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STRUCTURAL FRAMEWORK AND EVOLUTION OF THE SOUTHERN PART OF THE CORDILLERAN OROGEN, WESTERN UNITED STATES

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ABSTRACT. Post-Late Precambrian structural development of the southern Cordileran orogen, western United States, can be divided into three periods: (1) Late Precambrian through Late Paleozoic; (2) Early Mesozoic through Early Tertiary; and 3) Middle Tertiary to Recent. During the first time period, thick sequences of shelf, slope, and oceanic sedimentary rocks accumulated along the western, northeast-trending margin of the continent until Late Devonian time. At that time, oceanic and slope sedimentary rocks were thrust eastward across the continental margin and onto the shelf (Roberts Mountains thrust). Thrusting was probably caused by partial closure of a small ocean basin of behind-the-arc type which lay between the continent and an offshore Sierran-Klamath island arc, the latter presumably developed above an east-dipping subduction zone. During the Late Paleozoic an offshore paleogeography similar to that of pre-Mississippian time persisted. The end of this first time period was marked by Permo-Triassic eastward thrusting (Golconda thrust: Speed, 1971a, b) of the sedimentary rocks of the inner arc basin onto the continental margin. Unlike the similar Middle Paleozoic deformational event, the offshore island arc became welded to the continent, causing a major westward shift of the continental margin at the close of this period.

The second period of southern Cordilleran structural development was initiated by formation of an Early Mesozoic plutonic-volcanic arc of Andean type and northwestern trend *across* all previous northeast-trending paleogeographic belts. This cross-cutting relationship indicates that just before or immediately after the Permo-Triassic deformation a portion of the North American continental plate in the California area was truncated and displaced prior to the inception of eastward underthrusting along the modified continental margin (Hamilton and Myers, 1966). Early Mesozoic underthrusting followed older Paleozoic trends north of the truncated margin but paralleled the modified margin in the south. In response to underthrusting of the western margin of the continent, east-directed intracontinental thrusts developed behind the Mesozoic arc. The orogenic belt during this period thus became two-sided with divergent thrust systems bordering the arc. These two thrust systems tend to migrate in time away from the arc axis, but in other respects, for example in magnitude and style of thrusting, they are most dissimilar. Intracontinental thrusts in Nevada and Utah have northeast trends controlled by Paleozoic paleogeographic elements, including the hinge zone between areas of miogeosynclinal and platform sedimentation. However, in southern Nevada and southeastern California as these thrusts near the truncated continental margin (at a high angle to it), pre-Mesozoic stratigraphic controls on their structural style and trend were reduced. At approximately the intersection of the northeast-trending geosynclinal margin with the northwest-trending arc complex, Early and Late Mesozoic thrusts depart from the geosynclinal terrane and trend southeastward across platform sedimentary rocks and their cratonal basement. These thrusts closely parallel the eastern margin of the Mesozoic plutonic-volcanic arc complex. They are believed to have developed in response to synchronous underthrusting along the nearby and newly modified plate margin in southwestern California. These intracratonic thrusts clearly have no geosynclinal precursor.

The third period of structural development in the southern Cordillera extends from Middle Tertiary to Recent time. It is characterized by strike-slip and extensional fault tectonics related to major changes in plate interactions along the western margin of the continent (Atwater, 1970).

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INTRODUCTION

Regional patterns of paleogeography and structure suggest that the post-Late Precambrian history of the southern Cordilleran orogen between latitudes 45° and 32°N can be divided into three periods: (1) Late Precambrian through Late Paleozoic; (2) Early Mesozoic through Early Tertiary; and (3) Middle Tertiary (Oligocene?) to Recent. Each of these three periods can be related to plate interactions at an evolving continental margin. Unlike most other orogenic belts, the Cordilleran orogen appears to have developed by the interaction of oceanic and continental plates throughout its history. Microcontinental fragments or island arcs may have been swept locally into the continental margin, but no major continent-continent collisions have occurred.

LATE PRECAMBRIAN THROUGH LATE PALEOZOIC PERIOD

The beginning of this period is not clearly marked. Thick Eocambrian clastic sequences, more or less conformable with overlying Early Paleozoic miogeosynclinal clastic and carbonate strata and exhibiting similar isopach trends, indicate the formation of an Atlantic-type plate margin in Late Precambrian time. Stewart (1971) has recently commented on the possible Late Precambrian rifting event that gave rise to this Atlantic-type margin. Early Paleozoic (Cambrian to Devonian) rocks can be divided into three depositional sequences from east to west across the continental margin (Roberts, 1968, p. 106): (1) a thin cratonal or platform sequence; (2) a miogeosynclinal (miogeoclinal) sequence deposited on a broad continental shelf; and (3) a detrital-volcanic (eugeosynclinal) sequence deposited in part on oceanic crust. The edge of the continental plate lay between sequences 2 and 3, and it is probably represented by transitional assemblages deposited along the continental slope and rise and now found beneath and in slices within the east-directed Roberts Mountains thrust plate of Late Devonian-Early Mississippian age (Antler orogeny). The probable position of the continental margin is illustrated in figure 1.

The Cambrian to Devonian eugeosynclinal sequence now present in the Roberts Mountains allochthon measures more than 10 km in thickness and consists largely of shale, graywacke and other sandstones, bedded chert, intermediate to mafic pillow lavas, and siliceous to mafic pyroclastic rocks (Roberts and others, 1958). Similar Early Paleozoic rocks are also present to the west in the eastern Klamath Mountains and northern Sierra Nevada of California. These western rocks may represent either (1) a volcanic arc situated off the continental margin and separated from the mainland by a small ocean basin of behind-the-arc type (fig. 2A), or (2) an exotic island arc assemblage once separated from the continental margin by the full width of an Early Paleozoic ocean basin (fig. 3A). Variations of the first alternative have been suggested by many authors, among them Kay (1951), Osmond (1960), and Roberts (1968; his fig. 6a). The second alternative is made available to us by the development of plate tectonics concepts and has been pre-

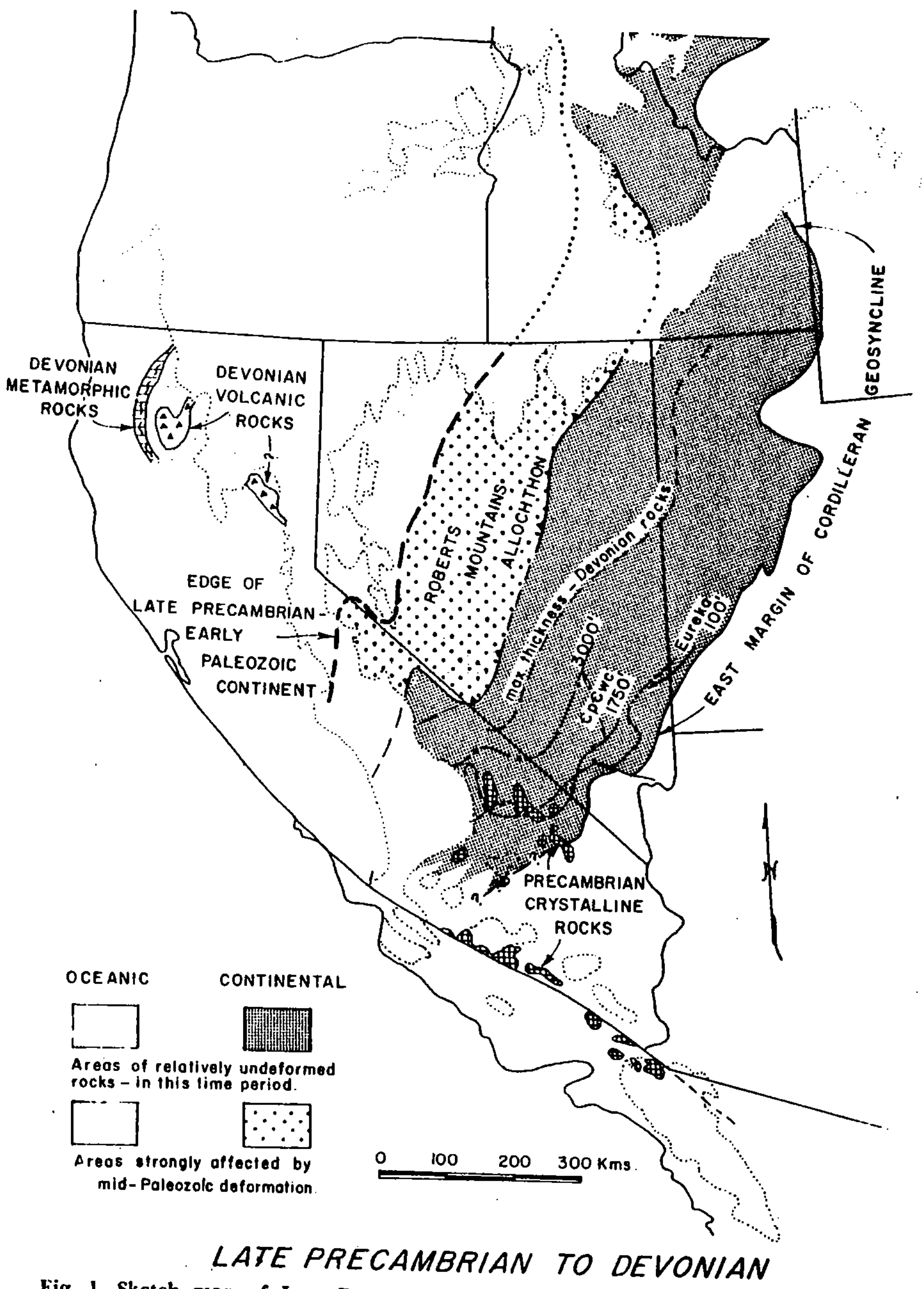

Fig. 1. Sketch map of Late Precambrian to Devonian paleogeography and areas affected by mid-Paleozoic deformation. On all paleogeographic maps, the only deformation eliminated is approximately 600 km of right-lateral displacement on the San Andreas fault. Right-lateral displacements in southern Nevada have not been removed. Isopach lines shown are from Poole and others (1967) for the maximum thickness of Devonian rocks, Stewart (1970) for the 3000 ft and 1750 ft isopachs in the Precambrian-Cambrian Wood Canyon Formation, and Ross (1964) for the 100 ft isopach in the Eureka Quartzite.

sented in modified form by Moores (1970). Relationships between Devonian and Mississippian structural events at the continental margin and the eastward emplacement of oceanic rock assemblages (in the Roberts Mountains thrust plate) atop miogeosynclinal strata are obscure. Emplacement of the allochthon is compatible with the evolution of both paleogeographic models speculated above (figs. 2B and 3B), although the case for the latter (fig. 3B) is seriously weakened by evidence for the continued presence after the orogenic event of a deep marine basin adjacent to the continent. A continent-island arc collision of the type shown diagrammatically in figure 3B should lead to accretion of the arc to the continent and the shifting of the accreted margin many kilometers to the west. Accretion of oceanic material to the western edge of the continent during the Mid-Paleozoic Antler orogeny appears to have been minimal. The Early Mesozoic Golconda allochthon includes oceanic sedimentary rocks and volcanics of Late Paleozoic age thrust eastward over rocks of the Roberts Mountains thrust plate. This relationship suggests that the position of the continental margin in Late Paleozoic time was not greatly different from that in the Early Paleozoic.

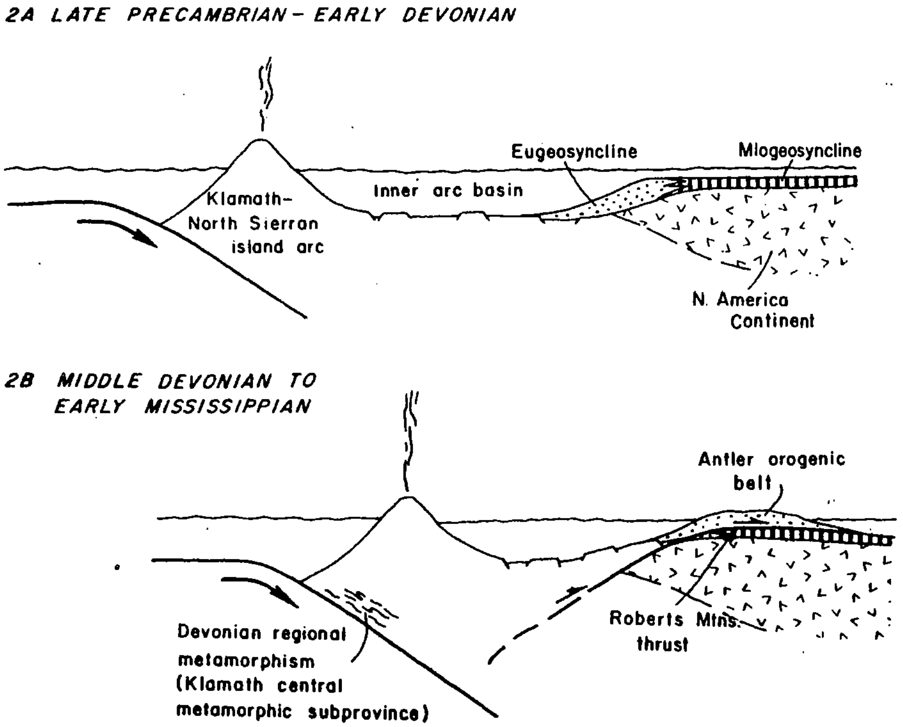

Fig. 2A. Sketch of the relationship between the Early Paleozoic island arc and the North American continent based on the hypothesis of an east-dipping Benioff zone.

2B. Overthrust of the Roberts Mountains thrust from the inner arc basin.

An additional explanation for the closing or partial closing of inner arc basins has recently been proposed by Karig (1971). This involves initial development and expansion of the inner arc basin, then a shifting of subductive activity to a position *behind* the arc and within the inner arc basin. The new subduction zone dips in a direction opposite to that of the old subduction zone. Thus the arc appears to migrate across the inner arc basin as the latter's oceanic crust is consumed. Opening and closing of the inner arc basin may occur more than once. This mechanism may offer an alternative means for the emplacement of oceanic crust over continental rocks (Karig, 1971), combining as it does the initial paleogeography of figure 2A with the postulated arc-continent collision of figure 3B. Details of Karig's hypothesis have yet to be published.

The eastward versus westward directions of subduction inferred beneath an Early Paleozoic Klamath arc by the two models (figs. 2A and 3A, respectively) might be resolved by a study of potash-silica compositional trends in the volcanic rocks (now meta-andesites and metarhyolites) of the Devonian Copley Greenstone (compare, Dickinson, 1970, p. 830-835). Folds with westward vergence were formed in the Klamath central metamorphic subprovince during Devonian regional

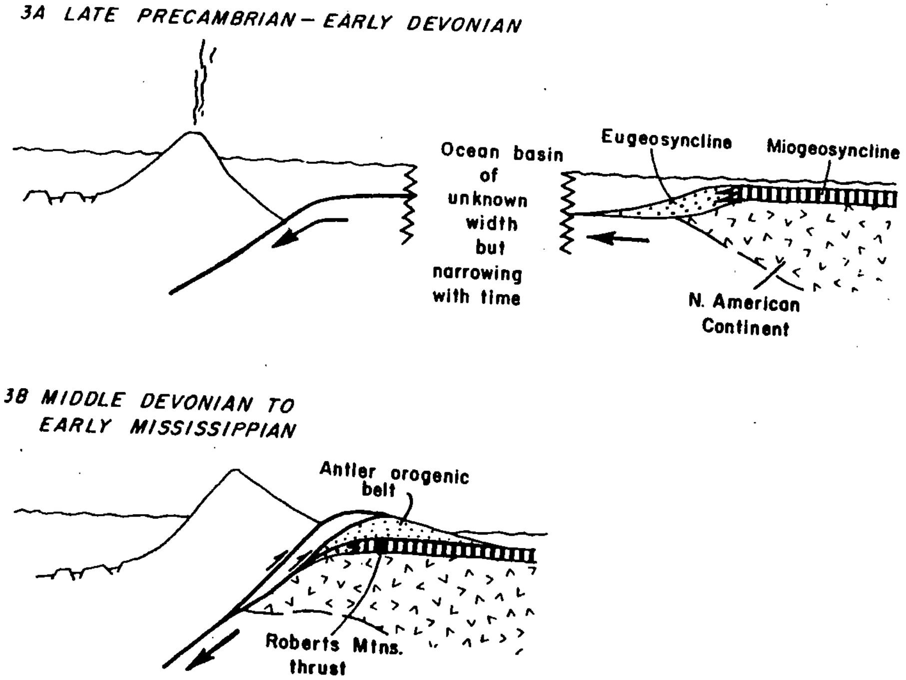

Fig. 3A. Sketch of the relationship between the Early Paleozoic island arc and the North American continent based on the hypothesis of a west-dipping Benioff zone and an ocean basin of unknown width between the arc and the continent.

3B. Emplacement of the Roberts Mountains thrust by subduction of the continental plate.

metamorphism roughly contemporaneous with the Antler orogenic event to the east (Davis, 1968) and may lend credence to the paleogeography indicated in figures 2A and 2B. We prefer the interpretation that this Devonian metamorphic terrane constitutes the basement (disrupted during Mesozoic time) for the Ordovician and younger detrital-volcanic sequence of the eastern Klamath region. We find little, if any, evidence supporting the Mesozoic emplacement of this metamorphic terrane as an exotic slice brought into the Klamath region from a place unknown (Hamilton, 1969a, p. 2418).

Following the Antler orogeny, Mississippian to Permian depositional patterns are generally parallel in trend to pre-Antler depositional sequences. Sedimentation continued in the miogeosynclinal trough east of the Antler orogenic belt but was augmented by thick Mississippian and Pennsylvanian clastic wedges shed eastward from the Antler high (fig. 4). To the west of the Antler orogenic belt and its thin Late Paleozoic sedimentary overlap asemblage (Antler sequence), deep water marine sedimentation of eugeosynclinal type was re-established (or continued) with the deposition of argillite, chert, sandstone, and mafic volcanics (for example, the Pumpernickel Formation, which together with the overlying Havallah Formation comprises the Havallah sequence of north-central Nevada, Roberts and Thomasson, 1964). Once again, the paleogeographic relationship of oceanic sedimentation off the continental margin to contemporaneous sedimentation in the eastern Klamath and northern Sierra Nevadan regions is somewhat unclear. However, since Klamath Permo-Triassic arc-type volcanics, volcanoclastic strata, and shallow-water carbonates rest depositionally on the older sequence containing Devonian arc-type volcanics, we are not dealing with a second island arc in addition to that postulated for Devonian time. Again, two major alternatives can be proposed for the relationship between a Late Paleozoic and Triassic Klamath-Sierran island arc and the depositional site for the Havallah and correlative sequences: (1) a Klamath-Sierran arc inherited from Mid-Paleozoic time lay west of a small ocean basin of inner arc type in which Havallah rocks were deposited (the Pumpernickel-Havallah trough of Roberts, 1968), that is, a paleogeography inherited from earlier times (see fig. 2A); (2) the Klamath-Sierran arc was an exotic island arc swept into the North American continent *for the first time* during Permo-Triassic time, an alternative that if correct would invalidate both earlier alternatives (figs. 2A and 3A) for Mid-Paleozoic paleogeography and would complicate an interpretation of the Antler orogenic event in terms of plate interactions. Accordingly, we favor the first alternative with its attendant implications about the paleogeography of Early Paleozoic time. Upward shoaling of the Havallah sequence (Roberts and Thomasson, 1964) is considered evidence favoring a restricted nature of the Pumpernickel-Havallah trough. The presence of an arc complex to the west of the trough is indicated by current data suggesting derivations of at least some of the clastic filling of the trough from the west (Roberts and Thomasson, 1964, p. D4).

As had happened previously during the Middle Paleozoic, oceanic rocks (Havallah sequence) were again thrust eastward over the Cordilleran continental margin during the Sonoma orogeny (Roberts, 1968; Speed, 1971a, 1971b), this time along the Golconda thrust. Emplacement of the Golconda allochthon is regarded by most recent workers as an Early Triassic event (Speed, 1971a, 1971b; MacMillan, 1971; Nichols, 1971) and part of widespread Permo-Triassic deformation involving oceanic sedimentary and volcanic rocks from Nevada and northern California to Alaska (Dott, 1961). This thrusting probably represents the closing of the inner arc basin that Roberts (1968) and we believe existed along the margin of the continent through Paleozoic time. Eastward displacement of the sedimentary-volcanic filling of this trough during the Antler and Sonoma orogenies corresponds with periods of andesitic volcanism in the Klamath-Sierra arc and, therefore, with times of inferred eastward subduction of oceanic crust beneath the arc. As will be developed below for Mesozoic time, east-directed Cordilleran thrusting (Roberts Mountains and Golconda plates) may be related to compressive stress transmitted continentward from the underthrusting oceanic plate.

In the southern Cordillera the Sonoma orogeny event appears to have added a large volume of oceanic (eugeosynclinal) rocks to the continental margin, causing its migration to the west (fig. 4). Overlying Mesozoic sedimentary and volcanic rocks are, in general, not representative of rocks formed in a deep oceanic environment. We infer that Paleozoic rocks added to the continental margin during the Sonoma orogeny were not of continental thickness. Only after subsequent Mesozoic orogeny and plutonism did this accreted marginal terrane attain continental thickness.

EARLY MESOZOIC THROUGH EARLY TERTIARY PERIOD

A major change in Cordilleran paleogeography occurred during Early Mesozoic or, more likely, Late Paleozoic time. The belt of Early Mesozoic plutonic and volcanic activity generally parallels pre-Middle Triassic geosynclinal and structural trends in northern Nevada and California but turns southeastward at about the latitude of Lake Tahoe and crosscuts geosynclinal facies boundaries, the Antler orogenic belt, cratonal sequences, and Precambrian crystalline basement in central and southeastern California, Arizona, and Sonora (fig. 5). We regard the plutonic rocks of Early Mesozoic age as defining the core region of an active arc system which produced extensive volcanic sequences now found to the east and west of the present Sierra Nevada axis. Evidence presented by Hamilton (1969a) and Dickinson (1970) suggests that the arc developed throughout Mesozoic time above an east-dipping zone of subduction. In the region of the Sierra Nevada and Klamath Mountains, the older plutonic rocks are generally found along the east side of the batholith, intermediate-age plutons along the west side, and the youngest plutons in the central region (Evernden and Kistler, 1970). The plutons are more closely bunched in the south-central Sierra Nevada

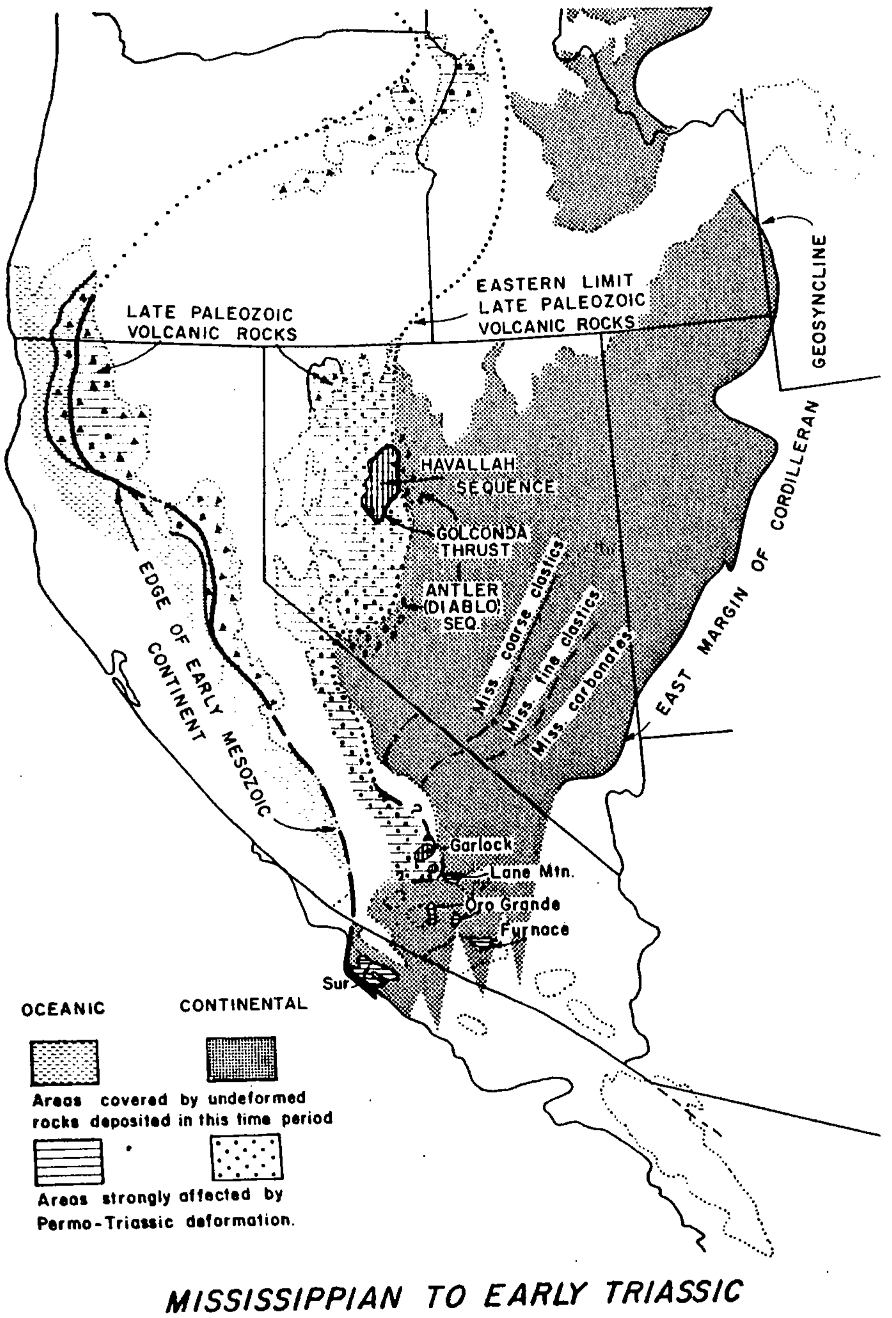

Fig. 4. Sketch map of Mississippian to Early Triassic paleogeography showing areas affected by Permo-Triassic deformation. Mississippian facies lines from Pelton (1966). Position of Antler and Diablo sequences from Silberling and Roberts (1962, fig. 3). Area of Permo-Triassic deformation in northwestern Nevada from Speed (1971a, b).

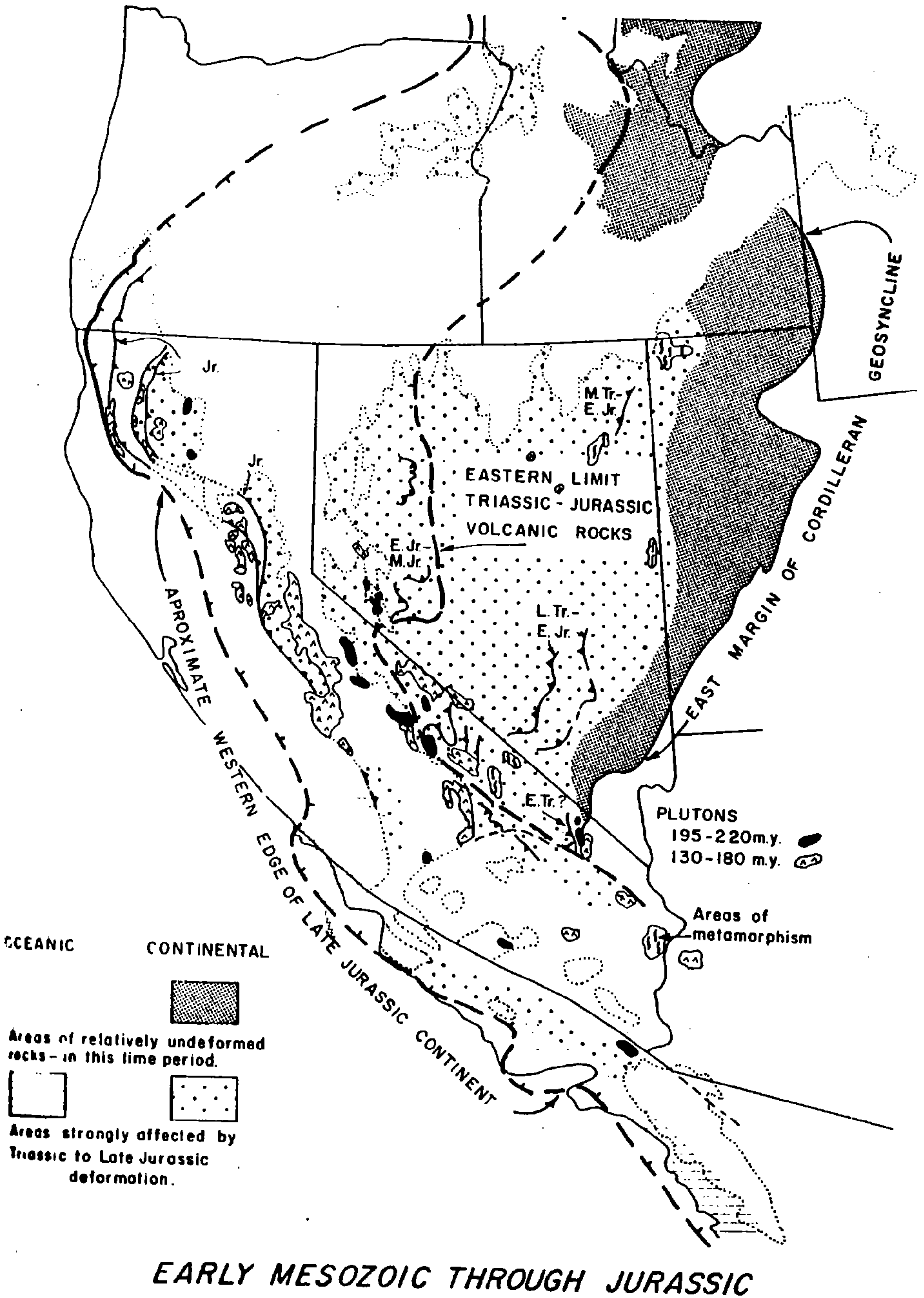

Fig. 5. Sketch map of Early Mesozoic through Late Jurassic paleography and areas affected by deformation during this time period.

where Dickinson (1970, p. 842-843) postulated a 50° eastward dip on the Mesozoic Benioff zone. In the Mojave region the plutonic belt is much broader and trends of plutons of different ages appear to be more complex than to the north.

The formation of an arc complex across miogeosynclinal and cratonal areas underlain by Precambrian crystalline crust indicates that at least this part of the arc was of Andean type. Interfingering of arc volcanic rocks with Triassic and Jurassic(?) shallow marine and nonmarine sedimentary rocks in the Mojave region (Grose, 1959; Abbott, 1971) substantiates this conclusion. In northern California and Nevada the substratum of the arc consisted of the accreted and evolving continental crust added to the continent during Permo-Triassic orogeny. Shallow-water Mesozoic sediments interfingered with arc volcanic rocks along the east side of the arc in west-central Nevada through Early Jurassic time (Stanley, Jordan, and Dott, 1971). In contrast, however, to the conclusion of Stanley, Jordan, and Dott (1971) that the arc was of island type in this area, we regard it as of Andean type, separated from the mainland by a shallow, south-closing marine embayment. Hamilton (1969b) has developed the concept of an Andean-type arc at length.

The crosscutting in Mesozoic time of Paleozoic geosynclinal and structural trends by a marginal arc complex of Andean type requires a Late Paleozoic or Early Mesozoic modification of the configuration of the continental margin of what is now the southwestern United States. A northwest-southeast truncation of the northeast-trending Paleozoic continental margin in this area is required, either by transform faulting or by rifting across a new spreading center, an idea first suggested by Hamilton and Myers (1966, p. 513) and again by Hamilton (1969a). The latter alternative, that of rifting, is preferred since it leads more directly to eastward subductive activity along the truncated margin. The exact nature of faulting, however, may never be clear, even if the missing continental fragment can be located. Faulting of the continental plate thus produced a new plate margin (fig. 4) in the southern part of the Cordilleran orogen, whereas the northern margin probably escaped truncation and thus trends parallel to older Paleozoic patterns. Wiebe (1970) has described superposed fold systems in Sur series rocks of the Salinian block, west-central California which may bracket in their times of origin the truncational event discussed above. In this area early northeast-trending folds of possible Paleozoic age are refolded about northwest-trending folds and intruded by granitic plutons—both (second folds and plutons) at least in part of Cretaceous age.

The timing of this truncational event is somewhat uncertain. It must predate the first phase of Mesozoic (Triassic) plutonic intrusion related to eastward subduction along the modified continental margin, a phase dated at approximately 220 ± 10 m.y. ago in the Sierra Nevada and San Gabriel Mountains (Everden and Kistler, 1970; Silver, 1971). Truncation presumably postdates Late Paleozoic deposition of platform (?) quartzites and carbonates in the western Mojave Desert and San Bernardino Mountains (no truly miogeosynclinal units are known from these areas). Pre-Cambrian rocks are exposed rather widely in southern California (fig. 1), but early Paleozoic, that is pre-Mississippian rocks are relatively unknown (except for perhaps the Chicopee Canyon Formation and Saragossa Quartzite). In the San Bernardino Mountains, the Furnace Formation of Mississippian-Pennsylvanian age consists of over 3200 m of dolomite and limestone and locally rests unconformably on the Precambrian (?) Baldwin gneiss (Hollenbaugh, 1970). Lithologically similar metasedimentary units of probable Carboniferous age occur elsewhere in southern California (Oro Grande Formation, Sur Series, and the lower part of the Lane Mountain sequence; fig. 4), but their upper and lower age limits are not known.

The time of truncation is probably represented in the western Mojave region by the unconformity between the Oro Grande Formation and overlying rocks assigned formally or tentatively to the conglomeratic Fairview Valley Formation (Dibblee, 1967, p. 25, 31-32). Conglomerate clasts include limestone pebbles, cobbles, and boulders containing fossils predominantly of Mississippian to Permian age and locally abundant clasts of granitic and porphyritic andesitic rocks. Deposition of the Fairview Valley Formation thus postdates initial andesitic volcanism and associated plutonism in this area.

The relationship between the time of Late Permian or Early Triassic continental truncation and the Early Triassic emplacement of the Golconda allochthon is of considerable interest, since the two events would appear to require radically different stress regimens. Speed (1971a; personal commun., 1971) is of the opinion that emplacement of the allochthon was followed by siliceous volcanism related to early Sierran plutonism. The requisite time lag, however, between the onset of subduction and the extrusion of magma formed during the subduction process could still permit emplacement of the allochthon *after* truncation but prior to subduction-related magmatism at high crustal levels. This sequence of events (in contrast to truncation after a Golconda thrusting) is favored by the anomalous presence of the eugeosynclinal Garlock Formation in the El Paso Mountains (California) north of the Garlock Fault. This formation, which is at least in part of Permian age, consists of approximately 10 km of limestone, quartzite, chert, chert conglomerate, phyllite, and greenstone (Dibblee, 1967, p. 29-31). Smith and Ketner (1970) have suggested that the Garlock Formation is also represented south of the Garlock Fault in the Mojave block by metasedimentary rocks exposed in Pilot Knob Valley. The close juxtaposition of Late Paleozoic eugeosynclinal rocks (Garlock Formation) with rocks of probable platform facies (Lane Mountain sequence, Oro Grande Formation) in the Mojave area, coupled with similarities in age and lithology of the Garlock Formation with coeval rocks of the allochthonous Havallah sequence in northcentral Nevada (Roberts and others, 1958; R. C. Speed, personal commun., 1971) suggest the possibility that the Sonoma thrust belt may extend as far south as the Mojave Desert (fig. 4). The north-south trend of such a belt would indicate that it crosscuts Paleozoic geosynclinal boundaries and thus, like Mesozoic magmatism, must postdate the truncational event. Available evidence, much of it circumstantial, thus places the time of continental truncation in the southwestern United States as Middle to Late Permian.

The history of Mesozoic underthrusting along the Pacific margin of California has been discussed at length by Hamilton (1969a) and Dickinson (1970) among others and will not be treated here. Two major zones of thrusting related to eastward subduction can be recognized in California (figs. 5 and 6): (1) an older (pre-latest Jurassic) zone within the Klamath Mountains and western Sierra Nevada (Davis, 1969); and (2) a younger (Late Jurassic to Early Tertiary), more external coastal zone involving the Franciscan and Great Valley sedimentary successions (Bailey and Blake, 1969; Ernst, 1970). The possibility that these two geographic zones represent a continuum of Mesozoic subduction activity which migrated from east to west cannot be discounted and has some merit in light of the semicontinuous ages of Sierran plutonism between 210 and 80 m.y. ago reported by Evernden and Kistler (1970). It is clear that the continental margin in California and southwestern Oregon was substantially modified during Mesozoic and Early Tertiary time, largely as a result of offshore sedimentation and the tectonic accretion of trench and deep-sea sediments and associated volcanic rocks. In northern areas accretion occurred along a margin consisting of Paleozoic eugeosynclinal volcanic and sedimentary rocks, whereas in southern California Mesozoic oceanic rocks were plastered against Precambrian crystalline basement and Paleozoic platform (?) assemblages—a further substantiation of the oblique truncation of the North American plate in Late Paleozoic time.

With the recognition in the 1960's of west-directed thrust plates along the western edge of the continent has come the realization that the Cordillera orogen is two-sided with respect to Mesozoic thrusting events (Burchfiel and Davis, 1968). The contemporaneousness of long-recognized east-directed thrusting in the Great Basin-Mojave Desert area with eastward subduction of a Pacific plate beneath North America suggests to us that the two dislocational zones are somehow related. It is to this point that we wish to turn.

Excluding the Golconda allochthon, which has already been described, major Mesozoic east-directed thrust plates developed widely (fig. 5) in the Great Basin and eastern Mojave areas prior to the Late Jurassic (for example, Ferguson and Muller, 1949; Burchfiel, Pelton, and Sutter, 1970; Riva, 1970; Burchfiel and Davis, 1971a, 1971b). Some of the thrusts are poorly dated and may represent Sonoma orogenic events, but distinctly younger thrusts are known; for example, in the Hawthorne-Tonopah area of west-central Nevada (Ferguson and Muller, 1949). No consistent pattern of spatial development can be demonstrated for these pre-Late Jurassic intracontinental thrusts. This is not the case,

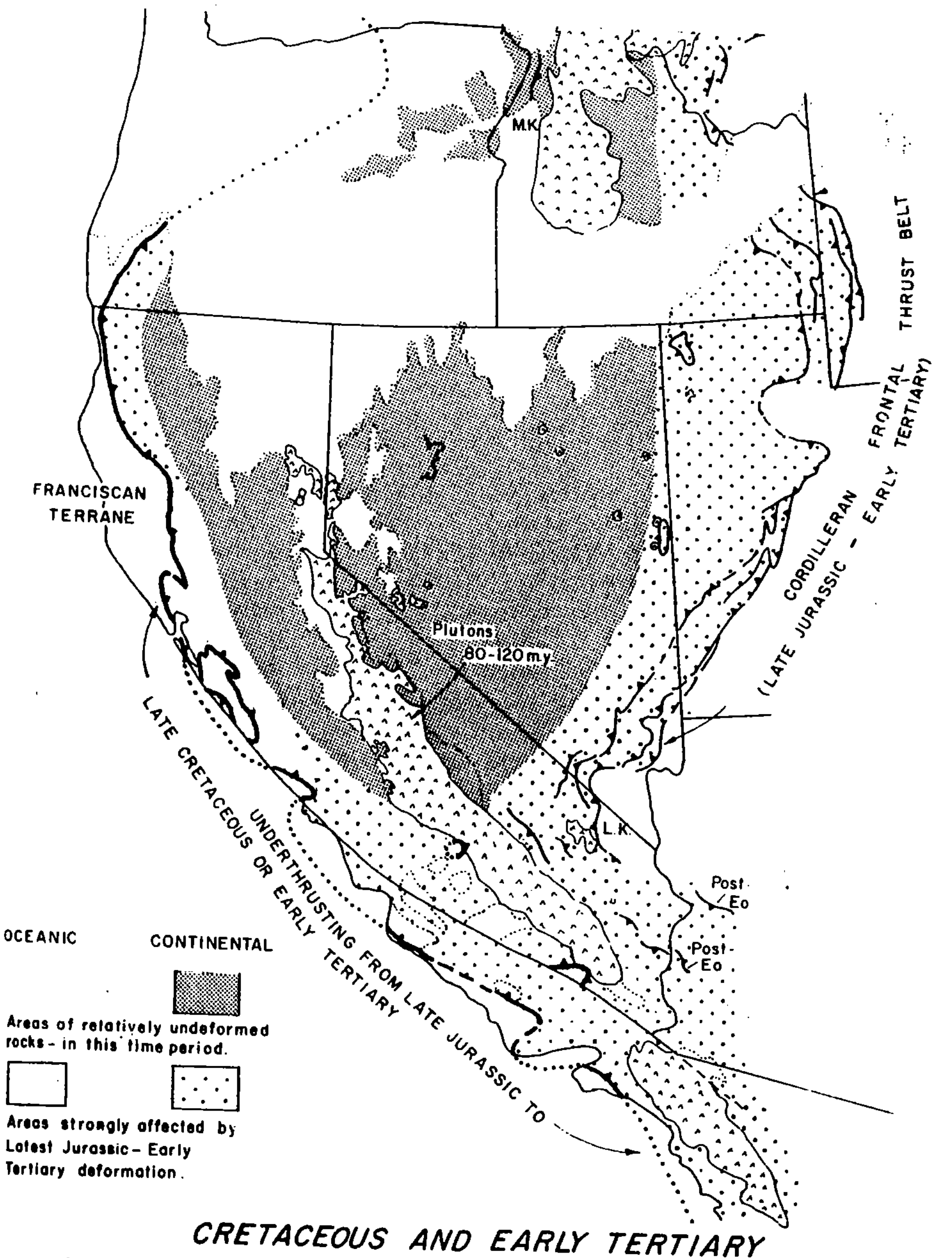

Fig. 6. Sketch map showing areas of deformation during Cretaceous and Early Tertiary time. Displacement of approximately 65 km on the Garlock fault has been removed.

however, for Late Jurassic (or Early Cretaceous) and younger thrusting along the eastern or foreland margin of the Cordillea geosyncline, which generally shows an eastward migration with time (Armstrong and Oriel, 1965; Price and Mountjoy, 1970).

Most workers regard the thrusts of the foreland (or frontal) belt as being of décollement type, that is, faults exhibiting stratigraphic control and not involving Precambrian crystalline basement. This style and the position of this belt is controlled by Paleozoic paleogeography, since thrusts in the foreland belt represent regional stratigraphic décollement across the Paleozoic hinge zone between areas of miogeosynclinal and platform sedimentation (fig. 7). The northeastern trend of the foreland thrust belt between Las Vegas and Salt Lake City thus parallels the hinge zone in this portion of the Cordillera.

South of Las Vegas, however, major changes occur in the nature of the foreland or frontal belt, specifically in a marked change of trend to the southeast and the extensive involvement of Precambrian crystalline rock in thrusting (fig. 6). The Clark Mountain region in the eastern Mojave Desert of southeastern California (Burchfiel and Davis, 1971b) is an area of transition between the two tectonic styles and trends. All thrust faults known to the southeast of this area in California and southwestern Arizona (Hamilton, 1964; Lasky and Weber, 1944; Miller, 1970) involve Precambrian basement and overlying strata (including Paleozoic platform units, Mesozoic sedimentary and volcanic rocks, and Early Tertiary continental sediments). This change in trend and tectonic style of the foreland thrust belt in the Clark Mountain area is related to Late Paleozoic truncation of earlier paleogeographic elements in the southwestern United States and the subsequent development of a Mesozoic plutonic-volcanic arc complex parallel to the truncated margin. As the foreland thrust belt nears the truncated continental margin (at a high angle to it), pre-Mesozoic stratigraphic controls on its structural style and trend were reduced. At approximately the intersection of the northeast-trending geosynclinal margin with the northwest-trending arc complex, the Cordillera frontal thrust belt turns southeastward away from the hinge zone to cut across platform rocks and their cratonal basement (fig. 7). The position of this portion of the frontal thrust belt (no longer a "foreland" belt as to the north) closely approximates the eastern margin of the Mesozoic plutonic-volcanic arc complex.

Early Mesozoic thrusts in the central Great Basin area (Burchfiel, Pelton, and Sutter, 1970) may exhibit a similar change in trend and style as the arc-complex is approached from the northeast. We have evidence for early Mesozoic thrusting in external parts of the frontal thrust belt in the Clarke Mountain area (Burchfiel and Davis, 1971a). The presence of both Early and Late Mesozoic thrust faults in this portion of the Cordillera orogen indicates a southward convergence and overlap in the eastern Mojave of older, more internal Mesozoic thrusts (fig. 7) and younger thrusts of external or frontal position. Detection and separation of such overlapping deformational events in the

thrust terranes of southeastern California and southwestern Arizona may prove extremely difficult.

The abrupt change in strike of Mesozoic and Early Tertiary thrusts in the southeastern Cordillera to a direction parallel to the truncated plate margin in this region strongly suggests that the intracontinental thrusts of the Cordilleran orogen are directly related to oceanic underthrusting along the western margin of the orogen. The eastern, west-dipping thrusts may terminate at depth in zones of crustal flow or against the east-dipping subduction zone, and their origin can best be attributed to compressive stresses transmitted eastward through the crust from the zone of continental underthrusting. Reconnaissance studies in the north-central Mojave Desert strongly suggest that elements of west-

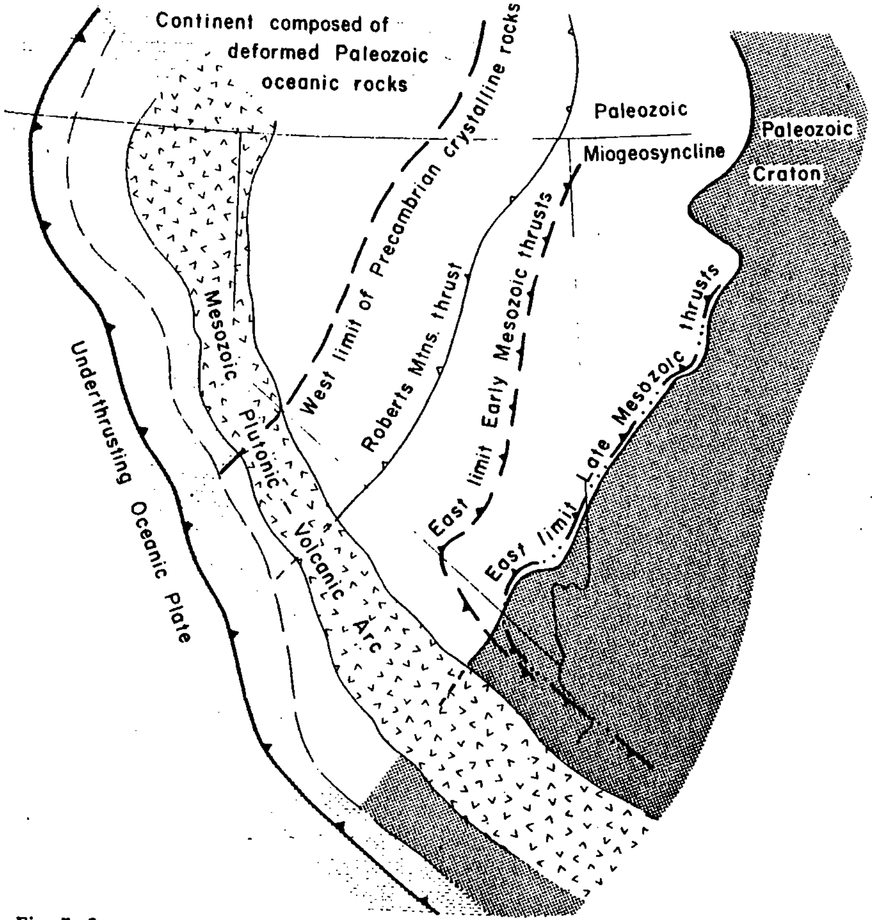

Fig. 7. Summary tectonic sketch map for the Late Mesozoic showing truncation of Paleozoic geosynclinal and deformational trends by a Mesozoic plutonic-volcanic arc of Andean type. An inferred southward convergence of Early and Late Mesozoic thrust zones is also shown as is the change in trend of such faults and their departure from the geosynclinal terrane in southeastern California.

and east-directed Mesozoic thrust systems approach within 80 to 120 km of each other on either side of a central batholithic terrane extending southward from the Sierra Nevada (fig. 6). It should be emphasized that the two regional thrust systems are not of equal significance; total displacements along the western system may exceed those along the eastern by an order of magnitude or more. The eastern thrust system is a major zone of dislocation and shortening *within* the continental crust of North America, whereas the western thrust system is a zone of interaction *between* the North American lithospheric plate and an underthrusting Pacific plate. Along the oceanic side of the continent, several thousand kilometers of oceanic crust have presumably passed beneath the plate margin (Hamilton, 1969a), whereas along the frontal thrust complex crustal displacements total only 80 (Armstrong, 1967) to 160 km (Bally and others, 1966). Thus, to consider that the eastern belt of thrusts constitutes a west-dipping subduction zone (Moores, 1970, p. 840) is to obscure current usage of this useful term.

The genetic relationship which we infer between the west- and east-directed thrust systems in southern California is not as obvious to the north where thrusts on the two sides of the orogen diverge from each other (fig. 6). This divergence is the result of the obliquity of Paleozoic paleogeography to the Mesozoic continental margin, and it is exaggerated by Late Tertiary distension across the Great Basin area. To the north the two thrust systems approach each other again in eastern Oregon, central Idaho, and southwestern Montana, where the zone(s) of Mesozoic underthrusting paralleled the Paleozoic continental edge, and where Basin and Range structures die out. Here also, as in the central Mojave region, a Mesozoic batholithic complex occupies the relatively narrow central terrane between east- and west-directed thrust systems (fig. 6).

Much favorable attention has been directed to the recent hypothesis by Price and Mountjoy (1970) that the foreland thrust belt in the southern Canadian Cordillera represents the detachment and eastward displacement of bedded sedimentary rocks from their crystalline substratum in association with the lateral spreading of an internal mobile belt or infrastructure. The extreme narrowness and structural characteristics of the thrust-bounded central terrane in the Mojave region of southern California appear to rule out the Price-Mountjoy tectonic model as an explanation for this portion of the "foreland" thrust belt. The northern part of the Mojave central terrane is clearly a southward continuation of the Sierra Nevada batholithic belt, not an infrastructural complex of Shuswap type. The widespread occurrence of Late Paleozoic (Carboniferous, Permian?) metasedimentary and Early Mesozoic metavolcanic rocks within the northern Mojave indicates that this terrane is structurally low (perhaps synclinorial) and stratigraphically high—not a zone of buoyant upwelling as is the Shuswap complex nor, incidentally, a tectonic high from which the eastward gravity sliding of allochthonous Precambrian and younger rocks could have occurred. Hamilton (1971) has described a metamorphic complex with infrastructural characteristics in the southeastern Mojave area near Blythe. Precambrian basement, Paleozoic platform strata, and Mesozoic sedimentary and volcanic rocks are present in the complex. Thrusting of Precambrian crystalline rocks and their Paleozoic cover in the Plomosa Mountains east of Blythe, however, clearly postdates the infrastructure-forming event (Miller and McKee, 1971, p. 721) and is therefore not related to it.

Instead, a compressional origin for northeast-directed intracratonal thrusts in the eastern Mojave and southwestern Arizona which is related to underthrusting of the nearby continental margin is supported (1) by rooting of the thrusts into Precambrian crystalline basement, (2) by their parallelism with the northwest-trending truncated continental margin, and (3) by their synchroneity with eastward oceanic underthrusting of that margin.

The frontal thrust belt northeast of the Clark Mountain area with its décollement characteristics and northeast trend is presumably no less compressional in origin, but here the zone of detachment and eastward yielding followed favorably oriented stratigraphic horizons above the west-dipping interface between crystalline basement and platform and miogeosynclinal cover. Eventual westward rooting into crystalline basement of at least some of the major thrusts in this belt is to be expected. A Mesozoic metamorphic terrane with infrastructural characteristics also lies to the west of this portion of the foreland thrust belt in eastern Nevada and western Utah (Misch and Hazzard, 1962; Armstrong and Hansen, 1966). However, a cause and effect relationship between the development of an internal infrastructure and Late Mesozoic thrusting along the eastern margin of the geosyncline (Las Vegas to Salt Lake City) seems invalid for this part of the Cordillera in light of conclusions by Misch (1971) and Armstrong (1971) that frontal thrusting generally postdated the time of infrastructural deformation.

In light of well-established evidence for zones of high heat flow behind active underthrust arcs in the west Pacific (for example, McKenzie and Sclater, 1968; Oxburgh and Turcotte, 1970), it occurs to us that development of Cordilleran infrastructural complexes east of the Mesozoic plutonic and volcanic arc may represent an independent and thermally-driven expression of behind-the-arc tectonics and one not directly related to the intracontinental thrusting we have discussed.

MIDDLE TERTIARY TO RECENT PERIOD

The third and present period in the development of the southern Cordilleran orogen began in Oligocene time when the East Pacific Rise migrated into the trench along the western margin of North America (Atwater, 1970). Migration of triple point junctions and subsequent plate interactions produced major changes in tectonic style which have been discussed by Atwater (1970), Hamilton and Myers (1966), and others and are not the subject of this paper.

CONCLUSIONS

Among the major conclusions of this paper are the following:

1. The post-Late Precambrian history of the Cordilleran orogen of the southwestern United States can be divided into three periods—Late Precambrian through Late Paleozoic, Early Mesozoic through Early Tertiary, and Middle Tertiary to Recent.

2. Throughout the Paleozoic the paleogeography of this part of the Cordilleran geosyncline probably consisted of an offshore island arc complex separated from the continental slope and shelf by a small ocean basin of behind-the-arc type. Initial regional deformation within the Cordilleran geosyncline—the Mid-Paleozoic Antler orogeny—was characterized by the eastward displacement (Roberts Mountains thrust) of eugeosynclinal units from within the small ocean basin over miogeosynclinal strata deposited on the continental shelf. The small ocean basin, although presumably narrower after the Antler orogeny, persisted throughout the rest of the Paleozoic. Pre- and post-Antler depositional sequences and the orogenic belt itself show north-northeast trends across the southwestern United States parallel to the Paleozoic continental margin.

3. A major change in the paleogeography of the southern Cordillera took place at the end of the Paleozoic. A new northwest-trending plate edge formed at that time in what is now central and southern California by the fault truncation of Paleozoic structural and stratigraphic belts and the removal by drift of a large piece of the Paleozoic North American plate.

4. In the Sonoma orogeny of Early Triassic time, presumably shortly after the truncational event described above, the small ocean basin which lay between island arc and continent and northeast of the line of truncation was closed. This was accomplished by (1) renewed eastward thrusting (Golconda thrust) of basin fill over the continental margin and the older Antler orogenic belt, and (2) accretion of the Klamath-Sierran island arc to the continent.

5. Mesozoic underthrusting of the modified continental margin by an oceanic plate created an Andean-type plutonic-volcanic arc which in southern areas crosscuts the Late Precambrian-Paleozoic continental plate edge and the geosynclinal-cratonal boundary. East-directed thrusting developed within the continent on the east side of the arc synchronously with underthrusting by the oceanic plate on the west side, thus producing a two-sided orogenic system with respect to Early Mesozoic through Early Tertiary thrust faulting.

6. The crosscutting of Paleozoic geosynclinal trends by the Mesozoic Andean-type arc complex exerted controls on the geometry of Mesozoic east-directed thrusting. Such controls are best illustrated by the geometry and tectonic style of the Late Mesozoic-Early Tertiary frontal ("foreland") thrust belt of the southern Cordillera. To the south of the intersection between the northeast-trending geosynclinal-cratonal boundary and the northwest-trending Mesozoic arc, the frontal thrust belt disrupts Precambrian basement and its cratonal cover and follows the eastern edge of the arc complex. To the north of this intersection, the same belt turns inland to follow the geosynclinal hinge zone because of easy yielding by regional stratigraphic décollement across it (fig. 7). The continuity of this diverse belt, its southern parallelism to the truncated continental margin, and its crosscutting of cratonal basement all suggest a direct compressional relationship between eastward underthrusting of the continent by an oceanic plate and the formation of east-directed thrust faults within the continental plate. A similar genetic relationship is visualized for older east-directed Mesozoic thrust in the Great Basin-Mojave area.

7. We see little need and little evidence for a Paleozoic-Mesozoic tectonic history of the southern Cordillera governed by alternate periods of eastward underthrusting of the continental margin and multiple collisions of that margin with west-dipping oceanic subduction zones (Moores, 1970). All major east-directed thrusts in the southern Cordillera can be interpreted as compressional features related to eastward underthrusting of oceanic crust beneath the North American plate. Eastward thrusting of oceanic rocks atop miogeosynclinal strata during the Mid-Paleozoic Antler and Early Mesozoic Sonoma orogenies can be attributed to stages in the compressive closing of a small inner-arc ocean basin located off the continental margin. These orogenic events are thought to be related to episodic (?) eastward subduction of oceanic crust beneath a Paleozoic Klamath-Sierran island arc. Mesozoic underthrusting occurred continuously (or nearly so) along a continental margin modified by Late Paleozoic rifting and Early Mesozoic accretion of the island arc complex. Compressive stresses engendered by underthrusting produced east-directed thrusts within the continental plate which parallel the plate margin or depart from it along stratigraphic trends reflecting Paleozoic paleogeography.

8. That portion of the Cordilleran fold and thrust belt in the Mojave Desert of southeastern California and in southwestern Arizona does not have a Paleozoic geosynclinal precursor but is developed across Precambrian crystalline basement with a thin sedimentary cover of platform type. This indicates that Cordilleran orogenesis in this area is not related to classical models of geosynclinal evolution leading to mountain building and supports broader suggestions by Coney (1970) that alpine-type orogenesis and geosynclinal development are not necessarily related. In the Cordilleran region of North America a pronounced lack of parallelism of the Mesozoic and Paleozoic continental margins exists only in the southwestern United States. This nonparallelism reveals that Mesozoic orogenesis in the Cordillera is related to plate interactions at the Mesozoic continental margin and *not* to a final, paroxysmal stage of geosynclinal development. The Paleozoic geosynclinal sedimentary accumulation when present does influence the geometry of east-directed thrust faulting, but a direct genetic relation-

ship between formation of the Cordilleran geosyncline and subsequent orogenesis seems most unlikely to us.

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GEOCHEMICAL MASS BALANCE AMONG LITHOSPHERE, HYDROSPHERE, AND ATMOSPHERE

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ABSTRACT. From O^{18} mass balance calculation, the total sedimentary mass of $2.4 \pm 0.4 \times 10^{24}$ g is obtained. A geochemical mass balance model is constructed by using Poldervaart's average crust rock and the constrains from O^{18}, C^{18}, and S^{34} isotope data. A mathematical model for the distribution of sedimentary mass as a function of age is also given and discussed. The weathering constant, w, for the last 700×10^{6} yr is $4.8 \pm 0.1 \times 10^{-9}$ yr^{-1} which corresponds to a mean residence time of sediment (1/w) $210 \pm 5 \times 10^{6}$ yr.

INTRODUCTION

In order to account for the present composition and amount of sedimentary mass as well as sea water, Goldschmidt (1933, 1954) suggested that at least 815×10^{21} g of igneous rock is weathered by reacting with 1400×10^{21} g of primary magmatic volatiles (mainly H_2O and with some CO_2, HCl, H_2, H_2S, N_2 et cetera). Rubey (1951) also showed that most of those primary magmatic volatiles should have been supplied continuously from the interior of the Earth, since the amount of H_2O, C, Cl, S, N_2, et cetera in the present sediment, hydrosphere, and atmosphere cannot be accounted for by those released from igneous rocks alone during the weathering.

The purpose of this paper is to present a simple geochemical mass balance between igneous rocks and primary magmatic volatiles on the one hand and the sedimentary mass, hydrosphere, and atmosphere on the other hand. The emphasis is kept on the charge balance and the mass balance of stable isotopes (O^{18}, C^{13}, and S^{34}) in the system.

Chemical weathering and "reverse weathering".—Chemical weathering bears analogy to an ion exchange or acid titration process, that is, hydrogen ion, H^+, from magmatic volatiles replaces metal cations in igneous rock and causes the reconstruction of rock materials. Table 1 illustrates this point. The moles of each rock forming minerals for the igneous rock in table 1 are the norms calculated from 100 kg of the average crust rock given by Poldervaart (1955). The iron is partitioned into ferric and ferrous compounds in table 1 according to the Fe^{2+}/Fe^{+3} ratio in the average crust rock and sedimentary rock given by Poldervaart (1955). The titration capacity is about 0.76 equivalent of H^+ per 100 g of igneous rock.

The "reverse weathering", first proposed by Mackenzie and Garrels (1966), is a general term for the clay mineral-and-salt-forming process. In this process, the metal cations replace H^+ ion as illustrated in table 2. The end components of clay minerals in table 2 are chosen quite arbitrarily and may not exist in sediments, but any clay mineral can be constructed by a proper mixture of those chosen components. The point is to make charge and material balance. Also in order to make the consumption of HCl minimum, all kaolinite was combined with cations to form other clay minerals.