favor a polarity reversal of the western arc from east-facing in the western Sierra Nevada to west-facing in the Klamath Mountains (Ingersoll and Schweickert, 1986). Such polarity reversals do occur along the strike of modern intra-oceanic arcs. However, this compromise requires drastically different tectonic settings for the deposition of the Galice and Mariposa formations, which have been recognized as probable stratigraphic and temporal equivalent units for over 100 years.

The Mesozoic Cordillera: Transition to an Andean-Type Continental Margin

By the Middle to Late Jurassic, all of the major terranes that compose basement west of the 0.706 line had been accreted, and the plate margin had reorganized into a single, eastward-dipping subduction zone. Opening of the North Atlantic Ocean initiated during the Middle Jurassic likely helped to catalyze this plate reorganization and the development of a strongly convergent Cordilleran orogenic belt (DeCelles, 2004). The Late Jurassic Nevadan orogeny records the final amalgamation of fringing arc systems and transition to a coherent ocean-continent subduction margin with the Farallon Plate subducting eastward beneath the North American Plate.

Although contraction was established in the central U.S. Cordillera (ca. 35–45°N latitude) during the Jurassic, the southern U.S. Cordillera experienced transtensional to extensional deformation during this time, related to slab roll-back, trench-retreat, and the opening of a back-arc basin. The Jurassic to Early Cretaceous back-arc basin system in the southwestern U.S. and northern Mexico includes the McCoy, Bisbee, Chihuahua, and Sabinas basins. Some models also suggest that the opening of the Gulf of Mexico during the Jurassic is related to extension in this back-arc system.

From Late Jurassic time onward, all of the physiographic and tectonic components that constitute a Cordilleran orogenic system were in place in the western U.S. (Fig. 5). From west-to-east, these are: (1) a trench/accretionary complex, (2) a forearc basin, (3) a

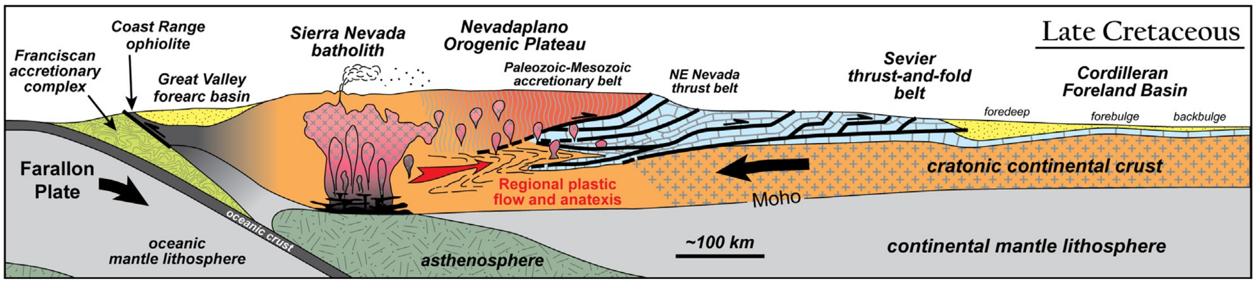

Fig. 5 Schematic Late Cretaceous cross-section of the Central Cordillera, showing the relationship between the Sevier fold-and-thrust belt and Cordilleran foreland basin on the east, metamorphic and igneous rocks of the hinterland, Sierra Nevada batholith, Great Valley forearc basin, and Franciscan accretionary complex on the west.

volcanic-plutonic continental magmatic arc, (4) an orogenic hinterland, (5) a retroarc thrust belt, and (6) a foreland basin system. These components can be thought of as belts or provinces that extend along strike for virtually the entire length of the Cordillera (Fig. 2).

The Mesozoic trench/accretionary complex is exemplified by the Franciscan complex in California and Oregon, which is analogous to the modern-day Cascadia accretionary complex (or prism) in Oregon and Washington State. The Franciscan complex consists primarily of a shale-matrix mélange and formed by scraping off and piling up trench sediments from the Farallon Plate as it was subducted (Wakabayashi, 2015). Most of the sediments are clastic and were derived from the magmatic arc. Many of the rocks in the Franciscan complex were partially subducted or underplated and experienced high-pressure/low-temperature metamorphism, diagnostic of subduction settings. Large (up to a few 10s of meters in diameter) blocks, colloquially referred to as "knockers," of blueschist and other high-pressure metamorphic rocks are present.

The Franciscan complex is located adjacent to the Great Valley forearc basin that contains up to ~10 km of unmetamorphosed sedimentary rocks, also derived primarily from the magmatic arc. The Great Valley sequence is Late Jurassic to early Paleogene in age and is time-equivalent with much of the Franciscan complex. The forearc basin is composed mainly of turbidites deposited in deep-water fan environments, although the youngest strata in the basin are dominated by shallow-marine and deltaic deposits as the basin was filled. The forearc basin was deposited on ophiolitic basement to the west and deposited on previously accreted terranes to the east. The Franciscan complex has been partially underthrust beneath the Late Jurassic Coast Range ophiolite (Fig. 5).

One of the most distinctive features of the Mesozoic Cordilleran orogenic system is the continental magmatic arc (Armstrong and Ward, 1993). The arc is largely preserved as a series of batholiths including the Peninsular Ranges, Sierra Nevada, and Idaho batholiths (Fig. 2). Other batholith-like igneous bodies once connected these regions (e.g., Mojave batholith), but have been dismembered by Cenozoic extension or are covered. The Mesozoic batholiths are chiefly composed of intrusive, calc-alkaline, intermediate to silicic rocks (quartz diorite, tonalite, granodiorite, granite), and display prominent east–west geochemical and isotopic gradients. Toward the east, rocks generally become more felsic, alkaline, oxidized, and isotopically evolved. Except for the Idaho batholith, the batholiths are metaluminous and were emplaced into previously accreted juvenile terranes. The Idaho batholith is largely peraluminous and was emplaced into Proterozoic basement. Most of the batholiths expose rocks emplaced at pressures of 3–5 kb (~10–15 km depth in the crust) with the deepest rocks exposed in the southern Sierra Nevada (>10 kb) (Chapman et al., 2012). Arc magmatism started during the Late Permian to Triassic and lasted until ~80 Ma in the Peninsular Ranges and Sierra Nevada batholith and until ~70 Ma in the Idaho batholith. Magmatic activity was characterized by periods of voluminous igneous activity (called high-flux events or arc flare-ups) separated by magmatic lulls. The Sierra Nevada and Peninsular Ranges batholith record high-flux events in the Late Triassic, Late Jurassic, and Late Cretaceous (Paterson and Ducea, 2015). Arc magmatism ceased during the Late Cretaceous as a result of low-angle to flat-slab subduction of the Farallon Plate.

Contractional deformation gradually expanded eastward during the Mesozoic to early Paleogene as the Cordilleran orogen was constructed. This deformation is preserved in part as a series of thrust belts including (from west to east) the Eastern Sierra, Luning-Fencemaker, central Nevada, and Sevier thrust belts. The Sevier fold-and-thrust belt is the youngest, least deformed, and least metamorphosed of the Cordilleran thrust belts and it bounds a region to the west generically referred to as the orogenic hinterland (Yonkee and Weil, 2015). In addition to upper-crustal deformation recorded in thrust belts, the hinterland has a complex history of middle to lower crustal thickening. Mid-crustal rocks exposed in the hinterland experienced Barrovian metamorphism during tectonic burial to depths as great as 40 km. The thickened crust has been proposed to have isostatically supported a high-elevation (~3 km) orogenic plateau called the "Nevadaplano," analogous to the Altiplano in the central Andes (DeCelles, 2004). The thickened crust also produced an increase in radiogenic heating and a higher geothermal gradient (after thermal relaxation). Heating of the middle to lower crust during the Late Cretaceous to early Paleogene caused local to regional crustal melting that is recorded by migmatites and a belt of peraluminous, muscovite-bearing leucogranite that roughly parallels the position of the Cordilleran metamorphic core complexes (Figs. 2 and 6; Miller and Barton, 1990). Some models have suggested that the presence of low-viscosity and relatively buoyant melt in the middle to lower crust in the hinterland helped drive core complex formation during the Cenozoic. The orogenic hinterland also experienced periods of extension and normal faulting during the Late Cretaceous, which has been associated with orogenic collapse, gravitational spreading, and delamination of mantle lithosphere (Wells, et al., 2012).

The thin-skinned Sevier fold-and-thrust belt is a classic example of a retroarc thrust belt and extends from Canada to southeastern California (Fig. 2). The thrust belt accommodated up to 300 km of shortening on low-angle thrust faults that displaced large thrust sheets composed of unmetamorphosed sedimentary rocks eastward. Thrust faults sole into a basal décollement near the top of the crystalline Precambrian basement. The thrust belt is best exposed in the Wyoming salient in western Wyoming, northern Utah, and southeast Idaho where it has been less overprinted by Cenozoic extension (Yonkee and Weil, 2015). The shortening history extends from ~120 to ~50 Ma, and faulting generally is propagated eastward (in-sequence deformation). The Sevier fold-and-thrust belt lends its name to the Sevier orogeny, which broadly encompasses all of the structural and magmatic processes that helped construct the Cordilleran orogenic system during the Jurassic to early Paleogene (exclusive of the Laramide orogeny—see below).

Subsidence related to flexural loading of the lithosphere by the Sevier fold-and-thrust belt (and precursor thrust belts) produced a foreland basin system located east of the thrust belt that consisted of foredeep, forebulge, and backbulge depozones or sub-basins (DeCelles, 2004; Fig. 5). Deposition of the Upper Jurassic Morrison Formation in a backbulge depozone is the earliest evidence for the presence of a Cordilleran foreland basin system. As the Sevier fold-and-thrust belt expanded eastward, the position of the flexural foreland basin migrated eastward such that the most distal sedimentary deposits are overlain by the most proximal. A regional unconformity separates the Morrison Formation from overlying Lower Cretaceous strata and has been interpreted to be

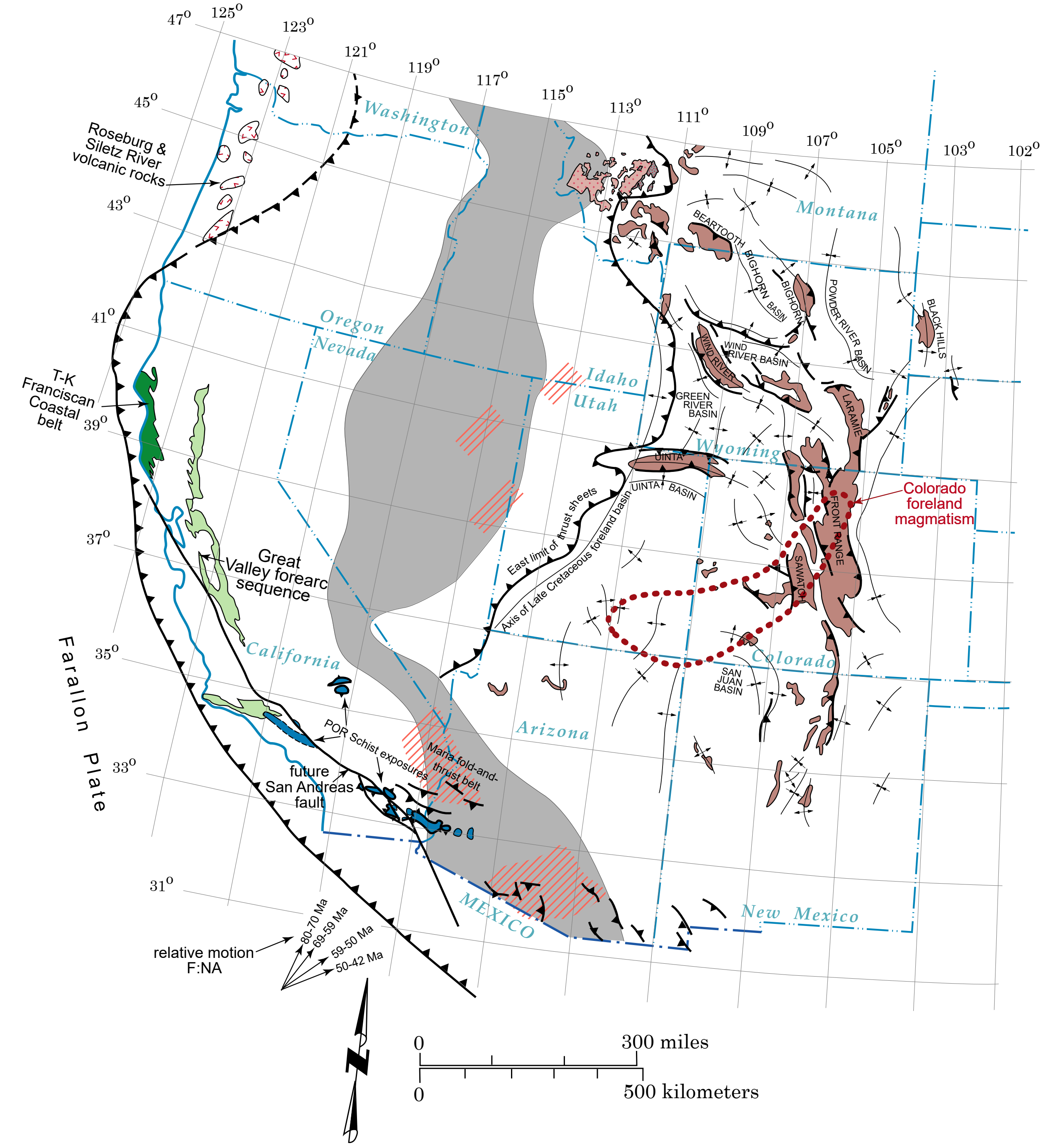

Fig. 6 Distribution of the effects of the Late Cretaceous-early Paleogene Laramide orogeny of the Central Cordillera. T-K = Tertiary-Cretaceous; POR = Pelona-Orocopia-Rand Schists; oblique red lines denote areas of Late Cretaceous, regional metamorphism; belt of Cretaceous-early Paleogene muscovite-bearing granites (peraluminous) is shown as gray shading; in western Montana, the late Cretaceous Boulder batholith, associated plutons, and coeval Elkhorn Mountains Volcanics are shown in dark pink with red plus signs; and structural features in the Rocky Mountains are from Hamilton (1978). The inferred plate-tectonic setting in the Late Cretaceous-early Paleogene is schematically shown; F = Farallon Plate, NA = North American Plate, relative motion from Saleeby (2003). Adapted from Miller, C. F. and Barton, M. D. (1990). Phanerozoic plutonism in the Cordilleran Interior, U.S.A. In Kay, S. M. and Rapela, C. W. (eds.) *Plutonism from Antarctic to Alaska, Geological Society Special Paper 241*, pp. 213–231. Boulder, Colorado: The Geological Society of America.

related to uplift and erosion above a flexural forebulge as it migrated eastward. Subsidence recommenced during the mid-Cretaceous as the foredeep depozone migrated eastward and shallow inland seaways transgressed southward from the Arctic Ocean and northward from the Gulf of Mexico. These seaways eventually linked together during the Late Cretaceous forming the Western Interior Seaway. In addition to flexural loading, subsidence patterns in the retroarc foreland basin have been linked to dynamic subsidence associated with mantle flow and slab processes. As the Cordilleran orogen and Sevier fold-and-thrust belt continued to grow, the foreland basin system filled with sediments and marginal marine to fluvial deposits prograded eastward across the basin by early Paleogene time.

Laramide Orogeny

Although the Laramide orogeny (ca. 80–40 Ma) can be considered an extension of the Sevier orogeny in terms of geodynamic processes (mountain building related to ocean-continent subduction), the character and expression of tectonic processes affecting the U.S. Cordillera during the Laramide orogeny are clearly distinct from previous episodes. The Laramide orogeny is fundamentally related to shallowing of the subduction angle of the Farallon Plate, which is generally ascribed to subduction of an oceanic plateau and younger, hotter more buoyant crust that may have been a conjugate to the Shatsky and Hess oceanic plateaus in the northwest Pacific Ocean (Liu et al., 2010). The Laramide orogeny takes its name from the "Laramie series," a lithostratigraphic term used in reference to coal-bearing nonmarine strata that lie above fossiliferous marine Cretaceous rocks in the Rocky Mountain region. Basement-involved uplifts associated with moderately to steeply dipping reverse faults that root into the deep crust are found throughout the area previously occupied by the Sevier foreland basin, which as a result has been called a "broken foreland province" (Fig. 6). The 'thick-skinned' structural style (also referred to as "Laramide-style") is dramatically different from the contemporaneous "thin-skinned" style of the Sevier fold-and-thrust belt (Yonkee and Weil, 2015). A series of relatively deep Laramide sedimentary basins formed adjacent to the basement-involved uplifts by flexural loading (Lawton, 2008). Unlike the older retroarc foreland basin deposits, depositional environments in the Laramide basins were entirely continental and include lacustrine, fluvial, and alluvial fan settings. The position of the Laramide uplifts and basins have been used to infer the geographic range of low-angle or flat-slab subduction from southwestern Montana to central New Mexico. However, no consensus has been reached on the exact mechanisms linking flat-slab subduction to Laramide-style deformation.

Low-angle subduction of the Farallon Plate during the Laramide orogeny resulted in subduction erosion and underplating of trench, accretionary complex, and forearc basin material (mainly quartzofeldspathic sediment derived from the magmatic arc) beneath southern California and southwestern Arizona. These rocks, called the Pelona, Orocopia, and Rand Schists, are now exposed in a series of tectonic windows associated with Cenozoic extension (Jacobson et al., 2011) (Fig. 6). Low-angle subduction also caused the Sierra Nevada and Peninsular Ranges magmatic arcs to shut-down around 80 Ma. At this point, continental arc magmatism migrated eastward through the Great Basin and Rocky Mountain regions, presumably following the trajectory of the more shallowing-dipping Farallon Plate. In the southern U.S. Cordillera, magmatism associated with the Laramide orogeny is found as far east as the Big Bend area of Texas (Chapman et al., 2018). Hydrated and metasomatized mantle xenoliths from the Colorado Plateau have been interpreted to be related to subduction of the Farallon Plate (Li et al., 2008).

The southern Andean orogenic system is commonly proposed as a present-day analogue for the Late Cretaceous-early Paleogene Laramide orogeny of western North America. Subduction of the Juan Fernandez Ridge (a seamount chain) is occurring at a low-angle and corresponds to a gap in the chain of Quaternary volcanic centers in the western part of the orogen and to an area of basement-involved uplifts (Sierras Pampeanas) in the eastern part of the orogen (Ramos et al., 2002).

Post-Laramide, Early Cenozoic Magmatic and Tectonic History

The post-Laramide Cenozoic history of the Central Cordillera is characterized by new patterns of magmatism and tectonic strain. The through-going tectonic belts, which characterized late Mesozoic time, were replaced by domains of extension, contraction, and strike-slip deformation.

During mid-Eocene time a broad belt of magmatism extended from southern British Columbia into central Idaho and northwestern Wyoming, and a roughly contemporaneous zone of magmatism existed in southernmost Arizona and New Mexico and extended farther south into Mexico (Sierra Madre magmatic zone). These zones of Eocene magmatism were separated by a broad amagmatic corridor in the west-central United States that became the site of a large, middle Eocene lake system. Accompanying the mid-Eocene magmatism in the Pacific Northwest, metamorphic core complexes developed in areas of large-magnitude crustal extension (Armstrong, 1982). Typical complexes are characterized by a hanging wall of upper-crustal rocks, sometimes including syntectonic volcanic and sedimentary deposits, separated from a footwall of mid-crustal igneous and metamorphic rocks by a plastic-to-brittle, normal-sense shear zone. Younger rocks are commonly structurally emplaced upon older rocks, and brittle deformation features, including low-angle detachment faults, are superposed on the crystal-plastic deformation of the normal-sense, mylonitic shear zone. This northern belt of magmatism and accompanying localized, large-magnitude crustal extension migrated southward in late Eocene and early Oligocene time. Initiation of core-complex development in the eastern Great Basin was later than in the Pacific Northwest, and large-magnitude crustal extension continued into the early Miocene in the Ruby-East Humboldt and Snake Range core complexes (eastern Nevada). Also, numerous examples of Miocene core-complex development are well documented from southeastern California across southern Arizona and into Sonora, Mexico. Still younger examples of core-complex development (late Miocene to Pleistocene) are present in other areas of large-magnitude extension in the Central Cordillera such as the ongoing rifting of continental crust in the northern Gulf of California, Mexico, and Salton Trough, California.

During the late Eocene through early Miocene, enormous amounts of volcanic ejecta erupted as ash-flow tuff sheets in the Great Basin (Nevada and western Utah). This "ignimbrite flareup" has significant implications for the crustal composition of the Great Basin, including substantial mafic magmatic intra- or underplating of the extended crust of the region. Volcanic ash from these enormous eruptions spread eastward in the upper atmosphere and formed a conspicuous air-fall component in post-Laramide, late Eocene to Miocene strata of the Rocky Mountains (especially in Wyoming and environs). By early Miocene time, the northern and southern magmatic zones had merged, and a continuous Neogene magmatic arc could be traced from the early Western Cascades arc into the Mojave-Sonoran volcanic zone.

The final collapse of the Mesozoic orogenic plateau (i.e., Nevadaplano) began at ca. 16–17 Ma and continued to 10–12 Ma (Colgan and Henry, 2009). The modern Basin-and-Range physiographic pattern, characterized by widely spaced high-angle normal faults, began to develop at ~10 Ma and continues to the present.

Elevations on the Colorado Plateau approximately range from 1.5 to 3.5-km with the highest elevations typically associated with igneous centers such as the San Francisco volcanic field in northern Arizona. In deep canyons (e.g., Grand Canyon) the elevation is considerably <1.5 km. The average elevation of the plateau is ~2 km, and the crustal thickness is ~45 km. Stratified rocks exposed on the Plateau indicate that the area was near sea level for much of the Phanerozoic and uplift occurred after the deposition of Upper Cretaceous marine sedimentary rocks. The western and southern margins of the Plateau are delineated by normal-fault systems related to the Basin and Range Province, whereas its northern and eastern margins merge into the eastern Rocky Mountains. The southeastern margin of the Colorado Plateau in central New Mexico is delineated by normal faults related to the Rio Grande rift. The processes that facilitated uplift of the Colorado Plateau remain controversial, as well as the age or ages of uplift. One tectonic model relates the uplift of the plateau to eastward, intracrustal flow toward the Colorado Plateau from the overthickened, Sevier hinterland (now part of the Basin and Range Province) (McQuarrie and Chase, 2000). Another model argues for uplift related to lithospheric attenuation as a byproduct of shallow-dipping subduction associated with the Laramide orogeny. Still other tectonic models favor a polyphase uplift history: initially during the Laramide orogeny and subsequently in the late Cenozoic as part of a regional uplift, including the Southern Rocky Mountains and Great Plains. Clearly, the cause of the uplift of the Colorado Plateau remains a major unresolved problem in Central Cordilleran tectonics.

As the San Andreas fault (transform) system developed off the west coast of Mexico, and the triple junction between the North American, Pacific, and Juan de Fuca Plates (Mendocino triple junction) migrated northwestward, the Neogene magmatic arc was shut off at its south end. In a broad area, east of the late Western Cascade arc, the Columbia River flood basalt province developed between ~17 and 14 Ma. Basaltic dike swarms of this age are present in north-central Nevada and indicate the initiation of rifting in that area that eventually produced the late Cenozoic Basin and Range Province.

Late Cenozoic Tectonic/Volcanic Systems and Seismicity

The late Cenozoic tectonic evolution of the Central Cordillera is dominated by four large-scale, tectonic and/or volcanic systems: (1) San Andreas (transform) fault and northwestward migration of the Mendocino triple junction, (2) crustal extension in the Basin and Range Province and Rio Grande Rift, (3) northeast-propagation of the Yellowstone hotspot track and concurrent northwest-propagation of the Newberry volcanic trend, and (4) Cascadia subduction zone and volcanic arc. The development of these features was in part concurrent, and elements of all four systems are presently active. A relationship between the San Andreas fault system and crustal extension in the Basin and Range Province has been suggested in several analyses of the late Cenozoic tectonic history of the Central Cordillera. However, effects associated with plate-boundary slip are only significant in the southwestern Basin and Range Province (e.g., Eastern California shear zone and Walker Lane belt). Late Cenozoic, regional crustal extension characteristic of the Basin and Range Province reflects the removal of the Farallon slab and subsequent asthenospheric upwelling coupled with northwest retreat of the Pacific Plate with respect to the interior of the North American Plate. At ~5 Ma, the Baja California Peninsula was rifted from mainland Mexico when the San Andreas fault system shifted inland from a former position on the Pacific side of the peninsula. The northwestern separation of Baja California from the mainland is an example of the interplate transfer of continental lithosphere.

The present-day seismicity of the Central Cordillera is concentrated in belts at least partly related to fundamental plate-tectonic boundaries (Fig. 7, after Drummond et al., 1982); these boundaries are either strike-slip or convergent. Off the western coast of Oregon, seismicity is related to the Cascadia subduction zone and Blanco fracture zone. Farther south in western California and offshore, the Mendocino triple junction and San Andreas fault system are the loci of present-day seismicity.

Other prominent belts of seismicity are within the North American Plate and include the Eastern California shear zone and its extensions into western Nevada (e.g., Walker Lane belt) (Fig. 7). The seismicity associated with this intraplate tectonic zone is interpreted as distributed strain associated with the plate-boundary zone. Still another prominent zone of intraplate seismicity is the Intermountain seismic belt (Fig. 7). It can be traced from southern Utah into western Montana and is particularly prominent in the Yellowstone National Park area. A segment of the Intermountain seismic belt follows the Wasatch line. This belt of seismicity reflects a combination of active normal faulting along the eastern margin of the Basin and Range Province (e.g., Wasatch front) as well as magmatism related to the Yellowstone hotspot.

Fig. 7 Present-day plate-tectonic setting of the Cordilleran orogen of western North America and adjacent northeastern Pacific Basin. ECSZ = Eastern California shear zone. Reproduced (but modified) with permission from Drummond, K.J., et al. (1982) *Pacific Basin sheet of plate-tectonic map of the circum-Pacific region (scale 1:20,000,000).* Tulsa, Oklahoma: American Association of Petroleum Geologists.

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