TOPICAL STUDIES

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TECTONIC SETTING OF ARIZONA THROUGH GEOLOGIC TIME

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ABSTRACT

Located near the southwestern extremity of the North American continental block, Arizona has undergone a complex tectonic evolution influenced by events along both the Cordilleran and Mesoamerican continental margins. The Precambrian basement rocks of Arizona represent Proterozoic continental crust that was formed by magmatism and deformation related to subduction and tectonic accretion south of the Archean core of the continent. Subsequent Precambrian shelf sedimentation covered parts of the previously consolidated crustal block. Most Paleozoic strata were deposited as platform cover extending across the trend of the transcontinental arch between the Cordilleran miogeocline and the Ouachita margin of the continent. Some upper Paleozoic sequences fill downwarped or downfaulted basins that developed within the Ouachita foreland region in response to continental collision along the Ouachita segment of the Hercynian orogenic belt. Thin Triassic terrestrial strata were deposited within the resulting Pangaea supercontinent. By mid-Mesozoic time, Jurassic arc magmatism related to subduction along the Pacific margin of the continent had begun in the southwestern part of the state, whereas amagmatic redbed sedimentation was dominant in the northeastern part of the state. Upper Mesozoic sedimentary strata include Lower Cretaceous deposits of the rifted Bisbee basin at the northwestern extremity of the Chihuahua trough in southern Arizona and Upper Cretaceous deposits of the Rocky Mountain foreland basin in northern Arizona. Laramide magmatism and deformation, most intense in southern Arizona, were related to subduction of oceanic lithosphere at a shallow angle within the mantle beneath the continent during latest Mesozoic and earliest Cenozoic time. Crustal thickening and uplift during the Laramide episode led to widespread Eocene erosion. Subsequent mid-Tertiary arc magmatism and associated extensional deformation, most intense in southern and western Arizona, thinned the overthickened crust to allow subsidence accompanied by syntectonic sedimentation. Late Cenozoic block faulting and basin filling were followed by integration of drainages to form trunk streams emptying into the nascent Gulf of California. Continental drift of the crustal block including Arizona carried the state from tropical latitudes during the Paleozoic to its present location within the temperate zone.

INTRODUCTION

Because of its position near the southwestern extremity of the Precambrian crustal block of the North American craton, the tectonic evolution of Arizona offers special insights into geologic history. In effect, Arizona provides a geographic bridge between the Cordilleran or Pacific margin of the continent and its southern margin, marked during the Paleozoic by the Ouachita orogenic belt and in later times bordered by the Caribbean or Mesoamerican region. The dual tectonic role that Arizona has accordingly played through time makes geologic relations within the state especially complex. Multiple episodes of deformation through geologic time have superposed numerous phases of both contractional and extensional strain upon the crustal block beneath Arizona (Davis, 1981). This paper presents a general overview of the key stages in the tectonic evolution of Arizona and provides a context for the detailed discussions that follow. The focus of the text is maintained on Arizona, whose regional position within a wider tectonic framework has been discussed elsewhere (Dickinson, 1981). Selected references are provided as a guide primarily to recent literature and may slight the contributions of earlier investigators, whose work is cited more fully elsewhere in this volume.

PROTEROZOIC CRUSTAL CONSOLIDATION

The Precambrian basement rocks of the United States can be subdivided into a number of age belts that trend from east-northeast to west-southwest across the midcontinent region (fig. 1). Archean rocks (>2500 Ma) extend from the Canadian Shield into the northern Rocky Mountains but are unknown in the southwestern states. Isotopic investigations of Precambrian exposures and Phanerozoic igneous rocks indicate that Proterozoic basement underlies all of Arizona, including areas where younger cover masks them at the surface (Farmer and DePaolo, 1984). Recent Nd-Sm isotopic studies suggest that the initial formation of Proterozoic continental crust may have occurred slightly earlier than implied by the age belts depicted on figure 1 and that crust as old as 2000-2250 Ma may be present in northwesternmost Arizona (Nelson and DePaolo, 1985). In

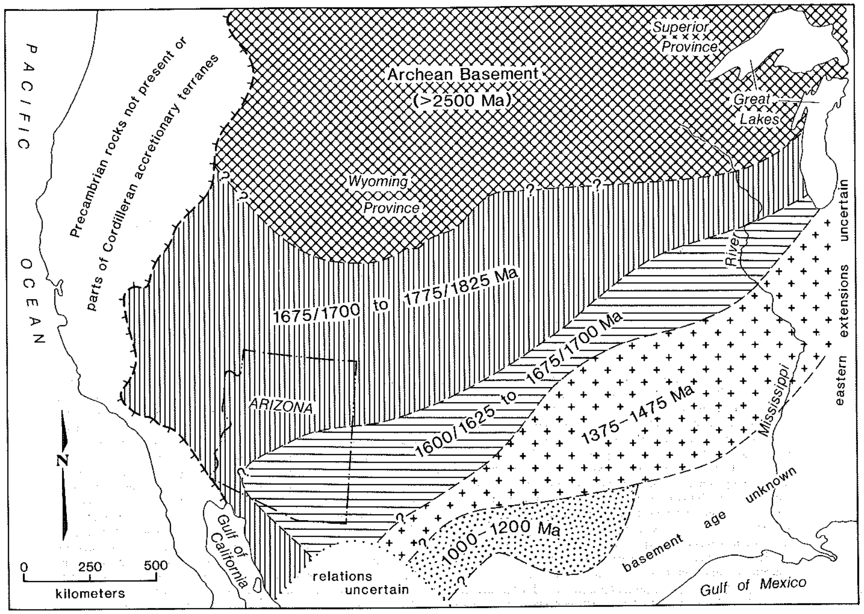

Figure 1. Proterozoic position of Arizona in relation to Precambrian age belts (simplified) of the North American craton. Modified after T. H. Anderson and Silver (1979), Van Schmus and Bickford (1981), J. L. Anderson (1983), Karlstrom and Houston (1984), and Thomas and others (1984).

the following paragraphs, subdivision of Proterozoic time follows the usage of Palmer (1983).

The oldest exposed igneous and metamorphic rocks in Arizona were formed by Early Proterozoic volcanism, sedimentation, plutonism, and deformation during the interval from 1825 to 1625 Ma (Livingston and Damon, 1968; Silver, 1978). Although many details of their geologic history are controversial, there is widespread agreement that the orogenic events responsible for their development involved subduction and arc magmatism (P. Anderson, 1980). This assumption is based upon the lithotectonic association of calc-alkalic volcanics, volcanogenic ore deposits, and granitic plutons with the products of dynamothermal metamorphism. The petrogenesis is generally attributed to the emergence of crustal materials from the mantle within regions where no Archean crustal blocks existed. The initial consolidation of continental crust within Arizona thus apparently occurred about 1750 Ma in response to ancient arc-trench tectonics that quite likely involved amalgamation of multiple magmatic arcs (Condie, 1982). In central Arizona, submarine volcanics in the Yavapai Supergroup of the Prescott-Jerome volcanic belt were succeeded by subaerial rhyolites in the Haigler Group of the New River-Payson volcanic belt, and overlying mature quartzites of the Mazatzal Group evidently reflect shelf or platform sedimentation on the newly formed continental crust (P. Anderson, this volume).

The tectonic processes that led to Proterozoic crustal consolidation in Arizona are still poorly understood. Strongly deformed, dominantly volcanogenic successions in central Arizona have estimated stratigraphic thicknesses locally in excess of 5 km (Donnelly and Hahn, 1981) and are intruded by somewhat younger granitic plutons. Within the region as a whole, however, volcanism and plutonism were broadly coeval during the period of orogenic magmatism. Over large areas farther south, wall rocks are dominantly metasedimentary strata (Condie and DeMalas, 1985), also intensely deformed. With present data, it is difficult to judge whether the various assemblages of Proterozoic rocks in Arizona were built in place by arc-trench systems, possibly including interarc basins and marginal seas, aligned along the southern flank of the Archean continental core, or instead were created elsewhere and accreted tectonically to the continental block. Our

present understanding of Phanerozoic orogenic belts suggests that both indigenous and exotic tectonic elements may be represented within the complex Proterozoic terrane of Arizona. In any case, all components of the terrane are inferred to be composed of materials that formed as juvenile crust in Early Proterozoic time but had been deformed and incorporated into a crustal block of continental thickness by mid-Proterozoic time (1500-1600 Ma).

Voluminous granitic batholiths of Middle Proterozoic age were emplaced into the nascent continental crust of Arizona about 1450 Ma (Silver and others, 1977). This intrusive episode occurred much later than the deformation associated with initial consolidation of the crustal profile, and the plutons are in that sense anorogenic bodies. They represent but a segment of an extensive belt of analogous batholiths that extends from the midcontinent region across the southern Rocky Mountains to the Mojave Desert (J. L. Anderson, 1983). With present knowledge, their tectonic affinities are impossible to ascertain with confidence. Analogy with Phanerozoic batholith belts suggests some relationship to crustal subduction or collision within a zone lying to the southeast, away from the Archean core of the continent (Nelson and DePaolo, 1985).

PROTEROZOIC PLATFORM DEVELOPMENT

Following an erosional interval of indeterminate length, Middle Proterozoic sedimentary strata of combined shallow-marine and coastal-plain origin were deposited upon parts of the Arizona basement terrane. Their original extent is uncertain, but sequences as much as 2.5 to 4.5 km thick are preserved in the Grand Canyon (D. P. Elston and McKee, 1982) and in the Apache Group of central Arizona (Shride, 1967). Intercalated basaltic lavas and intrusive diabase sills that provide the only age constraints for the sedimentary strata have yielded isotopic ages of about 1100 Ma (Lucchitta and Hendricks, 1983). Several internal disconformities indicate that basin evolution was complex in detail, but broad facies relations are generally undocumented.

The locally substantial thickness of the Middle Proterozoic succession and the presence of coarse clastics within it suggest that significant crustal deformation accompanied basin development. The nature of any associated tectonism is speculative, but the presence of intercalated basalt flows and diabase sills implies an extensional regime. Somewhat similar successions in the Death Valley region farther west have been related to the subsidence of a rift trough having the general character of an aulacogen (Wright and others, 1976), and a related structure may have extended into the crustal block beneath Arizona.

In central Arizona, approximately half a billion years elapsed between deposition of the youngest preserved Precambrian strata and the onset of Paleozoic sedimentation. Despite the duration of the hiatus, the unconformity beneath the Paleozoic strata of central Arizona displays only slight angular discordance. The widespread structural concordance of Middle Proterozoic and Middle Cambrian strata is dramatic evidence that a remarkably stable continental platform had developed in Arizona by Late Proterozoic time. Block faulting that disrupted the platform surface in the Grand Canyon region prior to Cambrian transgression was probably related to latest Precambrian rifting that delineated the trend of the Cordilleran miogeocline farther west (Stewart, 1972).

EARLY AND MIDDLE PALEOZOIC PLATFORM EVOLUTION

By Late Proterozoic time, Arizona lay within the interior of a vast supercontinent assembled during Proterozoic time (Stewart, 1976; Sears and Price, 1978). Subsequent rifting in latest Precambrian and earliest Paleozoic time spawned a number of separate continental blocks of which North America was one. Passive continental margins evolved subsequently along the Cordilleran and Ouachita margins of the craton as the rifted continents drifted apart. The southwestern projection of the stable continental interior extended into northeastern Arizona as the transcontinental arch. Pre-Pennsylvanian Paleozoic strata of Arizona were deposited in shelf seas and related environments that fringed and covered this continental basement platform (fig. 2).

Paleozoic strata in the center of Arizona do not exceed about a kilometer in aggregate thickness (Peirce, 1976). Sections twice as thick in the northwestern and southeastern corners of the state form the updip limits of sedimentary wedges that thicken toward the old Cordilleran and Ouachita margins of the continental block. Toward the northeast, Paleozoic sequences generally thin along the axis of the transcontinental arch. A thick Paleozoic succession of miogeoclinal character is present to the southwest near Caborca in Sonora, Mexico, but its present location may reflect displacements of uncertain magnitude along post-Paleozoic strike-slip faults (Stewart and others, 1984).

Disconformities within the pre-Pennsylvanian Paleozoic sequence of Arizona indicate that platform sedimentation was discontinuous, marked by repetitive transgression and regression of marine waters. The most distinctive and laterally continuous units within the succession lie at its base and at its top. As the initiation of Paleozoic sedimentation was diachronous, the basal strata are time-transgressive sandstone bodies of partly arkosic but dominantly quartzose composition assigned to the Tapeats Sandstone in the north, the Bolsa Quartzite in the south, and the Coronado Sandstone on the east (Hereford, 1977; Hayes, 1978). These Cambrian clastic units have close counterparts throughout the Cordilleran region and record the initial subsidence of the platform following rifting along the adjacent continental margin. The most widespread marine inundation of Arizona occurred during the Mississippian, when an extensive carbonate platform occupied much of

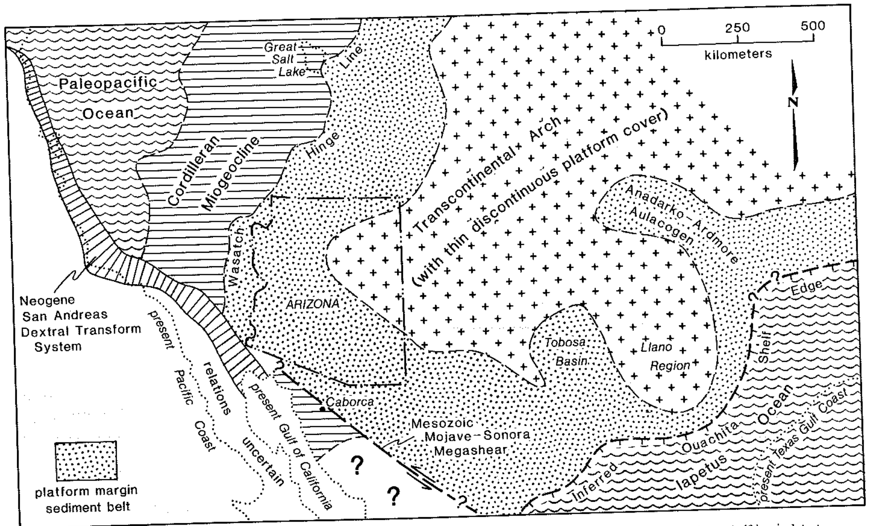

Figure 2. Early to middle Paleozoic position of Arizona in relation to passive continental margins formed by continental rifting in latest Precambrian (to Cambrian) time. Modified after Peiffer-Rangin (1979), Dickinson (1981), Gutschick and Sandberg (1983), and Stewart and others (1984).

Arizona and continued northward along the whole Cordilleran trend (Gutschick and Sandberg, 1983). The correlative Redwall Limestone of the Grand Canyon region and Escabrosa Limestone of southern Arizona form the local stratigraphic record of this vast carbonate province.

LATE PALEOZOIC AND EARLY MESOZOIC BASINS

During middle to late Paleozoic and earliest Mesozoic time, both the Cordilleran and Ouachita margins of the continent were affected by orogenies during which oceanic assemblages of strata were thrust as structurally imbricated allochthons across the edges of the continental block (fig. 3). Along the Cordilleran margin, the Antler and Sonoma orogenies were of Devono-Mississippian and Permo-Triassic age, respectively, whereas the intervening Ouachita-Marathon orogeny occurred during Permo-Pennsylvanian time (Dickinson, 1977). Orogenic events included the development of elongate thrust belts (none of which reached as far into the cratonic interior as Arizona), the subsidence of foreland basins adjacent to the thrust loads, and associated deformation of continental basement at varying distances from the thrust fronts. The full effects of the various pre-Jurassic orogenies along the continental margins upon the basement block beneath Arizona are not yet well understood.

Seemingly, events along the Cordilleran margin had little direct influence on the geologic record in Arizona. For example, the Mississippian Redwall-Escabrosa carbonate platform grew beyond the range of dispersal of orogenically derived clastic sediment into the Antler foreland basin. However, the seaward edge of this vast carbonate province may have been controlled by the flexurally arched flank of the foreland depression. If so, progradation of the edge of the carbonate platform (Rose, 1976) was sufficient to obscure any underlying structural control of its regional position. Similarly, Permian and Triassic platform sedimentation across Arizona displayed no clear evidence of disturbance by the Sonoma event. For example, the widespread Coconino Sandstone (plus Toroweap Formation) and Kaibab Limestone of mid-Permian age (Leonardian to Guadalupian) in northern and western Arizona have their counterparts in the generally correlative and lithologically similar Scherrer Formation and Concha Limestone (plus Rain Valley Formation) of southeastern Arizona (Knepp, 1983). Complex intercalation of laterally extensive Permian strandline and dune facies in central Arizona implies that the region was tectonically stable (Blakey and Middleton, 1983). Moreover, the Lower Triassic Moenkopi Formation contains similar facies of irregular thickness throughout its outcrop area within Arizona, although evidence for local deformation and intercalation of coarse clastics within the

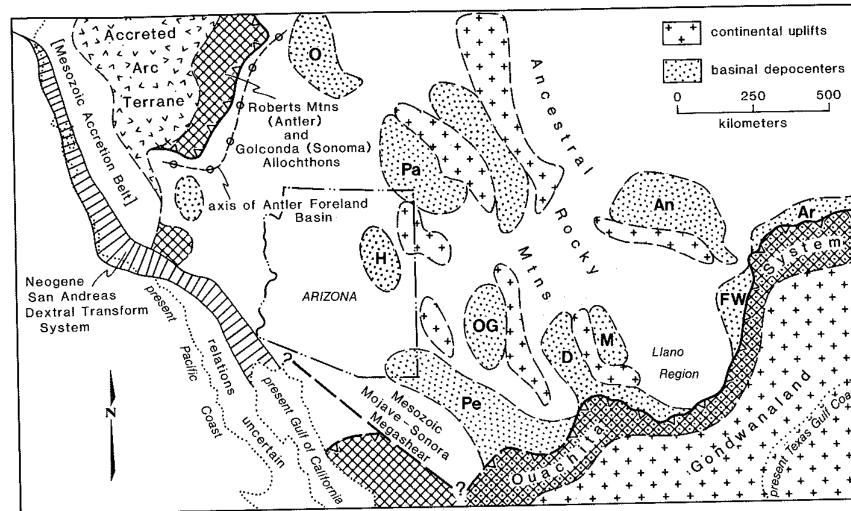

Figure 3. Late Paleozoic position of Arizona in relation to orogenic belts along the Cordilleran and Ouachita continental margins. Modified after Speed (1979), Dickinson (1981), Kluth and Coney (1981), and Dickinson and others (1983). Selected basins: An, Anadarko; Ar, Arkoma; D, Delaware; FW, Fort Worth; H, Holbrook; M, Midland; 0, Oquirrh; OG, Oro Grande; Pa, Paradox; Pe, Pedregosa. The Defiance-Zuni uplift extends into northeastern Arizona.

Moenkopi interval has been reported farther west in the Mojave Desert of California (Walker and Burchfiel, 1983).

By contrast, the Ouachita orogeny apparently left clear imprints of two general kinds on the geologic record in Arizona. Associated in time with the Ouachita event was the development of the Ancestral Rockies uplifts and basins across the region of the southern Rocky Mountains and the Colorado Plateau (fig. 3). These features reflected deformation of the interior of the continental block in response to stresses engendered by crustal collision along the Ouachita-Marathon suture belt (Kluth and Coney, 1981). The Ouachita system was a segment of the Hercynian orogenic belt, along which the Laurasian and Gondwanan continents were united to form the Permo-Triassic supercontinent of Pangaea. The thick Pennsylvanian and Permian successions of the Paradox and Holbrook basins adjacent to the Defiance-Zuni uplift in northeastern Arizona occupy depocenters whose subsidence can be attributed to Ancestral Rockies deformation (Lemke, 1985). In the Paradox Basin, syntectonic Pennsylvanian strata are capped by varied redbeds of the widespread Permian Cutler Formation.

Southeastern Arizona was also affected by tectonic downflexure of the foreland region in front of the Marathon thrust sheets, as they extended along strike into Chihuahua, Mexico. The limestone-bearing Pennsylvanian to Lower Permian section (Horquilla Limestone, Earp Formation, Colina Limestone) of the Pedregosa Basin in southeastern Arizona is thicker (1.5+ km) and more continuous than the Pennsylvanian to Permian redbed sequence (1 km) in the Supai Group and Hermit Shale of the Grand Canyon region in northwestern Arizona. Moreover, deposition of a thin but distinctive interval (Rea and Bryant, 1968) of coarse subaerial clastics ("jelly-bean conglomerate") of earliest Permian (mid-Wolfcampian) age (Armin, 1985b) in the middle of the Earp Formation of the Pedregosa Basin can be attributed to the transient tectonic upflexure of a forebulge adjacent to the downbowed belt of foreland basins (Armin, 1985a). Ouachita foreland deformation within the Pedregosa Basin probably ended before mid-Permian (by Leonardian) time, prior to deposition of the lithologically analogous redbed assemblages in the Epitaph Dolomite of the Pedregosa Basin and the generally correlative Supai Group (including the Schnebly Hill Formation of Blakey, 1979) in the Mogollon Rim region to the northwest (Peirce, this volume).

MIDDLE MESOZOIC MAGMATISM AND REDBED SEDIMENTATION

By mid-Mesozoic time, a persistent regime of subduction and arc magmatism had been established along the western

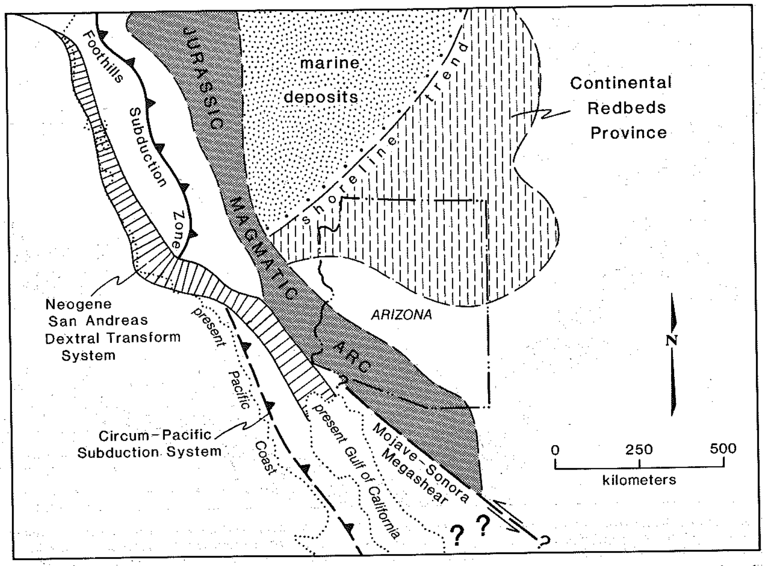

Figure 4. Middle Mesozoic position of Arizona in relation to the subduction zone and magmatic arc of an arc-trench system along the Cordilleran continental margin. Modified after Coney (1978) and Dickinson (1981).

borders of both North and South America. This Cordilleran orogenic system has continued to evolve, through many complex stages (Dickinson, 1976), until it now forms a segment of the globe-girdling circum-Pacific orogenic belt. Arc magmatism related to the subduction of slabs of oceanic lithosphere beneath the continental block played a significant role in the tectonic evolution of Arizona, which was also influenced by varied styles of intra-arc and backarc tectonics. Related subduction complexes, accretionary terranes, and associated strike-slip faults all developed close to the continental margin, but largely farther west than Arizona. In southwesternmost Arizona, however, strike-slip faults related to transform systems along the continental margin are present locally, and deformed Phanerozoic oceanic materials in the Orocopia Schist may represent part of an underthrust subduction complex.

In most segments of the circum-Pacific belt, subduction and arc magmatism linked by evolutionary stages to current tectonic regimes began no earlier than Late Triassic time, but no later than Early Jurassic time. In southern Arizona and nearby parts of California and Sonora, a regionally extensive belt (fig. 4) of Lower and Middle Jurassic arc volcanics and associated plutons is well documented, and evidence for early precursors of Late Triassic age has been reported from widely separated localities outside Arizona (Kistler, 1974; Schweickert, 1976, 1978). Sequences of Jurassic volcanic and volcaniclastic rocks as much as 2.5 to 7.5 km thick and Jurassic granitoid batholiths form significant parts of a number of mountain ranges across the southern third of the state (Hayes and Drewes, 1978; Haxel and others, 1980; Kluth, 1983), except for the southeasternmost corner adjacent to the panhandle of New Mexico. Jurassic magmatism continued in southern Arizona from mid-Early Jurassic (c. 195 Ma) until mid-Late Jurassic (c. 150 Ma) time, but then apparently shifted westward into the region of the Peninsular Ranges Batholith closer to the continental margin (Damon and others, 1981, 1983).

The region of the Colorado Plateau in the northern part of the state was not directly affected by mid-Mesozoic magmatism or tectonism. However, partly volcaniclastic sediment derived from the south or southwest is present in some mid-Mesozoic formations, and volcanic cobbles have yielded Triassic and Jurassic isotopic ages at several localities (Dodge, 1973; Peirce and others, 1985). A laterally extensive blanket of nonmarine redbed formations was deposited across the whole region as complexly intertonguing facies tracts that are difficult to date closely with confidence. The most characteristic strata are Upper Triassic fluvial and associated lacustrine deposits of the Chinle Formation (Blakey and Gubitosa, 1983), and Lower Jurassic eolian and associated fluvial deposits of the Glen Canyon Group (Kocurek and Dott, 1983). The main Chinle provenance lay to the south and may have included parts of the arc assemblage as far south as Sonora, Mexico (T. H. Anderson and others, 1984; Stewart and others, 1986), but the quartzose dune sands of the Glen Canyon Group were derived from the north. Overlying Middle to lower Upper Jurassic strata of the San Rafael Group include varied fluvial, eolian, and strandline facies (Blakey and others, 1983; Kocurek and Dott, 1983). In several mountain ranges of southern Arizona and southern California, quartzose Jurassic dune sands that were probably related genetically to the extensive Lower to Middle Jurassic eolian strata of the Colorado Plateau region occur interbedded with volcanogenic strata of the magmatic arc province (Bilodeau and Keith, 1979, 1986; Marzolf, 1983). In late Late Jurassic time, fluvial deposits of the Morrison Formation were spread as a sheetlike cover across the entire Colorado Plateau region from highland sources to the west and south along the Cordilleran orogenic system (Brenner, 1983).

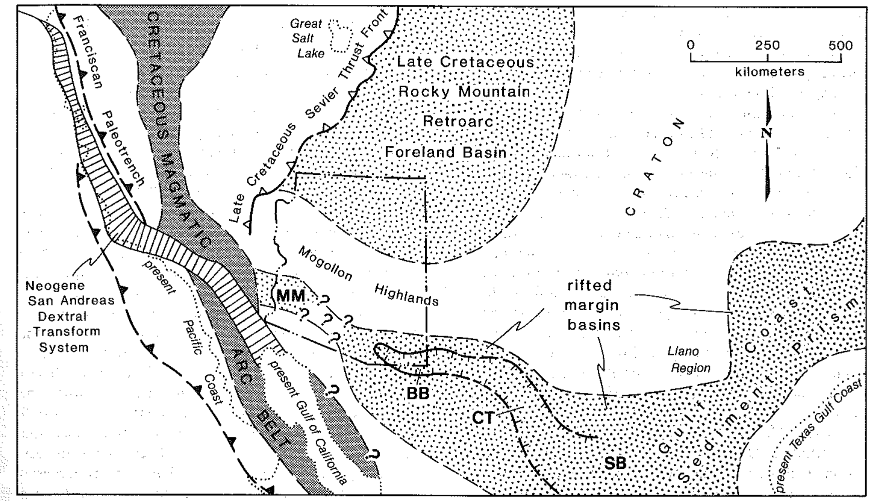

Figure 5. Late Mesozoic position of Arizona in relation to Cretaceous sedimentary basins, the Franciscan paleotrench system, and a Cretaceous magmatic arc delineated by the coastal batholith belt of the Sierra Nevada and Peninsular Ranges. Modified after Dickinson (1981) and Bilodeau (1982). Hachured line denotes Early Cretaceous backarc depocenter (aulacogen) of Bisbee basin (BB) and Chihuahua trough (CT); SB, Sabinas basin; MM, McCoy Mountains Formation and correlatives (see text for discussion).

LATE MESOZOIC RIFT AND FORELAND BASINS

Major late Mesozoic sedimentary basins of contrasting age and character developed in southern and northern Arizona within the backarc region east of a prominent belt of arc magmatism marked by the Jurassic-Cretaceous batholith belt of California and Baja California (fig. 5). In southern Arizona, subsidence mainly during the Early Cretaceous occurred as a result of backarc crustal extension related to sea-floor spreading within the nascent Gulf of Mexico during the Jurassic (Bilodeau, 1982). In northern Arizona, subsidence mainly during the Late Cretaceous occurred as a result of lithospheric downflexure of the Cordilleran foreland under the structural load of thrust sheets, whose emplacement to the west along the Sevier orogenic belt began in mid-Cretaceous time (Lawton, 1985). The overall geodynamic controls for the contrast in tectonic timing and style of the two types of basins are still poorly understood but were presumably related to major patterns of plate motion during concurrent opening of the Atlantic Ocean and continued circum-Pacific plate consumption.

Lower Cretaceous marine and nonmarine strata up to 3-4 km thick in the Bisbee Group of southeastern Arizona (fig. 5) extend downward without stratigraphic break to include beds intercalated with mid-Upper Jurassic (c. 150 Ma) volcanics and volcaniclastics (Vedder, 1984). These associated volcanogenic strata represent either the youngest local record of the mid-Mesozoic arc assemblage or a succeeding rift assemblage. Poorly dated and partly metamorphosed upper Mesozoic nonmarine strata up to 4-8 km thick in the McCoy Mountains Formation and its correlatives of southwestern Arizona occupy an analogous stratigraphic position immediately above Jurassic volcanics. McCoy strata may be equivalent to the Bisbee Group but are regarded by some as entirely older on the basis of paleomagnetic interpretations (Harding and others, 1983; Harding and Coney, 1985).

The Bisbee basin was a northwesterly extension of the Jurassic-Cretaceous Chihuahua trough, a structural arm of the Gulf of Mexico depression (Bilodeau and Lindberg, 1983). Rifting that formed the oceanic crust of the Gulf of Mexico evidently propagated into the continental block along the Chihuahua trough and Bisbee basin, which together with the Sabinas basin and other depocenters in northeastern Mexico thus represent a complex aulacogen. Facies patterns of coarse synrift deposits in the lower part of the Bisbee Group reflect sedimentation within a rifted region of fault-block topography. The rift phase of tectonic evolution in the Chihuahua trough and Bisbee basin may have been complicated by major sinistral strike-slip motions along a suspected Jurassic paleotransform, the so-called Mojave-Sonora megashear (Silver and Anderson, 1974), inferred by some to cut across northern Mexico from the Mojave Desert region to the Gulf of Mexico (Coney, 1978; Kluth, 1983). Following crustal extension during the rift phase of basin development, upper parts of the Bisbee Group accumulated during passive thermotectonic subsidence of the region that had been affected by crustal thinning. Bisbee sedimentation continued at diminishing rates into early Late Cretaceous time.

No strata equivalent to the main part of the Bisbee Group are present on the Colorado Plateau in northern Arizona, although thin Lower Cretaceous fluvial units are present farther north in Utah above the Upper Jurassic Morrison Formation, which they resemble sedimentologically. Prior to mid-Cretaceous time, the Morrison Formation and older units in northern Arizona were tilted gently to the northeast and beveled beneath an erosion surface of gentle relief. Subsequent mid-Cretaceous transgression of the continental interior seaway deposited basal Upper Cretaceous (Cenomanian) marginal-marine and marine beds of the Dakota Sandstone above a regional unconformity. Progressive overlap of successively older pre-Cretaceous units to the southwest beneath this sub-Dakota unconformity defines the northeast flank of the Mogollon highlands (fig. 5), a broad Cretaceous positive feature in central Arizona (Dickinson and others, this volume). The southwest flank of the Mogollon highlands was more abrupt and apparently coincided with the rifted edge of the Bisbee basin. The asymmetric Mogollon highlands can thus be regarded as a thermotectonically uplifted rift shoulder of the Chihuahua-Bisbee aulacogen. Following the Dakota transgression, marine and marginal-marine strata of the Mancos Shale and Mesaverde Group in northern Arizona represent the southern end of the Rocky Mountain retroarc foreland basin (fig. 5), which developed by broad downflexure of the continental surface throughout an extensive region lying to the east of Sevier thrust plates (Dickinson, 1976).

LARAMIDE MAGMATISM AND OROGENIC DEFORMATION

The most intense orogenic deformation that has affected Arizona since Early Proterozoic time occurred during the Laramide interval of Late Cretaceous and early Cenozoic time. The igneous centers responsible for most of the important porphyry copper mineralization within the state were associated with this Laramide tectonism (Titley, 1981, 1982; Damon and others, 1981, 1983). The Laramide episode of associated magmatism and deformation has been ascribed to the geodynamic effects of a marked change in the angle of dip of a subducted slab of oceanic lithosphere at depth beneath the continental block. Steep slab descent throughout most of Cretaceous time is reflected in the persistent locus of arc magmatism along the main batholith belt of California and Baja California relatively near the Franciscan paleotrench. In latest Cretaceous time, progressive flattening of the angle of slab descent is inferred to have caused the locus of slab-induced melting (where the subducted slab penetrates into the asthenosphere) to shift gradually inland beneath the continent (Coney and Reynolds, 1977; Keith, 1978). This effect allowed the belt of arc magmatism to migrate through Arizona from coastal regions farther west (fig. 6). Concurrently, enhanced compressive and (or) shear interaction between the ultimately subhorizontal subducted slab and the overriding continental lithosphere promoted contractional deformation and crustal thickening across a wide region including Arizona (Dickinson and Snyder, 1978).

Numerous isotopic ages for both volcanic and intrusive rocks establish that Laramide arc magmatism in Arizona began 75 to 80 Ma in mid-Late Cretaceous (Campanian) time and ended about 55 Ma in mid-Early Eocene time. Igneous activity was confined mostly to southern and western Arizona but also involved emplacement of isolated laccolithic stocks and subvolcanic necks within the Colorado Plateau region. The Laramide igneous suite comprises dominantly calc-alkalic rocks of mainly andesitic to rhyolitic composition, characteristic of continental-margin arc provinces. Eruptive centers are recorded by eroded stratovolcano piles and ignimbritic caldera fills (Lipman and Sawyer, 1985), as well as by varied subvolcanic stocks, with associated hypabyssal dike swarms and more deeply eroded granitoid plutons.

Closely following this magmatism of typical arc affinity, the crust of parts of southern and western Arizona was intruded by scattered batholiths of two-mica granite during Early to Middle Eocene time (about 55 to 45 Ma). These peraluminous magmas were doubtless produced by crustal melting (Farmer and DePaolo, 1984), perhaps as dehydration of subducted materials permitted rehydration of the structurally overlying lower crust of Proterozoic age (Reynolds and Keith, 1982), or simply because crustal thickening during Laramide deformation promoted melting within a deep crustal root (Haxel and others, 1984).

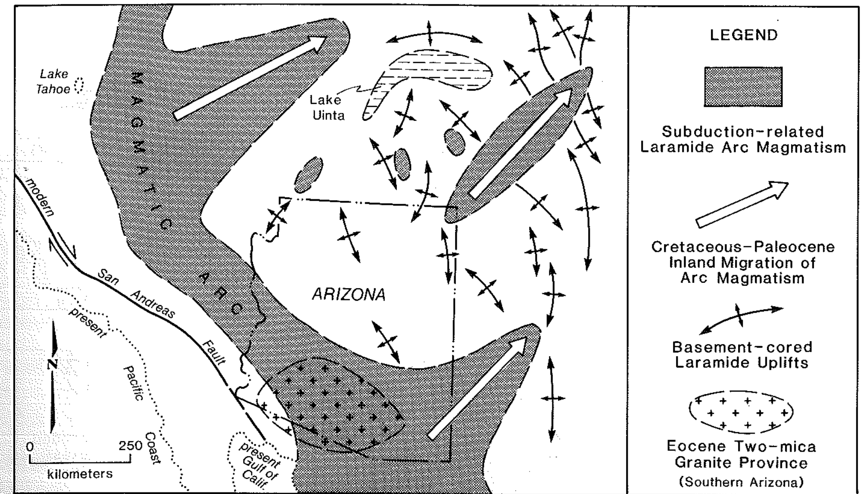

Figure 6. Latest Cretaceous and early Cenozoic position of Arizona in relation to Laramide magmatism and deformation. Modified after Dickinson (1979, 1981), Reynolds (1980), and Keith (1984).

No volcanic equivalents of this intrusive suite are presently known and none may exist, for reduction of confining pressure during the rise of hydrous magma through the crust may force complete crystallization within subterranean magma chambers.

The onset of Laramide deformation was recorded in southeastern Arizona by the deposition of synorogenic clastic successions in locally downfaulted and (or) downfolded basins. These strata, assigned to the Fort Crittenden Formation and correlative units, probably began to accumulate about 75 to 80 Ma during Campanian time, and analogous coarse clastic sequences have been dated as young as near the Cretaceous-Tertiary time boundary (about 65 Ma). Laramide folds and thrust faults involving these and older strata have been mapped in most mountain ranges of southern and western Arizona (Reynolds, 1980; Drewes, 1981), and the monoclinal flexures of the Colorado Plateau region date from the same general episode of deformation. Mylonitic fabrics were developed within shear zones located at deep-seated structural levels during the Laramide deformation (Haxel and others, 1984), and Laramide positive features were probably thrust-bounded basement-cored uplifts (Davis, 1979). Crustal thickening across the southern half of the state was apparently sufficient to induce general regional uplift, and the Eocene landscape is inferred to have been an extensive erosion surface of varied relief. Eocene sediment was transported to the northeast (Peirce and others, 1979; Young, 1979; Cather and Johnson, 1984), against the present grain of the Mogollon Rim, from the uplifted ground of southern and western Arizona toward the Claron basin of southwestern Utah, the Chuska basin of northeastern Arizona, the San Juan basin of northwestern New Mexico, and the Baca basin of western New Mexico (Nations and others, 1985).

MID-TERTIARY MAGMATISM AND EXTENSIONAL DEFORMATION

The post-Laramide period of early Tertiary erosion in southern and western Arizona coincided with a pronounced null in arc magmatism within the Cordilleran region of the western United States. By inference, the descent of subducted oceanic lithosphere beneath the continent was at such a shallow angle that no penetration of the asthenosphere was achieved, and arc magmatism was accordingly suppressed almost entirely. The same time interval, centered on the Eocene, represented the peak of Laramide deformation within the central Rocky Mountains (Chapin and Cather, 1981).

The succeeding mid-Tertiary interval, from the end of the Eocene until mid-Miocene time (about 37 to 15 Ma), was one during which arc magmatism was rejuvenated within Arizona and other parts of the intermountain region and was accompanied and (or) succeeded by widespread extensional deformation (fig. 7). These related magmatic and tectonic events have been ascribed to steepening of slab

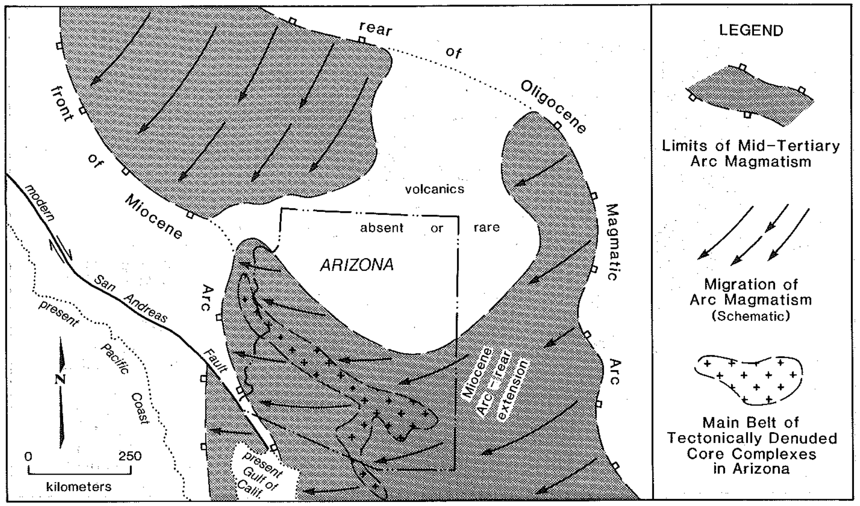

Figure 7. Mid-Cenozoic position of Arizona in relation to migratory mid-Tertiary arc magmatism and associated extensional deformation. Modified after Coney (1979) and Dickinson (1979, 1981).

descent beneath the continental block and thus to a reversal of the geodynamic influences that had earlier caused Laramide deformation (Dickinson, 1981). Consequently, eastward migration of arc magmatism was supplanted by westward migration, and crustal contraction was supplanted by crustal extension. Mid-Tertiary crustal thinning of the previously overthickened crustal profile within the region of intense Laramide deformation in southern and western Arizona allowed subsidence of that previously uplifted region. As neither the magmatic nor the structural aspects of the mid-Tertiary events affected the Colorado Plateau, this episode of subsidence accomplished a reversal of drainage along the Mogollon Rim in central Arizona and established the Colorado Plateau as a positive area relative to the remainder of the state.

Mid-Tertiary arc magmatism of generally alkali-calcic character began in southwestern New Mexico near the beginning of Oligocene time, and its inception swept irregularly westward through central and southern Arizona during Oligocene and earliest Miocene time (Shafiqullah and others, 1978; Reynolds and others, 1986). Andesitic to latitic lavas and rhyodacitic to rhyolitic domes and ignimbrite sheets are characteristic components of the regional igneous suite, which locally includes granitoid plutons as well. Although the westward migration of arc magmatism implies renewal of relatively steep slab descent beneath the region, the position of the rejuvenated magmatic belt still lay well east of the locus of analogous Cretaceous igneous activity near the Pacific Coast. Mid-Tertiary ignimbrite outcrops in southeastern Arizona can be regarded as erosional outliers of the vast ignimbrite plateau of the Sierra Madre Occidental farther south. Basaltic andesites erupted during Early Miocene time at scattered localities throughout southwestern New Mexico and southeastern Arizona have been interpreted to reflect a tendency for incipient interarc rifting along the continental flank of the magmatic belt (W. E. Elston and Bornhorst, 1979).

Mid-Tertiary extensional tectonics that began while the Oligocene-Miocene volcanism was underway and continued until about mid-Miocene time (c. 15 Ma) produced dramatic structural effects that reflect significant crustal extension and thinning. Steeply tilted homoclines of mid-Tertiary volcanics and coarse nonmarine clastics abut downdip into basement rocks along low-angle normal faults that were active during the deposition of the clastic sediments. Displacements on such faults amounted to as much as several kilometers. Analogous mid-Tertiary deformation also placed unmetamorphosed mid-Tertiary and older strata, together with unconformably underlying Precambrian basement, directly against so-called core complexes (fig. 7), composed of more deep-seated plutonic and metamorphic rocks of varying ages (Coney, 1980; Davis, 1980). The contacts between cover rocks and core rocks are denudational detachment faults now displaying gently dipping to subhorizontal attitudes. Tectonic

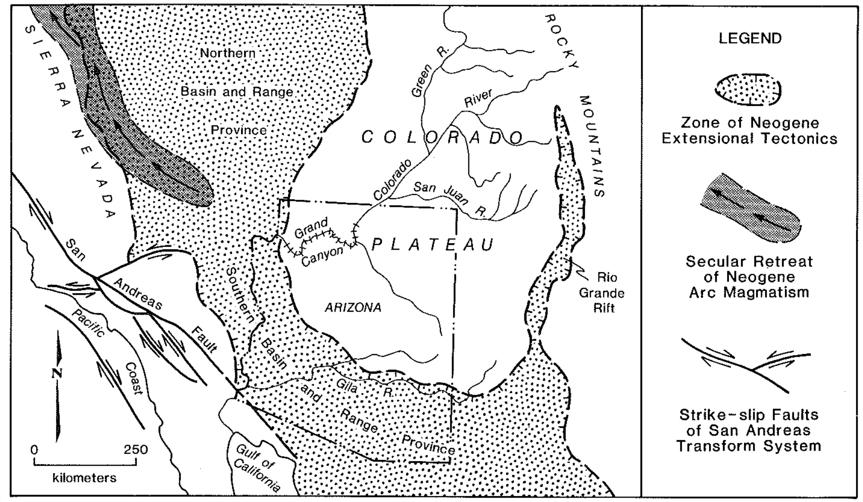

Figure 8. Late Cenozoic position of Arizona in relation to the Basin and Range province and the Colorado Plateau of the intermountain region. Modified after Dickinson (1979, 1981).

denudation of the core complexes was accomplished by movements of as much as several tens of kilometers along deeply rooted shear zones that experienced brittle fracture at shallow structural levels but accommodated ductile shear to produce mylonitic fabrics at structural levels deep within the crust (Rehrig and Reynolds, 1980; Davis, 1983; Spencer, 1984; Reynolds and Spencer, 1985). Such mylonitic zones are now exposed to view near the upper surfaces of the tectonically denuded core complexes, where they occur beneath kinematically related detachment faults and are overprinted by brittle deformation and chloritic alteration adjacent to the detachment faults. Mylonitic fabrics inherited from Laramide deformational events also occur within the interiors of some core complexes.

LATE CENOZOIC BLOCK FAULTING AND SUBSIDENCE

Volcanics and sediments of Late Miocene age (about 12 to 5 Ma) in southern and western Arizona are generally not strongly tilted but are disrupted by normal faulting of the Basin and Range Province (Shafiqullah and others, 1980). Basin and Range extensional tectonism in the intermountain region (fig. 8) has been generally coeval with development of the San Andreas transform system along the continental margin (Eaton, 1979). The generation of associated generally basaltic volcanism has thus not been related to subduction but rather to upwelling of mantle beneath the region of crustal extension in the absence of a subducted slab at depth (Dickinson and Snyder, 1979). A secular eastward expansion of the region containing scattered basaltic eruptive centers may have been related to gradual enlargement of the area lacking a subducted slab beneath it as the San Andreas transform lengthened progressively with time (Seager and others, 1984).

Basin and Range faulting formed numerous local nonmarine basins elongated generally from north to south in southern and western Arizona (Scarborough and Peirce, 1978). Thicknesses of basin fill imply structural relief of 2-4 km between the pre-mid-Miocene basin floors and adjacent mountain blocks, and the floors of the deeper basins are now 1-2 km below sea level (Eberly and Stanley, 1978). Some basins with interior drainage have continued to fill with Neogene sediment up to the present time. Other basins that record net accumulation of sediment up through some part of Pliocene time are now undergoing dissection by integrated drainages such as that of the Gila River. Drainage integration was probably not possible on a regional scale until the nearby Gulf of California began to open within the San Andreas transform system near the Miocene-Pliocene time boundary (Shafiqullah and others, 1980; Nations and others, 1985). As major Basin and Range deformation in Arizona predated opening of the Gulf of California, most syntectonic sediments were probably associated with bolson systems confined within individual structural depressions. In some way not yet well understood geodynamically, development of the rhombochasmic Gulf of California structural depression may have terminated major extensional strain within the nearby Basin and Range Province of Arizona.

The most important modern drainage in Arizona is that of the Colorado River, whose immense delta lies at the head of the Gulf of California. As drainage into that transtensional rift trough was impossible much before Pliocene time, the striking canyons incised into the Colorado plateau by the river and its tributaries are evidently Pliocene and younger erosional features, at least in their present form. The major incision of the Grand Canyon itself probably occurred about 5 Ma, near the Miocene-Pliocene time boundary (Nations and others, 1985). Although positive relative relief of the Colorado Plateau had been established by mid-Tertiary time (Peirce and others, 1979), further crustal thinning and relative subsidence of the adjacent Basin and Range Province doubtless occurred in response to Neogene extensional faulting. The Transition Zone of central Arizona delineating the edge of the relatively undisturbed Colorado Plateau block is thus evidently a composite tectonic boundary whose morphology reflects a combination of mid-Tertiary and Neogene extensional effects (Zoback and others, 1981) whose relations are still not fully understood (Eaton, 1982). The present absolute elevation of the Colorado Plateau (fig. 8) probably incorporates the effects of broad regional uplift of the entire intermountain region in response to Neogene upwelling of anomalously hot mantle having a lower density than is normal for subcontinental mantle (Damon, 1979).

EFFECTS OF CHANGING PALEOLATITUDE

The successive tectonic settings of a particular crustal segment, such as Arizona, are a function of locally evolving plate boundaries and plate interactions, as discussed above. However, the overall paleogeographic setting is a function not only of local tectonics but of changing paleolatitude in response to continental drift. Significant aspects of the stratigraphy and paleogeomorphology of Arizona cannot be understood without reference to the paleowander path of the continent. During Phanerozoic time, Arizona moved through about 60 degrees of paleolatitude (fig. 9) and an uncertain amount of paleolongitude. The shifting configurations of surrounding or nearby crustal blocks have also influenced aspects of paleogeography, such as prevailing oceanic currents and terrestrial climatic patterns.

Paleomagnetic data on the APW (apparent polar wander) path of the North American craton and published reconstructions of the global configurations of the various continental blocks through time allow a general appraisal of the changing paleogeographic setting of Arizona during the Phanerozoic. Its Precambrian setting is much more uncertain, but Arizona probably lay in tropical or subtropical latitudes during most of the time that its Proterozoic rocks were formed (fig. 1).

The carbonate-rich lower and middle Paleozoic sequence (Cambrian to Mississippian) accumulated while the Arizona portion of the continental platform (fig. 2) was washed by warm tropical to equatorial seas in which carbonate-secreting organisms must have been abundant. Associated quartzose sand is the type of detritus delivered to such shelf seas from nearby emergent but low-lying land areas subjected to deep weathering in warm humid climates.

Pennsylvanian and Permian successions include an initially bewildering array of offshore carbonates, terrestrial and strandline redbeds, sabkha and brine-pool evaporites, and quartzose sandstones of both marine and eolian origin. The assemblage can be reconciled with a paleogeographic picture of Arizona situated within the tropical trade-wind belt along the northwestern fringe of the immense Pangaean landmass (fig. 3). Shelf seas producing carbonate sediment are inferred to have fringed trade-wind deserts where redbed and evaporite associations were developed in the lee of extensive Hercynian highlands. Immense quantities of quartzose sand were transported longshore from more northerly (then northeasterly) reaches of the Cordilleran margin under the influence of oceanic circulation driven by the trade winds. The same prevailing wind pattern drove some of the sand onshore into coastal and interior dune fields.

As Arizona moved rapidly into and through the subtropics during early to middle Mesozoic time, the redbed succession of the Colorado Plateau was deposited within a subtropical desert belt (fig. 4). Knowledge of the exact latitudinal positions of Arizona at various stages during this drift phase is clouded by uncertainties concerning the Jurassic paleowander path of North America (Steiner, 1983; Gordon and others, 1984; May, 1985). The eolian sandstones and associated braided fluvial deposits of the Glen Canyon Group evidently represent the record of a vast erg that extended inland from an embayed shoreline protected by offshore island arcs lying to the west (Kocurek and Dott, 1983). During deposition of the succeeding San Rafael Group, regional transgression restricted the size of the erg but did not affect the arid to semiarid nature of bordering terrestrial environments.

Beginning in Late Jurassic time, the paleolatitudinal position and paleogeographic setting of Arizona have been generally comparable to those of the present day. Throughout that period, Arizona has remained within the temperate zone of prevailing westerlies (fig. 9). Consequently, its climate has remained subject to the rain shadows of various highland barriers that have stood to the west from time to time. As now, however, the marine influence of the Gulf of Mexico, and of the Atlantic Ocean generally, has been a constant moderator of aridity. During late Mesozoic time (fig. 5), the presence of the great interior Cretaceous seaway of the mid-continent, and of the extensive marine embayments of northern Mexico, would have enhanced these ameliorating effects. Nevertheless, the intermittent development of Mesozoic and Cenozoic

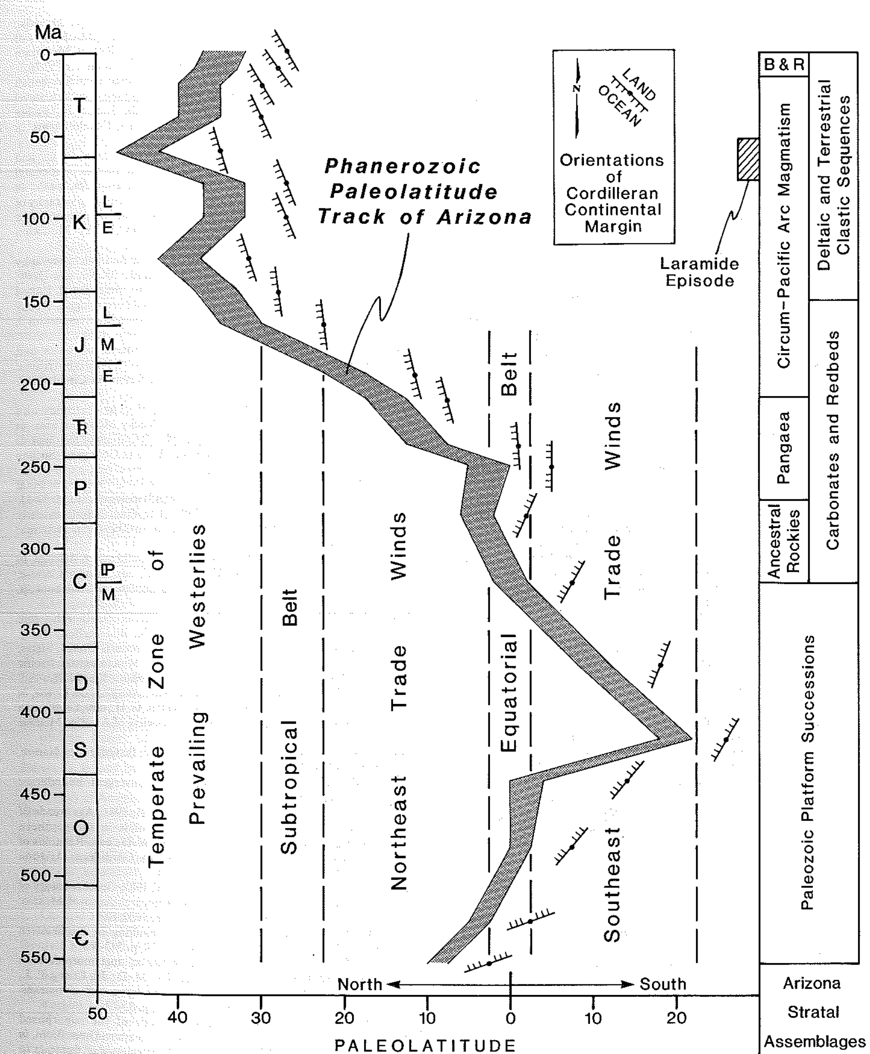

Figure 9. Changing paleolatitude of Arizona and orientation of the nearby Cordilleran continental margin through Phanerozoic time (see text for discussion). Approximate paleolatitudes interpolated from paleocontinental maps of Smith and others (1981) with ages adjusted to DNAG scale (Palmer, 1983). "B & R" denotes Basin and Range tectonism.

highlands of varied origins in southern and western Arizona has taken place within an essentially persistent climatic regime. As a result, piedmont fanglomerates and more distal fluvial and lacustrine deposits ranging in age from latest Jurassic to Holocene display remarkably similar sedimentological features throughout the region.

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PROTEROZOIC PLATE TECTONIC EVOLUTION OF ARIZONA

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ABSTRACT

The tectonic processes that built new crust at convergent continental margins during the Proterozoic were actualistic to modern plate tectonics, but differed in detail sufficiently to warrant recognition that a unique style of plate tectonics operated during the Proterozoic era. Arizona is a key reference section for tectonic interactions and the plate tectonic processes that accreted the continental crust of the United States from 2.0 Ga to 1.3 Ga.

Arizona's Proterozoic tectonic evolution began with rifting of the Archean Wyoming craton at about 2.0 Ga and growth of Proterozoic oceanic crust throughout Arizona. Archean-derived clastics filled a shelf-slope wedge along the Wyoming craton margin that was deformed and intruded by basic dikes and possibly plutons prior to 1.8 Ga. On an upper Proterozoic oceanic crust of primitive tholeiites, layered mafic-ultramafics, spilite, keratophyre, pelagic sediments, and chert, the Prescott-Jerome belt developed as an intraoceanic island arc from 1800 Ma to 1740 Ma above a subduction zone dipping southeast under the Archean fragment detached from the Wyoming craton. Three tholeiitic volcanic provinces of the Bradshaw Mountains, Mayer, and Black Canyon Creek Groups developed sequentially across the arc to form a southeast trend of alkali enrichment that may have included a calc-alkaline province farther southeast.

A major 1750-1740-Ma change in plate motions caused subduction to flip and thereafter dip northwest under the Wyoming Archean craton. This flip shut off formative volcanism and produced plutons and batholiths with a northwest alkali-enrichment trend across the Prescott-Jerome arc. As the allochthonous arc swept toward the Wyoming craton, the intervening ocean basin was consumed to create the Antler-Valentine volcanic belt as an incipient continent-margin arc fronting the deformed clastic wedge at the continental margin. The Bagdad volcanic belt (previously formed in a spreading-center, arc, or oceanic-island setting), together with (1) fore-arc basin sediments and melange to the south that remained from the earlier subduction under the Prescott-Jerome arc, (2) the Antler-Valentine volcanic belt, and (3) the craton-margin clastic wedge to the north, resisted subduction as the ocean basin closed. Across the United States, all similar oceanic and arc elements were coalesced into a new Proterozoic crust that was accreted to the Archean margin by about 1730 Ma.

Northwest-dipping subduction produced granodiorite-tonalite batholiths and plutons across the Prescott-Jerome arc and made it an emergent continent-margin arc that was separated from the Wyoming craton by a wide, shallowly submerged, back-arc basin of accreted oceanic elements. By 1730 Ma, a chain of submarine calc-alkaline Union Hills Group volcanoes had formed along the new southeast front of the arc, turbidite graywackes were shed into intervolcanic basins, and volcaniclastic detritus was dispersed into a fore-arc basin to the southeast. From 1730 to 1720 Ma, the trench started to shift oceanward in progressive increments as a subduction complex grew to the southeast, which caused both the fore-arc basin to prograde over the melange and the subduction dip to flatten.

As subduction flattened, plutonism stepped farther inboard into the oceanic collage behind the arc, extending the alkali-enrichment trend of arc plutonism to the northwest. Continued subcrustal heating produced widespread fusion of oceanic, arc, and sedimentary crusts behind the Prescott-Jerome arc, so that by 1720 Ma the Northwest Gneiss Belt was pervaded by huge calc-alkaline batholiths as it underwent major orogeny, high-grade regional metamorphism, crustal thickening, and stabilization.

Concurrently, vertical structural readjustments in the continent-margin arc formed grabens at pluton edges for Texas Gulch clastics and felsic volcanism in the old emergent Prescott-Jerome part of the arc, and for Alder Group clastic sedimentation along the submerged front of the arc. These sedimentary events signified a major ca. 1720-Ma hiatus in evolution of the continent-margin arc, after mafic volcanism ended but before primary felsic magmas were emplaced into the arc front. This hiatus occurred as the trench stepped farther southeastward to create throughout southeast Arizona a very wide Pinal terrane of detritus shed from the arc and fore-arc basin, accreted oceanic sediments, and possibly allochthonous crustal pieces swept in from southeasterly intraoceanic settings.

Formation or accretion of the Dos Cabezas arc moved the trench out of Arizona and established the Pinal terrane as a wide inter-arc basin between the Dos Cabezas arc and the central Arizona magmatic arc. Very shallow subduction under the Pinal basin from 1705 to 1695 Ma caused crustal fusion and resulting felsic magmatism across the frontal 350 km of the continental margin. Felsic volcanics overwhelmed Alder clastics as huge felsic magmas were emplaced into the central Arizona arc to crystallize as granite batholiths beneath ignimbrite carapaces. Calc-alkaline rhyolites erupted in the Dos Cabezas and Ray-Aravaipa belts above shallow depths on the subduction zone, whereas alkali-calcic ignimbrites erupted at the front of the central Arizona magmatic arc above greater depths on the subduction zone. Felsic tephra were shed oceanward into the inter-arc Pinal basin coextensively with its younger quartz-wacke sedimentation.

Thus by 1690 Ma, the central Arizona magmatic arc became fully emergent and, together with emergent older terranes behind it, formed a newly evolved Proterozoic continental crust. As the arcs eroded, Mazatzal strata succeeded felsic volcanics as fluvial, estuarine, littoral, and shallow-marine conditions prograded back across the central Arizona arc, and as open-marine conditions in the Pinal basin and shoaling in the Dos Cabezas arc persisted to 1680 Ma.