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NATURE AND CONTROLS OF CORDILLERAN OROGENESIS, WESTERN UNITED STATES: EXTENSIONS OF AN EARLIER SYNTHESIS

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ABSTRACT. Portions of an earlier synthesis of Cordilleran tectonics (Burchfiel and Davis, 1972) have been amplified in this companion paper. Special attention is directed to (1) the timing and nature of Precambrian pre-geosynclinal rifting, (2) an expanded model for the Antler and Sonoma orogenies, (3) crustal ductility controls on localization and style of Mesozoic and Early Cenozoic thrust faulting, and (4) the origin of Laramide basement uplifts in the Rocky Mountains.

The history of the Cordilleran orogen begins with an inferred event, the late Precambrian rifting of a proto-North American continent and the subsequent drifting away of the western fragment (using present geographic orientation). Dispute exists as to whether rifting occurred prior to deposition of the late Precambrian Belt-Purcell Supergroup or before deposition of the latest Precambrian Windermere Group and younger geosynclinal strata. The possibility is raised here that the two sedimentary sequences represent separate rifted margin accumulations and that two periods of fragmentation and drift, not one, may have modified the continental margin in late Precambrian time.

By the beginning of Cambrian time a clastic sedimentary wedge had formed across a coupled continent-ocean boundary from shelf to deep-sea floor. A major change occurred in Middle Ordovician paleogeography with the formation offshore of a Klamath-Sierran island arc and the attendant entrapment of a marginal basin between arc and continent. The Antler and Sonoma orogenies of north-central Nevada are interpreted in the broader context of accelerated plate convergence in the arc region and the marginal basin during Late Silurian to Early Mississippian and Permo-Triassic time respectively. It is proposed that two-stage closure of the marginal basin occurred along its eastern margin by eastward subduction of oceanic crust beneath the continent and by eastward obduction of the basin's volcanic and sedimentary fill atop the continental shelf (Roberts Mountains and Golconda allochthons). Episodic subduction beneath the continental margin is indicated by short-lived periods of arc-type volcanism east of that margin soon after emplacement of Antler and Sonoma thrust plates.

Mesozoic and Early Cenozoic structures in the United States portion of the Cordilleran orogen are the product of subduction tectonics and the development of an Andean-type magmatic arc along the western edge of the American plate. This plate margin had been strongly modified by accretion of the Klamath-Sierran arc in northern areas during the Sonoma orogeny and by truncation of Paleozoic structural and stratigraphic elements in southern areas during a Late Permian or Early Triassic period of continental rifting and drift. Thrust faulting along the western plate boundary can be attributed largely to eastward subduction of an oceanic plate or plates beneath the continent. Accretion of oceanic, arc, and continental margin deposits to the continent progressed generally westward, so that thrust faults are progressively younger in that direction. Heat added to the leading edge of the American plate by magmatism produced a marginal zone of high ductility relative to eastern portions of the plate. During convergence of the oceanic and North American plates the more rigid part of the latter plate moved westward into and beneath this ductile zone to produce eastward-yielding, intracontinental thrust faults. Eastward migration of thrusting east of the arc was related to an eastward shifting in time of plutonism and regional metamorphism and. hence, the eastward shifting of the zone of high ductility contrast across which yielding occurred. The geometry of east-directed thrust faulting was also influenced by the presence of west-thickening wedges of sedimentary rocks, including those of the Precambrian Belt-Purcell Supergroup, the late Precambrian-Paleozoic Cordilleran miogeosyncline, and the Mesozoic Mexican basin, although thrusting is no less well-developed in the cratonal terrane of Arizona and southeastern California where "geosynclinal" sedimentation did not occur.

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In Late Cretaceous (early Laramide) time, approximately 75 m.y. ago, the pattern of underthrusting changed along the margin of the North American plate, and a gap in magmatic activity developed in the plutonic belt of California, Nevada, and Utah as plutonism shifted eastward from this region. Although magmatic and tectonic activity continued along earlier patterns in areas north and south of this gap, Late Cretaceous thrust faulting ceased in the latitude of the gap. A temporal and spatial coincidence is observed, however, between eastward shifting of Laramide igneous activity and the development in the Rocky Mountains region of basement uplifts—a coincidence that suggests to us that the magmatic and tectonic phenomena are related. Laramide plutonism within the lower crust of this cratonal region increased its ductility. The basement uplifts are attributed to compressive shortening of the thermally-weakened craton in response to intraplate stresses generated by plate convergence. The basement uplifts are thus interpreted as a fundamental part of the Cordilleran orogen related to subduction along a plate margin 1000 to 1500 km farther west. Intraplate yielding in the region of uplifts was transferred at its northern and southern ends to segments of the Laramide fold and thrust belt farther west, probably by diffuse zones of strike-slip faults. The great differences in Laramide structural style reflect areal differences in crustal character (crustal thickness, prior depositional, tectonic, and magmatic histories) and changing patterns of crustal ductility engendered by subduction-related magmatism.

INTRODUCTION

In 1972, Burchfiel and Davis published a synthesis of the Cordilleran orogen entitled "Structural framework and evolution of the southern part of the Cordilleran orogen, western United States". This companion paper builds on that synthesis and draws on much new data published since that time. Special attention is given herein to (1) the timing and nature of Precambrian pre-geosyncline rifting, (2) an expanded model for the Paleozoic Antler and Sonoma orogenies, (3) crustal ductility controls on localization and style of Mesozoic and Early Cenozoic thrust faulting, and (4) the origin of Laramide basement uplifts in the Rocky Mountains.

PRECAMBRIAN RIFTING

The history of the North American Cordilleran mountain system begins with an inferred event, the late Precambrian rifting of a proto-North American continent along a line generally parallel to but inland from the present western continental margin; rifting was followed by subsequent drifting away of the western fragment (using present geographic coordinates). Direct structural evidence for this event is lacking, and its timing is in dispute. Gabrielse (1972) has presented a strong case that Belt-Purcell strata in Canada represented a continental terrace wedge of Atlantic or miogeosynclinal (miogeoclinal) type. This sedimentary wedge was presumably deposited along a rifted continental margin after a rifting event bracketed in time between the oldest ages of Belt sediments (1400-1450 m.y.b.p.) and the youngest ages of crystalline basement beneath them (1600-1700 m.y.b.p.). This view is contested by Stewart (1972), who regards continental rifting and separation as post-Belt in age, occurring at some time after 850 m.y.b.p. and before deposition of the latest Precambrian Windermere Group and similar Lower Cambrian strata as a clastic wedge across the rifted continental margin.

Pre-Belt rifting is given support by the preservation in the western United States of Belt and presumably equivalent strata in elongate troughs or basins which may have originated as aulacogens transverse to a rifted continental margin (Hoffman, 1973; Burke and Dewey, 1973). The Belt trough in western Montana, northern Idaho, northeastern Washington, and southern Canada trends northwest to north-northwest (Harrison, 1972) and may have been flanked both to the northeast and southwest by older basement rocks (Armstrong, 1974); only the southeastern part of this trough is shown in figure 1. Farther south in the Uinta Mountains area of Utah and Colorado is another thick sequence of Precambrian strata, possibly equivalent to Belt sediments in age, which was deposited in an east-west trending trough (Crittenden and others, 1971). Recently, Wright and others (1974) have suggested that Precambrian sedimentary rocks of the Pahrump Group in southeastern California were deposited in a fault-bounded west-northwest trending trough. They believe that the Pahrump rocks may be of "Beltian" age, but this age assignment has not been substantiated.

The existence of three possible Belt-age aulacogens in the western United States implies the existence of an accompanying rifted continental margin somewhere to the west. Younger Precambrian (Windermere Group) to Middle Cambrian sedimentary rocks form a westward-thickening clastic wedge that rests disconformably and unconformably atop the older Precambrian sedimentary rocks in all three transverse basins (Stewart, 1972). It is not yet clear whether these younger sedimentary rocks of the Cordilleran miogeosyncline represent evolution of the older Belt-Purcell continental terrace wedge or, alternatively, indicate the occurrence of a second, post-Belt, pre-Windermere episode of continental rifting. The first alternative appears much less probable. In Canada, times of Belt-Purcell and Windermere sedimentation were separated by the East Kootenay (British Columbia) and Racklan (Yukon Territory, Mackenzie Mountains) orogenies. These poorly dated and incompletely understood events may be correlative. They were accompanied in some areas by regional metamorphism of greenschist to sillimanite grade and by open to tight folding of Belt-Purcell strata. The contact between Belt-Purcell and overlying Windermere or equivalent strata is typically unconformable, with discordancies up to 45° in East Kootenay-affected areas and at even greater angles in the Mackenzie Mountains. In this latter area Windermere deposition was preceded by regional doming, block faulting, and mafic intrusion (Douglas, 1968; Gabrielse, 1972), all suggestive of continental rifting.

Two continental terrace wedge accumulations, Belt-Purcell Supergroup and Windermere Group and conformable Paleozoic strata (the Cordilleran miogeosyncline), may require *two* periods of continental fragmentation and drift. This extremely interesting problem remains unresolved. Whether initial Precambrian rifting was pre-Belt or pre-Windermere, it is accepted here that by the beginning of Cambrian time the western margin of the North American continent was the site of a clastic sedimentary wedge which extended across a coupled continent-ocean boundary from shelf to deep-sea floor.

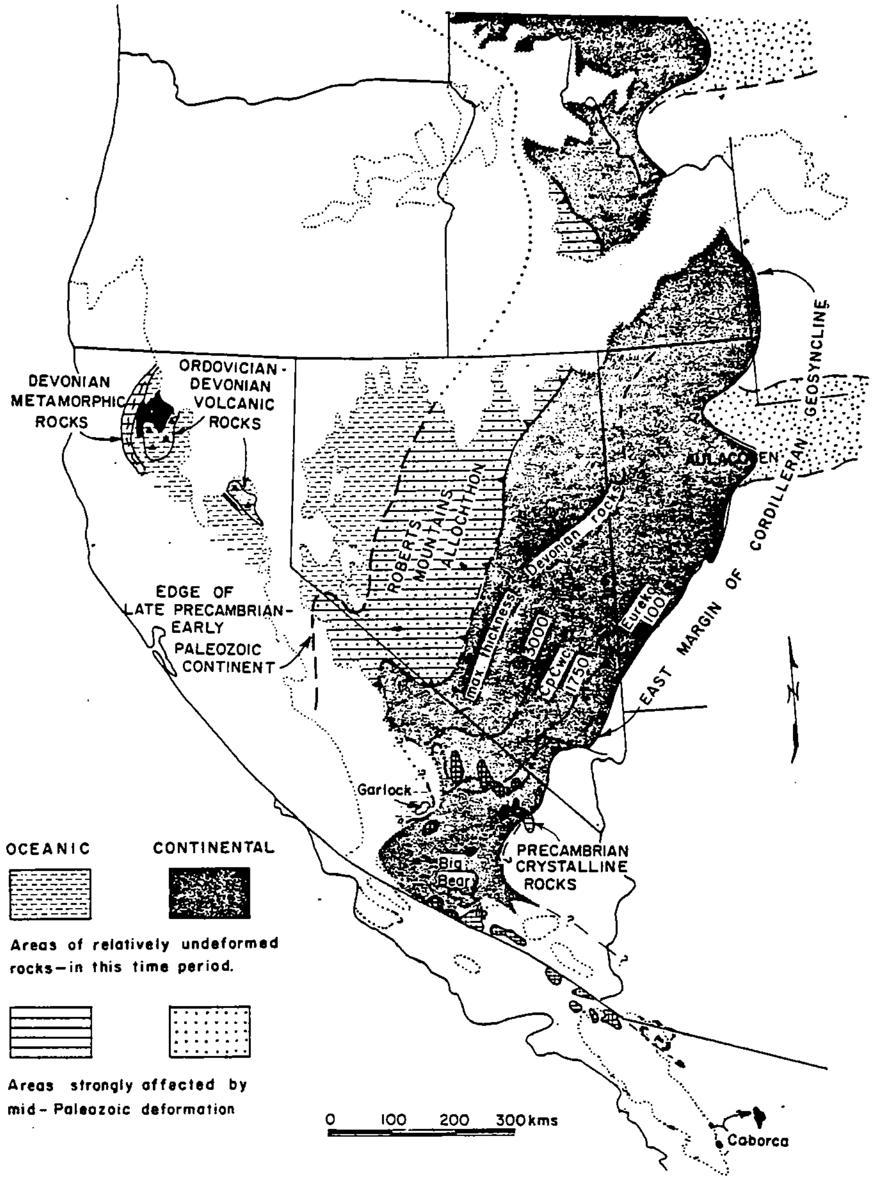

Fig. 1. Sketch map of late Precambrian through Devonian paleogeography and areas affected by Mid-Paleozoic deformation. On all paleogeographic maps, the only deformation eliminated is right-lateral displacement on the San Andreas fault. Right-lateral displacements in southern Nevada have not been removed. Isopach lines are from Poole and others (1967) for the maximum thickness of Devonian rocks, Stewart (1970) for the 900 and 530 m (3000 and 1750 ft) isopachs in the Precambrian-Cambrian Wood Canyon Formation, and Ross (1964) for the 30 m (100 ft) isopach in the Eureka Quartzite. Dotted areas east of the geosynclinal boundary are sites of possible Belt-age aulacogens. Black areas are exposures of ophiolites.

OCEANIC SETTING OF THE PALEOZOIC "EUGEOSYNCLINE"

As discussed below, the so-called "Cordilleran eugeosyncline" is seen to be a composite terrane consisting of varied paleogeographic elements. Assemblages of Paleozoic sedimentary and volcanic rocks in the "eugeosyncline" of California and Nevada have come from such diverse depositional settings as the continental rise, one or more marginal basins, a volcanic island arc and its migrating trench, and the deep ocean basin itself. Carbonate sedimentation characterized the shelf miogeosyncline after Early Cambrian time, but offshore Cambrian and Ordovician "eugeosynclinal" deposits were predominantly cherts, basaltic volcanic rocks, shales (some graptolitic), and sandstones; Silurian and Devonian sequences are similar but apparently lack volcanic rocks. These rocks are collectively referred to as the siliceous assemblage in contrast to the carbonate assemblage of the shelf. They are known only from allochthonous sequences in the east-directed Roberts Mountains thrust plate of Late Devonian-Early Mississippian age.

Rutland (1973) has challenged our earlier interpretation (Burchfiel and Davis, 1972) that rocks in the Roberts Mountains allochthon were originally deposited on oceanic crust, and he suggests instead that they were deposited on thinned Precambrian continental crust. Our initial interpretation, based on the lithologic character of the siliceous assemblage, has been made even more creditable by the recent discovery in central Nevada of serpentinized peridotites associated with the Roberts Mountains allochthon (Poole and Desborough, 1973). Chemical and petrologic data from these rocks compare favorably with ultramafic rocks from known ophiolite sequences. In addition, chemical analyses from early Paleozoic volcanic rocks of the allochthon show that some of the rocks compare favorably with abyssal oceanic tholeiites (J. Rogers, personal commun., 1973). Other volcanic rocks have K_2O/SiO_2 ratios too high for their high MgO contents for them to be calc-alkaline volcanic rocks. They may be volcanic rocks from sea mounts, although this cannot be confirmed at present. Thus geological relations and geochemical data suggest to us that early Paleozoic "eugeosynclinal" rocks west of the autochthonous miogeosynclinal assemblage were deposited on oceanic crust.

A good case can be made that rocks of the siliceous assemblage initially deposited off the continental margin in an open ocean were deposited in a marginal or inner arc basin after the Middle Ordovician formation of an offshore island arc. In the eastern Klamath Mountains of northern California keratophyric volcanic rocks and younger, Upper Ordovician and Silurian shallow water sedimentary rocks (limestones, conglomerates, graywackes) lie above the Trinity mafic-ultramafic complex (Potter and Scheidegger, 1973; Rohr and Boucot, 1971). This complex has been dated as Early Ordovician (480 m.y.b.p.; Hopson and Mattinson, 1973) and interpreted as an ophiolite sequence of upper mantle and oceanic crust (Lindsley-Griffin, 1973). Cobbles derived from the complex are found in Upper Ordovician conglomerates, indicating uplift of the ophiolite sequence to a position above sea level by Late Ordovician time.

Uplift of the the ophiolite complex provided an oceanic crust-upper mantle basement for the Klamath island arc which is known to extend southward into the northern Sierra Nevada. Uplift is attributed to geanticlinal buckling of the sea floor adjacent to an incipient trench, believed here to have been situated to the west of the geanticlinal arc for reasons discussed below. Cretaceous formation of the Puerto Rican arc is considered to be an event closely analogous to formation of the Ordovician Klamath-Sierran arc (Donnelly and other, 1971; Mattson and Schwartz, 1971).

The width of the marginal sea trapped between the Late Ordovician Klamath-Sierran arc and the western edge of the North American continent is not known, although it was probably not great (less than 1000 km?). Siliceous pyroclastic rocks have been found in Silurian and Devonian chert-shale sequences of the siliceous assemblage (Roberts and others, 1958) and could only have come from Klamath and Sierran volcanic areas to the west where siliceous volcanism was occurring at that time.

ANTLER AND SONOMA OROGENIES

The Antler orogeny of Late Devonian-early Mississippian time has long been equated primarily with eastward emplacement of the Roberts Mountains thrust plate in north-central Nevada (fig. 1). Thrusting produced impressive telescoping in excess of 100 km of siliceous assemblage rocks atop carbonate assemblage rocks of equivalent age. The nature of the Antler event raises a number of important questions: (1) why did the orogeny occur?; (2) how was an assemblage of oceanic sedimentary and volcanic rocks moved up and across shelf sediments along the continental margin?; and (3) what has happened to the basement of oceanic crust on which the now allochthonous rocks of the Roberts Mountains plate were originally deposited? A broader view of the Antler orogeny is helpful in answering these questions. Devonian events in the Klamath-Sierran arc to the west indicate increased orogenic activity there also and suggest that emplacement of the Roberts Mountains thrust plate in Nevada was but one phase of an expanded Antler orogeny—extended in time and broadened in areal extent.

Regional metamorphism (greenschist to amphibolite facies) and the juxtaposition by thrusting of the Trinity ophiolite above probable oceanic crustal rocks (Salmon Hornblende Schist) and overlying sediments (Grouse Ridge Formation) are the major expressions of "Antler" orogeny in the Klamath Mountains (Davis, 1968). Metamorphism synchronous to thrust faulting has been dated as Early Devonian (380 m.y.b.p.; Lanphere, Irwin, and Hotz, 1968). Thrust faulting was west-directed on the basis of the vergence of overturned folds in metamorphic rocks beneath the Trinity ophiolite allochthon. Early Devonian thrust faulting is thought to be an expression of increased subductive activity along the western margin of the eastern Klamath geanticlinal arc. Increased subductive activity was accompanied, as would be expected, by increased volcanic activity in the eastern Klamath-northern Sierran arc. The first major volcanic units in the Klamath portion of the arc are andesites and quartz keratophyres (Copley Greenstone and Balaklala Rhyolite) of latest Silurian or Early Devonian to early (?) Middle Devonian age. Compositionally similar volcanic rocks in the northern Sierra Nevada (Sierra Buttes and overlying Taylor formations) are younger. Sedimentary rocks in the upper part of the Sierra Buttes formation contain Late Devonian ammonites.

The Early to Late Devonian history of the Klamath-Sierran arc is thus indicative of the initiation of strong plate convergence in the arc area. This is the context in which Antler events on the mainland to the east should be viewed. Late Devonian-Early Mississippian thrust faulting of the oceanic siliceous assemblage eastward over the continental shelf (Roberts Mountains allochthon) is attributed to partial closure of the marginal sea during this time of strong plate convergence (Burchfiel and Davis, 1972; Silberling, 1973; Davis, 1973).

The mode of basinal closure appears complicated and requires additional study. Thrusting of oceanic lithosphere (ophiolite sequence) onto continental margins has been termed "obduction" by Coleman (1971). The Roberts Mountains allochthon appears to us to be an obducted slab. As mentioned above, tectonic slices of serpentinized periodotitic rocks intermixed with highly deformed mafic volcanic and oceanic sedimentary rocks occur discontinuously at numerous localities in central Nevada. Although some ultramafic slices may have been emplaced during the Permo-Triassic Sonoma orogeny, serpentinite detritus in late Paleozoic marine conglomerates indicates Antler-age emplacement for at least some ultramafic bodies (Poole and Desborough, 1973). Partial closing of the marginal basin by obduction, as we originally proposed (Burchfiel and Davis, 1972), can account for the Roberts Mountains allochthon, but an obductive model alone fails to explain the general absence in the allochthon of the oceanic lithosphere on which the siliceous assemblage was deposited (Davis, 1973). Scraps of gabbroic and ultramafic rocks in the Roberts Mountains plate indicate the existence of former oceanic basement, but the bulk of this basement cannot be accounted for in the Antler terrane.

We propose that two processes, presumably operating synchronously, were responsible for partial closure of the marginal basin during Antler orogeny: (1) the volcanic and sedimentary fill of the basin was displaced upward across the continental margin; (2) the oceanic basement beneath these deposits was subducted eastward beneath the continental margin. Evidence for eastward subduction is meager, but the occurrence in the Antler belt of post-Antler, Early to early Late Mississippian basaltic, andesitic, and more siliceous volcanic rocks (Nelson and Goughs Canyon formations; Silberling, 1973) is supportive of it and difficult to explain otherwise. The relatively small quantity of these post-Antler volcanics suggests limited melting at depth and, by inference, limited subduction of oceanic lithosphere during basin closing. It is possible that the zone of principal convergence between the North American and Pacific plates shifted during the Devonian from the west side of the offshore arc to the east side of the marginal basin, but it seems likely that eastward subduction occurred at both locales during latest Devonian and Early Mississippian time—a situation perhaps analogous to active subduction along the paired Marianas and Mindanao trenches of the present western Pacific.

The geometry envisioned of combined obduction and subduction may appear fanciful, but similar obductive-subductive splitting of a converging plate has been independently proposed for the Eastern Alps (Oxburgh, 1972). Obductive overriding in the Alpine example is estimated to be at least 100 km, a figure compatible with minimum displacement of the Roberts Mountains allochthon.

The late Paleozoic was, in general, a time of renewed or continued sedimentation following the Antler orogeny (fig. 2). Only a cursory description will be given of sedimentational environments across the orogen. The eastern Klamath region was the site of marine deposition through Early Permian time and continued, but decreased, arc-type volcanic activity (as compared with the Devonian). Sediments are predominantly clastic (argillite, wacke, siltstone) and vary from deep water (Mississippian) to shallow water (Late Mississippian-Early Permian) in their depositional environments (Watkins, 1973); Lower Permian carbonates were deposited on a shallow shelf. On the continent to the east the Roberts Mountains allochthon constituted the new continental shelf. The Antler belt was a site of repeated uplift and erosion, and the source for detritus shed both eastward and westward into shallow and deep marine basins respectively. Sediments of the Antler Sequence were deposited unconformably on deformed rocks of the allochthon and range in age from Late Mississippian to Middle Permian; they are lithologically quite diverse (conglomerate, sandstone, limestone) but predominantly shallow marine.

In marked contrast to the shallow marine and, locally, emergent conditions that prevailed throughout much of the late Paleozoic in the Klamath arc and Antler shelf, Pennsylvanian (and older?) Havallah Sequence sediments deposited geographically between these areas are of deep marine type and resemble those of the pre-Antler siliceous and volcanic assemblage (Silberling, 1973). Thick sequences of interbedded chert, argillite, terrigenous clastic rocks (some turbidites), and mafic volcanic flows (commonly pillowed) indicate the continued existence of the pre-Antler marginal basin between arc and continent. This basin was presumably narrower in late Paleozoic time, but the presence of thick mafic flows in the lower part of the Havallah Sequence is suggestive of behind-the-arc spreading as found in some contemporary marginal basins in the western Pacific. Reconnaissance studies in the chemistry of volcanic rocks in the Havallah Sequence (J. Rogers, personal commun.,

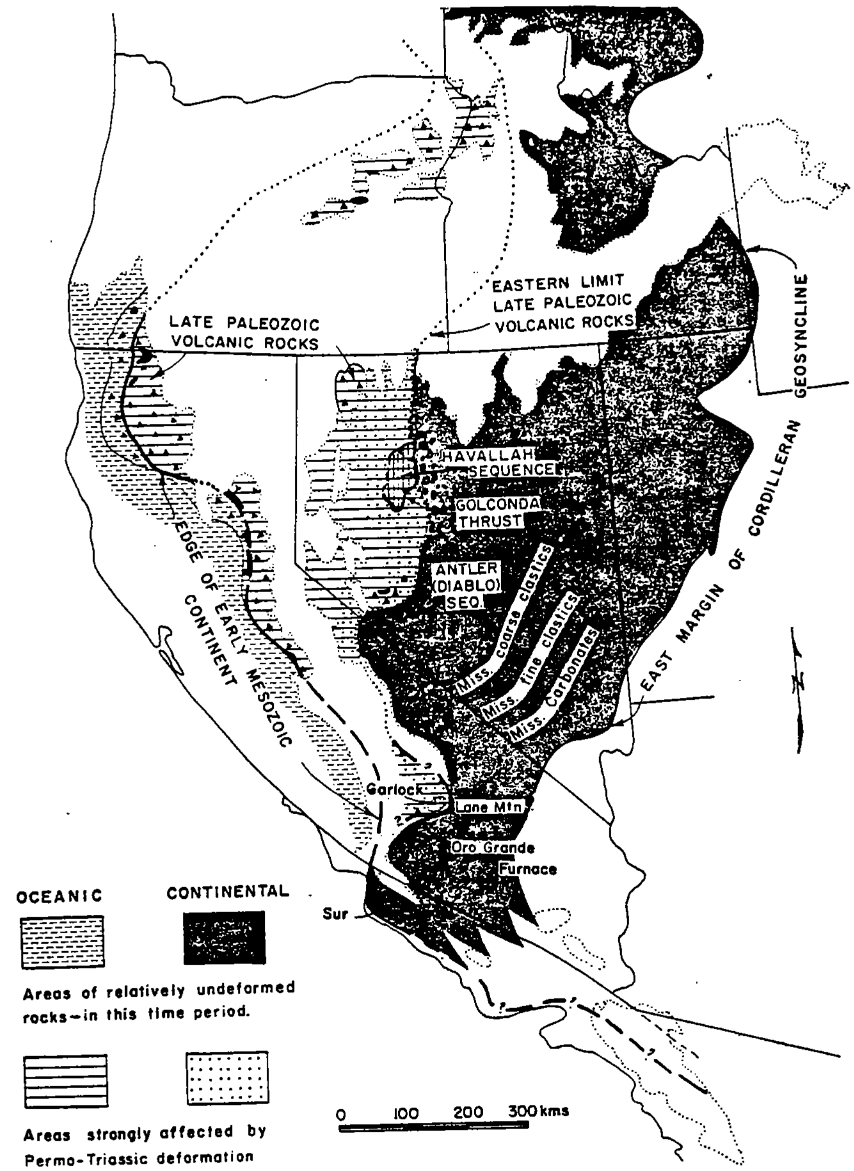

Fig. 2. Sketch map of Mississippian to earliest Triassic paleogeography showing areas affected by Permo-Triassic deformation. Mississippian facies lines from Pelton (ms). Position of Antler and Diablo sequences from Silberling and Roberts (1962, fig. 3). Area of Permo-Triassic deformation in northwestern Nevada from Speed (1971a, b) and Silberling (1973).

1973) indicate three volcanic suites are present: (1) oceanic tholeiite (2) island arc calcalkaline rocks, and (3) possible oceanic island volcanic rocks. The calcalkaline rocks are found in outcrops west of rocks containing the oceanic volcanic suites but still east of the Sierra Nevada batholith. This spatial distribution supports the paleogeography presented earlier by Burchfiel and Davis (1972) and Silberling (1973) of a marginal sea floored in part by oceanic crust lying between a late Paleozoic island arc to the west and a continental margin to the east.

In Late Permian and Early Triassic time the Cordilleran orogen apparently reexperienced the Antler event. The similarity of the Sonoma orogeny to the Antler orogeny, 100,000,000 years before, is so striking as to suggest strongly a repetition of the Antler orogenic mechanism. The Sonoma orogeny, like the Antler event before it, is generally equated with the eastward thrusting (Golconda thrust) of oceanic sedimentary and volcanic rocks (Havallah Sequence) across the continental shelf. But, as in the case of the Antler orogeny, this view is too restrictive. The Klamath arc shows several indications of increased subductive activity in Permo-Triassic time. Late Permian-Early Triassic (?) calcalkaline volcanic activity (Dekkas Andesite, Bully Hill Rhyolite) closely resembles that of the Devonian. To the west, oceanic sedimentary and volcanic rocks of late Paleozoic age (assigned to the western Paleozoic and Triassic subprovince) were subducted eastward beneath the Devonian metamorphic rocks described earlier (central metamorphic subprovince). Blueschists occur within or below the tectonic zone (Siskiyou thrust zone) between the two subprovinces (Davis, 1968), and one sample yields a Triassic age of 215 m.y.b.p. (K/Ar; M. Lanphere, personal commun., 1973).

Eastward obduction of the Havallah Sequence is considered to represent the final closing of the marginal basin east of the Klamath arc in response to a renewal of strong plate convergence off the western edge of the continent. Eastward subduction of oceanic crust beneath the continental margin is invoked to explain the absence of such crust in the Golconda allochthon and the occurrence of a short-lived period of andesitic and rhyolitic volcanism east of the former continental margin soon after thrusting (Koipato Group; Early-Middle Triassic). The restricted areal extent and apparent small volume of the Koipato volcanics are compatible with the eastward subduction of a small oceanic plate of limited east-west width.

Speed's recent conclusion (1974) that the early Triassic continental shelf was downwarped and covered with arc-derived, deep-water turbidite deposits before emplacement of arc-associated rocks in the Golconda allochthon atop it does not support the interpretation presented above. Rather, it implies westward subduction of the marginal basin beneath a volcanic arc to the west, with a subsequent collision of shelf and arc. This alternative model for the Sonoma orogeny was discussed, but not favored, by Burchfiel and Davis (1972); on the basis of Speed's studies it remains viable. Analysis of compositional variation in Permian and Triassic volcanic arc rocks of the eastern Klamath Mountains and the Koipato Group farther east might indicate the direction (westward or eastward) of subduction during closure of the marginal basin.

MESOZOIC AND EARLY CENOZOIC TECTONICS

The Sonoma orogeny produced a major change in the paleogeography of the western Cordilleran orogen. Final collapse of the marginal basin, whether by westward or eastward subduction, was accompanied by collision and accretion of the Paleozoic Klamath-Sierran arc complex to the North American plate and an abrupt westward shifting of the continental margin. Following Hamilton and Myers (1966) and Hamilton (1969), we have inferred (Burchfiel and Davis, 1972) that in Permo-Triassic time, probably shortly after the Sonoma orogeny, the southwestern part of the North American plate was truncated—either by rifting across a spreading center or by transform faulting. Unfortunately, we are not aware of any new information that indicates either the mechanism of truncation or the present position of the displaced Paleozoic "eugeosynclinal", miogeosynclinal, and cratonal rocks originally lying southwest of the line of truncation. Nevertheless, by early Mesozoic time the western margin of the North American plate had become strongly modified. In the north, the plate margin had shifted westward with the accretion of Paleozoic arc rocks, but in general it remained parallel to Paleozoic trends. In the south, the truncated plate margin trended northwestward across Paleozoic structural and paleogeographic elements with their northeastward trends. This truncated margin probably extended from central California at least as far south as the Trans-Mexico volcanic belt.

From west to east the main features of Mesozoic through Early Tertiary structure and paleogeography were (figs. 3, 4, 5, and 6): (1) relatively west-directed thrust faults produced by eastward subduction of oceanic rocks beneath the North American plate; (2) a volcanic-plutonic arc of Andean type along the modified western margin of the North American plate; (3) east-directed thrust faults that developed east of the arc and affected rocks of the Paleozoic miogeosyncline as far east as its transition to the craton and, in southern areas, rocks of the craton itself; and (4) a region of basement uplifts that developed within the craton 1000 to 1500 km from the plate margin.

Mesozoic magmatic activity in the western portion of the North American plate resulted from the eastward subduction beneath it of an oceanic plate or plates during much of Mesozoic time (Hamilton, 1969; Dickinson, 1970). The Mesozoic volcanic-plutonic arc began to develop about Middle Triassic time, and the oldest plutonic rocks date approximately 210 m.y.b.p. (Lanphere and Reed, 1973). Igneous activity occurred throughout most of Mesozoic time, but the degree of continuity of activity is controversial. Several workers have discussed this problem, and the most recent data by Lanphere and Reed (1973) suggest two and perhaps three intrusive epochs: (1) 79 to 106 m.y.b.p.; (2) 132 to 158

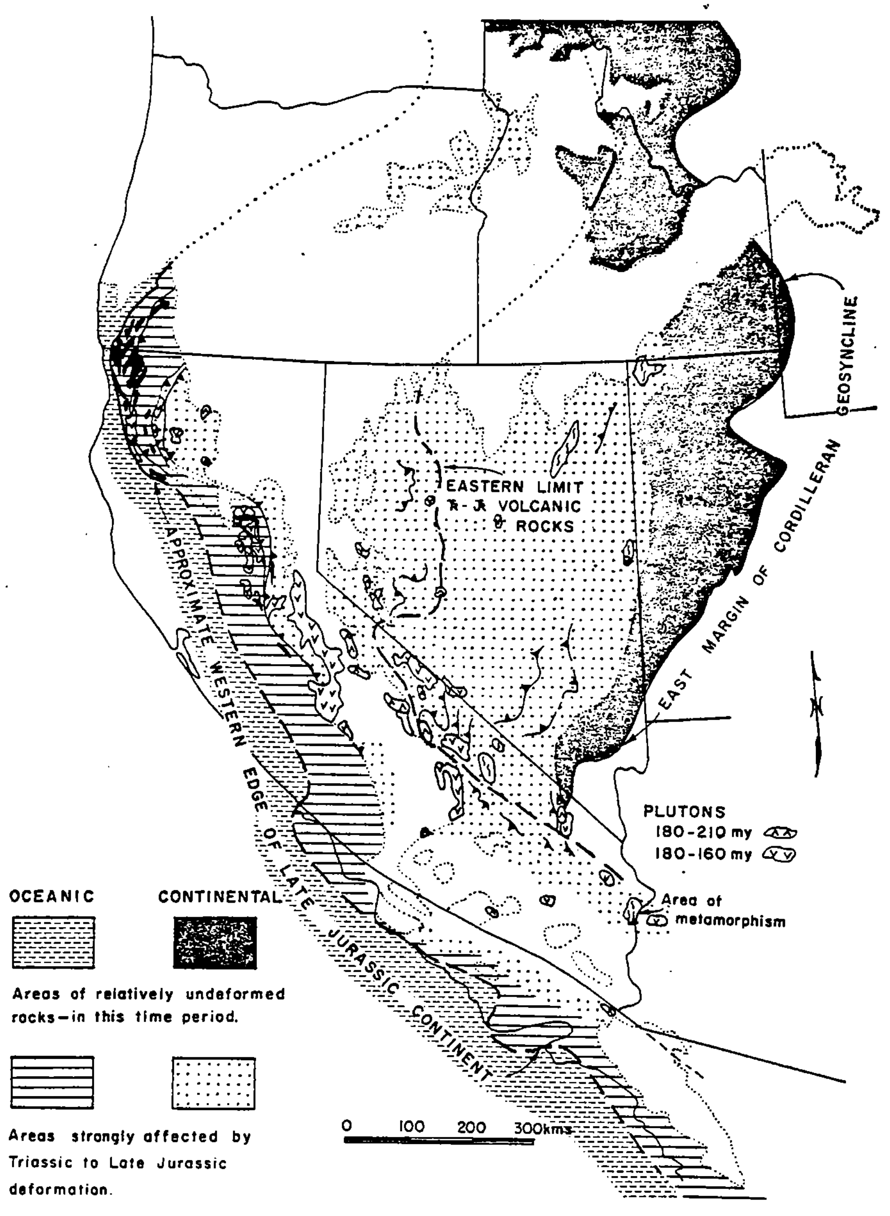

Fig. 3. Sketch map of early Mesozoic to Late Jurassic paleogeography and areas affected by deformation during this time period.

m.y.b.p.; and (3) an undefined epoch older than 160 m.y.b.p., with the oldest dates at 210 m.y.b.p. Because a few concordant age pairs fall in the intervals between these epochs the alternative hypothesis of continuous magmatism can not be eliminated. Younger igneous rocks are also present in the western United States, but an important change in magmatic and structural events occurred at about 75 m.y.b.p. as discussed below.

Structures resulting from Mesozoic subduction are present west of the arc in Idaho, Oregon, and western California and Mexico. Although most structures in these areas can be attributed to east-directed underthrusting of the continental margin, recent studies in the Sierran Foothills indicate that the history of Mesozoic subduction tectonics is more complicated than we had thought earlier (Burchfiel and Davis, 1972). Moores (1972) and Schweikert and Cowan (1974) have suggested the Late Jurassic collision in the Foothills area of an offshore, east-facing island arc with the continent and its west-facing Andean-type arc. The polarity of this inferred arc has not yet been substantiated; its areal extent and the duration of its igneous activity remain uncertain.

Accretion of oceanic, arc, and continental margin deposits progressed generally westward so that thrust faults are progressively younger in that direction. Oceanic crust and underlying mantle are major accretionary components as indicated by the presence of numerous bodies of ophiolite within western portions of the plate (figs. 3 and 4). Structural events west of the arc are subdivided commonly into a Late Jurassic Nevadan orogeny and several Cretaceous and Early Tertiary deformations. Closer examination of these events suggests deformation may have been more or less continuous from early Mesozoic onward and occurred over a span of time similar to that recorded in the Sierran volcanic-plutonic arc (Armstrong and Suppe, 1973).

East of the early Mesozoic arc, east-directed thrust faults developed within all Paleozoic paleogeographic elements. In western Nevada thrust faults originated in Paleozoic "eugeosynclinal" rocks and early Mesozoic back arc sedimentary and volcanic rocks. Age of these thrust faults is Early and Middle Jurassic (Ferguson and Muller, 1949). Riva (1970) has demonstrated the presence of early Mesozoic thrusting and folding in northeastern Nevada which could range in age from Middle Triassic to Early Jurassic. In the miogeosyncline on either side of the California-south central Nevada state line are several large thrust faults and associated folds that involve rocks as young as Early and Middle Triassic and are cut by plutons 180 m.y. old. These thrusts belong to an early Mesozoic period of thrusting (Burchfiel, Pelton, and Sutter, 1970) that may be earlier than or synchronous with deformation in western and northeastern Nevada. Farther southeast in southeastern California are thrusts cut by plutons 200 m.y. old (Burchfiel and Davis, 1971) and a newly discovered thrust that is unconformably overlapped by the Upper Triassic (?)-Lower Jurassic Aztec Sandstone (Novitsky and Burchfiel, 1973). Thrust faults in southeastern California involve Paleozoic mio-

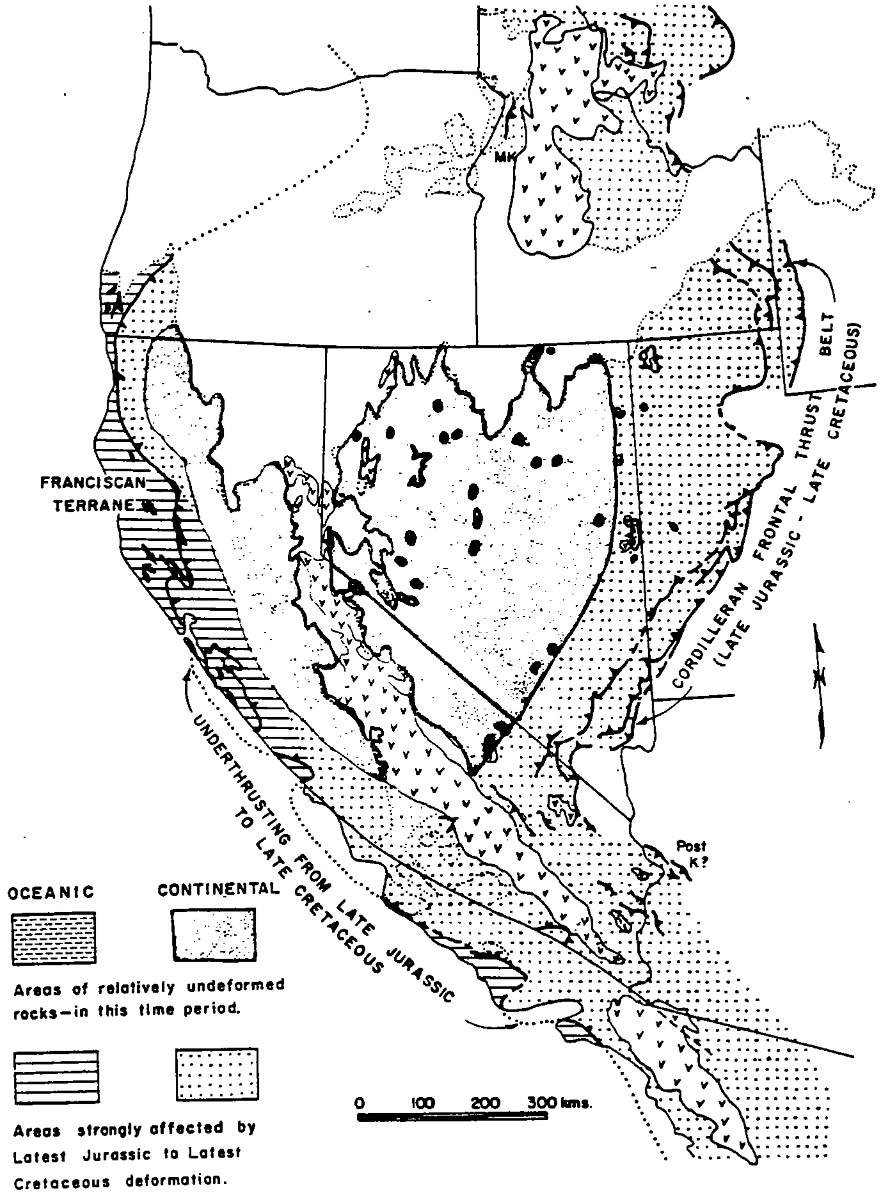

Fig. 4. Sketch map of latest Jurassic to latest Cretaceous paleogeography and areas affected by deformation during this time period. Left-lateral displacement of approximately 65 km on the Garlock fault in southeastern California (Davis and Burchfiel, 1973) has been removed.

geosynclinal and cratonal facies and their Precambrian crystalline basement. Whether these various events belong to one or more episodes of deformation and magmatism is not yet known. Presently we group them in an undifferentiated period of early Mesozoic deformation which ranges in age from Middle Triassic to Middle Jurassic.

Thus during early Mesozoic time the Cordilleran orogen became structurally two-sided (Burchfiel and Davis, 1968) with east-directed thrust faulting on the east side of the magmatic arc occurring synchronously with oceanic underthrusting of the continental plate to the west of the arc. We have concluded from these relationships (Burchfiel and Davis, 1968, 1972) that the two belts of deformation are spatially, temporally, and genetically related; a revised model to explain these relationships is presented after this section. The two-sided nature of the Cordilleran orogen is best demonstrated during Late Jurassic to Late Cretaceous time. Franciscan metamorphism and eastward underthrusting of oceanic lithosphere beneath the North American plate ranged in age from 150 to 70 m.y.b.p. (Suppe and Armstrong, 1972) and is coeval with plutonism in the volcanic-plutonic arc (Armstrong and Suppe, 1973; Lanphere and Reed, 1973). Franciscan rocks were accreted against older Mesozoic rocks, thus building the continental margin westward (Bailey and Blake, 1969; Ernst, 1970).

East of the arc, thrust faults developed from west to east until rock units transitional between miogeosyncline and craton were involved in thrusting. In southeastern California, thrust faults strike south and southeast, leaving the Paleozoic geosynclinal terrane and cutting through the craton. Nearly all late Mesozoic thrust faults in this region involve Precambrian crystalline rocks and strike parallel to and along the eastern edge of the late Mesozoic magmatic arc (Burchfiel and Davis, 1972, fig. 7). This major change in structural trend and style occurs near the California-Nevada state line and presumably continues into Mexico, although data southeast of California is scanty.

Late Mesozoic plutonism occurred farther eastward in Nevada and to the north than in early Mesozoic time, but in southeastern California and to the south early and late Mesozoic igneous activity is superposed (Armstrong and Suppe, 1973). Associated with the Mesozoic plutonic and volcanic rocks, but characteristically lying east of their major areas of development, are numerous isolated metamorphic terranes that probably represent exposed culminations of a metamorphic belt which is continuous at depth. Metamorphism of amphibolite grade affects miogeosynclinal and cratonal rocks of Precambrian and Paleozoic age (Armstrong, 1968; Armstrong and Hansen, 1966; Lanphere and others, 1964; Hamilton, 1964 and 1971), as well as Mesozoic and Early Tertiary(?) granitic, volcanic, and sedimentary rocks (Hamilton,1971; Pelka, 1973). Todd (1973) has reported regional metamorphism of a Middle Tertiary (25 m.y.b.p., Rb/Sr) adamellite stock in northwestern Utah. Meager age data suggest that metamorphism began at least 180 m.y. ago and continued into the Tertiary, but it is not known if this represents one long period of metamorphism or several spatially and temporally distinct periods. It is likely that metamorphism is synchronous with magmatism, spans a long period of time, and will be tied ultimately to magmatic epochs.

The eastern or frontal thrust belt of the Cordilleran orogen lies to the east of the metamorphic terranes mentioned above. In this belt east-directed thrust plates of Late Jurassic to Late Cretaceous age define a zone of crustal dislocation that extends from British Columbia and Alberta, Canada to southeastern California and probably into Sonora, Mexico. During the Late Cretaceous an important change took place in the location of deformation by thrust faulting. Formation of folds and thrusts in the eastern thrust belt ceased before the end of the Cretaceous in a sector from central Utah to southeastern California (Armstrong, 1968; Burchfiel and Davis, 1971; Burchfiel and Hickcox, 1972; Coney, 1972). In central and western Utah thrust plates along the easternmost part of the orogen are unconformably overlain by the Late Cretaceous Price River Formation (Hintze, 1962; Armstrong, 1968; Burchfiel and Hickcox, 1972). The oldest part of the Price River Formation is Campanian, which dates approximately 80 m.y.b.p. on the absolute time scale (Hale and Van de Graaff, 1964; McGookey, 1972). Basal Price River rocks are certainly not the same age throughout central Utah but are probably no younger than earliest Maastrichtian (70 m.y.b.p.). In southeastern California the youngest thrust faults and folds are intruded by post-tectonic plutons radiometrically dated at 90 ± 5 m.y.b.p. (Burchfiel and Davis, 1971). Thus in this sector of the eastern thrust belt compressive deformation ceased between 90 ± 5 m.y. and 70 m.y. ago, the end of the Sevier orogeny of Armstrong (1968; our fig. 6).

North and south of this sector of the thrust belt, deformation continued through the Late Cretaceous into the Early Tertiary and ceased in Middle or Late Eocene time. Thrust faults in Wyoming, Montana, and Canada cut Eocene rocks (Scholten, 1968, 1973; Bally, Gordy, and Stewart, 1966). Thrust faults and folds in Arizona, New Mexico, and Mexico deform Late Cretaceous and Early Tertiary rocks (Drewes, 1969; Lasky and Webber, 1944; Corbitt and Woodward, 1973; Gries and Haenggi, 1970). The period from latest Cretaceous to Eocene (70 to 50 m.y.) is the time of the "classic" Laramide orogeny (Armstrong, 1968; Tweto, 1973). Thrust faults developed during Laramide deformation have a structural style similar to those developed in the earlier Cretaceous Sevier orogenic event but generally lies somewhat east of the Sevier structures (figs. 5 and 6).

Laramide age structures of a different style are also present in the western United States and lie well east of the thrust belt developed during the Sevier orogeny (fig. 6). Laramide age structures in Montana, Wyoming, Utah, Colorado, New Mexico, and Texas, unlike the low angle thrust faults that characterize the thrust belt to the northwest and southwest, consist of large uplifts of Precambrian crystalline basement rocks with draped covers of Paleozoic and Mesozoic sedimentary

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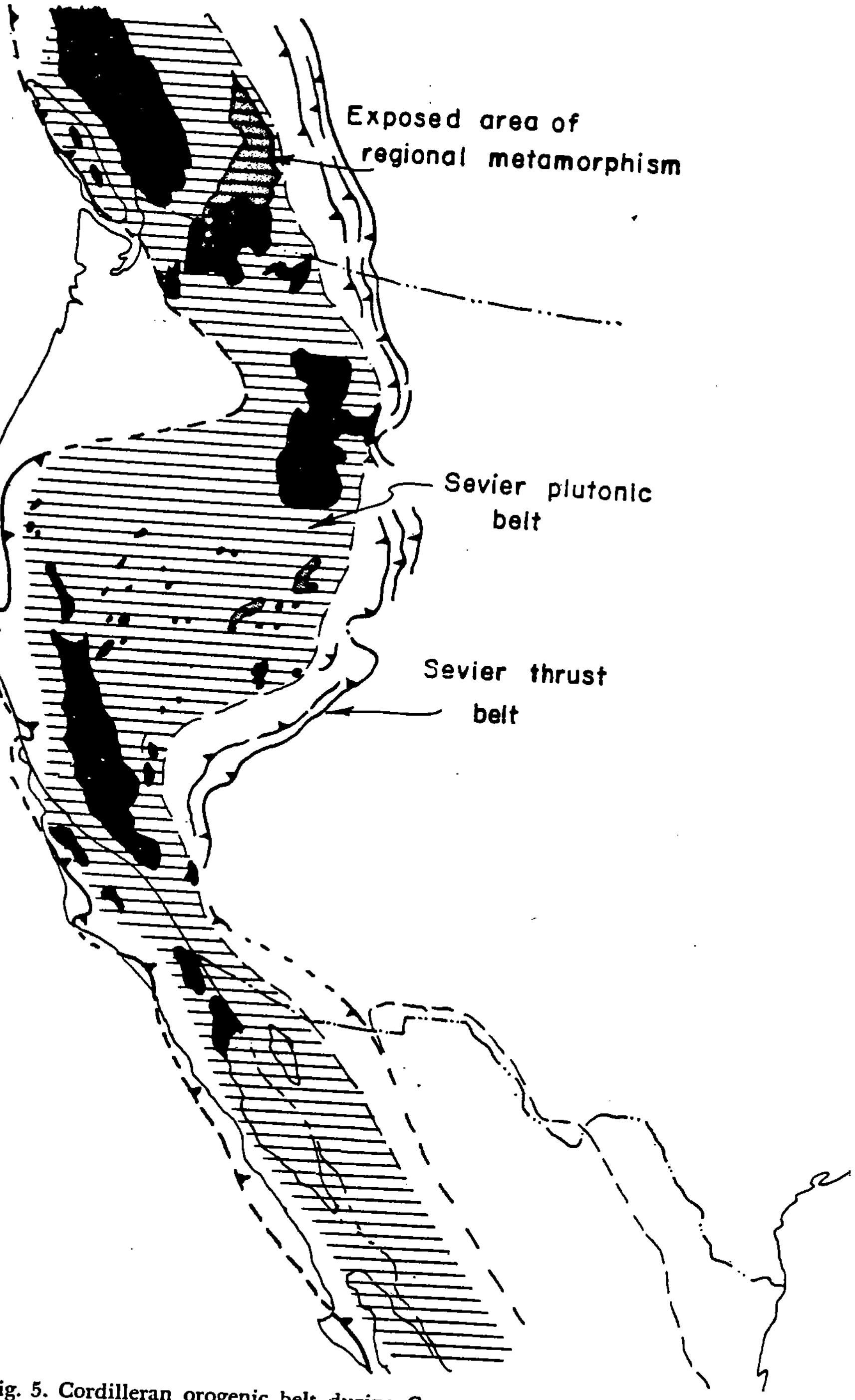


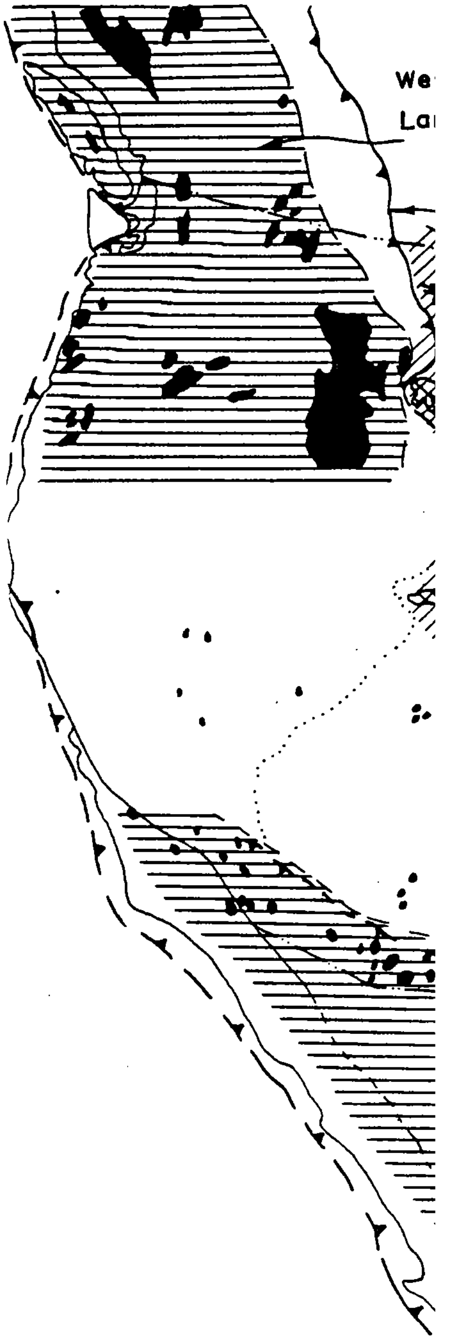
Fig. 5. Cordilleran orogenic belt during Cretaceous Sevier orogeny (latest Jurassic to latest Cretaceous, that is, pre-75 m.y. age). Areas of Sevier age plutons in black; areas of metamorphism shaded. Horizontal lines show zone of high ductility of crustal rocks. Two-sided structural character of the orogen is shown by relatively west-directed thrusts produced by eastward subduction of an oceanic plate along the west side of the North American plate and east-directed intraplate thrust faults, antithetic to the main subduction, along the east side of the zone of high ductility.

rocks. The uplifts are characterized by differential vertical displacement of Precambrian basement rocks of up to 9 or 10 km and bounding low- to high-angle reverse faults that steepen at depth (Sanford, 1959; Prucha, Graham, and Nickelson, 1965). This style of structure is sufficiently different from that of the Cordilleran thrust belt that Prucha, Graham, and Nickelson (1965) suggested it merits "consideration apart from that of other terranes of the North American Cordillera". Three cross sections are presented in figure 7 to demonstrate some but not all the variation in structures from this region. We will refer to these structures as basement uplifts, because their origin is not well understood and a wide range of hypotheses have been proposed for them.

Whereas the Laramide thrust belt in Wyoming and northward is developed within geosynclinal rocks, the province of Laramide basement uplifts lies almost wholly within the Paleozoic and Mesozoic craton. Only at its northwestern end does the province enter the geosynclinal region, and here it developed synchronously with the Laramide thrust belt (Ryder and Scholten, 1973). It is highly significant that the province of basement uplifts lies mostly opposite the sector of the thrust belt that terminated development at the end of the Sevier orogeny.

Igneous activity in the western part of the North American plate also underwent a significant change during the Late Cretaceous (Coney 1971, 1972). During most of Mesozoic time a plutonic-volcanic Andean-type arc was active as discussed above. Although the problem of the continuous or episodic character of magmatism has not yet been resolved satisfactorily (Gilluly, 1973), it appears that during most of Mesozoic time magmatism was characteristic of much of the western part of the North American plate in the United States and southern Canada. About 75 m.y. ago a change occurred in the pattern of igneous activity, which as Coney (1971) has suggested may mark a change in the direction of motion of the North American plate. Igneous rocks intruded during Laramide time (75-50 m.y. ago) are present in Canada and Idaho, in southeastern California and Arizona (and presumably western Mexico), but they are very rare in central and northern California, Nevada, and western Utah (Armstrong and Suppe, 1973; Cross, 1973). Igneous rocks of Laramide age are also present farther east in southwestern Montana (Adel Mountain, Elkhorn Mountain, and Livingston volcanic rocks) central and southwestern Colorado (Colorado Mineral Belt), northeast and southern Arizona, and southwestern New Mexico. These latter areas of igneous activity lie east of areas of earlier Sevier magmatism in terranes that had lacked igneous activity since the Precambrian. The Laramide igneous rocks of Colorado and parts of Arizona lie east of the gap in Laramide magmatic activity of the main batholith trend of the Cordillera (compare figs. 5 and 6). Of considerable importance is the general spatial coincidence of this Laramide igneous activity with the region of basement uplifts.

In summarizing the areal distribution of deformation and magmatism during Late Cretaceous-Early Tertiary time, the following data are important: (1) low-angle thrust faults developed from Canada to Mexico



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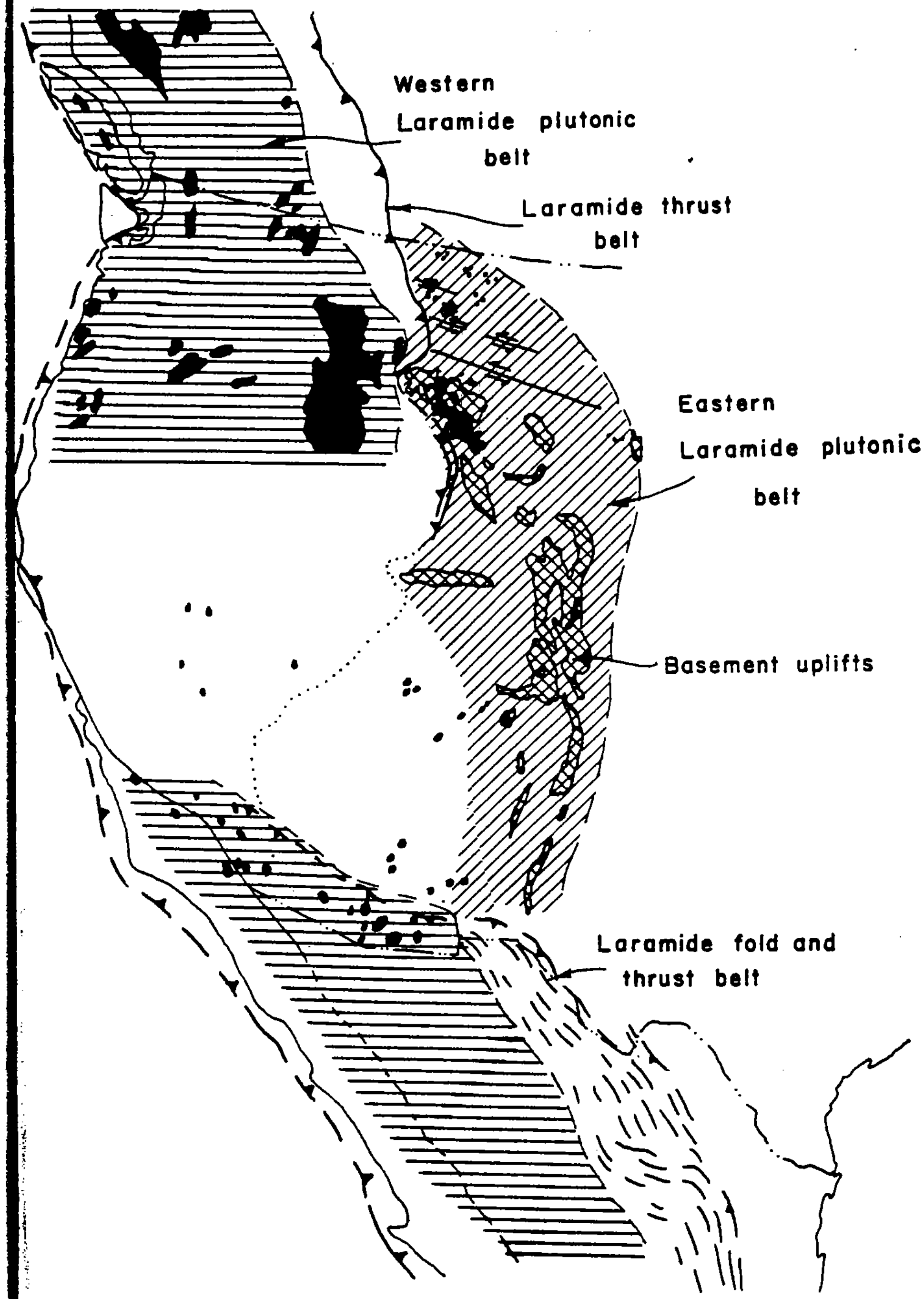


Fig. 6. Cordilleran orogenic belt during Laramide orogeny (latest Cretaceous to Middle or te Eocene time). Areas of Laramide age plutons and volcanic rocks are shown in black. Hori- ntal lines show zone of high ductility of crustal rocks flanked by belts of low angle thrusting d illustrate two-sided structural character continued from the Sevier orogeny. Diagonal lines ow cratonal area of deformed Precambrian crystalline rocks underlain by crustal rocks of pected high ductility. Region of basement uplifts shown in cross-hatched pattern. Rocks of gh ductility beneath the region of basement uplifts probably lie at greater depth than in e region bounded by low-angle thrust faults.

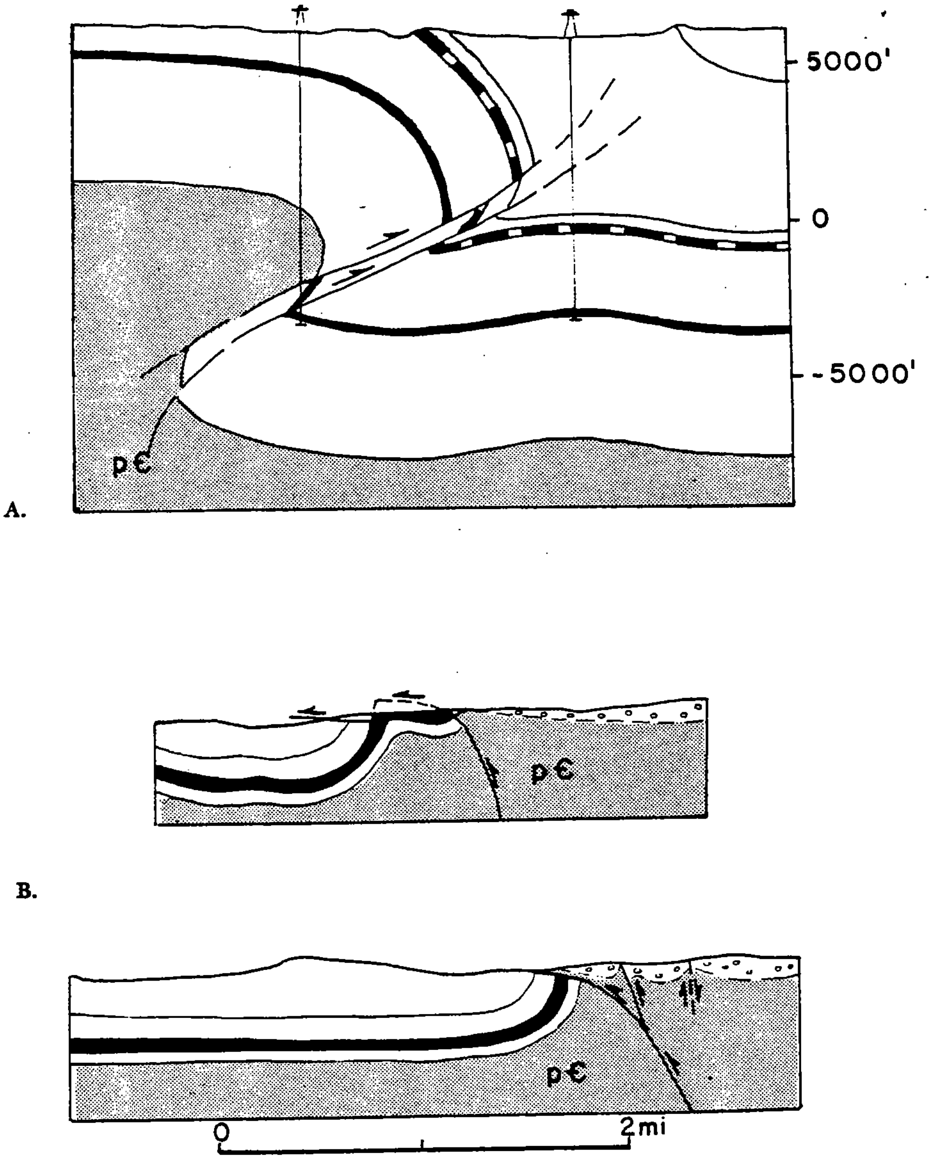
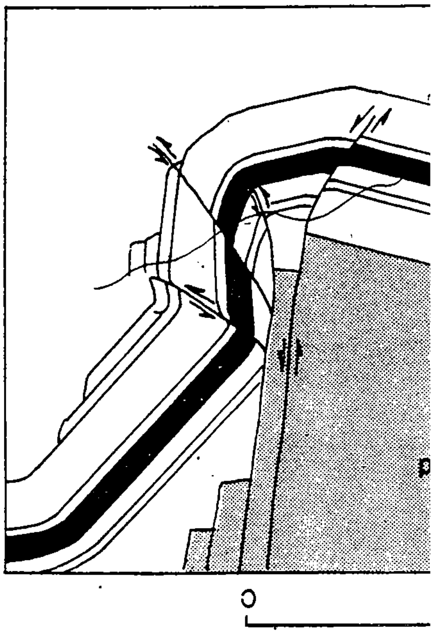


Fig. 7. Sections through three uplifts representing the range of geometric interpretations of basement uplifts.

A. Fold-thrust geometry of Willow Creek thrust fault, Blue Mountain, Colo. (after Anderman, 1961; Berg, 1962). Precambrian rocks are the sedimentary rocks of the Uinta Series (shaded) overlain by a sequence of Cambrian through Cretaceous sedimentary rocks. Dashed unit is the Cretaceous Dakota Sandstone. Permian rocks are shown in solid black.

B. Vertical uplift with Williams Range thrust fault (near Kremmling, Colo.) steepening at depth (after Howard, 1966). Precambrian rocks are metamorphic basement (shaded) overlain by Jurassic Morrison Formation through Tertiary rocks. Open circles are Tertiary rocks. Cretaceous Benton Group is black.



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DUCTILITY CONTROLS ON M INTRAPLAT

The following model is prop Mesozoic and early Cenozoic intr sented above. Following truncati latest Paleozoic or earliest Mesozo Mesozoic time along an unmodifi

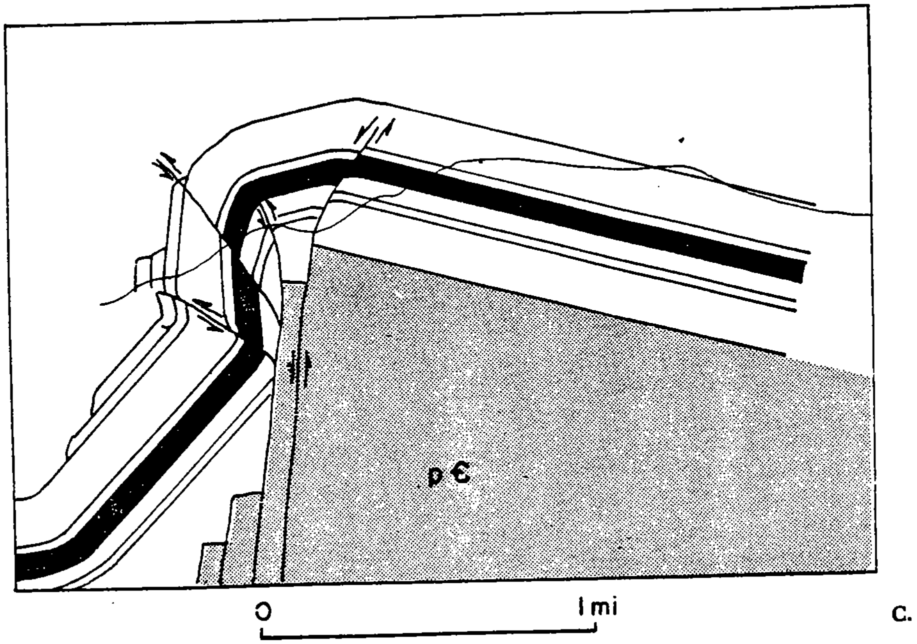

Fig. 7

C. Drape folding over vertical uplift, Rattlesnake Mountain, Wyo. (after Stearns, 1971). Precambrian rocks are metamorphic basement (shaded) overlain by Cambrian through early Mesozoic rocks. Black unit is the Ordovician Bighorn Dolomite.

along a continuous belt of Jurassic to Late Cretaceous age; (2) the belt of low-angle thrust faults lies along the eastern margin of a terrane or zone of batholiths that were emplaced synchronously with thrusting (210 to 75 m.y. ago); (3) low-angle thrusting ended in Late Cretaceous time (pre-Maastrichtian) in a sector from central Utah to southeastern California at approximately the same time as magmatism ceased in corresponding latitudes in the batholith belt to the west (Coney, 1972; Armstrong, 1973); (4) to the north and south Laramide low-angle thrusting continued in regions where magmatism persisted in the main plutonic belt from 75 m.y. to approximately 50 m.y. ago; and (5) in the central Cordillera, largely adjacent to the gap in Laramide magmatism of the main batholith belt, Laramide igneous activity shifted eastward and coincides generally with the region of Rocky Mountains basement uplifts of the same age.

DUCTILITY CONTROLS ON MESOZOIC AND EARLY CENOZOIC INTRAPLATE DEFORMATION

The following model is proposed to explain the relations between Mesozoic and early Cenozoic intraplate magmatism and tectonism presented above. Following truncation of the North American plate in latest Paleozoic or earliest Mesozoic time, underthrusting began in early Mesozoic time along an unmodified plate margin north of central California and along the truncated margin from central California south into Mexico. Mesozoic thrust faulting along the eastern side of the Cordilleran orogen was directly related to convergence between the North American plate and an oceanic plate (or plates) to the west. Eastward subduction of the oceanic plate produced magma that intruded the leading edge of the North American plate to form a Mesozoic plutonic-volcanic arc of Andean type. Magmatic heating of the western edge of the North American plate formed a marginal zone relatively more ductile than portions of the plate farther east. Although convergence of the two plates was taken up primarily by eastward subduction of the oceanic plate, enough intracontinental differential stress was generated that cooler, more rigid eastern portions of the plate moved westward into and beneath the marginal ductile zone. The result of this intraplate deformation was ductile shortening at deeper crustal levels and brittle shortening by east-directed thrust faulting at shallower levels. Although at any given time the main region of intraplate yielding occurred along the eastern boundary of the ductile zone (the site of highest ductility contrast), local yielding with variable vergence occurred within the ductile zone, for example, in the metamorphic complexes described by Armstrong and Hansen (1966) in eastern Nevada and western Utah and by Hamilton (1971) in southeastern California. A minor amount of west-directed thrusting is reported from within the ductile zone in British Columbia (Wheeler and others, 1972) and in north-central Nevada (Silberling and Roberts, 1962; Wallace and Silberling, 1962).

To our knowledge the general concept of ductility controls on the localization and style of east-directed Cordilleran thrust faulting was first expressed by Peter Misch (1960). Misch related thrust faulting in the eastern fold and thrust belt to the interaction between a rigid foreland (cratonal) basement to the east and a mobile geosynclinal terrane to the west. Although his conceptual framework and geometric interpretations differ considerably from those proposed here (and in Burchfiel and Davis, 1972), he did regard the eastward thrust faulting of geosynclinal rocks as occurring in response to westward underthrusting by the cratonal basement (1960, p. 41):

> The more active role was played by the basement which was strong enough to transmit stress without significant internal yielding. It is only on the basis of this distinction between an *active unit*, defined as *stress-transmitting and non-yielding*, and a *passive unit*, defined as *stress-absorbing and yielding*, that concepts such as "underthrusting" and "absolute direction of movement" are meaningful. The proposition of such underthrusting from the foreland toward the geosyncline involves, of course, the premise of crustal shortening.

Moores (1970) and Coney (1972) adopted Misch's general view of westward underthrusting of the geosyncline by the craton but in different plate tectonics frameworks.

In western Nevada the early Mesozoic thrusts lie east of the belt of early Mesozoic plutons in the Sierra Nevada (fig. 3). During later

Mesozoic time plutonic activity migrated eastward as far as western Utah (fig. 4; Armstrong and Suppe, 1973), as did the eastern boundary of the ductile zone. It is not surprising, therefore, that late Mesozoic yielding of the crust by thrust faulting also migrated eastward in time. Eastern portions of late Mesozoic thrust plates are of décollement type, where they occur within the anisotropic Paleozoic and Mesozoic miogeosynclinal wedge. In western areas it is hypothesized that thrust faults at the base of the plates pass into the zone of high ductility where Precambrian crystalline rocks of the continental crust were deformed. Thus shortening of the sedimentary cover is an expression of crustal shortening farther west (Burchfiel and Davis, 1968; Armstrong and Dick, 1974).

Eastward migration of thrust faulting in the frontal thrust belt is best documented in its Idaho-Wyoming segment (Armstrong and Oriel, 1965; Rubey and Hubbert, 1959). The oldest thrust faults (latest Jurassic and earliest Cretaceous) lie in the western portion of the belt because they were closest to the boundary of the ductile zone. Thrust faults in the frontal belt propagated eastward away from this boundary—the zone of crustal shortening—as far as critical shear stresses for fracture could be transmitted. Where thick sedimentary sequences were present, thrust plate detachment (décollement) was controlled by stratigraphic anisotropy. When shortening was initiated the first thrust plate to form moved eastward relative to younger underlying rocks, although the mechanism is more easily visualized in terms of a westward underthrusting by the lower plate. As shortening continued, rocks east of the first thrust fault to form were brought closer to the zone of crustal yielding and the region where critical shear stress for fracture was present. When rocks of the lower plate were brought into the region of critical shear stress, a new thrust fault developed in the lower plate of the first thrust. The process just described is self-limiting, however, unless lateral migration of the thermally controlled zone of crustal yielding also occurs—as it did along much of the length of the Cordillera with an eastward shifting of Mesozoic magmatic activity.

In southeastern California, early and late Mesozoic plutonic activity was superposed, however (fig. 4; Burchfiel and Davis, 1972; Armstrong and Suppe, 1973). Hence, eastward migration of the zone of high ductility did not take place, and early and late Mesozoic thrust faults and folds in the area are irregularly superposed. Because of the lack of a Paleozoic miogeosynclinal wedge in this region (fig. 2), thrust faulting was generally not stratigraphically controlled, and Precambrian crystalline rocks are present in most thrust plates. The distances from the front of the plates to the zones of crustal shortening behind them may have been less than for the décollement-style thrusts. It is likely that these thrust faults propagated a shorter distance from the zone of crustal shortening before intersecting the surface in the California-Arizona region than farther north where the anisotropy of the miogeosynclinal wedge was a factor in their geometry.

Southeastward into Mexico Laramide thrust faulting again exhibits a probable décollement style (Gries and Haenggi, 1970; de Cserna, 1970). The reappearance in Mexico of this style of deformation is not the result of a reappearance of the Cordilleran geosyncline but is due to the presence there of the Mexican sedimentary basin. A thick sequence of Jurassic and Cretaceous sedimentary rocks with basal redbeds and evaporites was deposited in central and eastern Mexico in this basin. Its northern end extends across the Mexican border into southeastern Arizona and southwestern New Mexico. It is here that the style of Laramide deformation begins to change from basement-involved thrust faults into the décollement-style folds and thrusts of eastern Mexico (figs. 5 and 6). Deformation of Sevier age in this area is not known. We suggest that Laramide shortening in the sedimentary rocks of the Mexican basin was an expression of crustal shortening farther west, specifically along the eastern margin of a pluton-controlled zone of ductility as postulated for Cordilleran areas farther north. Magmatic activity was widespread in Mesozoic time in western Mexico (de Cserna, 1970), but age relations between magmatism there and sediment deposition in the Mexican basin and between the time of deformation(s) in the two areas are largely unknown. Preliminary data indicate that plutons of Sevier age are present in western Mexico and generally lie west of Laramide age plutons (Gastil, 1973), a relation that suggests Sevier age deformation may also be present in western Mexico (but west of the Mexican basin where it has not been recognized). The existence of Sevier deformation in western Mexico is also indicated by the presence in the Mexican basin of Late Cenomanian to Paleocene flysch deposits containing volcanic detritus and by an eastward migration of Late Cretaceous shorelines (de Cserna, 1970).

Although Sevier deformation and magmatism thus appear to have been continuous along the length of the western margin of the North American plate, a gap developed (as described above) in Laramide deformation and magmatism along Sevier trends as these phenomena shifted eastward into the North American craton. This restricted shifting of Laramide deformation into the Rocky Mountains of Wyoming to New Mexico strongly suggests that the region of basement uplifts is a region of crustal shortening that forms a connecting link between shortening by thrust faulting in the Idaho-Montana-Canada and Arizona-Mexico sectors of the Cordilleran orogenic belt. In Canada thrust faulting of Sevier age and style continued through Laramide time. Southward into Montana, Idaho, and to a limited extent in Wyoming, shortening also continued into Laramide time in the eastern part of the frontal fold and thrust belt, but additional shortening began to occur to the east in the area of the northern basement uplifts. Since crustal shortening is probably more or less constant in nearby areas within the North American plate, the amount of shortening in the fold and thrust belt probably diminished southward as shortening in the region of basement uplifts increased southward. The total amount of Laramide crustal shortening is accommodated in the central region of the basement uplifts. Farther south the percentage of total shortening represented by basement uplifts decreases as shortening also occurs in the belt of low-angle thrust faults in Arizona and southwestern New Mexico. In Mexico presumably all shortening occurs within the Cordilleran fold and thrust belt.

This interpretation of the geometry of the deformation in map view is similar to that proposed by Sales (1968). The trend of the northern basement uplifts is northwest and changes to north-south southward (fig. 6). As shortening in the North American plate shifts from the area of basement uplift to the fold and thrust belt farther north and west, a left-lateral shear must occur in the plate. A very crude geometric analogy would be a trench-to-trench transform fault. The left-lateral shear appears to be represented by a very diffuse zone of several faults, such as the Lake Basin fault zone, plus distortion of the northwest part of the region of basement uplifts to produce northwest trends (Sales, 1968). The connection between the two zones of shortening in the south, which appear to have an en echelon relation to each other, is much less clear. Most likely the connection is accomplished by a diffuse zone of right-slip faults (Albritten and Smith, 1957).

The magnitude of these connecting zones, of faults should be approximately equal to the magnitude of the shortening within the North American plate. An estimate of shortening during Laramide time is difficult to make and the best data are from Canada (Bally, Gordy, and Stewart, 1966). Bally, Gordy and Stewart estimate 40 km of thrusting during the Eocene and up to 100 km from Late Cretaceous to Late Eocene or Oligocene. If all the displacement on Laramide thrust faults is produced by crustal shortening, 100 km thus represents a maximum figure for intraplate shortening during Laramide time.

The origin of the basement uplifts is unclear, and several hypothesis have been proposed: (1) vertical uplift (Bengston, 1956; Eardley, 1951, 1963; Sanford, 1959); (2) uplift due to thrusting (Fanshawe, 1939; Love, 1939); (3) fold-thrust uplift of basement (Berg, 1962; Sales, 1968); and (4) wrench or strike-slip faulting (Stone, 1969). The critical argument with respect to regional analysis is whether or not the basement uplifts require shortening of crustal rocks. Hypotheses 1 and 4 require no lateral shortening, but hypotheses 2 and 3 do.

The most recent work on the origin of basement uplifts is by Stearns (ms, 1971), who studied the Rattlesnake Mountain fold in Wyoming. Stearns demonstrated that Paleozoic rocks have uniform thickness over the entire fold. If the basement rocks had been raised vertically without lateral shortening and Paleozoic rocks draped passively over the uplifts, thinning of the Paleozoic rocks on the flanks would be expected. Stearns concluded that shortening of the crust was required to produce this structure and other similar structures which he studied in reconnaissance. Considering only the Rattlesnake Mountain fold, he calculated 40 percent shortening; however he suggested that

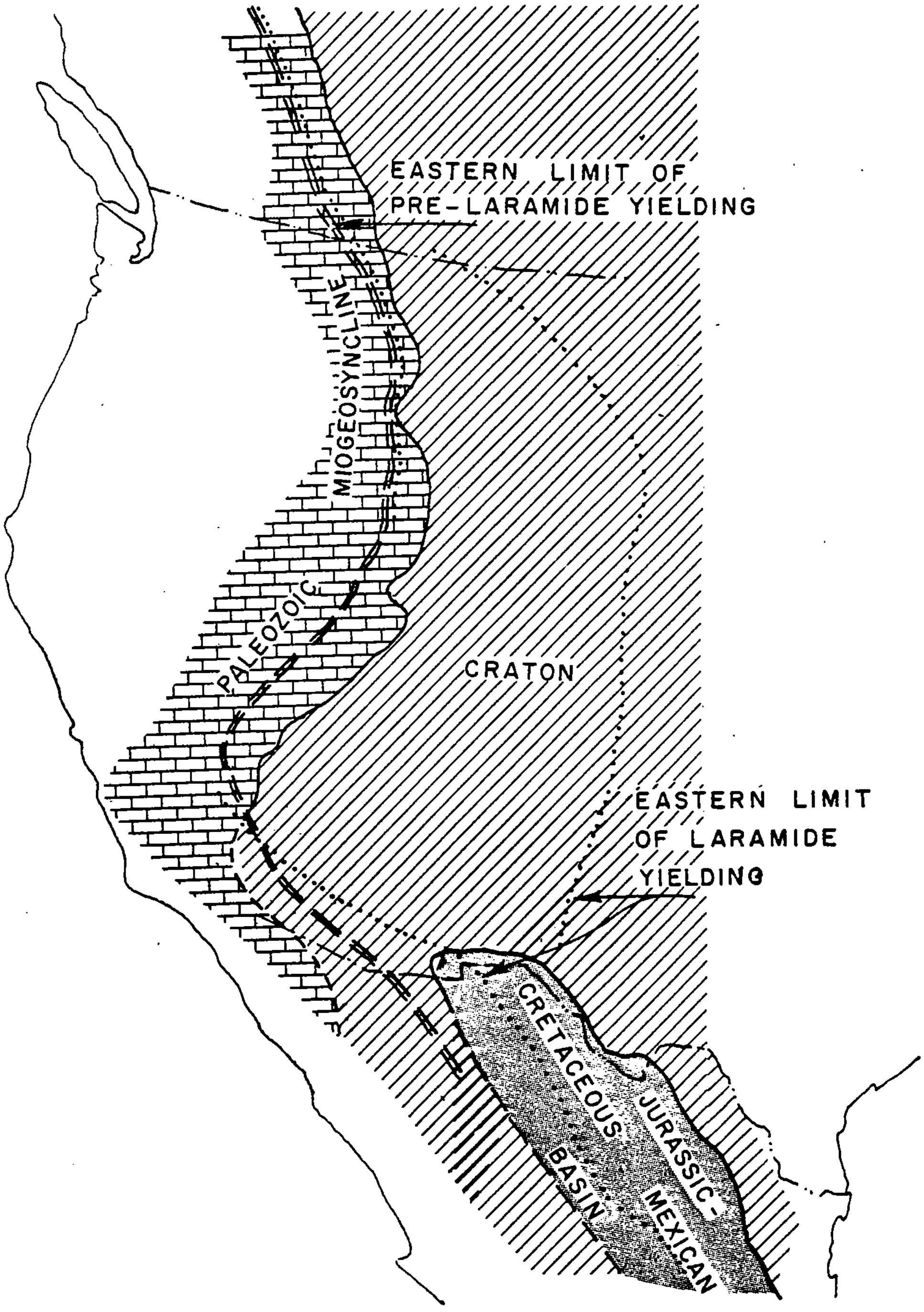

Fig. 8. Summary figure showing eastern limits of pre-Laramide (double dashed line) and Laramide (dotted lines) intraplate yielding. Laramide yielding by thrust faulting along discontinuous western dotted line overlaps northern and southern portions of eastern Laramide region where yielding occurred by basement uplifting. In central region crustal shortening of Laramide age occurred only in the cratonal area of basement uplifts.

there is a detachment of the Paleozoic sedimentary rocks from the basement in the basin adjacent to the fold and that the sedimentary rocks moved laterally from the basins into the fold. Stearns thus considered that shortening also occurred in the basins and that the amount of shortening over the entire region (basins and uplifts) was only 5 to 10 percent. Finally, he concluded that 5 percent shortening was a maximum, and even that could be reduced by "(1) invoking more low angle faults in the basement, (2) dilation of the sedimentary section due to fracturing, (3) normal faulting in the sedimentary rock layers that does not continue into the basement, and (4) assuming a lower average dip for the drape folds".

Stearns model for crustal deformation is based on Hafner's (1951) theoretical model and Sanford's (1959) theoretical and experimental models for vertical uplifting. Both these models predict low-angle to high-angle faults that steepen at depth and bound the uplifted blocks. Neither model incorporates or implies lateral shortening. Stearns, however, demonstrates that Hafner's model can accommodate up to 10 percent shortening. The width of the region of basement uplifts, plus parts of the adjacent basins, varies from 150 to 330 km. Thus if Stearns' estimate of 5 to 10 percent shortening is accepted, the magnitude of shortening would range from 8 to 17 km to 15 to 33 km respectively.

Magnitudes of shortening based on Stearns' estimates appear to be too small when compared to the maximum magnitude of Laramide shortening in Canada of approximately 100 km. Mechanisms of thrusting that do not involve shortening, such as that proposed by Price (1973), might reduce the amount of crustal shortening in Canada, but it is the opinion here that they cannot reduce it significantly. Additional Laramide shortening could be distributed along other zones within the plate but west of the region of basement uplifts, thus reducing the amount of shortening required in the region of basement uplifts. At present, no structures of this type are known, but many structures in Nevada and Western Utah are poorly dated. It can also be argued that the estimate of Bally, Gordy, and Stewart (1966) for Laramide shortening in Canada is too small because compressional Laramide structures west of the thrust belt may not have been recognized. Until all structures in the Cordilleran orogen are accurately dated (if this is ever possible), estimates of shortening will be only approximate, and the 100 km figure presented by Bally, Gordy, and Stewart (1966) is used here only as an approximation. We believe that maximum shortening in the area of basement uplift may be equal to this estimate and is accordingly greater than commonly supposed. Shortening of this magnitude is compatible with that inferred in models proposed by Berg (1962) and Sales (1968).

The cause of the localization of basement uplifts within the craton and farther east of the western subductive plate margin than basement yielding in any other part of the orogen is not obvious. In our opinion, however, basement shortening is probably related to a thermally-controlled increase in crustal ductility beneath the region of basement uplifts. Certainly the observed eastward shift of Laramide magmatism into the region suggests that heat was added at least locally to the crust in this area, although the patterns of Laramide igneous activity and basement uplifting do not correspond closely. In fact, there are large areas in the region of basement uplifts where igneous rocks of Laramide age are unknown. It is possible that much of the Laramide magma generated at depth never rose into presently exposed levels of the thick Rocky Mountains crust. Folding and diapiric movement of plutons into the thermally weakened lower crust of the region of basement uplifts can be postulated. Response of the upper crust to compression was more brittle, leading to the formation of drape folds in the sedimentary cover over a faulted and cataclastically deformed basement. Asymmetry (vergence) of uplift structure is both to the east and west, suggesting that the crust behaved regionally as an isotropic material except locally, such as in the Uinta Mountains, where older lines of weakness were reactivated.

Eastward shifting or displacement of Laramide igneous activity into the Rocky Mountains craton presumably reflects changes in the geometry of subduction beneath the western margin of the North American plate. One explanation for the observed phenomena might be the development in latest Mesozoic time of two transform (or tear) faults in the subducting oceanic plate. Transform faults with generally eastward strike may have bounded a central, shallow-dipping portion of the subducting plate that developed between persistent, more steeply dipping segments to the north and south. The fact that the northern and southern portions of the eastern Laramide magmatic province latitudinally overlap western areas of Laramide igneous activity suggests that the relative motion between oceanic and North America plates was not parallel to the transform faults postulated here but had a component of north or south motion relative to them. This circumstance would cause north-south migrations of the magmatic belts in the overlying and intruded North American plate.

Although we are not sure of the validity of the post-Laramide double subduction system postulated by Lipman, Prostka, and Christiansen (1972) as underlying the western United States, such a system could evolve from the Laramide geometry of subduction hypothesized above. If the geometry of the transform-bounded oceanic plate became unstable, this shallow-dipping plate might have become imbricated eastward in Eocene time by east-dipping fracture across it—thus producing temporarily two downgoing slabs and two active magmatic zones. According to Lipman, Prostka, and Christiansen (1972) subduction of the more easterly slab had ceased by Miocene time.

CONCLUSION

We have proposed (Burchfiel and Davis, 1972) that the history of the Cordilleran orogen in the western United States can be divided into three periods of structural development: (1) late Precambrian through late Paleozoic; (2) early Mesozoic through Early Tertiary; and (3) Middle

Tertiary to Recent. The first two periods, as amplified in this companion paper, are each represented by a dominant paleogeography and characteristic tectonic activity.

Paleozoic paleogeography after Early Ordovician time was dominated by the presence of an offshore Klamath-Sierran island arc constructed on oceanic crust and separated from the continent by a marginal basin. The diversity of pre-Middle Triassic tectonic, metamorphic, and igneous (largely volcanic) events in the arc region and on the continental margin can be accounted for by a single unifying plate concept—that the arc and marginal basin were the sites of accelerated convergence between the Pacific and American plates during latest Silurian to Early Mississippian and Late Permian to Early Triassic time.

We conclude according to this broad conceptual framework of Paleozoic plate interaction that traditional views of the Antler and Sonoma orogenies have been too narrow. Emplacement of the Roberts Mountains and Golconda allochthons in north-central Nevada, for example, are not the primary expressions of the Antler and Sonoma events but only attendant dislocational effects produced during stages in the progressive closure of the marginal basin behind the arc. The commonly held view that the Antler orogeny is atypical (for example, Gilluly, 1965), because it was unaccompanied by regional metamorphism or igneous activity, can be abandoned if Devonian regional metamorphism and widespread arc volcanism in the Klamath Mountains are recognized as Antler events in the expanded orogenic context we proposed here.

The first period of Cordilleran structural development in the western United States (excluding the Pacific Northwest) ended in earliest Triassic time with the Sonoma orogeny, the final closure of the marginal basin, and accretion of the Klamath-Sierran arc to the continent. The second period began with subduction of oceanic lithosphere along the western continental margin—a margin modified by arc accretion to the north and by Late Permian or Early Triassic continental rifting and truncation across southern areas. This period, which persisted through Early Tertiary time, is characterized by an Andean-type arc paleogeography (Hamilton, 1969) and by accompanying subduction-related magmatic activity in the western portion of the North American plate. The most characteristic tectonic expression of this period is intraplate crustal shortening behind the arc, locally as far inland from the western plate margin as 1500 km. Intraplate yielding represented a response to compressive stresses generated within the leading edge of the North American plate, and the geometry of yielding was largely controlled by the thermal regimen of the plate. Heat added to western areas of the continent by plutonism above the subducted oceanic lithosphere produced a marginal zone of high crustal ductility relative to eastern areas. East-directed thrust faulting within the plate was largely localized, in agreement with Coney (1972), across the zone of high ductility contrast. The locale of Mesozoic east-directed thrusting shifted eastward in time along much of the length of the orogen as the ductile zone increased in east-west breadth.

We propose that the somewhat enigmatic region of Rocky Mountains basement uplifts represents an additional expression, other than thrust faulting, of thermally-controlled Cordilleran intraplate shortening. In latest Cretaceous time a major north-south gap developed in the plutonic terrane of the Cordillera as magmatic activity shifted eastward into the Rocky Mountains region of southern Montana to northern New Mexico. Laramide plutonism, particularly within lower levels of the thick crust of this region, is inferred to have led to thermal weakening of this cratonal terrane and its subsequent yielding under compression by the formation of thrust fault-bounded basement uplifts and basin subsidences. The eastward shifting of Laramide igneous activity into the Rocky Mountains area of basement uplifts can be explained by a change in the geometry of subduction beneath the North American plate. Specifically, we suggest that the oceanic plate being subducted may have developed a central, shallow-dipping segment between more persistent, steeper dipping segments to the north and south. If so, it is likely that the central segment was bounded by intraplate transform or tear faults that have no expression in the overlying North American plate other than the latitudinally-restricted patterns of Laramide igneous activity and variable tectonic style.

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