Plate-Tectonic Evolution of the Western U.S.A.

by Warren Hamilton

Changing interactions of lithospheric plates provide the framework for this overview of the 3.1 Ga geological history of some 3 million km² of mountains, deserts, plateaus and plains. The author traces the Precambrian to Neogene development of the Western U.S.A. in terms of plate collisions, subduction events, and deformation of lithospheric slabs, with some interpretations based on his work in southeast Asia and other regions of complex tectonics.

Introduction

The rocks of the western U.S.A. are well exposed in many regions (Fig. 1), and spectacular geological relationships are common. Relief is high, and all states from the Rocky Mountains west have peaks higher than 3800 m, except 3400 m in Oregon. The landscapes are in large part relics from the cooler, wetter climates of the Pleistocene when climatic zones were displaced 500-1000 m below their present altitudes, or to comparable extents southward. The relics are most obvious in the glacial landscapes of mountains, but most alluvial fans of the hot southern deserts were also initiated largely under open grass-and-woodland conditions.

Precambrian Basement

Archean rocks (2.6-3.1 Ga) crop out in uplifts of latest Cretaceous and Cenozoic ages in Wyoming, southwestern Montana, and elsewhere (see Reed, this issue, and especially his Fig. 1). Upper crustal granite-greenstone belts and subjacent gneisses occur in southern Wyoming, whereas northern Wyoming and Montana assemblages consist mostly of rocks eroded to midcrustal levels - granites, tonalitic and felsic gneisses, and amphibolite-facies metasediments.

From Colorado and New Mexico west to California, the exposed Precambrian is comprised mostly of mid-crustal Proterozoic gneisses and granites (1.4-1.8 Ga). This terrain is a poorly understood collage of collided oceanic island arcs overprinted by continental magmatic arcs and complicated by rifts and perhaps by anorogenic magmatism. The magmatic rocks, however, display in their isotopes no incorporation of Archean felsic material. The northernmost Proterozoic terrain was thrust onto the Archean craton at about 1.7 Ga, as the ocean between them closed by southward subduction, and Early Proterozoic miogeoclinal strata deposited on the southern margin of the Archean subcontinent were then thrust northward. Exceedingly thick clastic strata deposited in the Middle Proterozoic Belt basin are broadly exposed in northwest Montana and northern Idaho.

Rifting and the Cordilleran Miogeocline

Structures within the Archean and Proterozoic terrains trend generally west-southwestward toward truncations at a continental margin created by rifting in Late Proterozoic time. The western limit of Precambrian crust trends from the central Sierra Nevada to western Idaho; all continental crust west of that was added by tectonic and magmatic processes in Phanerozoic time. The present location of the missing Precambrian subcontinent is not known.

Syn-rift strata, known best in eastern California, were deposited in local basins. By latest Proterozoic time a continental-shelf wedge of mostly clastic strata, including

widespread but stratigraphically limited glacial sediments, was being deposited. Clastic-shelf sedimentation continued through the Early Cambrian, with younger strata transgressing farther inland onto the cratonic basement. The continent had moved into lower latitudes by Middle Cambrian time, and shallow-water strata of the rest of the lower and middle Paleozoic are mostly carbonate rocks, except in near-source environments.

Continental shelves of latest Proterozoic and Cambrian ages virtually ring North America (see Bally, this issue). The continent and the oceanic lithosphere attached to it thus formed a large, slow-moving plate, away from which moved faster plates that converged by subduction and collision to form the Gondwana megacontinent. During Middle Ordovician and later Paleozoic time, the eastern side of North America was subjected variously to arc-continent collisions, subduction, and continent-continent collisions (see articles by Rodgers, and Sheridan, this issue).

Subduction can occur only beneath an advancing side of a plate, not beneath a retreating one, and the first major Phanerozoic deformation in the western U.S.A. followed the Late Devonian collision of North America and northern Europe and, presumably, a change in the direction of motion

Figure 1: Physiographic provinces of the western U.S.A. X - Major young volcanoes above subducted Gorda lithosphere.

Figure 2: Selected tectonic elements of west-central U.S.A.

of North America. Stable-margin sedimentation ended in the west in Early Carboniferous time with the "Antler orogeny," when continental-rise and -slope rocks of early and middle Paleozoic ages were pushed relatively eastward

atop correlative shelf strata in Nevada and Idaho. The deep-water rocks may have been thrust ahead of an eastward-advancing island arc that collided with the continent, but that hypothetical arc did not then remain attached to the continent and may have migrated westward away from North America following the reversal of subduction consequent on this collision.

Figure 3: A section across the convergent plate margin of Middle Cretaceous central California. An accretionary wedge is exposed in much of the Coast Ranges, fore-arc basin in eastern Coast Ranges and Great Valley; and a magmatic arc in medial Sierra Nevada. The diagram incorporates data from dimensionally similar modern Sumatra, and concepts derived from study of crustal sections of various ages elsewhere.

Accretionary-wedge mélanges of Jurassic age are known along the length of the U.S. Cordillera, in southwestern California, western Sierra Nevada, Klamath and Blue

Late Carboniferous Shortening of the Craton

In Late Carboniferous time, a belt trending west-north-westward across what had previously been the craton of Colorado and Utah was moderately shortened to form broad basins and basement uplifts, including the Uncompahgre uplift of Colorado known to be bounded by major reverse faults. From these uplifts were derived thick red beds that grade out into marine strata and dominate the Upper Carboniferous and Lower Permian sedimentary record of the western interior. The crustal shortening likely was a by-product of the collision of Africa plus South America with the south edge of North America.

Early Mesozoic Convergent-Plate History

The Triassic and Jurassic history of the far west was dominated by subduction-related geology (Fig. 2). A variety of structural and magmatic complexes apparently record complex interactions of plates like those of modern East Asia and the western Pacific, where many large and small interacting plates have fast-evolving and highly varied boundaries.

Upper Paleozoic shallow-water strata accumulated on the eroded remnants of the Carboniferous Antler complex, and in Early Triassic time coeval volcanic and sedimentary rocks of the ocean floor were thrust eastward upon them in western Nevada during the "Sonoma orogeny." The eastward-migrating oceanic island arc, which collided with the continent to produce the deformation, this time remained attached and is now exposed in northwest Nevada and the eastern Klamath Mountains.

During the later Triassic and earliest Jurassic there were island arcs offshore, and within Late Triassic time there was subduction beneath the continent, for arc granites of that age are present in inland California, and voluminous silicic volcanic ash was dispersed to the interior southwest. Much later, Jurassic plate consumption was accommodated beneath island arcs somewhere offshore, but intermittent subduction beneath the continent is recorded by granites and voluminous coeval ashflows.

The Klamath Mountains and western Sierra Nevada display composite Jurassic island arcs, which were partly assembled offshore in the manner of the modern Philippine Islands, by arc-arc collisions, and the aggregate collided with the continent in Late Jurassic time ("Nevadan orogeny"). The arcs are exposed mostly as low-grade metamorphic assemblages of variably spilitized (enriched in Na and depleted in Ca by seawater hydrothermal reactions) basaltic, andesitic, and dacitic volcanics and volcanoclastics intruded by petrologically primitive plutons. Arc substrates are exposed, for example in western Idaho and northwest Washington, as terrains dominated by tonalitic, amphibolitic, and trondhjemitic gneisses.

Mountains, western Idaho, and northwestern Washington. Some mélanges contain shredded bits of atolls bearing western Pacific, near-equatorial Late Carboniferous and Permian faunas such as those found in Jurassic mélanges in western Canada, northeast Asia, Japan, New Zealand, southern Chile, and Tethyan regions. These faunas are both paleoclimatically and paleobiogeographically out of place with respect to all but the Tethyan continents against which they are accreted. In the Early Mesozoic, more than 10,000 km of paleo-Pacific lithosphere was subducted beneath North America, and beneath intervening island arcs subsequently added to North America. Additional oceanic lithosphere generated at intervening spreading centers and behind migrating island arcs must also have been subducted.

Rifting during Triassic(?) time removed the southwest corner of the pre-existing continent from southern California and northwest Mexico. Another fragment was removed from western Idaho and north-central Washington. These rifted margins were engulfed by Cretaceous batholiths and are not well understood.

Cretaceous and Paleogene Subduction System

Westward-moving North America was enlarged by the Late Jurassic collision of composite island arcs, which previously had been a thick crustal mass on the front of an eastward-

Figure 4: The eastern edge of the Cathedral Peak granite (Late Cretaceous) north of Tioga Pass, sharp contact (arrows) of light granite is subparallel to foliation in dark metamorphic rocks, which range from upper Paleozoic metasediments to lower Mesozoic metavolcanics nearest the contact. The pluton, part of the Sierra Nevada batholith, is capped by its own volcanic ejecta.

moving paleo-Pacific plate. Convergence continued between continental and oceanic plates, and a new, east-dipping subduction system broke through west of the enlarged continent. Probably most subduction systems beneath continents are initiated similarly by reversals of subduction following collisions.

During Cretaceous and early Tertiary time there was continuous subduction of oceanic lithosphere beneath most of the western U.S.A. (Fig. 3). Beneath California and Oregon, the rate of convergence was moderate from about 135-75 Ma, much more rapid until about 40 Ma, then slower again. Convergence was at a large angle to the continental margin throughout this period. Interactions between the many plates involved large strike-slip components and continued into Cretaceous time in Washington, and into the early Tertiary in Canada.

During the 135-75 Ma period of convergence, subduction was moderately steep, and a steady-state tectonic and magmatic system operated. An accretionary wedge and a magmatic arc were produced along the continental margin, and a fore-arc basin formed between them along most of California. A strip of marginal-basin oceanic lithosphere, formed behind the eastward-migrating composite Jurassic arc, was left attached to the upper plate alongside California during the subduction reversal and so became the leading edge of the overriding continental plate of Cretaceous time.

This oceanic lithosphere is exposed as a thick ophiolite sheet in the Coast Ranges, and forms the basement beneath the western Great Valley (Figs. 2, 3). Basal strata on the ophiolite are Upper Jurassic abyssal turbidites, which pre-date the collision and subduction reversal. Cretaceous and Paleogene strata postdate reversal and record deposition in a longitudinal basin in which water was initially deep but gradually became shallower as sedimentation progressed until a shelf developed atop a structural basin.

Structurally beneath the ophiolite in the Coast Ranges lies a vast tract of accretionary-wedge *mélange* (Fig. 3), the Franciscan Complex, which is exposed onshore as mostly Cretaceous (Paleogene in northern California). Here, deep-water clastic sediments are shredded to lenses of resistant sandstones in scaly-clay matrixes, and there are also slabs of less-disrupted strata. Voluminous polymict *mélange* contains, in scaly-clay matrixes, lenses of ophiolite, abyssal pelagic sediments, and high-pressure metamorphic rocks. The *mélange* also encloses fragmented seamounts and atolls conveyed in from more southern latitudes.

All fossiliferous rocks are of Jurassic and younger ages, so probably no pre-Jurassic seafloor was subducted. High-pressure metamorphic rocks (jadeitic metagraywacke and low-grade blueschist) form coherent tracts beneath eastern exposures of the Coast Range ophiolite. Higher grade rocks, including eclogite, garnet amphibolite, high-grade blueschist, occur as fragments in the *mélange*. The strata deposited atop the ophiolite are barely metamorphosed, and the mode of transport of the high-pressure metamorphic rocks upward to their present structural positions beneath the ophiolite is unclear.

The Cretaceous magmatic arc (about 135-80 Ma) is represented by a batholithic belt in Baja California, western Mojave Desert, Sierra Nevada, northwestern Nevada, Idaho, and northern Washington, and by a strip displaced north-westward along the late Neogene San Andreas fault in the California Coast Ranges (Fig. 2). The distance of the batholiths inland from correlative accretionary-wedge complexes indicates a moderate inclination of the then subducting oceanic lithosphere (Fig. 3). At any one time, Cretaceous magmatism in the California batholiths was limited to a narrow belt, with successive belts becoming younger eastward. Isotopic signatures of eastern plutons

Figure 5: Selected tectonic elements of western interior U.S.A. Most uplifts and basins indicated are Laramide (very Late Cretaceous and early Paleogene). Outcrops of Precambrian basement rocks east of foreland thrust belt and north of southern Basin and Range province are shaded. For explanation of double circle see text.

indicate that their magmas incorporated much old continental crust, or sedimentary rocks derived from such crust, whereas western plutons were emplaced in island arcs and other complexes that had been accreted to the continent during Triassic and Jurassic time.

The Cretaceous batholiths are exposed at varying depths of erosion. Shallow rocks are mostly tonalite and mafic granodiorite in the west, felsic granodiorite and adamellite in the east; mid-crustal rocks typically are tonalitic gneisses in the west, migmatites and hydrous-magma adamellites in the east. The Sierra Nevada batholith is exposed mostly at upper-crustal levels. Its great plutons reached the surface and were capped by caldera complexes (Fig. 4), but sub-jacent gneisses and locally granulites are exposed in the south. The Idaho batholith is eroded entirely to mid-crustal

levels. The Baja California batholith widely preserves its volcanic cover in the west but is eroded to mid-crustal levels in the east.

The preservation of the thin, ophiolitic leading edge of Cretaceous California (Fig. 3) demonstrates that the continent was not crumpled against oncoming Pacific lithosphere. Subduction does not represent sliding down a slot fixed in the mantle; a Benioff seismic zone represents a position, not a trajectory, of a subducting plate that sinks beneath an overriding plate as the subduction hinge migrates oceanward. The regime above a subducting plate is commonly one of extension or neutrality, not shortening. Depending on the extent of the mantle component in rising arc magmas, the crust may be thinned or thickened in continental magmatic arcs, and the surface may be at sea level or far above it. Nearly steady-state subduction at moderate rate is recorded by the Cretaceous geology of the Western U.S.A. and by analysis of sea-floor-spreading geometry.

Foreland Fold-and-Thrust Belt

During middle to Late Cretaceous and early Paleogene time, eastward-thinning strata of the western interior were imbricated eastward onto the craton, and a foreland fold-and-thrust belt formed (Fig. 5). From southern Nevada to southern Montana, the affected wedge consisted of the continental shelf of latest Proterozoic and Paleozoic strata plus overlying and frontal basin deposits. In northern Montana, the wedge was that of the eastern part of the thick Middle Proterozoic strata of the Belt basin, and the thrust belt extends far to the east of the limit of Paleozoic shelf strata. Overthrust, imbricate and compressional structures, varying widely with the competence of stratigraphic units, formed within the thickening and eastward-spreading tectonic wedge. The cratonic basement beneath the eastern part of the sliding wedge was unaffected, and its surface sloped upward to the east.

As the wedge thickened and expanded eastward with time, it developed a convex upper surface. Thrusting was a response to gravitational spreading due to crustal thickening farther west, but the cause of that thickening is debated. As most of the thrusting occurred during the middle and late part of the great Cretaceous batholiths time of growth, and since shortening structures are continuous from batholiths to thrust front, arc-magmatic crustal thickening can be invoked as the driving mechanism. By analogy with active thrust belts such as those of the central Andes and medial New Guinea, the surface of the magmatic arc at this time may have been at an altitude of 4 km or so.

In southeastern California and southwestern Arizona no stratal wedge was present for the continental shelf to the west had been removed by Triassic(?) rifting, and no thrust belt formed inland from the Cretaceous batholith. Lesser thrusting occurred in eastern California and Nevada during Late Triassic(?) and Jurassic time. Except in northern Montana, the thrust belt has been greatly disrupted by Cenozoic extensional faulting and rotations.

Laramide Tectonics

Plate interactions changed late in Cretaceous time, and very different tectonic patterns resulted. North of Oregon, a fast-moving eastern Pacific plate was being subducted obliquely with a large right-slip component, whereas in Californian latitudes a different eastern Pacific plate was being subducted more directly. Overriding of oceanic lithosphere by the continent here was uncommonly rapid between about 75 and 40 Ma. In this southern sector, continental arc magmatism ceased in the western batholithic belt and diffused eastward as far as Colorado. Many unusual tectonic features accord with the inference that the continental lithosphere was eroded from below against hot, young oceanic lithosphere that could not sink fast enough to get out of the way of the rapidly advancing continent.

The best-understood product of this interaction is the Laramide crustal shortening of the Rocky Mountain region of the craton, from central New Mexico to Montana, during late Late Cretaceous and early Paleogene time (Fig. 5). The typical products of this deformation are large, asymmetric anticlines of Precambrian basement rocks, bounded on one or both sides by reverse faults or steep monoclines against deep basins that subsided and received sediments concurrent with rise of uplifts. Major uplifts and basins have lengths of 200-500 km and structural reliefs of 10 km. Individual uplifts were inaugurated at various times from early Campanian to Middle Eocene, but there was temporal continuity of shortening throughout the province as a whole.

Figure 6: Death Valley, southern California, looking SE. Foreground Panamint Mountains block is allochthonous above detachment fault at base of range. Western slope of Black Mountains front (left from center on far side of valley) is Pliocene normal fault rotated to gentle dip, from which upper-plate strata have been stripped.

Although minor deformation affected the Colorado Plateau and Great Plains, the major structures lie in a belt trending northward and widening through New Mexico into Colorado, where they splay out in successive arcs to the west across Utah and west-northwest, northwest, and north across Wyoming into adjacent states. Surface geology, reflection profiling, and oil-exploration drilling prove great basement shortening, increasing to the north and northwest as both the width of the belt and the number of major structures within it increase.

The shortening across the Rocky Mountains represents a rotation of the Colorado Plateau relative to the continental interior. The geometry of the compressive structures and of associated oblique-slip structures indicates that this rotation was about 4° clockwise relative to an Euler pole in or near central New Mexico (Fig. 5). This rotation is inferred to record a slowing of the southwest, by drag against subducting lithosphere, relative to the faster advancing interior of the continental plate. A subsequent clockwise rotation of the Colorado Plateau relative to continental interior by a lesser amount, about an Euler pole in central Colorado, is required by the middle and late Cenozoic opening of the Rio Grande rift.

That the continental plate was indeed eroded tectonically from beneath is indicated by windows through it in early Tertiary uplifts in southern California. Here, subducted oceanic sedimentary and ophiolitic rocks, metamorphosed near the end of Cretaceous time, are exposed with tectonic contact beneath Cretaceous and older middle-crust gneisses and granites and lower crust granulites. Cretaceous magmatic-arc rocks formed at depths near 30 km, some 70 km

above the subducting slab at the time of magmatism. These are in direct contact with younger subducted oceanic rocks, so something like 70 km of basal continental lithosphere must have been removed.

In the central Coast Ranges of California, a megathrust that places Cretaceous granites atop Cretaceous accretionary-wedge mélangé may have had a similar origin. In southwestern California, thick mylonite zones of latest Cretaceous age indicate imbrication of the middle crust there, likely as part of the same event. A zone 40–150 km north-east of the lithosphere windows underwent severe metamorphism, deformation, and hydrous-granite invasion at this time, perhaps as a result of voluminous hot water released from the subducted sediments.

Middle and Late Cenozoic Tectonics

Oceanic lithosphere of several plates formed east of the East Pacific Rise was subducted continuously beneath the U.S.A. during Cretaceous and early Paleogene time. Convergence was faster than spreading, and early in the Oligocene the junction between the rise and the great Mendocino transform fault intersected the trench off northern Mexico. As spreading continued north and south of the intersection, the Pacific plate, west of the rise, was enlarged toward the continent, whereas eastern oceanic plates were progressively subducted. The Pacific plate has continued to move northwest relative to the U.S.A., and the result of the plate interactions has been the formation of a right-lateral strike-slip boundary, between the Pacific and North American plates, that has lengthened with time (see Crowell, and Stone and Wallace, this issue).

The western states have been greatly extended in diverse structural modes during Eocene through Quaternary time. In the Basin and Range province (Fig. 2), middle Tertiary extension orthogonal to the continental margin followed and accompanied widespread crustal heating by silicic and hybrid arc-extensional magmatism. Late Basin Range extension has been directed northwestward relative to the continental interior. Structures originating in the middle and upper crust are widely exposed, and are similar for both the early and late sets, accommodating a doubling in width of the province.

Brittle upper-crust blocks rotated above gently inclined master faults (detachments), and rose isostatically as they were unloaded, stranding range-size blocks above them while slip continued on still-dipping segments (Fig. 6). Exposed structures become increasingly ductile in sequence from gouge, chloritic microbreccia, mylonite, to mylonitic gneiss as their depth of formation increases. Seismic reflection profiles support the inference that the middle crust spreads by the separation of lenses bounded by ductile shear zones beneath the ramp systems of the brittle upper crust, whereas the deep crust flattens in a pervasive ductile mode. Much basaltic magma from the mantle, melted by the loss of pressure consequent on extension, was added to the deep crust. Some also reached the surface, but secondary crustal melts are more widespread as erupted materials.

The Snake River Plain is an eastward-propagating rift filled by volcanic rocks (Fig. 1, 5). Little if any continental crust remains beneath its mature medial parts. Melts erupted early during the extension of each sector are mantle basalts, followed by secondary crustal-melt rhyolites, and last by more mantle basalts. The high east end of the province, the Yellowstone Plateau, is now in the crustal-melt stage. Late Quaternary caldera eruptions of rhyolitic ashflows and lavas have been extremely voluminous, and a large magma chamber is still present here at shallow depth.

Elsewhere, rifting broke the continental crust rather than merely thinning it. New oceanic lithosphere is now forming in the Gulf of California, whereas in the onshore California end of the rift, sedimentation maintains a sediment surface

near sea level atop an oceanic spreading center (see Crowell, this issue). The broad tract of isotopically primitive Neogene basalts in southern Oregon and northeastern California (Fig. 2) fills a complex rift and has itself been further stretched in a basin-and-range mode. The Miocene basalt of the Columbia River plateau of northeastern Oregon and southeastern Washington fills another gap.

As late as Oligocene time, the Klamath Mountains were against the northern Sierra Nevada and northwestern Nevada (which then lay much farther east relative to the continental interior) and were connected to the Blue Mountains (Fig. 1), which in turn lay against the southern Idaho batholith. Much of this Neogene deformation represents adjustments of the shape of the continent to the transform boundary between the North American and Pacific plates (see Crowell, this issue).

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