Geologic Framework of West-Central Arizona

by

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Abstract

The geology of west-central Arizona is complex and understood only in a reconnaissance fashion. The oldest rocks are Precambrian (approximately 1.7 b.y. B.P.) gneiss, schist, quartzite, and amphibolite, which in the Precambrian were metamorphosed, deformed, and intruded by several generations of plutons. These rocks and structures are unconformably overlain by a cratonic sequence of Paleozoic carbonate and clastic strata. Representatives of Mesozoic rocks include intermediate to felsic volcanic and plutonic rocks of probably mid-Mesozoic age and overlying thick sections of clastic rocks, which are intruded by Late Cretaceous plutons. At least three deformational and metamorphic events of probably Cretaceous and Tertiary ages affected the region after deposition of the Mesozoic clastic rocks. Evidence for Tertiary mylonitization and subsequent dislocational phenomena is exposed in at least four mountain ranges that have characteristics of metamorphic core complexes. Dislocation was accompanied by listric normal faulting and tilting of mid-Tertiary volcanic and sedimentary sections. Late Tertiary Basin and Range faulting occurred after 15 m.y. B.P. and has evidently been inactive for at least several million years.

Introduction

The geology of west-central Arizona, although incompletely understood, provides insight into the variety of geologic components that constitute the regional tectonic framework of southwestern North America. Geologic studies of west-central Arizona (Figs. 1 and 2) have largely been of a reconnaissance nature, with the area receiving much less detailed quadrangle-scale mapping than most other parts of the western United States. History of geologic studies in part of the area has recently been summarized by Keith (1978).

Western Arizona experienced an era of brief geological and hydrological reconnaissance in the early 1900s (Lee, 1908; Bancroft, 1911; Blanchard, 1913; Ross, 1923; Darton, 1925; see additional references in Keith, 1978) but was essentially unmapped until the studies of Wilson (1933, 1960). After Wilson's pioneering works in the region, scattered areas within west-central Arizona were studied in the mid-1960s (Ciancanelli, 1965; Jemmett, 1966; Parker, 1966; Miller, 1966, 1970; Metzger, 1968). Within the past decade, geologic studies in the area have been initiated at an accelerated pace (Gassaway, 1972; Shackelford, 1976; Varga, 1976, 1977; Rehrig and Reynolds, 1977, in press; Harding, 1978; Eberly and Stanley, 1978; Keith, 1978; Otton, 1978; Crowl, 1979; Marshak, 1979; Robison, 1979; Suneson and Lucchitta, 1979; Davis and others, in press; Shafiqullah and others, this volume). Results of these geologic mapping, isotopic dating, and stratigraphic studies have shed new light on the geology of the region. This necessitates recasting previous workers' observations in accordance with new and somewhat provocative concepts. It is in this spirit that this paper is presented to the geologic community. The paper must be regarded as incomplete simply because much needed data are not presently available. Nevertheless, the following is a state-of-the-art summary of the geologic framework of west-central Arizona, within which results of upcoming studies may be considered.

Geologic Framework

West-central Arizona is well endowed with rocks representing Precambrian, Paleozoic, Mesozoic, and Cenozoic eras. Some periods of time are well represented by both rocks and structures, while others are merely recorded by unconformities. With this in mind, it is perhaps most instructive to view the geology of west-central Arizona in chronological order (Fig. 3). In this manner, the various events can be envisioned in their proper time perspective.

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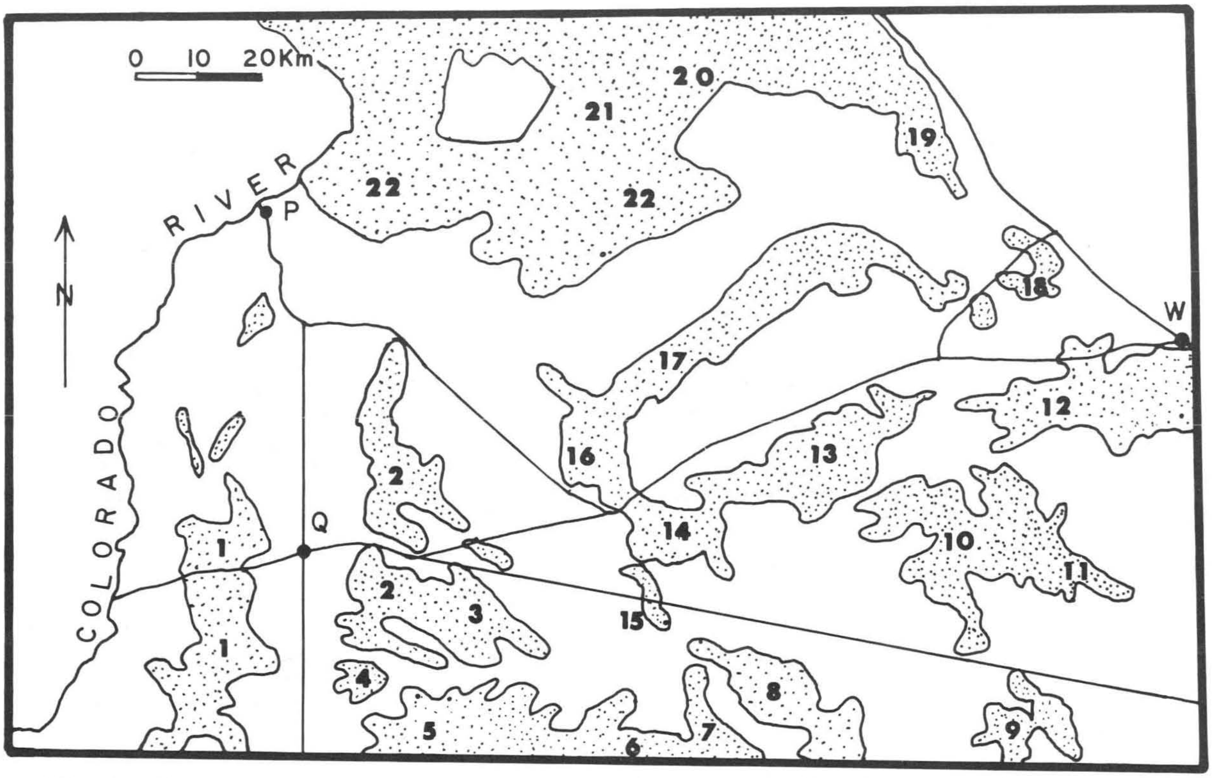


Fig. 1. Location map and mountain ranges of west-central Arizona. Letters indicate positions of Parker (P), Quartzsite (Q), and Wickenburg (W). Mountain ranges are numbered as follows: (1) Dome Rock Mountains, (2) Plomosa Mountains, (3) New Water Mountains, (4) Livingston Hills, (5) Kofa Mountains, (6) Little Horn Mountains, (7) Cemetery Ridge, (8) Eagletail Mountains, (9) Palo Verde Hills–Saddle Mountain, (10) Big Horn Mountains, (11) Belmont Mountains, (12) Vulture Mountains, (13) Harquahala Mountains, (14) Little Harquahala Mountains, (15) Black Rock Hills, (16) Granite Wash Mountains, (17) Harcuvar Mountains, (18) Merrit Pass Hills, (19) Black Mountains, (2) Artillery Mountains, (21) Rawhide Mountains, (22) Buckskin Mountains.

Precambrian Metamorphic and Intrusive Rocks

Outcrops of Precambrian rocks (Fig. 2) are most abundant in eastern parts of west-central Arizona where younger cover rocks have been removed by erosion, but smaller outcrops also occur in most ranges of the region. The oldest Precambrian rocks (1.7 b.y. B.P., see Anderson and Silver, 1976) are high-grade metamorphic rocks consisting of quartzofeldspathic gneiss, amphibolite, mica schist, and minor quartzite. These rocks are generally interlayered with or intruded by variably foliated, granitic to dioritic sills, dikes, and lenses. Foliation in metamorphic and interlayered rocks is *mostly* steeply dipping and strikes north to east-northeast, or less commonly northwest. Most of these rocks represent metamorphosed sediments, although others are clearly metavolcanic or metaplutonic.

In many places, the metamorphic rocks are intruded by Precambrian granodioritic to granitic plutons. Granodioritic plutons are generally equigranular, while some younger granitic varieties are commonly megacrystic. Locally, the plutons have a weak foliation parallel to that in the adjacent metamorphics.

Paleozoic Strata

Patches of Paleozoic strata are exposed in many ranges in the region. Some of the best exposures are in the Plomosa, Harquahala, Little Harquahala, and Rawhide Mountains. These exposures consist of interbedded limestone, dolomite, quartzite, and siltstone. Depending on the mountain range and geologist, these rocks have been correlated to stratigraphic sections of either the Grand Canyon-Colorado Plateau region or southeastern Arizona. The basal unit of the section in west-central Arizona is invariably a white to brown or maroon quartzite, which is approximately 100 m or less thick. It resembles and has been correlated with Cambrian Bolsa Quartzite of southeastern Arizona (Miller, 1970; Shackelford, 1976; Varga, 1977; Rehrig and Reynolds, in press). Overlying the quartzite are less than 50 m of sandy shale interbedded with locally calcareous, fine-grained quartzite. These rocks have been correlated with the Cambrian Abrigo Formation of southeastern Arizona (Miller, 1970) and the Bright Angel Shale of the Grand Canyon (Shackelford, 1976). In a few areas a dolomitic limestone is present, which may overlie the Abrigo Formation and be correlative with Cambrian Muav Limestone of the Grand Canyon (Miller, 1970).

The top of the Abrigo Formation is almost everywhere a structurally modified disconformity, which is overlain by mid-Paleozoic carbonate strata. The stratigraphically lowest unit is composed of less than 100 m of dolomitic limestone, dolomite, and sandy dolomite equivalent to the Devonian Martin Formation of southeastern Arizona (McKee, 1951; Wilson, 1962, p. 29; Miller, 1970; Shackelford, 1976; Reynolds and DeWitt, unpublished data). Overlying this formation are strata correlative to either the Mississippian Escabrosa Limestone of southeastern Arizona (Miller, 1970) or the Redwall Limestone of the Grand Canyon (Wilson, 1962, p. 32; Shackelford, 1976; Varga, 1977; Reynolds, unpublished data). These rocks are approximately 120 m thick and generally consist of a lower unit of tan-weathering dolomite, overlain by an upper section of cherty limestone.

One of the most distinctive Paleozoic units of west-central Arizona overlies the Redwall or Escabrosa Limestone equivalent and resembles the Pennsylvanian-Permian Supai Formation of the Colorado Plateau. This unit is composed of 170 to 365 m of white, pink, maroon, or light-brown quartzite, which is interbedded with limestone and minor red mudstone (McKee, 1951; Miller, 1970; Shackelford, 1976; Varga, 1977; Reynolds, unpublished data). Overlying the Supai Formation equivalents are 200 to 335 m of white to gray vitreous quartzite, which locally exhibits large-scale cross-bedding (Miller, 1970; Varga, 1977; Rehrig and Reynolds, in press). These quartzites are clearly correlative with Permian Coconino Sandstone of the Grand Canyon. The uppermost unit of the Paleozoic section, 200 to 335 m of chert-bearing limestone, is similar to and correlated with Permian Kaibab Limestone of the Colorado Plateau-Grand Canyon region (McKee, 1951; Miller, 1970; Varga, 1977; Rehrig and Reynolds, in press).

Structural configuration of the Paleozoic strata described above varies from nearly undeformed to highly folded, faulted, and overturned. Similarly, metamorphic condition of the section varies from essentially unmetamorphosed to moderately or highly metamorphosed where the clastic strata are phyllitic or schistose, and siliceous carbonate rocks contain wollastonite (Ciancanelli, 1965; Miller, 1966).

Mid-Mesozoic Volcanic and Granitic Rocks

Exposed in the western half of the region are intermediate to silicic, volcanic, and plutonic rocks of probable mid-Mesozoic age (Miller, 1970; Shackelford, 1975; Crowl, 1979; Rehrig and Reynolds, in press; Marshak, 1979). The volcanics are best exposed in the Dome Rock, Plomosa, and Little Harquahala Mountains. They range in composition from dacitic and quartz latitic to rhyolitic; include flows, ash-flow tuff, and coarse agglomerate; and are locally interbedded with volcanic conglomerates and sandstone, red mudstone, and assorted clastic rocks. Thickness of the volcanic section is significant, locally being as much as 5 km (Crowl, 1979). The rocks are commonly somewhat metamorphosed and are locally schistose (Crowl, 1979).

Granitic plutons exposed in several places such as the Dome Rock Mountains may represent magmas that were *roughly* synchronous with the volcanics. One of the best exposed is the Middle Camp quartz monzonite of Crowl (1979), which intrudes the lower part of the Dome Rock Mountains volcanic section. This intrusion and some equivalent plutons (W. A. Rehrig, 1976, pers. comm; L. T. Silver, 1978, pers. comm.) are characterized by abundant phenocrysts of K-feldspar.

The volcanic and granitic rocks are most likely mid-Mesozoic in age. They locally overlie or intrude the Paleozoic section (quartz porphyry of Miller, 1970; W. A. Rehrig, 1978, pers. comm.) and underlie sedimentary rocks of probably late Mesozoic age (Miller, 1970; Pelka, 1973; Harding, 1978; Crowl, 1979; Marshak, 1979; Robison, 1979). An important age constraint is provided by an Early to Middle Jurassic U-Pb date on the volcanics of the Dome Rock Mountains determined by L. T. Silver (as reported in Crowl, 1979). This date suggests a *general* temporal correlation of these sections to Jurassic volcanics and plutons of southeastern Arizona (Hayes and Drewes, 1978) and southeastern California (Pelka, 1973).

Late Mesozoic Clastic Strata

One of the most enigmatic rock units of west-central Arizona and adjacent southeastern California consists of an extremely thick sequence of largely clastic sedimentary rocks of highly variable clast size. These rocks include the continental red beds and Livingston Hills Formation of Miller (1970), the McCoy Mountains Formation (Pelka, 1973), and numerous exposures of rocks mapped by Wilson (1960) as Mesozoic sedimentary rocks. The rocks are widely distributed throughout northern Yuma County and make up large parts of the Dome Rock, Plomosa, Little Har-

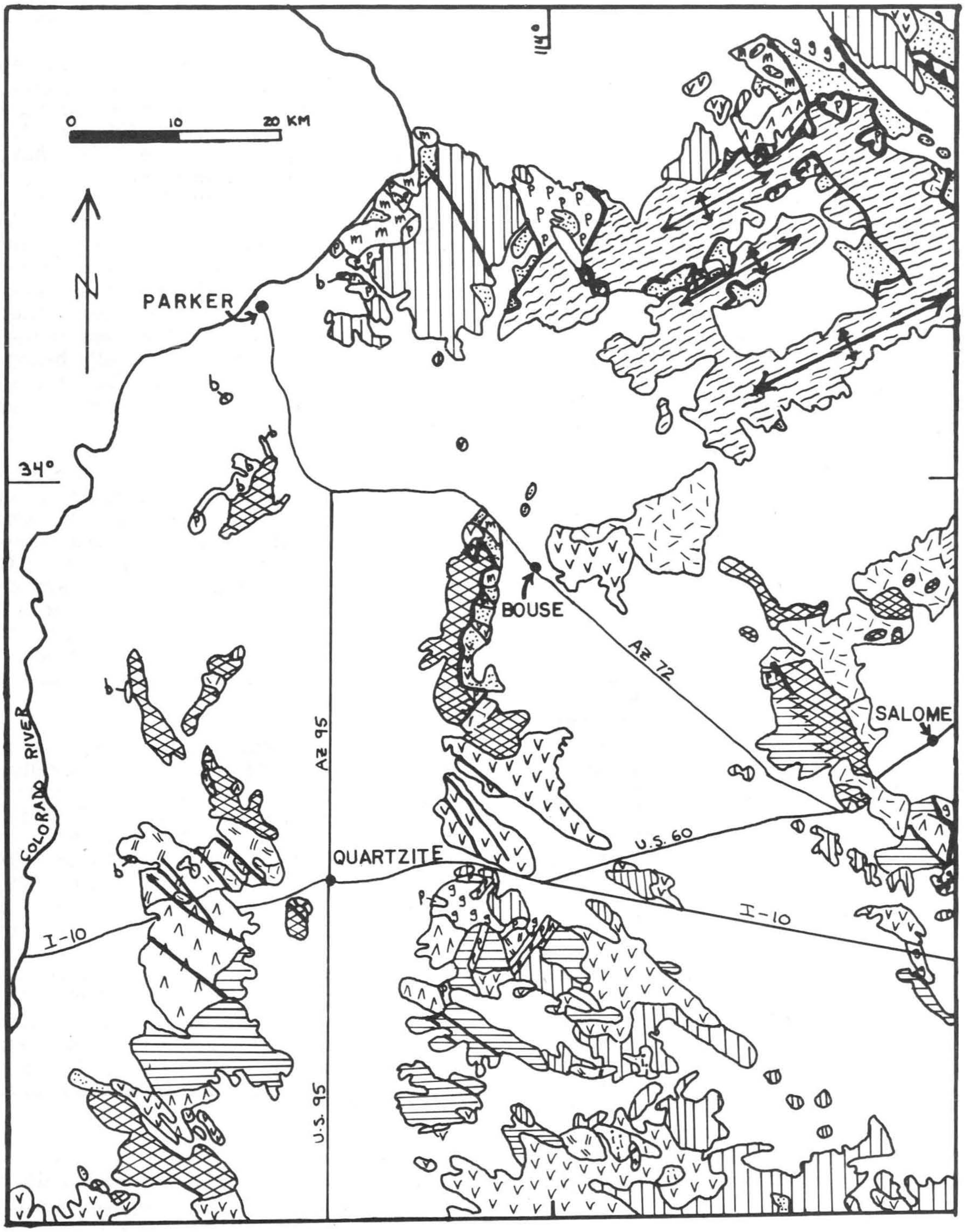
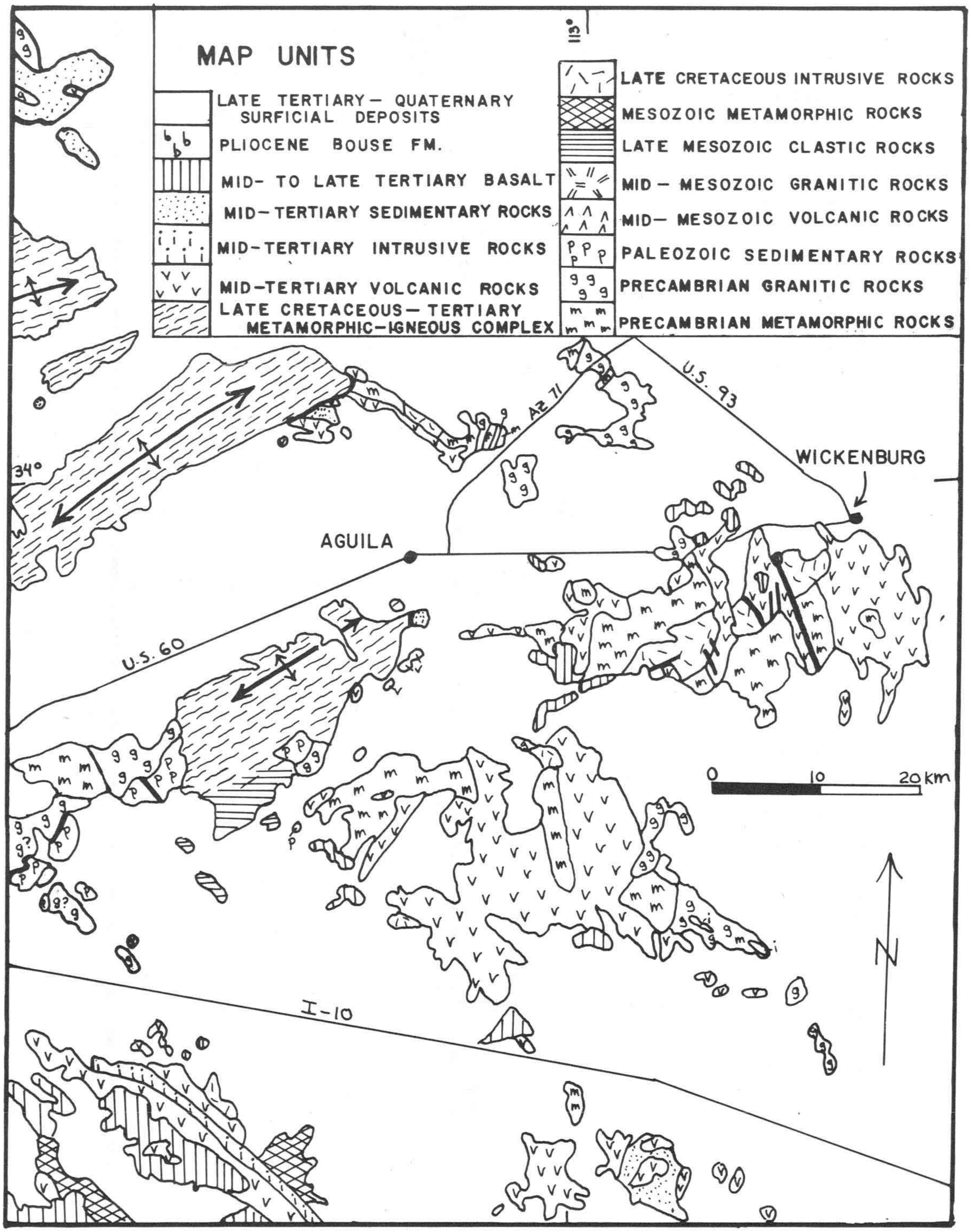


Fig. 2. Geologic map of west-central Arizona. Data from Wilson and others (1969) modified using maps of Ciancanelli (1965), Jemmett (1966), Miller (1966, 1970), Shackel-



ford (1975), Rehrig and Reynolds (in press), Rehrig and others (this volume), Marshak (1979), Arizona Public Service (1975), and regional and detailed mapping by S. Reynolds.

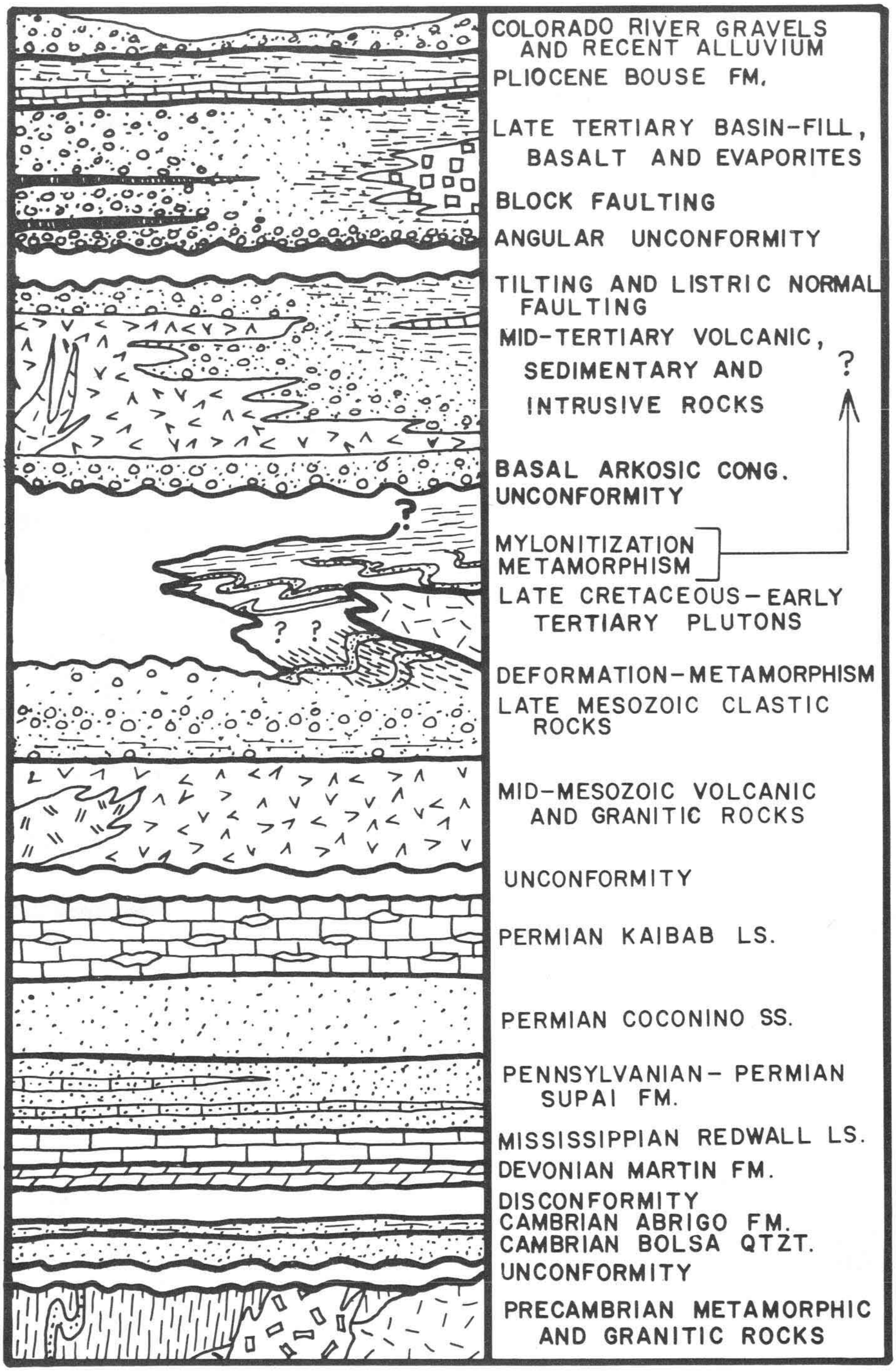


Fig. 3. Chronology of rock units and major events

quahala, Harquahala, Granite Wash, and Buckskin Mountains (Fig. 2). They consist of interbedded conglomerate, sandstone, quartzite, siltstone, shale, and minor limestone. In places they are highly metamorphosed to quartzite, marble, phyllite, schist, and gneiss (Wilson, 1962; Rehrig and Reynolds, in press; Marshak, 1979). The rocks have recently been studied and described by Miller (1966, 1970), Pelka (1973), Harding (1978), Marshak (1979), Robison (1979), Rehrig and Reynolds (in press), so little detail needs to be included here. Independently, several workers have concluded that the more quartzitic rocks such as the continental red beds represent the lower part of the section, while the less mature strata (Livingston Hills Formation) occupy the upper parts of the sequence (Miller, 1966, 1970; Marshak, 1979; Robinson, 1979; L. Harding and P. Coney, 1978, pers. comm.). The rocks depositionally overlie the mid-Mesozoic volcanics (Miller, 1970; Pelka, 1973; Harding, 1978; Crowl, 1979; Marshak, 1979; Robison, 1979) and are intruded by Late Cretaceous (70-85 m.y. B.P.) plutons in the Granite Wash Mountains (Rehrig and Reynolds, in press) and in southeastern California (E. DeWitt, 1979, pers. comm.). Also, the McCoy Mountains Formation is reported to contain fossil wood that is Cretaceous or younger (Hayes, 1970; Pelka, 1973).

Late Cretaceous Plutons

Late Cretaceous plutons crop out over large areas in several ranges, including the Little Harquahala and Granite Wash Mountains. In most ranges such as the Dome Rock Mountains, however, Late Cretaceous magmatism is represented only by small stocks, plugs, and dikes (see Crowl, 1979). The plutons and smaller intrusions are equigranular to slightly porphyritic and range in composition from diorite to granite. They range from undeformed to pervasively foliated and lineated. Rehrig and Reynolds (in press) have studied two large plutons in the Granite Wash Mountains. In this area, the northeastern quarter of the range is underlain by the Tank Pass granite, which, to the south, is intruded by the Granite Wash Pass granodiorite and its mafic border phase. Both plutons are Late Cretaceous based on field relationships and supporting K-Ar and Rb-Sr isotopic analyses (Rehrig and Reynolds, in press, and unpublished data). Detailed mapping and isotopic dating of the remainder of possible Late Cretaceous intrusive rocks in west-central Arizona remain to be done.

Late Cretaceous–Tertiary Metamorphic and Igneous Complexes

Significant factors in the geologic evolution of west-central Arizona are Late Cretaceous to middle Tertiary metamorphism, plutonism, and deformation, which have only recently been recognized (Rehrig and Reynolds, 1977, in press; Shackelford, 1977; Davis and others, in press). This interval of metamorphism, plutonism, and deformation is responsible for formation of high-grade gneisses and mylonitic rocks in the Rawhide, Buckskin, Harcuvar, and Harquahala Mountains. These four ranges are examples (Rehrig and Reynolds, 1977, in press) of unique metamorphic-deformational centers, which have recently been referred to as "metamorphic core complexes" (Crittenden, Coney, and Davis, 1978; Coney, 1973, 1978a, 1979, in press; Davis and Coney, 1979; Davis, in press). Metamorphic core complexes are distributed in a zone through the interior portions of the North American Cordillera from Canada to Mexico. These complexes possess certain distinctive lithologic, metamorphic, structural, and geochronologic characteristics (Coney, 1979, in press; Davis and Coney, 1979; Davis, in press; Rehrig and Reynolds, in press; Reynolds and Rehrig, in press). These characteristics, as discussed in the papers referenced, are summarized below.

The metamorphic core complexes are characterized by metamorphic and mylonitic rocks whose *gently dipping foliation* defines broad, asymmetrical arches or domes (Fig. 4). Rocks exposed in the structurally lowest parts (cores) of the complexes are gently inclined amphibolite-grade gneiss and undeformed to highly foliated plutonic rocks of variable composition (commonly including muscovite granites). The gneisses are ductilely deformed and commonly exhibit passive to flexural flow folds and a locally developed mineral lineation. Up structural section, both igneous and metamorphic rocks of the core are progressively overprinted by a mylonitic fabric, which crosscuts earlier fabrics. Mylonitic foliation in these rocks is gently dipping and contains a conspicuous lineation, which is regionally consistent in trend from one mountain range to another (see Banks, in press; Davis, in press; Rehrig and Reynolds, in press). The term "mylonitic," in this usage, describes rocks that possess a foliation and in thin section exhibit comminuted, brittlely deformed feldspars and recrystallized quartz that occurs in sutured aggregates (for additional discussion, see Reynolds and Rehrig, in press). The rocks are very similar to photographs of hand specimens and photomicrographs of protomylonite, mylonite, and mylonite gneiss as presented in the classification of Higgins (1971). The gently inclined mylonitic foliation and its northeast- to east-northeast-trending lineation are perhaps the most characteristic features of metamorphic core complexes that occur in a northwest-trending zone through southern and western Arizona (Rehrig and Reynolds, in press; Davis, 1977, in press; Banks, in press).

On some gently dipping sides of the complexes, higher levels of the mylonitic rocks become increasingly jointed, brecciated, chloritic, and hematitic up structural section until the rock is best described as a chloritic breccia. Within this upward transition, the well-developed mylonitic fabric of the basement becomes progressively disrupted and destroyed. Above the chloritic breccia is a ledge of microbreccia, which is less than a meter thick, weathers tan or brown, and has a chracteristic dark-gray, resinous appearance on fresh surfaces. In most outcrops and thin sections, neither the chloritic breccia nor microbreccia have a well-developed foliation. Instead, both are composed of highly jointed and brecciated masses, which contain unoriented, microscopic

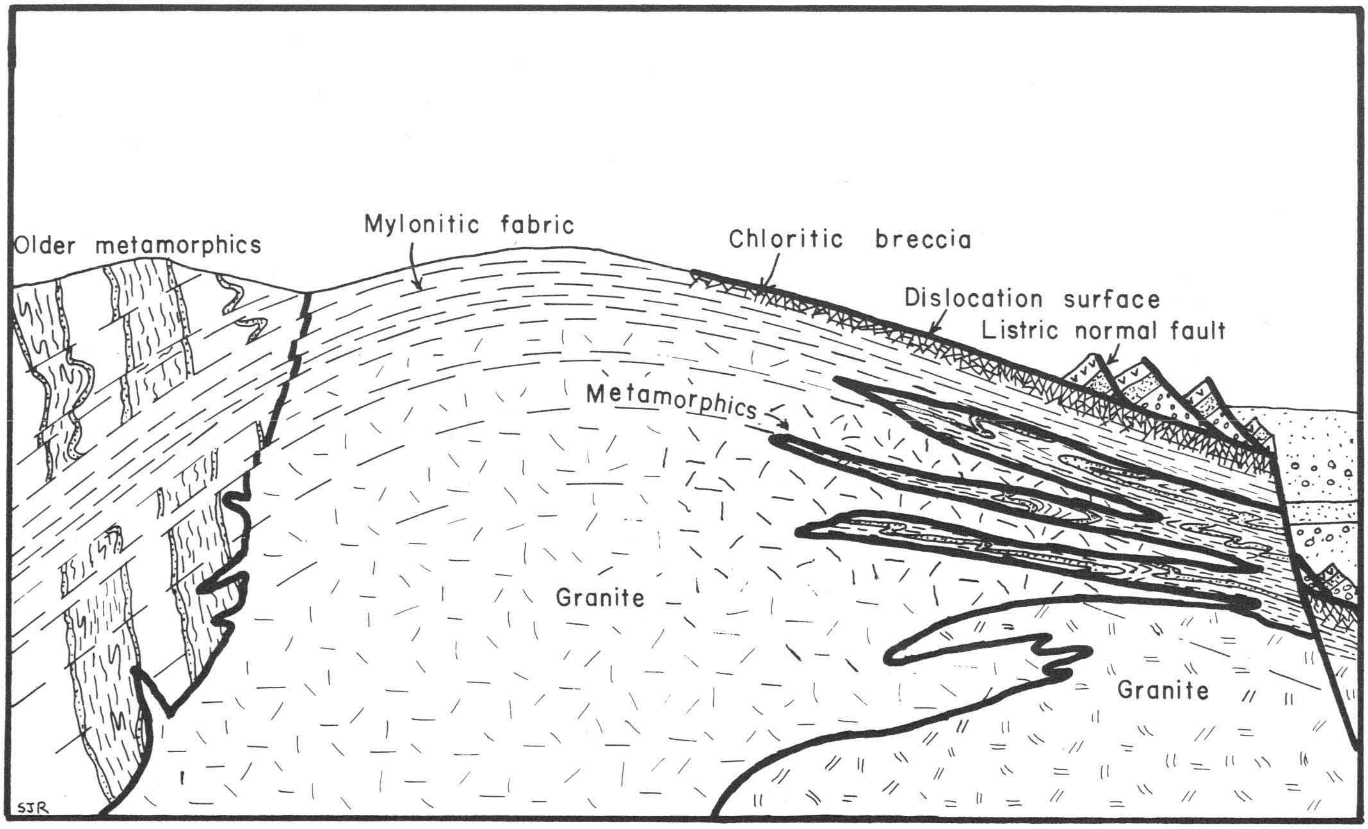


Fig. 4. Schematic cross section across a "typical metamorphic core complex"

to mesoscopic, angular fragments.

The top of the microbreccia ledge is a planar, low-angle dislocation surface, which is polished and commonly slickensided. Overlying the dislocation surface, in contrast to the chloritic breccia and mylonitic rocks of the footwall, are tilted, distended, allochthonous rocks of variable age (Precambrian to Miocene). These allochthonous rocks generally lack the mylonitic fabric so characteristic of rocks below the dislocation surface and chloritic breccia (Coney, 1979, in press; Davis and Coney, 1979; Davis, in press; Rehrig and Reynolds, in press). However, some notable exceptions to this "rule" do exist (Davis and others, in press; Reynolds, unpublished mapping in South and Harcuvar Mountains). Typical upper plate rocks are cut by numerous faults, which generally have normal separation and merge downward into the dislocation surface (Shackelford, 1975; Davis and others, in press).

Metamorphic, mylonitic, and plutonic rocks of the Arizona complexes repeatedly yield K-Ar biotite ages of between 20 and 30 m.y., although older dates were locally obtained (Damon and others, 1963; Creasey and others, 1977; Banks, in press; Keith and others, in press; Reynolds and Rehrig, in press; Shafiqullah and others, this volume). Much plutonism and mylonitization is clearly late Oligocene-early Miocene (Reynolds and Rehrig, in press; Creasey and others, 1977; Banks, in press; Keith and others, in press), but some may also locally be as old as Eocene (Davis and others, in press; Keith and others, in press). Rocks as young as Miocene (16 m.y. B.P.) are allochthonous above the dislocation surface, so some movement on the surface must be at least this young (Shackelford, 1975; Davis and others, 1977, in press; Rehrig and Reynolds, in press; Peirce, Scarborough, Shafiqullah, Damon, and Reynolds, unpublished data).

The Harquahala, Harcuvar, Buckskin, and Rawhide Mountains essentially have all the characteristics outlined above (Shackelford, 1975; Davis and others, in press; Rehrig and Reynolds, 1977, in press). The four ranges are composed of thick sequences of quartzofeldspathic gneiss and mica-bearing schist interlayered with amphibolite, foliated granitic rocks, and local marble and quartzite. Foliation in the metamorphic rocks is gently dipping and defines large northeast-trending arches, which parallel and control the topographic axis of each range (Fig. 2; see Rehrig and Reynolds, in press). Field and isotopic studies define a major Late Cretaceous to early Tertiary metamorphic event, which is probably spatially and temporally associated with plutons of the same age (Rehrig and Reynolds, in press). The metamorphism may locally represent the lower levels of the large Late Cretaceous plutons such as the Tank Pass granite in the Harcuvar and Granite Wash Mountains.

This metamorphic fabric and associated granites are cut by a gently inclined mylonitic foliation that contains northeast- to east-northeast-trending lineation. Mylonitic fabric is evidently best developed in structurally high exposures in the northeastern parts of the ranges (Rehrig and Reynolds, in press). The mylonitic fabric is most likely early to middle Tertiary in age because it clearly postdates the Late Cretaceous-early Tertiary plutons and metamorphic fabric. In addition, mylonitic rocks in the ranges have so far yielded early and middle Tertiary K-Ar biotite and hornblende ages (Shackelford, 1977; Rehrig and Reynolds, in press; Davis and others, in press; Shafiqullah and others, this volume).

In their structurally highest exposures, mylonitic rocks are converted up section into chloritic breccia and microbreccia. A dislocation surface is well exposed above the microbreccia throughout much of the Rawhide and Buckskin Mountains (Shackelford, 1975; Davis and others, in press; Rehrig and Reynolds, in press) and in more isolated exposures along the northeastern ends of the Harcuvar and Harquahala Mountains (Rehrig and Reynolds, in press). The most common allochthonous rocks above the dislocation surface are Oligocene(?)-Miocene conglomerate, sandstone, siltstone, and volcanics, but rocks of Precambrian, Paleozoic, and Mesozoic ages are also locally present in allochthonous positions (Shackelford, 1975; Davis and others, in press; Rehrig and Reynolds, in press). Upper plate rocks dip, on the average, moderately southwest and are cut by northwest-striking listric normal faults. Relative tectonic transport of upper plate rocks is mostly northeast (Shackelford, 1975; Davis and others, 1977, in press; Rehrig and Reynolds, in press).

Cretaceous-Tertiary (?) Regional Deformation and Metamorphism

Besides the metamorphic core complexes discussed above, additional ranges in the region contain deformed and metamorphosed equivalents of Precambrian rocks, Paleozoic strata, mid-Mesozoic volcanics, and late Mesozoic clastic rocks. These include the Dome Rock (Crowl, 1979; Marshak, 1979), Plomosa Jemmett, 1966; Miller, 1966, 1970; Harding, 1978; Marshak, 1979), western Harquahala (Varga, 1977), Little Harquahala (Wilson, 1960; Marshak, 1979; Rehrig and Reynolds, in press), and Granite Wash Mountains (Ciancanelli, 1965; Marshak, 1979; Rehrig and Reynolds, in press; E. Dewitt, 1978, written comm.). The geometry and kinematics of deformation in the various ranges have not been completely worked out, but some preliminary conclusions can be discussed.

In the Dome Rock Mountains, mid-Mesozoic volcanic and granitic rocks and late Mesozoic clastic strata have been deformed and metamorphosed to greenschist grade (Crowl, 1979; Marshak, 1979). Bedding in the rocks dips southeast, while cleavage dips moderately north. Cleavage-bedding intersections trend northeast to east, parallel to axes of some folds that are overturned to the southeast (Crowl, 1979; Marshak, 1979). Across La Posa Plain to the east, bedding in slightly metamorphosed, late Mesozoic clastics in the Livingston Hills dips moderately south and is cut by gently dipping cleavage (Miller, 1966; Harding, 1978). Cleavage in greenschist-grade metamorphosed Paleozoic strata and volcanic rocks farther north in the southern Plomosa Mountains (Miller, 1966, 1970) dips moderately north. In the northern Plomosa Mountains (Jemmett, 1966; Marshak, 1979; Reynolds, unpublished reconnaissance), metamorphic rocks are widely exposed in the western half of the range. Included in these rocks are schist, quartzite, marble, and metamorphosed clastic rocks, which evidently represent metamorphosed equivalents of parts of the Paleozoic and Mesozoic sections. Precambrian gneisses are also exposed in the area and may be protolith to some of the metamorphic rocks (Jemmett, 1966).

In the Granite Wash Mountains (Ciancanelli, 1965; Rehrig and Reynolds, in press; Marshak, 1979), late Mesozoic clastics are relatively unmetamorphosed in westernmost outcrops of the range. To the east, these strata can be traced into progressively more deformed and metamorphosed phyllite, schist, and gneiss. Foliation containing a northeast-trending mineral lineation locally parallel to cleavage-bedding intersections is intruded by two Late Cretaceous plutons (Rehrig and Reynolds, in press; Marshak, 1979).

In the Little Harquahala Mountains (Wilson, 1960; Rehrig and Reynolds, in press; Marshak, 1979), Mesozoic volcanic rocks and clastic strata are slightly metamorphosed and locally cut by a cleavage. Paleozoic strata are folded by a large, northeast-trending syncline, which verges southeast and has overturned much of the section (Wilson, 1960; Rehrig and Reynolds, in press). The structure continues into the western Harquahala Mountains where the syncline and a complementary anticline are well exposed in Paleozoic rocks (Varga, 1977). Low-angle faults cut the Paleozoic rocks in both ranges (Varga, 1977; Rehrig and Reynolds, in press).

Metamorphic rocks are exposed in several localities in the Colorado Indian Reservation north of the Dome Rock Mountains, along the foothills of the Eagletail Mountains, and in many areas of southern Yuma County, (Wilson, 1933). Lithologic and structural details of these areas have not been thoroughly studied, but preliminary reconnaissance indicates that rocks mapped by Wilson (1960) as Mesozoic gneiss are generally metaplutonic or metavolcanic, while exposures mapped as Mesozoic schist are either metasedimentary or metavolcanic.

In southeastern California, adjacent to the region of consideration, large south-verging folds are exposed in metamorphosed Paleozoic and Mesozoic rocks of the Big Maria Mountains (Hamilton, 1971, 1978, pers. comm.). In the McCoy Mountains, the next range to the southwest, mid-Mesozoic volcanics and overlying late Mesozoic clastic rocks dip south and are cut by a cleavage, which dips north (Pelka, 1973). These rocks and structures are very similar to those discussed earlier in the Dome Rock Mountains.

In summary, the region experienced a major metamorphic and deformational event(s) that postdates late Mesozoic clastic rocks. *If* metamorphism and deformation are the same age as in the Granite Wash Mountains, they must partly predate emplacement of the Late Cretaceous plutons. K-Ar dates on metamorphosed parts of the Granite Wash section are Late Cretaceous to earliest Tertiary, indicating that metamorphism in this mountain range was over by then (Rehrig and Reynolds, in press). However, the minimum age of *all* the metamorphism and deformation in the entire region is not tightly constrained, so some may be Tertiary as suggested by Varga (1977). In any event much of the deformation apparently has consistent south to southeast vergence over significant parts of the region. It is uncertain what temporal, kinematic, or genetic relationships exist between this event (or events) and plutonic and high-grade metamorphic (nonmylonitic) events exposed in the metamorphic core complexes.

Structural geology of the region has not been worked out in sufficient detail to demonstrate what relationship, if any, this deformational-metamorphic event has to low-angle faults exposed in the various ranges. In the Dome Rock Mountains, a reverse fault (Crowl, 1979) has an orientation roughly parallel to north-dipping cleavage and a sense of displacement that is kinematically consistent with development synchronous to the cleavage and south-southeast-overturned folds. In the Plomosa Mountains, Miller (1966, 1970) has mapped an imbricate sequence of low-angle faults, which dip east, have mostly reverse separation, and juxtapose correlative rocks of somewhat different metamorphic grade. The faults clearly displace late Mesozoic clastic strata but predate mid-Tertiary volcanics (Miller and McKee, 1971). In the Little Harquahala Mountains (Rehrig and Reynolds, in press) and nearby Black Rock Hills, Mesozoic volcanic and clastic rocks are commonly in low-angle fault contact with a brecciated chloritic Precambrian(?) granite. Similarly, folded Paleozoic strata of the Little Harquahala Mountains generally overlie the granite along a near-horizontal fault surface. The fault truncates northeast-striking, steeply dipping limbs of a major northeast-trending fold, suggesting that faulting postdates folding. Exposures of the fold and Paleozoic rocks continue northeastward into the western Harquahala Mountains where Varga (1977) has indicated that folds and faults mutually deform one another.

The examples described above are merely meant to point out the presence and widespread distribution of low-angle faults in the region. Some low-angle faulting was probably synchronous with the deformational-metamorphic event discussed earlier, but other faults almost surely postdate the event.

Mid-Tertiary Rocks and Deformation

Outcrops of middle Tertiary rocks and evidence of mid-Tertiary deformation are widespread throughout west-central Arizona. Mid-Tertiary stratigraphic sections are generally dominated by intermediate to felsic volcanics and red-colored, coarse- to medium-grained clastic rocks. The basal Tertiary unit is almost invariably an arkosic conglomerate, which contains abundant clasts of granitic and metamorphic rocks but little volcanic debris. This unit is generally overlain by either a predominantly volcanic or clastic sequence. The most common volcanic rock types include (1) welded to nonwelded, ash-flow tuff of latite, quartz latite, trachyte, and rhyolite; (2) flow-breccia and flow-banded masses of rhyolite and trachyte; (3) flows and flow-breccia of dark-colored andesite; (4) ash and cinder deposits of andesitic to rhyolitic composition; (5) flows of basalt and basaltic andesite, which are commonly vesicular; and (6) small intrusive equivalents of these rock types. Mid-Tertiary dikes are abundant and have a pronounced northwest to north-northwest trend (Rehrig and Heidrick, 1976).

Mid-Tertiary clastic rocks include (1) locally thick sections of interbedded reddish arkosic conglomerate, sandstone, siltstone, and mudstone; (2) polylithologic and monolithologic breccia, which can be composed of a wide variety of volcanic, plutonic, metamorphic, or sedimentary clasts; and (3) fine-grained lacustrine sequences of interbedded light-colored shale, siltstone, limestone, ash-fall tuff, tuffaceous sandstone, chalcedony, and gypsum. Interfingering of the three types of clastic rocks locally occurs, but an individual section is generally dominated by one of the above rock types.

Details of mid-Tertiary sections have been worked out in several localities (Laskey and Webber, 1949; Jemmett, 1966; Gassaway, 1972; Shackelford, 1975; Eberly and Stanley, 1978; Otton, 1978; Suneson and Lucchitta, 1979; Davis and others, in press; Rehrig and others, this volume; Shafiquallah and others, this volume; Scarborough and Peirce, 1979, pers. comm.; Reynolds, unpublished detailed and reconnaissance mapping). From the results of these studies, some generalizations can be made. The stratigraphically lowest unit is almost always the basal arkosic conglomerate, and the highest units are commonly basalt or basaltic andesite (Wilson, 1960; see following section on late Tertiary). Between these two bounding units, the relative stratigraphic positions of intermediate to felsic volcanics versus clastic sequences varies from place to place.

The best indications of the intensity of mid-Tertiary tectonism are the moderate southwest and northeast dips of Tertiary sections. The dipping sequences are commonly cut by northwest- to north-northwest-trending, listric normal faults (Shackelford, 1976; Davis and others, in press), which locally dip approximately perpendicular to bedding. In some areas, a downward decrease in dip of the faults can be demonstrated (Shackelford, 1976; Davis and others, in press). In other areas, the same situation seems required by wholesale rotation of the mid-Tertiary section. The listric normal faults flatten and merge downward with the dislocation surface in the Rawhide Mountains, where the faults and dislocation surface are well exposed (Shackelford, 1976). A large northwest-trending reverse fault exposed in the Rawhide and Buckskin Mountains offsets the dislocation surface and must be either middle or late Tertiary in age (Shackelford, 1976). Other styles of deformation (collapse, resurgence, etc.) probably accompanied evolution of major volcanic centers in the Kofa Mountains, Eagletail Mountains, Wickenburg area, and other localities where thick sections of ash-flow tuff, volcanic breccia, and flow-banded rhyolite occur.

Another manifestation of Tertiary deformation *may* be exposed in the Plomosa Mountains where Miller (1966, 1970) mapped a series of N. 60° W.-trending faults, which have right-lateral strike-slip separation of over 5 km. Miller (1966) indicated that the faults displaced late Mesozoic clastic strata but did not affect mid-Tertiary volcanics of the Kofa and New Water Mountains. However, Miller and McKee (1971) suggested that this episode of faulting might deform mid-Tertiary volcanics of the Plomosa Mountains. Existing published data are equivocal regarding the age relationship between the N. 60° W.-trending strike-slip faults and mid-Tertiary volcanics.

Although the volcanic rocks of the region are shown on the 1969 Arizona state geologic map (Wilson and others, 1969) as Cretaceous, stratigraphic and isotopic studies indicate that they are probably all middle Tertiary (Eberly and Stanley, 1978; Rehrig and Reynolds, in press; Shafiqullah and others, this volume). K-Ar ages of the intermediate to felsic volcanics cluster from 25 to 15 m.y. The basalts are generally younger (mostly 15 to 6 m.y. B.P.), and many are more appropriately considered as part of the late Tertiary Basin-and-Range disturbance (see next section). However, some basalts and basaltic andesites were clearly extruded during the mid-Tertiary (Shafiqullah and others, this volume).

The major tilting event in the region in part postdates intermediate to felsic volcanics dated at 20 to 17 m.y. B.P. but largely predates basalts that are as old as 13 to 15 m.y. B.P. (Eberly and Stanley, 1978; Shafiqullah and others, 1976; Suneson and Lucchitta, 1979; Davis and others, 1977, in press; Miller and others, 1977; Otton, 1978; Rehrig and Reynolds, in press; Rehrig and others, this volume). The thicker mid-Tertiary clastic sections (shown on the Arizona state geologic map of 1969 as Tertiary or Cretaceous sedimentary rocks) are also tilted and apparently range in age from approximately 25 to 14 m.y.

Late Tertiary Basalts, Sediments, and Block Faulting

Late Tertiary rocks of the region are relatively flat-lying basalts, tan-colored fanglomerate, sandstone, and siltstone, and evaporites (Metzger, 1951; Kam, 1964; Peirce, 1976b; Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Suneson and Lucchitta, 1979, pers. comm.). These rocks generally occupy fault-bounded basins (Eberly and Stanley, 1978; Scarborough and Peirce, 1978) and are best exposed where protected by a cap of overlying basalt or along terraces flanking the larger, modern drainages. These rocks are mostly synchronous with and postdate Basin-and-Range block faulting (Eberly and Stanley, 1978; Peirce, 1976b). The rocks and sediments range in age from approximately 15 m.y. to recent, although the main episode of deposition accompanied block faulting from 15 to 5 m.y. B.P. (Eberly and Stanley, 1978; Peirce, 1976b; Scarborough and Peirce, 1978).

Distributed along the present Colorado River topographic trough are scattered exposures and more extensive subsurface occurrences of the Bouse Formation (Metzger, 1968; Lucchitta, 1972). The Bouse Formation is less than 250 m thick and consists of a basal limestone overlain by clay, silt, and sand. Associated with the Bouse Formation are extensive tufa deposits, which mantle pre-Bouse bedrock. The Bouse Formation is marine to brackish water and probably Pliocene in age (Metzger, 1968; Lucchitta, 1972). Overlying the Bouse Formation are gravels deposited by the Colorado River.

Regional Tectonic Evolution

The following is an interpretive summary and synthesis of major events in the geologic-tectonic evolution of west-central Arizona. These events can and should be considered within the regional tectonic framework of southwestern North America (Burchfiel and Davis, 1972, 1975; Coney, 1973, 1978a, 1978b; Hamilton, 1978).

In Arizona, the Precambrian was a time of tectonic unrest, crustal construction, and stabilization via a series of depositional, metamorphic, and plutonic episodes (Anderson and Silver, 1976; Silver, 1978). Deposition of clastic and volcanic rocks was closely followed by metamorphism, deformation, and plutonism around 1.6 to 1.7 b.y. B.P. (Silver, 1978). An additional plutonic event resulted in emplacement of megacrystic granites at approximately 1.45 b.y. B.P. (Silver, 1978). Besides possible emplacement of diabase dikes in late Precambrian time, the next youngest rocks in west-central Arizona are Paleozoic. Equivalents of younger Precambrian Apache Group rocks are evidently absent in the area. By Paleozoic time, the area had been stabilized and was part of the craton (Peirce, 1976a; Coney, 1978a). Any thick miogeoclinal sedimentation must have been well to the west during the entire Paleozoic, as the region possesses only a thin (approximately 1 to 1.5 km thick) apron of Paleozoic strata resting on older Precambrian basement.

After the Paleozoic interval of relative tectonic quiescence, the area experienced major mid-Mesozoic volcanism, plutonism, and tectonic instability (Coney, 1978a; Rehrig and Reynolds, in press). The mid-Mesozoic volcanics and plutons are evidently calc-alkaline (Crowl, 1979) and most likely represent initiation of a northeast-dipping subduction zone beneath the region (Coney, 1978a). The mid-Mesozoic magmatic arc probably connects in a northwest-trending belt (Coney, 1978a, 1978b) with volcanics and plutons of apparently similar age in California (Burchfiel and Davis, 1975; Pelka, 1973) and southern Arizona (Hayes and Drewes, 1978). Mid-Mesozoic magmatism in west-central Arizona was terminated as the arc either swept or jumped westward to the Peninsular batholith of southern and Baja California (Coney and Reynolds, 1977; Coney, 1978a, 1978b).

Deposition of late Mesozoic clastic sediments most likely accompanied formation of subsiding basins, which, in large part, postdate the mid-Mesozoic magmatism. The basins probably received Precambrian granitic and Paleozoic quartzite and carbonate clasts from the north and volcanic debris from the south or southwest (Pelka, 1973; Harding, 1978; Marshak, 1979; Robison, 1979). One possible tectonic setting could be a northwest-trending trough or graben, which had Precambrian and Paleozoic rocks along its northeastern margin and volcanics on its southwestern side (Pelka, 1973, 1979, pers. comm.; Robison, 1979; Harding, 1979, pers. comm.). The volcanic debris could have been derived from the older mid-Mesozoic rocks or synchronous volcanics associated with the Cretaceous Peninsular batholith. The general lack of actual volcanic flows or thick tuffs in the clastic section implies that concurrent volcanism was well to the west, which supports the first option.

Clastic sedimentation was followed by plutonism and metamorphism in the Late Cretaceous and early Tertiary as magmatism swept northeastward across Arizona (Coney and Reynolds, 1977). Metamorphism was, in part, synchronous with plutonism and formed high-grade gneissic and migmatitic terrains exposed in the metamorphic core complexes. Mylonitization in the complexes postdates the main, high-grade metamorphic event and is probably early or middle Tertiary in age (Rehrig and Reynolds, in press; Davis and others, in press). Outside of the complexes preexisting rocks were regionally metamorphosed to greenschist (and locally higher) grades and deformed, forming a widespread cleavage accompanying south to southeast tectonic transport. This metamorphic-deformational event is possibly Cretaceous.

A period of widespread early Tertiary erosion (Scarborough and Peirce, 1978; Shafiqullah and others, 1978; Coney, 1978a) was followed by deposition of a basal arkosic conglomerate. Mid-Tertiary volcanism, clastic sedimentation, and deformation progressed mostly from 25 to 15 m.y. B.P. Mid-Tertiary regional dike swarms trend northwest to north-northwest, indicating northeast to east-northeast extension (Rehrig and Heidrick, 1976). Mylonitic fabric in Arizona core complexes is partly this same age (25 to 20 m.y., see Reynolds and Rehrig, in press) and possesses lineation that trends northeast to east-northeast, perpendicular to the dikes. The mylonitic fabric probably represents a somewhat ductile manifestation of northeast to east-northeast extension (Shackelford, 1975; Davis and others, 1975; Coney, 1979, in press; Davis and Coney, 1979; Davis, in press; Davis and others, in press; Rehrig and Reynolds, in press; Reynolds and Rehrig, in press).

Listric normal faulting and concurrent antithetic rotation of Tertiary strata mostly occurred between 25 and 15 m.y. B.P., possibly being most intense late in the interval (Shackelford, 1975; Suneson and Lucchitta, 1979; Davis and others, in press). Faulting and rotation accommodated northeast to east-northeast extension (Shackelford, 1975; Rehrig and Reynolds, in press). Timing constraints and field relationships (such as brittle conversion of mylonitic rocks into chloritic breccia) indicate that much listric normal faulting of Tertiary rocks and movement above the dislocation surface postdate mylonitization in the metamorphic core complexes (Davis and others, in press; Rehrig and Reynolds, in press; Reynolds and Rehrig, in press; Peirce and Shafiqullah, 1979, pers. comm.). Mylonitic foliation, chloritic breccia, and the dislocation surface all exhibit archlike morphologies, indicating that *some* arching of the metamorphic complexes is a late, presumably Miocene phenomenon (Davis and others, in press; Rehrig and Reynolds, in press).

Block-faulting formed most of the present-day basins and ranges between 14 and 5 m.y. B.P. (Shafiqullah and others, 1976; Peirce, 1976b; Eberly and Stanley, 1978; Scarborough and Peirce, 1978). Variably sized clastics were shed into the downdropped basins and evaporites were deposited in some closed basins (Peirce, 1974; 1976b; Scarborough and Peirce, 1978). The bounding faults are evidently steep and have been inactive for a significant period of time because pediments are well developed and most mountain fronts have sinous boundaries. The region was moderately tectonically stable when the Bouse Formation was deposited in a partly marine embayment accompanying development of the Gulf of California (Metzger, 1968; Lucchitta, 1972). The Bouse Formation was progressively covered by gravel as the Colorado River established its present drainage. Basins that had earlier been characterized by internal drainage became interconnected as part of the integrated Colorado-Gila River system (Eberly and Stanley, 1978).

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