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EARLY PROTEROZOIC ROCKS (1710-1615 Ma) IN CENTRAL TO SOUTHEASTERN ARIZONA[1]

by
Clay M. Conway
U. S. Geological Survey
2255 N. Gemini Drive, Flagstaff, Arizona 86001
and
Leon T. Silver
Division of Geological and Planetary Sciences
California Institute of Technology, Pasadena, California 91125

[1]Contribution No. 4527, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California

ABSTRACT

The interval 1710-1675 Ma was a period of major sedimentation and felsic magmatism in central to southeastern Arizona. Strata formed at this time occupy a basin or group of closely related basins referred to here as the Pinal basin. In the Tonto Basin-Mazatzal Mountains region, the northern, shoreward part of the Pinal basin, the strata of the Tonto Basin Supergroup are largely subaqueous but shoal upward and contain abundant fluvial and shallow-water quartz arenite and subaerial felsic volcanic rocks in upper parts. The Diamond Rim Intrusive Suite contains widespread hypabyssal units that were emplaced contemporaneously with rhyolite caldera volcanism. The Hess Canyon Group and underlying Redmond Formation in the Salt River area are similar to strata in the upper part of the Tonto Basin Supergroup and may occupy similar positions relative to the Pinal Basin. The Pinal Schist throughout the southeastern part of the state occupies more distal, generally deeper parts of the Pinal basin. In the Pinal Schist, fine-grained sedimentary rocks (shale and subgraywacke) predominate, but felsic volcanic rocks, quartzite, and arkose are important constituents of some sections.

The 1710-1675-Ma rocks were deformed in the interval 1675-1625 Ma and intruded by syntectonic to posttectonic granitic plutons at 1640-1615 Ma. The deformation is attributed to the Mazatzal orogeny and is characterized at upper crustal levels in the Tonto Basin-Mazatzal Mountains region by foreland folding and thrusting. Strata were folded on shallow-plunging, northeast-trending axes and thrust to the northwest.

INTRODUCTION

This discussion reviews important early geologic studies, draws from our past and ongoing research, and incorporates material from recent work of others. In addition to summarizing what is known of the 1710-1615-Ma rocks, we have two major objectives. The first, which springs from advances in geochronology, stratigraphy, and petrology, is an attempt at broad correlations. The second is to examine the question of petrotectonic evolution and to propose a working hypothesis for the tectonic setting and overall orogenic history.

We consider that sufficient information is now available for definition or clarification of several lithostratigraphic terms and further clarification of the nature of the Mazatzal orogeny. These are set forth in this introduction and are basic to the remainder of the paper.

Certain sequences of Early Proterozoic stratified rocks in central to southeastern Arizona (figs. 1, 2) were deposited in the interval 1710-1675 Ma (Silver, 1965, 1967, 1978; Silver and others, 1986). For present purposes these strata can be placed in two major groupings, the Pinal Schist (Ransome, 1903) and the Tonto Basin Supergroup (Conway and others, 1987, in press). Occurrences of stratified rocks dominated in most places by graywacke, from the White Ledges to Bisbee (fig. 1), have been referred by various workers to the Pinal Schist. We use the Pinal Schist in this paper to include all these occurrences except that at White Ledges for which group and formation names have been proposed (fig. 2). Conway and others (1987, in press) proposed to include the Alder, Red Rock, and Mazatzal Groups of the Tonto Basin-Mazatzal Mountains (TBMM) region in the Tonto Basin Supergroup. Units of the Tonto Basin Supergroup extend into the New River

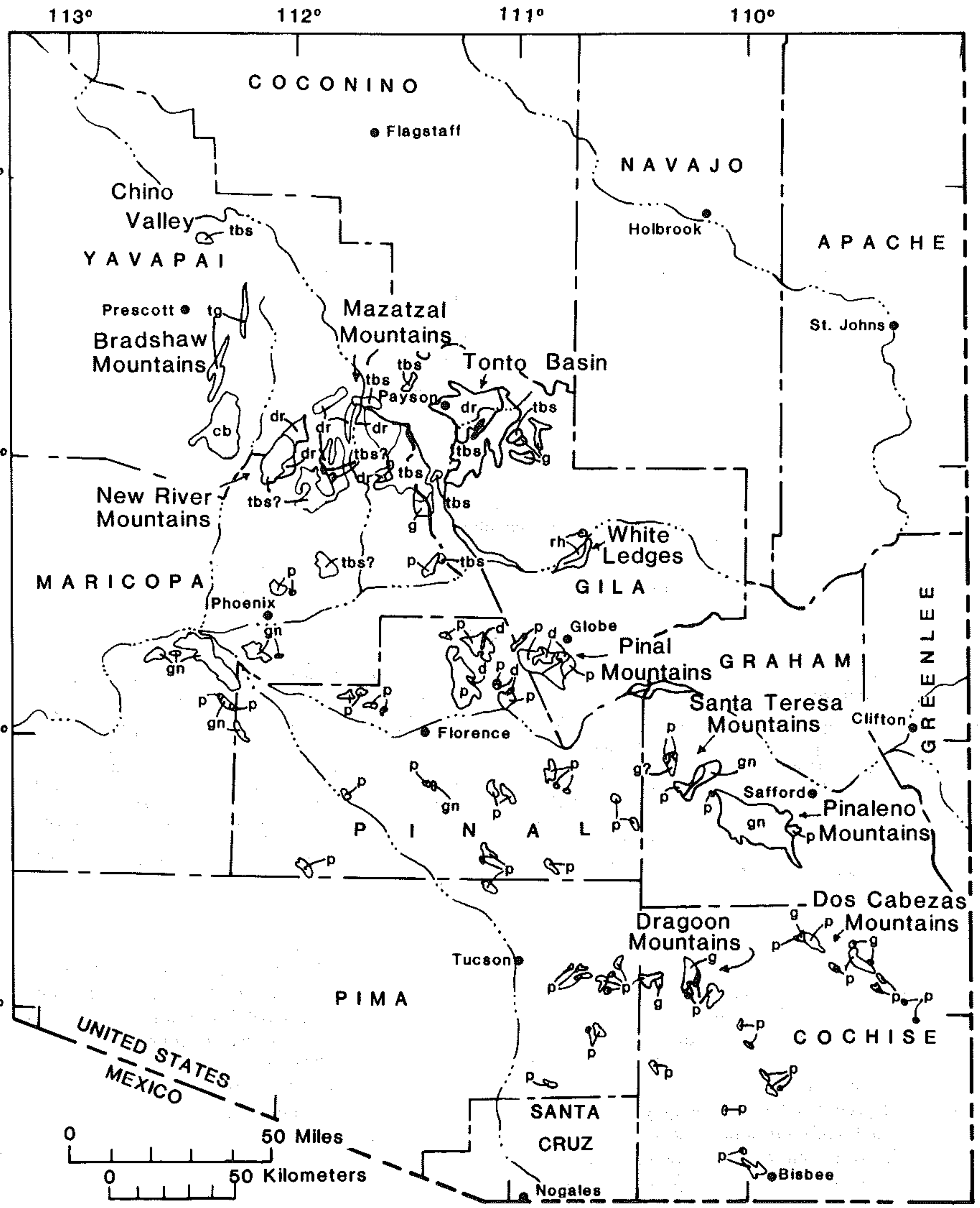


Figure 1. Map showing outcrop areas of 1710-1615-Ma rocks in central to southeastern Arizona. Map unit symbols: cb—Crazy Basin Quartz Monzonite, d—diorite, including Madera Diorite, dr—Diamond Rim Intrusive Suite, g—late- to posttectonic granitic rocks, gn—gneiss, probably including Pinal Schist and younger intrusive rocks, rh-Redmond Formation and Hess Canyon Group, undivided, p—Pinal Schist, tbs—Tonto Basin Supergroup, tg—Texas Gulch Formation (may be older than 1710 Ma),

Mountains region (Anderson, this volume; Conway, unpublished mapping). Hypabyssal rocks, roughly the same age as associated volcanic strata, are locally present in central to southeastern Arizona. They are particularly abundant in the TBMM where they are included in the Diamond Rim Intrusive Suite (Conway and others, 1987, in press).

Deformed strata of the Tonto Basin Supergroup in the Mazatzal Mountains constitute the type area for the Mazatzal orogeny (Wilson, 1939). Granite bodies near Sunflower in the central Mazatzal Mountains and at Young in the Tonto Basin area may postdate this deformation (Silver, 1965). These granites and a number of mostly granitic bodies that intrude strata of the Pinal Schist in central to southeastern Arizona (fig. 1) are 1640-1615 Ma (Silver and Deutsch, 1963; Silver, 1969, 1978). Some of these granite bodies may be syntectonic, but at least one, the 1625-Ma Johnny Lyon Granodiorite (Silver, 1978) is clearly posttectonic. Thus it appears that a deformational event (or series of events) occurred in central to southeastern Arizona roughly between 1675 and 1625 Ma. Evidence for deformation and metamorphism in this time interval elsewhere in the southwestern United States and Mexico (Pasteels and Silver, 1966; Anderson and Silver, 1971) implies widespread effects of an incompletely defined major crustal event. This event postdates the deposition of the Tonto Basin Supergroup and the Pinal Schist, which in our view (see concluding sections of this paper) formed as continental to continental-margin successions. Thus we see the 1675-1625-Ma event(s) as being distinct in time and in character from earlier tectonic event(s) that resulted in consolidation of primarily calc-alkaline arc materials to create new continental crust in this part of the North American craton. We propose to restrict the Mazatzal orogeny in time to deformation that postdated deposition of the Tonto Basin Supergroup and the Pinal Schist. We leave open its full definition as regards time of culmination (but suggest it ended by about 1625 Ma), regional extent, and structural and metamorphic manifestations. In TBMM, it is basically an event of continental-margin, northwest-directed, foreland folding and thrusting and possible late left-lateral translation.

Recent studies in the TBMM (Wrucke and Conway, 1987; Conway and others, 1987) suggest that upper parts of the Tonto Basin Supergroup unconformably overlie the Gibson Creek batholith and East Verde River Formation (Conway and others, in press), which have age and petrologic affinities with the Yavapai Series and associated batholithic rocks in the Jerome-Prescott region. It has been suggested by several workers (see Conway and Karlstrom, 1986) that the Texas Gulch Formation, which unconformably overlies a pluton that intrudes strata of the Yavapai Series, is correlative with the Alder Group of the Tonto Basin Supergroup. Whether this is correct and whether the Gibson Creek batholith and the East Verde River Formation are correlative with the Yavapai Series and associated batholiths remains for further investigation. These and related problems were discussed extensively by Anderson (this volume), Conway and others (1987), and Karlstrom and others (1987).

The petrotectonic model we construct in this paper is strongly dependent on lithologic characteristics of quartz arenites and alkalic, rhyolitic ash-flow tuff of the Tonto Basin Supergroup, which indicate accumulation on (relatively) stable continental crust. This model suggests the crustal substrate included the Gibson Creek batholith, the East Verde River Formation, and the Yavapai Series and associated batholiths.

EARLY GEOLOGIC STUDIES

Early studies, as we refer to them here, include works completed prior to the initiation of modern geochronology (about 1960).

Ransome (1903) was the first to describe rocks of the Pinal Schist. He designated the Pinal Mountains in Gila County as the type locality and described the Pinal as consisting of very fine- to medium-grained metasedimentary rocks. Ransome (1904) then used the name Pinal for exposures of similar rocks in the Bisbee quadrangle, Cochise County. Except for mapping separately small exposures of metarhyolite near Ray, Ransome (1919) did not subdivide the Pinal; he worked out little internal structure and stratigraphy and made no estimate of thickness. The name Pinal has since been applied to widely scattered exposures of generally fine-grained clastic rock of mildly schistose character throughout southeastern Arizona.

Ransome (1915, 1916) also published the first descriptions of Proterozoic rocks in the Mazatzal Mountains region. He (1916, fig. 14) described and sketched in cross-section a relationship he discovered at Tonto Natural Bridge, between Payson and Pine, where a thick Proterozoic quartzite succession with a basal conglomerate of "granite" clasts rests on "granite." Later studies (Wilson, 1939; Conway, 1976) showed that both clasts and subjacent body are actually rhyolite. This site was to be a source of controversy (see below).

Darton (1925) described the stratigraphic succession at White Ledges near the Salt River in Gila County, rocks which he considered to be the Pinal Schist. He also briefly described contact and stratigraphic relations of Proterozoic quartzites in the Tonto Basin and Mazatzal Mountains region.

Eldred Wilson (1922, 1939) made landmark contributions to the understanding of Precambrian rocks in Arizona. In the Mazatzal Mountains he defined the sequence (descending) Mazatzal Quartzite (now called the Mazatzal Peak Quartzite)-Maverick Shale-Deadman Quartzite and referred several other quartzite bodies in the region to the Mazatzal Quartzite. He found the Deadman Quartzite to rest on rhyolite (his Red Rock Rhyolite), which he considered to be older than a sequence of "shale, grit, quartzite, and conglomerate" (his Alder Series) in the central Mazatzal Mountains and younger than a complex of mafic volcanic rocks (his Yaeger Greenstone) in the northern and northeastern Mazatzal Mountains (fig. 3). Wilson correlated the Yaeger Greenstone in the Mazatzal Mountains with the type Yaeger Greenstone in the Black Hills, Yavapai County, where the name was taken from the Yaeger mine.

Wilson did not consider the unconformity at the base of the Deadman Quartzite to represent a major orogenic-erosional episode. To explain the deposition of the Deadman on the Red Rock Rhyolite and not on the presumed younger Alder Series, he inferred (1939, p. 1161) that "after deposition of the Alder beds the region underwent uplift" during which the Alder locally was eroded away.

The name "Mazatzal revolution" was proposed by Wilson (1937, 1939) for the orogenic event in which strata of the Mazatzal Mountains were deformed, and he suggested that this event affected a region much larger than central Arizona. Hinds (1936a, 1936b), who had seen an early version of Wilson's (1937) Ph.D. study, called this event the "Mazatzal orogeny." He proposed, partly on the basis of quartzite resting on "granite" at Tonto Natural Bridge (Ransome, 1916; Wilson, 1922) and partly on what he perceived to be much greater deformation in pre-quartzite rocks of the region than in the quartzite, that this event had been preceded by another major orogenic episode, which he called the "Arizonan orogeny."

Authorship, definition, and nature of the Mazatzal orogeny, as well as the existence of the Arizonan orogeny, were vigorously debated in the late 1930s (Stoyanow, 1936; Wilson, 1936, 1937, 1939, 1940; and Hinds, 1936a, 1938). Hind's arguments for an Arizonan orogeny have not been widely accepted (Anderson, 1951), but Wilson's concept of the Mazatzal orogeny, though still undergoing revision, is an important concept in the understanding of the Arizona Proterozoic crust.

A report on the geology of the Dragoon quadrangle, Cochise County (Cooper and Silver, 1964) contains an important petrologic study of the Pinal Schist. From a systematic study of widespread and well-preserved graded bedding and small-scale deformational structures, a continuous section in the Johnny Lyon Hills was found to be approximately 2,500 m thick and possibly underlain by as much as 3,600 m additional feet in nearby areas of the Little Dragoon Mountains.

The presence of ubiquitous graywacke-slate cycles, graded bedding, abundant volcanic debris, intercalated volcanic flows, and the absence of clean sandstones, carbonate rocks, and of sedimentary structures indicating a shallow-water environment (i.e., cross-bedding and ripple marks) were cited by Cooper and Silver (1964, p. 20-21) as evidence for accumulation of the Pinal in a geosyncline. They considered the Pinal as similar in character to the Yavapai Schist of Jaggar and Palache (1905) (central Arizona) and the Vishnu Schist (Grand Canyon). Silver (1955), however, in reporting his study of the Johnny Lyon Hills portion of the Dragoon quadrangle, contrasted the Pinal Schist of southeastern Arizona with the Yavapai Schist, noting the much greater abundance of volcanic rocks in the Yavapai. He suggested the Yavapai was eugeosynclinal, whereas the graywacke-rich Pinal might be transitional between eugeosynclinal and miogeosynclinal facies, which would imply (assuming contemporaneity) a major continental shield to the south. Silver argued from regional structural trends and from the assumed perpendicularity of compressive forces to sedimentary troughs in other deformed geosynclines of the world that the Proterozoic geosyncline trended east-west to northeast-southwest. He concurred with Wilson (1939) and Anderson (1951) that though "multiple orogenies could have occurred in Arizona, . . . the simplest explanation calls for only one period."

Gastil (1958) deciphered the stratigraphic succession of a folded and faulted section of Proterozoic volcanic and volcaniclastic rocks in the Tonto Basin area of Gila County. He divided the 4,600-m-thick section into five formations. He correlated the lowermost formation (his Alder Formation, now called the Breadpan Formation of the Alder Group by Conway and others, in press) of slate, graywacke, quartzite, and conglomerate with Wilson's (1939) Alder Series in the Mazatzal Mountains and suggested that rhyolite of the overlying Flying W Formation was equivalent to Wilson's Red Rock Rhyolite and that a quartzite-slate-quartzite sequence of the superjacent Houdon Formation could be equated with Wilson's Deadman-Maverick-Mazatzal succession of the Mazatzal Mountains (fig. 3). (Houdon Formation was earlier spelled "Houden" Formation (Gastil, 1958). It has been recently changed to "Houdon" Formation in accordance with revised spelling of the place-name Houdon Mountain in the Sheep Basin Mtn. 7½′ quadrangle.) He concluded that his Board Cabin and Haigler Formations are younger than the Mazatzal Quartzite of Wilson (1939). Gastil postulated that rhyolite of the Haigler Formation was comagmatic with the granite at Young and with large masses of granite, granophyre, and intrusive rhyolite between Hells Gate and Payson.

GEOCHRONOLOGY

Isotopic geochronology, in particular U-Pb zircon geochronology, is important to integration of regional stratigraphic and structural elements in complex orogenic terranes such as the Early Proterozoic of Arizona.

A 1625 ± 10-Ma age determined for the postdeformational Johnny Lyon Granodiorite (Silver and Deutsch, 1963; Silver, 1978) established a minimum age for the deformation of the Pinal Schist. Felsic volcaniclastic rocks and rhyodacite intrusive sheets in the Pinal Schist of that locality were found to be 1700-1675 Ma (Silver, 1963, 1978, unpublished data) thus placing an older limit on the time of deformation.

In subsequent studies, Silver and colleagues (Silver, 1965, 1967, 1969, 1978, unpublished data; Silver and others, 1977, 1986; Ludwig, 1974; Conway, 1976) determined 1640-1615-Ma ages for plutonic bodies in the Dos Cabezas Mountains, Mazatzal Mountains, Tonto Basin, and elsewhere. They determined 1710-1675-Ma ages for volcanic rocks in the Pinal Schist of Cochise County and Pinal County, in strata at White Ledges, and in TBMM. Thus, the Pinal Schist and the Tonto Basin Supergroup in TBMM were found to be in part contemporaneous and apparently to have been deformed prior to a closely timed episode of plutonism. Inasmuch as the 1710-1675-Ma suite included the Mazatzal Mountains strata in the type area of Wilson's (1939) Mazatzal orogeny, the establishment of synchronous regional deformation allowed identification of the Mazatzal orogeny in southeastern Arizona and bracketed the event(s) in central to southeastern Arizona between approximately 1675 and 1625 Ma.

Whereas geochronology has demonstrated a general contemporaneity for volcanic rocks of the Pinal Schist and Tonto Basin Supergroup, it neither proves nor disproves certain correlations proposed by Gastil (1958), Livingston (1969a), and Livingston and Damon (1968) for these stratified rocks. These must rely on careful stratigraphic studies.

A major finding of early regional geochronological investigations (Silver, 1967, 1969; Anderson and others, 1971; Silver and others, 1977) was that volcanic and plutonic rocks in Arizona roughly northwest of the Mazatzal Mountains and the New River Mountains (P. Anderson, this volume; DeWitt, this volume) were distinctly older than the Pinal Schist and the Tonto Basin Supergroup. The volcanic rocks to the northwest (Yavapai Series of Anderson and others, 1971) were found to be largely 1775-1745 Ma and intruded by voluminous and variable batholiths mostly 1745-1730 Ma. Rocks of these ages were not known then from the Mazatzal Mountains or to the southeast. A boundary of unknown structural character appeared to trend northeastward across the center of the state of Arizona between the northwestern, older, and southeastern, younger, terranes. These discoveries cast doubt on several earlier proposed correlations between the Mazatzal Mountains and the Black Hills and resulted in abandonment of the Alder Series in the Black Hills region and the Yavapai Series and Yaeger Greenstone in the Mazatzal Mountains (Anderson and others, 1971).

Recent geochronologic and field studies have added complications to the concept of a two-province boundary. The Gibson Creek batholith and probably the East Verde River Formation in the TBMM (Silver and others, 1986) are similar in age and petrologic character to rocks of the Yavapai Series and associated batholiths. Stratified rocks at Bagdad, included in the Yavapai Series by Anderson and others (1955), may be similar in age (Bryant and Wooden, 1986) to oldest known rocks of the Tonto Basin Supergroup (the lower part of the Alder Group has not been dated). Several plutons in the region northwest of the Mazatzal Mountains and the New River Mountains are about 1700 Ma (Karlstrom and others, 1987). Issues arising from these findings (Conway and others, 1987; Karlstrom and others, 1987) are not discussed further in this paper except for possible connections between 1700-Ma plutonism in the northwestern region and 1700-Ma volcanism in the Tonto Basin Supergroup.

K-Ar and Rb-Sr age data (Livingston, 1962; Livingston and Damon, 1968; Wasserburg and Lanphere, 1965; Lanphere, 1968) are for some rocks in broad agreement with the zircon U-Pb ages but are generally younger. Lanphere (1968) concluded that Rb-Sr ages considerably younger than zircon ages in rocks of the Yavapai Series were the result of loss of radiogenic strontium and should therefore be considered minimum ages. Loss of radiogenic daughter product may have similarly affected other apparent Rb-Sr as well as K-Ar ages of Arizona's Early Proterozoic rocks.

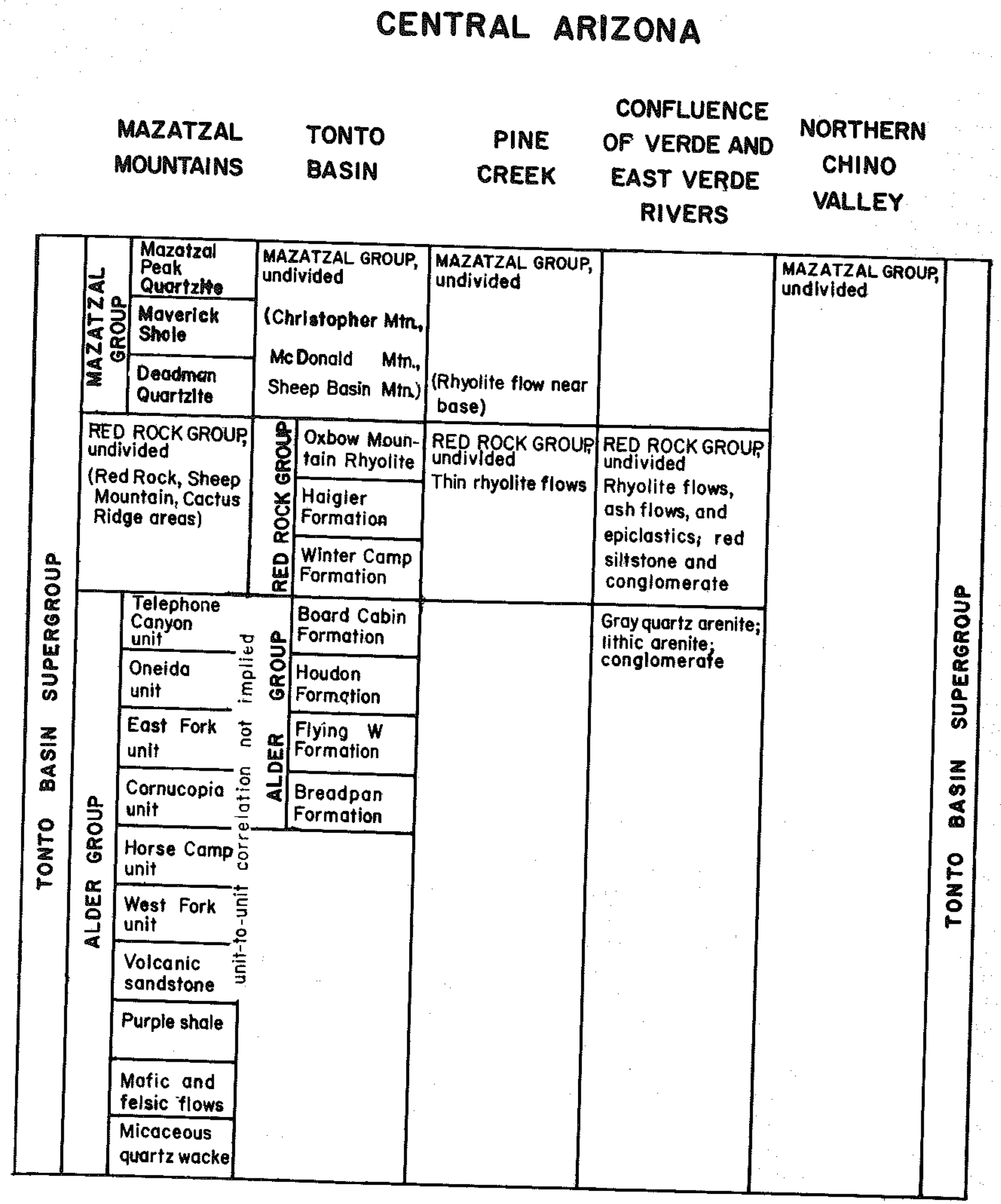
Ages and age ranges as quoted in this paper are entirely from U-Pb zircon data and come partly from published literature (see tabulation of data for central Arizona by Karlstrom and others, 1987). Full definition of the age ranges, however, also relies on extensive unpublished data (L. T. Silver).

DISCUSSION OF GEOLOGY BY AREA

Tonto Basin-Mazatzal Mountains Region

Stratigraphy and structure are better known in the TBMM and New River Mountains regions (Conway, 1976; Wrucke and Conway, 1987; P. Anderson, 1986, this volume) than in other exposure areas of 1710-1615-Ma rocks. P. Anderson (1986, this volume) proposed a stratigraphy that varies somewhat from that of Conway and others (in press) and that applies to the TBMM plus the New River Mountains-Cave Creek region. In the TBMM area, our differences with Anderson are primarily in lithologic subdivision and in names; we are in broad agreement on the nature of the overall stratigraphic succession (P. Anderson, 1986, 1987, oral and written commun.). A major difference, however, is that Anderson would place some mafic units within the Alder Group of Conway and others (in press) in his Union Hills Group, beneath his Alder Group. We do not include a review of Anderson's work in this paper because of his extensive summary in this volume.

A generalized structural and lithologic framework for TBMM is shown in figure 4, and simplified stratigraphic columns for the stratified rocks are given in figure 5. In the



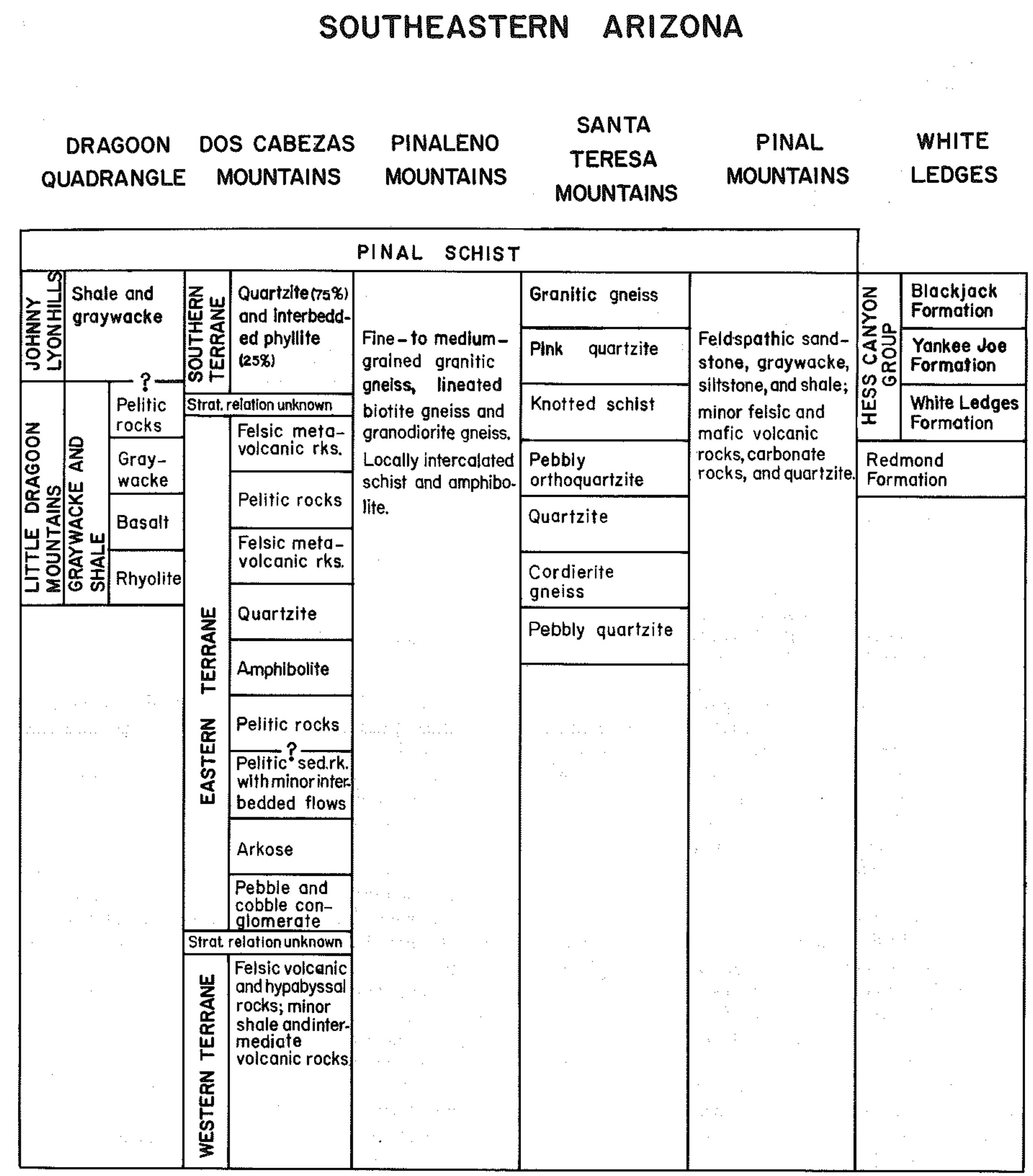


Figure 2. Correlation of 1710-1675-Ma strata in central to southeastern Arizona. For central Arizona, all map units shown in columns are included in the Tonto Basin Supergroup. For southeastern Arizona, all map units shown in columns are included in the Pinal Schist except the White Ledges area. For southeastern Arizona, there is no intention to imply unit-to-unit correlation between columns. Sources from numerous authors as cited in the text under geology by area. See also caption for figures 3 and 5.

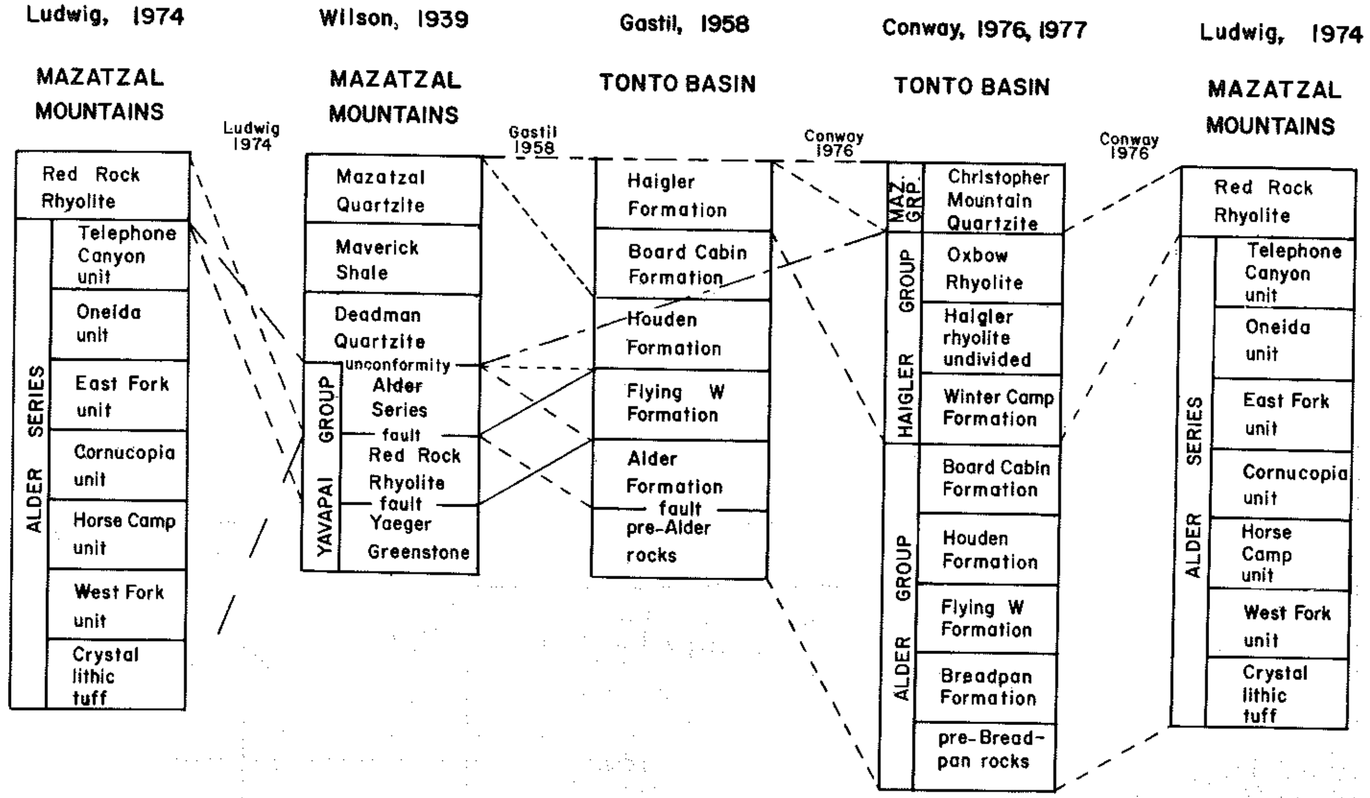


Figure 3. Stratigraphic successions and correlations previously proposed for strata of the Tonto Basin Supergroup in the Tonto Basin-Mazatzal Mountains area. The Mazatzal Mountains column (Ludwig, 1974) is given twice to enable clarification of the proposed correlations . The columns and correlations of Conway (1976, 1977) are updated in figure 2.

following paragraphs, only brief justification is given for correlation, and only brief descriptions are given of the rocks. We address these topics extensively elsewhere (Conway and others, 1987, in press) and much information is given in figures 2, 4, and 5. Valuable data for this region may also be obtained from Martinsen (1975), Kovas (1978), Trevena (1979), Anderson and Wirth (1981), Horstman (1980), Hall-Burr (1982), Hobbs (1982), Conway and others (1983), Vance (1983), Wrucke and others (1983), Alvis (1984), Pendergrass (1984), Anderson (1986), Karlstrom and Conway (1986), Conway and Wrucke (1986), Puls (1986), Sherlock (1986), and Roller and Karlstrom (1986).

Previously proposed stratigraphic successions and correlations for TBMM are shown in figure 3. The regional stratigraphy now proposed (figs. 2, 4, and 5; Conway and others, in press) is based largely on recent field studies (Ludwig, 1974; Conway, 1976; Wrucke and Conway, 1987) and U-Pb zircon ages discussed earlier. Ludwig (1974) determined, in contradiction to Wilson (1939), that the Red Rock Rhyolite rests on the Alder Group in the central Mazatzal Mountains. Conway (1976) found that quartzite at Christopher Mountain in the Tonto Basin, assigned to the Houdon Formation by Gastil (1958), rests on the Oxbow Mountain Rhyolite and the Haigler Formation. Reconnaissance mapping by Conway, Ludwig, and Silver and mapping by Vance (1983) has suggested that, with facies changes and lapouts, the Board Cabin Formation and Houdon Formation of Tonto Basin are broadly correlative with the upper part of the Alder Group in the Mazatzal Mountains. The thick rhyolite sequences above the Alder Group in the Tonto Basin and Mazatzal Mountains are comparable alkali rhyolite ash-flow tuff suites (Ludwig, 1974; Conway, 1976; Wrucke and Conway, 1987). Above these rhyolites, regionally, are the thick reddish-brown quartzite sequences (Wilson, 1939) that we assign to the Mazatzal Group. These are distinguished not only by stratigraphic position but petrographically from the generally grayish quartzites of the upper part of the Alder Group.

The Tonto Basin stratigraphy (figs. 2 and 5; see Conway and others, in press) follows Conway (1976 and fig. 3) except for nomenclatural changes. These changes are that the Haigler Formation is used basically as proposed by Gastil (1958), the Winter Camp and Haigler Formations and the Oxbow Mountain Rhyolite comprise the Red Rock Group, and the Christopher Mountain Quartzite (Conway, 1976, 1977) is not used. The Alder Group is not formally subdivided in the Mazatzal Mountains because there are some structural and stratigraphic problems that need to be resolved (Roller and Karlstrom, 1986; Conway and others, 1987). Ludwig's (1974) informal subdivisions (with slight nomenclatural modification) as well as new lithologic units in the lower part of the Alder (Wrucke and Conway, 1987) are shown in figure 5. The name Mazatzal Peak Quartzite (Anderson and Wirth, 1981) is proposed to replace the name Mazatzal Quartzite in the Mazatzal Mountains, and the Deadman, Maverick, and Mazatzal Peak are placed in the Mazatzal Group for the following reasons (Conway, 1976): (1) Mazatzal was the original name (Wilson, 1922) applied to the entire sequence in the Mazatzal Mountains, not just to the upper quartzite unit. (2) It seems desirable to continue the long-held usage of the name Mazatzal for various undivided quartzite sequences in the region without implying that they are correlative only with the upper (quartzite) unit in the Mazatzal Mountains.

Extensive exposures of granite, granophyre, and intrusive rhyolite in the TBMM area (fig. 4) are included in the Diamond Rim Intrusive Suite (Conway and others, in press, 1987). These units have ages (1703-1692 Ma, Silver and others, 1986) similar to those of the Red Rock Group and the upper part of the Alder Group. Some bodies of this intrusive suite intrude the Red Rock and Mazatzal Groups whereas others are overlain by the Mazatzal Group. These hypabyssal rocks are part of a silicic alkalic magma series that includes volcanic rocks of the Red Rock Group and the upper part of the Alder Group. They probably represent shallowly emplaced, sill-form magma bodies in the roots of one or more calderas from which the volcanic rocks were erupted (Conway, 1976; Conway and others, 1987).

Several granite bodies in the TBMM area are distinctly younger than the hypabyssal rocks that are coeval with the rhyolite. Granite in the Young (fig. 4) and Sunflower areas are about 1625 Ma (Silver, 1965, 1967). These bodies are incompletely mapped, and granites of this generation may be more abundant in this region than is now recognized.

Bradshaw Mountains-Chino Valley Region

Wilson (1939) suggested that quartzite in northern Chino Valley belonged to the then-named Mazatzal Quartzite. Subsequent studies (Krieger, 1965; Bradshaw, 1974; Trevena, 1979; Wirth, 1980; Conway and others, 1981) have confirmed a similarity in petrographic characteristics and thickness to the Mazatzal Group in TBMM. These studies have also shown that paleocurrent directions in the quartzite near Del Rio are similar to those of quartzite in the Mazatzal Group in TBMM and that differences in sedimentary facies are compatible with a facies change in the regional paleocurrent regime (see section on magmatism, sedimentation, and tectonic setting). The quartzite has a conformable contact in a small exposure area with rhyolite that may be interbedded or beneath the quartzite (C. M. Conway, unpublished mapping). Except for this, contacts of the quartzite are with Phanerozoic rocks, so a physical relationship to the Yavapai Series of the region has not been determined.

The Texas Gulch Formation in the Bradshaw Mountains region rests unconformably on the Brady Butte Granodiorite and on strata of the Big Bug Group (of the Yavapai Series), which the granodiorite intrudes (Blacet, 1966, 1985; Anderson and others, 1971; O'Hara and others, 1978; Karlstrom and Conway, 1986; P. Anderson, this volume). Composed largely of sandy to tuffaceous felsic debris and purple to greenish-gray shale (Anderson and Creasey, 1958; Blacet, 1968; Anderson and Blacet, 1972), the Texas Gulch has lithologic affinity to some parts of the Alder Group in the central Mazatzal Mountains (P. Anderson, this volume; Conway and Karlstrom, 1986). However, it also has lithologic affinity to parts of the Big Bug Group of the Yavapai Series (K. E. Karlstrom, 1987, oral commun.).

The question arises whether the Texas Gulch Formation is part of a widespread supracrustal sequence that would include the Tonto Basin Supergroup. Zircons from a felsic tuffaceous part of the Texas Gulch Formation have yielded a tentative maximum age of 1710 Ma (L. T. Silver, unpublished data). Should this epiclastic rock contain foreign zircons derived from the underlying Yavapai Series or plutons, or more distant sources, the age of Texas Gulch volcanism could be younger than 1710 Ma. This conflicts, however, with recent data obtained by S. A. Bowring (1987, oral commun.) in which zircons from the Texas Gulch Formation yielded an apparent age of about 1740 Ma. At present, therefore, the Texas Gulch age is uncertain and we neither know nor postulate that it is age equivalent to the Tonto Basin Supergroup. We include discussion of the Texas Gulch Formation in this paper only because of the possiblility that it is 1710 Ma or younger.

The Crazy Basin Quartz Monzonite is a large pluton in the southern Bradshaw Mountains (fig. 1) that is 1699 Ma (Karlstrom and others, 1987). Because it is mostly coarse grained and contains large K-feldspar phenocrysts, it resembles Middle Proterozoic granites (about 1400 Ma) that are scattered throughout Arizona. A granite body of similar petrographic character in western Arizona (Bryant and Wooden, 1986) also has about a 1700-Ma age. The Crazy Basin Quartz Monzonite was apparently emplaced at the same time that the rhyolite calderas were developing in TBMM. Whether the Crazy Basin pluton is related genetically to the 1700-Ma calderas or whether its emplacement argues for original wide crustal separation and evolution in an entirely different tectonic regime is a fertile topic for future research (see Karlstrom and others, 1987; Conway and others, 1987).

New River Mountains

Anderson and Guilbert (1979), P. Anderson (this volume), and Maynard (1986) concluded that strata in the New River Mountains-Cave Creek region are generally correlative with strata of the Tonto Basin Supergroup. Reconnaissance mapping and rock chemistry (C. M. Conway, unpublished data) has shown that the distinctive silicic alkalic magmatic suite (granite, granophyre, rhyolite) of TBMM extends into the New River Mountains and surrounding region, although no unit-to-unit correlations were made. A tentative 1700-Ma age has been determined (S. A. Bowring, 1987, oral commun.) for rhyolite from the New River Mountains. An attempt is made in figure 1 to portray distributions of rocks in the New River Mountains region that may be equivalent to the Tonto Basin Supergroup and to the Diamond Rim Intrusive Suite. The reader is referred to P. Anderson (this volume) for details of structure and stratigraphy in this region.

White Ledges

Darton (1925) considered volcanic and sedimentary rocks at White Ledges, along the Salt River in southern Gila County, to be a part of the Pinal Schist. Livingston (1962, 1969a, 1969b) and Livingston and Damon (1968) mapped and divided these strata into the Redmond Formation, composed mostly of felsic ash-flow tuff, and the overlying Hess Canyon Group, consisting of the White Ledges Formation (quartzite), Yankee Joe Formation (shale and siltstone), and Blackjack Formation (quartzite and siltstone) (fig. 2). Mapping by Cuffney (1977) resulted in subdivision and refinements of Livingston's (1969) stratigraphy. Sedimentological studies of the quartzite units (Trevena, 1979, Cuffney, 1977) suggested a nearshore marine (largely tidal-flat) depositional environment.

Livingston (1969a) suggested, on the basis of lithologic sequence and permissive geochronology, that the rhyolite-quartzite-shale-quartzite sequence at White Ledges corresponds to the Red Rock Group-Deadman Quartzite-Maverick Shale-Mazatzal Peak Quartzite succession in the Mazatzal Mountains. Trevena (1979) considered Livingston's proposed correlation with the Mazatzal Mountains quartzite units to be consistent with a regional pattern in facies changes. Anderson and Wirth (1981) favored the correlation with the Mazatzal Group in the Mazatzal Mountains. Alternatively, we suggest the Hess Canyon Group may be correlative with either the Houdon Formation in the Tonto Basin or to neither the Houdon nor the Mazatzal. The Houdon Formation is a quartzite-shale-quartzite succession and is petrographically (gray quartzite with generally reduced oxides) more akin to the Hess Canyon Group than is the Mazatzal Group. We do not reject the correlation with the Mazatzal Group; we only suggest caution. Deposition of quartzite sequences in the northern part of the Pinal Basin was repetitive. In particular, quarzite-shale-quartzite deposition, presumably reflecting a transgression-regression cycle, was clearly repeated twice in the Tonto Basin Supergroup (Mazatzal Group and Houdon Formation) and, regionally, may have been further repeated.

Pinal Mountains Region

Little has been added to Ransome's (1903, 1905, 1919, 1923) pioneering studies of the Proterozoic rocks in the Pinal Mountains. Most of the studies in the area in recent decades have been directed at mineralization, particularly in the important Laramide porphyry copper deposits of the district. No systematic lithologic subdivision and no estimate of thickness have been made of the Pinal Schist in this area.

Ransome (1903, 1919) described the Pinal in the Pinal Mountains as cryptocrystalline gray slaty sericite schist largely derived from "quartzose sediments," sandstone, and shale. He thought the minor "amphibolite" was dike material or intercalated tuff. In the only instance of map unit subdivision, Ransome (1919) mapped an "uncommon variety" of the Pinal near Ray, Arizona which he thought to be altered rhyolite. He described embayed quartz eyes that are apparently partially resorbed quartz phenocrysts.

Reports and maps published subsequent to Ransome's work (Cornwall and others, 1971; Cornwall and Krieger, 1975a, 1975b, 1978; Creasey and others, 1983; Peterson, 1960, 1969; Peterson, 1962, 1963; Schmidt, 1967; Theodore and others, 1978; and Willden, 1964) described the Pinal Schist as quartz sericite, quartz-muscovite, or quartz-sericite-chlorite schist with protoliths in some reports ascribed to arkosic sandstone, feldspathic sandstone, or graywacke, siltstone, and shale. Minor rock types described are amphibolite, felsite, rhyolite, carbonate, and quartzite. Foliated, fine- to medium grained, and well-bedded Pinal in the Teapot Mountain quadrangle, described by Creasey and others (1983), is predominantly sandstone and siltstone, with lesser amounts of argillite and carbonate rocks. Willden (1964) mapped felsic metavolcanic rocks in the Christmas quadrangle (15′) that contain rounded, embayed quartz phenocrysts. Theodore and others (1978) mapped eight different lithologies in the Mineral Mountain area but provided no descriptions or evidence for stratigraphic succession. A northeastward strike for steeply dipping and generally parallel foliation and bedding is shown by most workers. Dips are usually vertical to northwesterly. Most authors note that relict bedding is present in the Pinal, but rarely are stratigraphic top directions given. From tentative facing criteria, Peterson (1963) suggested that northwestward-dipping beds in the Pinal Ranch quadrangle (7½′) are upright. No major folds have been mapped within the Pinal Schist of the region, but the bedding-foliation relations imply major isoclinal folding.

In the Pinal Mountains region, the Pinal Schist is generally at greenschist-grade regional metamorphism. An exception is the large exposure of the Pinal in the Mineral Mountain quadrangle that was metamorphosed to the amphibolite facies (Theodore and others, 1978; Schmidt, 1967).

A rhyodacite in the Pinal Schist three miles from Ray, has yielded a U-Pb zircon date (L. T. Silver, unpublished data) similar to that in the Pinal Schist of the Dragoon quadrangle. Timing of sedimentation, volcanism, deformation, and plutonism in the Ray area are highly analogous to that in the Dragoon area.

Early Proterozoic diorite and related rocks that intrude the Pinal Schist have been assigned to the Madera Diorite (Ransome, 1903; Livingston, 1969a), a name that has been geographially extended from the type area in the Pinal Mountains to noncontinuous occurrences of diorite, quartz

diorite, and granodiorite in nearby ranges. The definition of the Madera Diorite is inadequate at present and the regional distribution is poorly known. It includes several intrusions between the Pinal range and Ray, Arizona. Some exposures presently mapped as the Madera Diorite by some workers are continuous with bodies mapped as the Ruin Granite by other workers. The Madera Diorite is basically an andesine-quartz-biotite rock with minor orthoclase or microcline and accessory hornblende, magnetite, apatite, and zircon. It is massive to intensely foliated and in many places is altered. Foliation (locally gneissic) is more intense near its contacts with the Pinal Schist and is parallel to foliation in the Pinal (Ransome, 1903).

Pinaleno Mountains and Santa Teresa Mountains

The central to northern Pinaleno Mountains are underlain largely by amphibolite-grade quartzo-feldspathic gneiss (Thorman, 1981; Bergquist, 1979; Blacet and Miller, 1978; and Swan, 1976). Thorman (1981) applied the term "granitic to granodioritic gneiss" to this metamorphic suite, but considered the rocks to be of sandstone or felsic volcanic parentage and to be of Pinal Schist affinity. Despite the high metamorphic grade, P. Anderson (1985, written commun.) reported the presence of relict primary minerals and textures. A small exposure of stratified rocks on the southwestern flank of the mountains near Bar X Canyon contains intercalated muscovite-bearing quartzite, quartzite metaconglomerate, and quartz-feldspar muscovite gneiss that clearly are of sedimentary origin. Except for this exposure and a small septum of amphibolite, metagraywacke, meta-andesite, and arenaceous schist (Bergquist, 1979) in the northwestern Pinaleno Mountains, the presumed Pinal of the Pinaleno Mountains has not been subdivided and no estimate of thickness has been made.

Granitic gneiss in the Santa Teresa Mountains (Blacet and Miller, 1978) may be a northwestern extension of the gneiss of the Pinaleno Mountains. This unit, described as belonging to the Pinal Schist, consists of granitic gneiss, biotite gneiss, granodiorite gneiss, and protoclastic gneiss, with intercalated schist and amphibolite. The granitic gneiss structurally, and possibly stratigraphically, overlies a gently southeastward-dipping section consisting largely of quartzite (fig. 2) that is at least 2,100 m thick at Cottonwood Mountain (Blacet and Miller, 1978). The quartzite has relict sedimentary structures from which stratigraphic facing was obtained.

A small southwestern extension of the granitic gneiss as mapped by Blacet and Miller (1978) is continuous with the Laurel Canyon Granodiorite (Simons, 1964). The granodiorite as described by Simons is locally schistose and metamorphosed to the same degree as the Pinal Schist. We speculate it is a syntectonic pluton of the 1640-1615-Ma generation.

Gneiss in the southern Pinaleno Mountains has been intruded by at least five Proterozoic plutons, three of which have been dated by the Rb-Sr method at 1636 ± 14 Ma, 1384 ± 39 Ma, and 1405 ± 65 Ma (Swan, 1976). All the plutons are considered by Thorman (1981) to be of the 1400-Ma generation of regional anorogenic plutons, but this may be questioned because of the pervasive foliation in two of the plutons parallel to that in adjacent paragneiss. Possibly some of these plutonic rocks are of the 1640-1615-Ma generation.

Davis (1980) and Rehrig and Reynolds (1980) considered the Pinaleno Mountains block to be a metamorphic core complex. As such, it has a middle Tertiary mylonitic overprint that remains to be completely defined and distinguished from the Proterozoic metamporphism.

The Dos Cabezas Mountains

Progress has been made in recent years in mapping of the Pinal Schist in the Dos Cabezas Mountains (Erickson, 1968, 1969, 1981; Erickson and Drewes, 1984a, 1984b; Drewes, 1981, 1982, 1984, 1985, 1986; and Condie and others, 1985). Mapped stratified lithologies include feldspathic quartzite, arkose, conglomerate, quartzite, phyllite, and felsic volcanic rocks. Intrusive masses of rhyodacite and quartz porphyry are considered by Condie and others (1985) to be contemporaneous with the stratified rocks. Some amphibolite masses in the east-central part of the range are intrusive, but many others are metamorphosed basalt and dacite (P. Anderson, this volume). All these rocks were metamorphosed to greenschist facies (Erickson, 1981) or lower amphibolite facies (Condie and others, 1985)

The stratified and hypabyssal rocks occur in western, eastern, and southern (south of Apache Pass fault) parts of the mountains (Erickson, 1968 and fig. 2). Each area has a distinctive suite of rocks, so that no clear-cut correlation exists between them (Erickson, 1981, Condie and others, 1985). According to Erickson (1981), the stratified sequence in the western terrane is 10 km thick and composed of shale and admixed crystal tuff grading upward into a thick sequence of extrusive dacite and andesite. Minor amphibolite (sills or flows) and one thin limestone lens occur in the sequence. Condie and others (1985) considered the western terrane to be composed of approximately equal amounts of felsic volcanic and felsic hypabyssal (rhyodacite) rocks. The eastern and southern terranes, in contrast, are composed largely of sedimentary rocks. The 6-km-thick eastern section consists of pebble and cobble conglomerate overlain by arkose, overlain in turn by pelitic sedimentary rocks with minor interbedded flows (Erickson, 1968, 1981). This section also contains minor felsic volcanic and interbedded quartz arenite near its base (Condie and others, 1985). Drewes (1984) has mapped the eastern (upper?) part of the eastern terrane as containing about equal parts of phyllite and metavolcanic rocks and minor quartzite. The section is apparently upright and dips generally southward. The 3-km-thick section in the southern terrane is composed of quartzite (75%) and interbedded phyllite (25%) (Drewes, 1981, 1984; Erickson, 1981). The southern terrane is separated from the western and eastern terranes by the Apache Pass fault. Erickson (1985, written commun.)

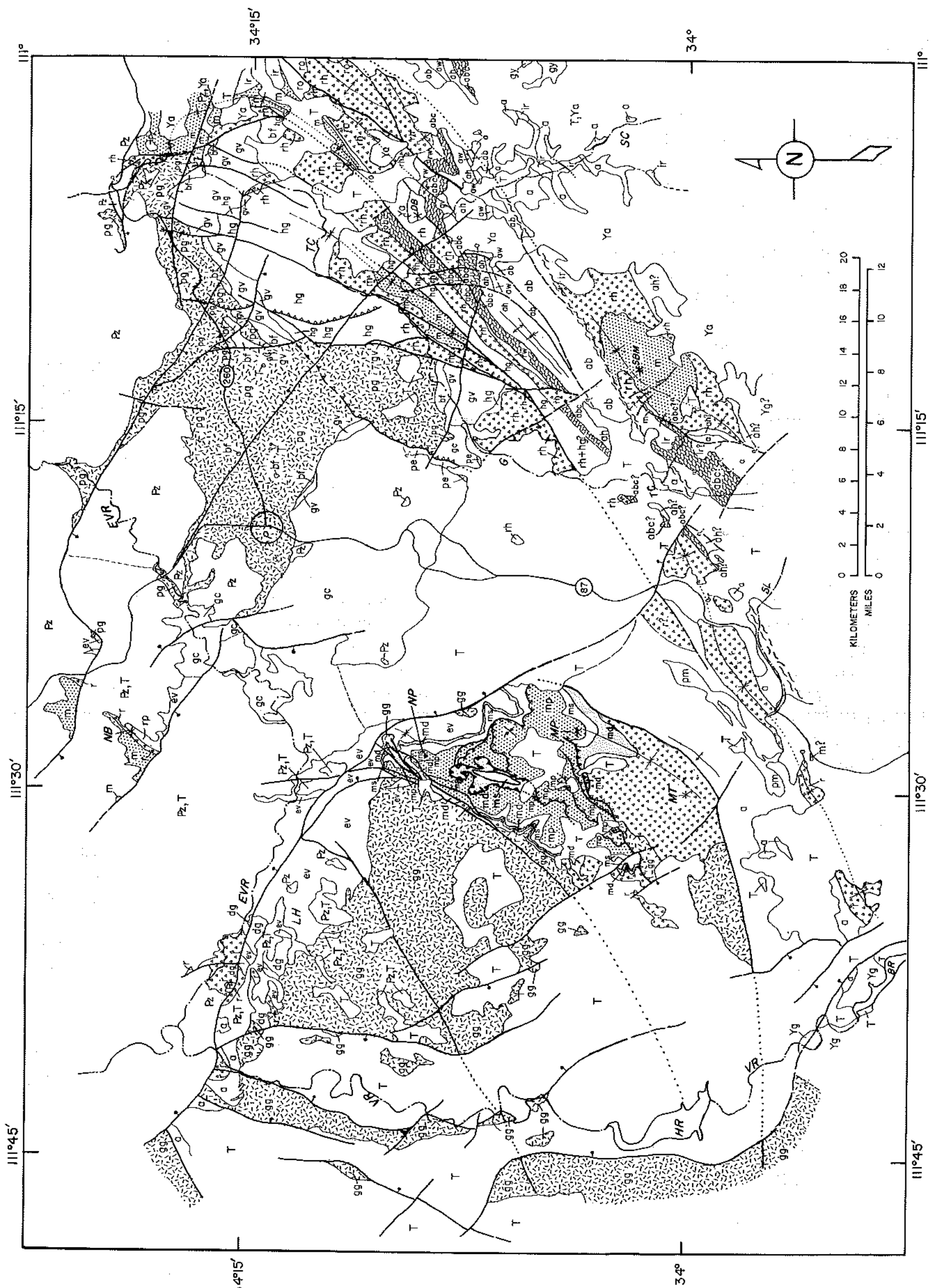
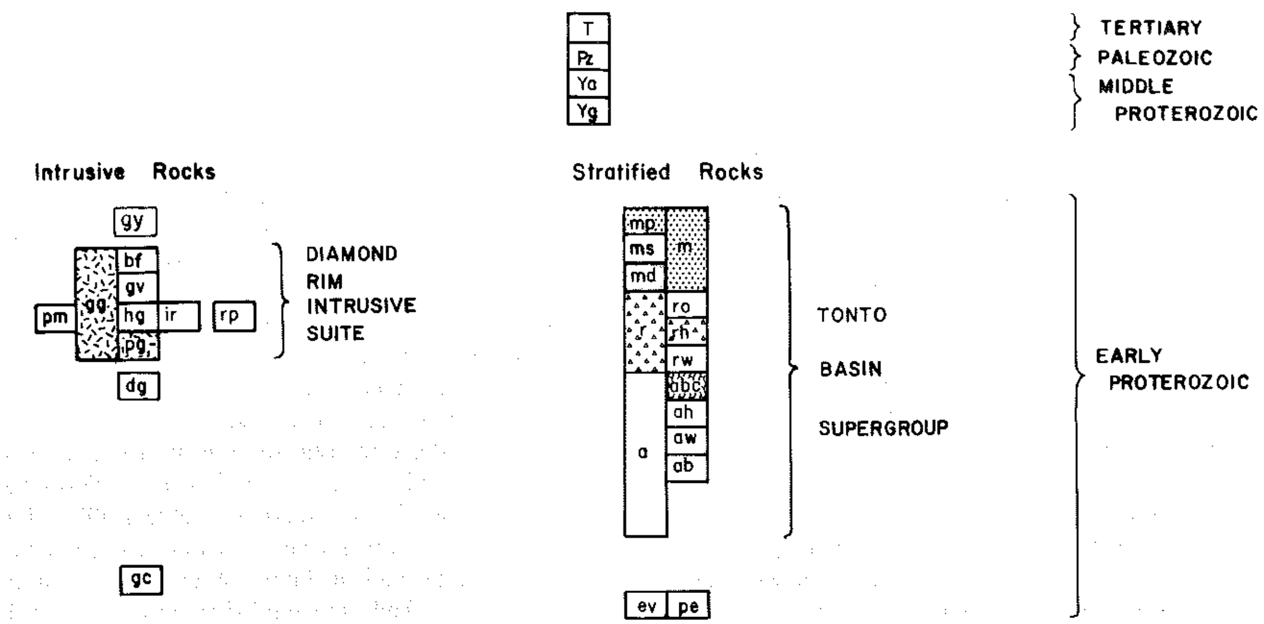


Figure 4. Generalized geologic map of the Tonto Basin-Mazatzal Mountains region, from T. Brady (unpublished mapping), Conway (1976; unpublished mapping), Gastil (1958), Ludwig (1974), Puls (1986), J. Roller (unpublished mapping), G. Weir (unpublished mapping), and Wrucke and Conway (1987). Geologic names used in this figure are from Conway and others, in press.

EXPLANATION



T Sedimentary and volcanic rocks (Tertiary)
P Sedimentary rocks (Paleozoic)
Ya Apache Group and diabase, undivided (Middle Proterozoic)
Yg Coarse porphyritic granite (Middle Proterozoic)

Early Proterozoic Intrusive Rocks

gy Granite near Young
gg Granite, granophyre, minor intrusive rhyolite. Broadly correlative with Payson Granite, Green Valley Hills Granophyre, and Hells Gate Rhyolite
bf Bear Flat Alaskite
gv Green Valley Hills porphyry
pm Pine Mountain Porphyry
hg Hells Gate Rhyolite
ir Intrusive rhyolite. May be correlative in part with Hells Gate Rhyolite
rp Rhyolite porphyry near Natural Bridge
pg Payson Granite
dg Diorite and gabbro in Limestone Hills
gc Gibson Creek batholith

Early Proterozoic Stratified Rocks

Mazatzal Group
mp Mazatzal Peak Quartzite
ms Maverick Shale
md Deadman Quartzite
m Undivided
Red Rock Group
ro Oxbow Mountain Rhyolite
rh Haigler Formation
rw Winter Camp Formation
r Undivided
Alder Group
abc Board Cabin Formation
ah Houion Formation
aw Flying W Formation
ab Breadpan Formation
a Undivided
ev East Verde River Formation
pe Pendants near Gisela

Fault, dashed where uncertain
Thrust fault, dashed where uncertain
Contact, dashed where uncertain
Syncline, overturned syncline
Anticline
Porphyritic granite dike related to unit Yg
Shear zone

Geographic place-names:
BR - Bartlett Reservoir
DB - Diamond Butte
G - Gisela
EVR - East Verde River
HR - Horseshoe Reservoir
LH - Limestone Hills
NB - Natural Bridge
NP - North Peak
MP - Mazatzal Peak
MT - Mt. Peeley
P - Payson
SL - Slate Creek
SC - Spring Creek
SBM - Sheep Basin Mountain
TC - Tonto Creek
VR - Verde River

considered the rocks of the southern terrane to contrast strongly with those to the north and suggested major lateral displacement on the Apache Pass fault.

No ages have been reported for the Pinal strata of the Dos Cabezas Mountains, but late-kinematic granitic bodies of the Dos Cabezas are 1625 Ma (Silver, 1978).

The thick section of arkosic sedimentary rocks in the eastern terrane, first described by Erickson (1968, 1969) and suggested to be largely of granitic provenance by Condie and others (1985) is anomalous in the Pinal Schist and Tonto Basin Supergroup. Granitic debris is known only in trace amounts in the White Ledges section (Trevena, 1979) and in the Johnny Lyon Hills (Silver, 1955). Arkosic rocks associated with quartzite and felsic volcanic rocks are common, however, in Early Proterozoic rocks of central to southern New Mexico (Condie and others, 1985; Condie and DeMalas, 1985).

Dragoon Quadrangle

Silver (1978) summarized the Proterozoic geology of Cochise County with emphasis on the reference section for the region in the Dragoon 15′ quadrangle. The Pinal Schist in the Dragoon quadrangle consists of shale, graywacke, sericite schist, metabasalt, and rhyolite flows metamorphosed at greenschist grade. From a systematic study in the Dragoon quadrangle of widespread and well-preserved graded bedding and small-scale deformational structures, a continuous section of the Pinal in the Johnny Lyon Hills was found to be approximately 2,500 m thick and possibly underlain by an additional 3,600 m in nearby areas of the Little Dragoon Mountains (Cooper and Silver, 1964). Hypabyssal felsic rocks cutting the Pinal are, at least in part, contemporaneous with the stratified volcanic rocks at 1700 to 1680 Ma (Silver, 1978, 1963). The Pinal Schist was deformed prior to the intrusion by the 1625-Ma Johnny Lyon Granodiorite and the granodiorite was then cut by north-northeast-trending shear zones.

The Pinal Schist of the Dragoon quadrangle is lithologically similar to and geochronologically indistinguishable from the type Pinal Schist in the Pinal Mountains and is likewise similar in lithology and in age, where dated, to many other exposures of the Pinal in southeastern Arizona (Silver, 1978). Eastern exposures of the Pinal (e.g., Dos Cabezas Mountains, Santa Teresa Mountains, White Ledges) differ in having a locally greater volcanic component, locally abundant arkose, and quartzite (Condie and others, 1985; Condie and DeMalas, 1985).

SEDIMENTATION, MAGMATISM, AND TECTONIC SETTING

The Pinal Schist and Tonto Basin Supergroup are characterized by an abundance of shaly quartz-rich graywacke and siltstone, felsic volcanic and volcaniclastic rocks, and quartz-rich arenites in the middle to upper parts of some sections. Conglomerate, usually of local derivation, for example, rhyolite-clast conglomerate associated with rhyolite flows, and intermediate to mafic volcanic rocks locally are abundant. Arkosic rocks are absent in TBMM and western exposures of the Pinal Schist. They are evidently common only in the Dos Cabezas, Chiricahua, and Dragoon Mountains (Copeland and Condie, 1986). Carbonate rocks are scarce. In TBMM, quartz arenite occurs almost entirely in the upper half (upper part of the Alder Group and the Mazatzal Group) of upward-shoaling and upward-maturing sections. Quartzite-shale-quartzite successions (Mazatzal Mountains, Tonto Basin, White Ledges) attest to two or more cycles in which a sea probably trangressed northward, then regressed. Paleocurrent data from quartzite in the Mazatzal Group and Hess Canyon Group at a number of localities (Trevena, 1979, 1981; Conway and others, 1981; Anderson and Wirth, 1981) document easterly to southwesterly transport directions. Transport directions from quartzites in the Dos Cabezas may also be southerly (Condie and others, 1985). Fluvial quartz arenites in the northern part of the region give way to fluvial, tidal, and offshore quartz arenites southward (Trevena, 1979; Anderson and Wirth, 1981). Coarse clastic detritus (coarse sandstone and conglomerate) is relatively common in the northern part of the region and uncommon to the south.

These regional relations indicate that a migrating north shore of the Pinal basin existed in what is now central to southeastern Arizona. Sediments may have been derived from the craton to the north, but perhaps mostly from erosion of local contemporaneous volcanic deposits. Sedimentation in the southerly, presumably deeper, parts of the basin was dominated by passive, still-water deposition and distal turbidity flow. Late in the history of basin filling, particularly to the north, deposition of remarkably thick sections of mature quartz sand dominated.

Condie and DeMalas (1985) and Copeland and Condie (1986) emphasized the absence of quartzite and arkose and paucity of volcanic rocks in the Pinal Schist of the Pinal Mountains, Dragoon quadrangle, and surrounding region in contrast with an easterly belt of the Pinal in the Dos Cabezas Mountains, Santa Teresa Mountains, White Ledges, and possibly TBMM. Although recognizing variations (some systematic) in Pinal strata we consider the age control and sedimentological systematics, as described above, to support our model of a large basin or closely related system of contemporaneous basins. The absence of quartzite to the west may be due to nondeposition of quartz arenite as a function of variation in drainage or basin geometry or to erosion of higher level strata in Proterozoic time.

We suggest that, regionally, shorelines trended generally northeastward, and that facies changes in northeastward to eastward directions (Condie and DeMalas, 1985) may relate in part to high ground at felsic magmatic centers and (or) local uplift. This is in general agreement with Copeland and Condie (1986) who suggested that the western assemblage of Pinal Schist was deposited in a basin at the

southwestern termination of a regionally northeast-trending felsic arc that includes the eastern Pinal assemblage. They suggest that the western assemblage accumulated in an intra-arc basin, or preferably, in a northwest-trending aulacogen.

The absence of arkosic (granitic) detritus in the TBMM area and its abundance in the Dos Cabezas Mountains, farther removed from the most logical source area, the older craton (1710- to 1775-Ma rocks in central to northwestern Arizona) to the northwest, are intriguing. An explanation may lie in the possibility that high-level granitic bodies contemporaneous with felsic volcanism (in the Dos Cabezas region?) were exposed to erosion within a few million years of formation and thus became local sources for the arkose. Another explanation, perhaps less likely, is that basement granite of an older orogenic terrane was exposed in the Dos Cabezas region or elsewhere. It may have been older continental basement that, in the extreme case, could have been entirely rifted away to form an ocean basin. Thus the Pinal basin would have begun as a continental rift basin and the major rifting, which exposed granite to erosion, would have been at an unknown site to the south. The absence of granitic debris to the north would be explained by lack of major rift faulting and the enormous thickness of the clean nearshore quartzite would be explained by gradual regional subsidence associated with the rifting.

Thin, sparse beds of granitic detritus occur in the Hess Canyon Group (Trevena, 1979). These are beds of coarse, immature, K-feldspar- and quartz-rich arkose from a few centimeters to several meters in thickness interbedded with dark-gray shale and siltstone in the middle part of the Yankee Joe Formation. Paleocurrent data in the quartzite of the Hess Canyon Group indicate a northerly source, yet in extensive mapping of the Tonto Basin Supergroup to the north the senior author has not observed granitic detritus. The granitic debris in the Yankee Joe Formation may have had a different provenance than the northward-derived quartz-rich sandstone of the Hess Canyon Group. A possible source area, with no specific units as candidates, is between the White Ledges and the Dos Cabezas, because Condie and others (1985) suggested the arkose in the Dos Cabezas was derived from the north.

A major conclusion from analysis of sedimentation is that, whatever the problems in basin reconstruction, the thick quartz arenite successions are fundamentally of continent-margin character (Trevena, 1979; Conway and others, 1981; Conway and Silver, 1984). These rocks were deposited in a continental environment, but one of crustal unrest. Whether the depositional basin was throughout its history a passive continental margin or a large interior continental basin, or first a continental rift basin that opened to form a new ocean basin are alternatives to be explored.

Volcanic activity was unevenly distributed in the Pinal basin(s). Large felsic volcanic centers were perhaps numerous and may have formed a magmatic arc or chain along the northern basin margin in the TBMM and New River Mountains region. This arc extended into north-central New Mexico (Silver, 1984; Silver and others, 1986). In the Pinal Schist outcrop region a felsic magmatic center was apparently located at the present site of the Dos Cabezas Mountains.

Felsic magmatism in the TBMM was broadly contemporaneous with quartz arenite deposition in the upper part of the Alder Group and the Mazatzal Group. Early volcanism (Alder Group) may have been mostly in shallow seas but the later thick volcanic sections (Red Rock Group) were deposited largely subaerially (Gastil, 1958; Conway, 1976). These were apparently subaerial ash-flow tuff caldera fields of the type widespread in the Tertiary volcanic fields of the western United States. Widespread contemporaneous granophyre and granite are the hypabyssal products of this magmatism. An important feature of these felsic igneous rocks is their silicic, alkali-calcic composition. They are typical of so-called alkali rhyolites or high-silica rhyolites that have been documented worldwide in Phanerozoic tracts that have formed only in continental crust, either in rift environments or above hotspots, and commonly in bimodal association with lesser quantities of basalt (Ewart, 1979; Christiansen and Lipman, 1972; Hildreth, 1981). For example, the chemical and petrographic similarities of the TBMM suite to rhyolite of the Yellowstone Plateau is remarkable (Conway, 1976; Conway and Silver, 1976). Given the association with quartz arenite, the argument is compelling that the high-silica magmas of TBMM are of continental derivation, and the regional geologic relations discussed above suggest a continental-margin site. This is further supported by trace-element abundances indicative of magma origin in continental crust (Conway and Nealey, 1987; Nealey and Conway, 1987). Similarly, trace elements in the Dos Cabezas igneous rocks (Condie and others, 1985) and elsewhere in the central to southeastern Arizona 1710-1675-Ma terrane support an origin "in or near continental crust or in continental-margin arcs" (Condie, 1986).

Identification of the continental crustal material on which the 1710-1675-Ma suites were developed is a problem beyond the scope of this paper. Our preferred working hypothesis is that the basement consisted of a terrane only some 30 to 60 million years older, which would include the Gibson Creek batholith and the East Verde River Formation in TBMM and the Yavapai Series and associated batholiths to the northwest. This idea has been developed more extensively elsewhere (Conway and others, 1987), and alternative models were given by P. Anderson (1986, this volume) and Karlstrom and others (1987).

MAZATZAL OROGENY

Unifying stratigraphic and deformational characteristics and consistent narrow age intervals of stratified and late-tectonic to posttectonic plutonic rocks permit the hypothesis that a single major orogenic event occurred in

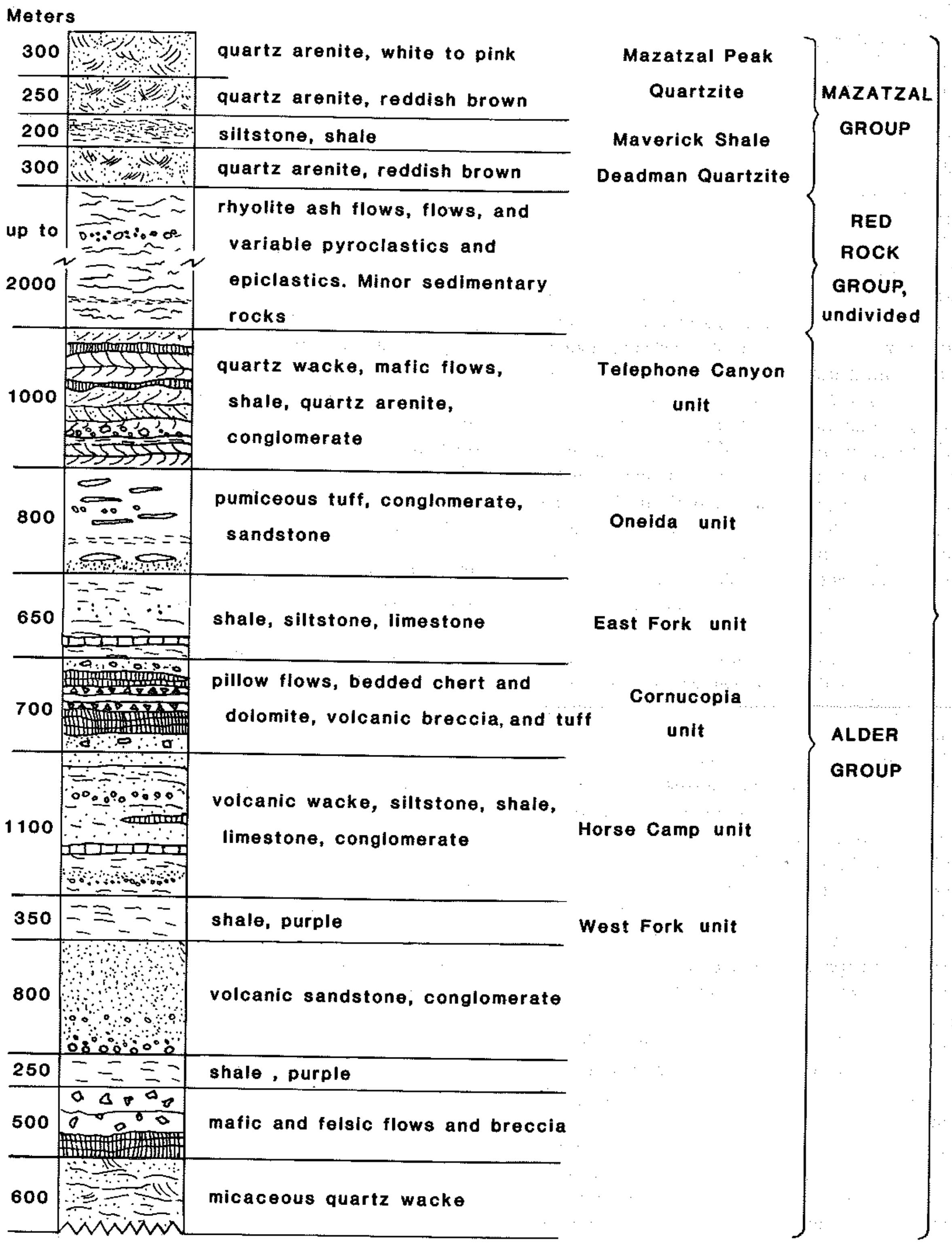


Figure 5. Stratigraphic columns for the Tonto Basin Supergroup (Conway and others, in press) in the Mazatzal Mountains and in Tonto Basin, largely from Conway (1976), Gastil (1958), Ludwig (1974), and Wrucke and Conway (1987). The informal names for units in the Alder Group in the Mazatzal Mountains are from Ludwig (1974).

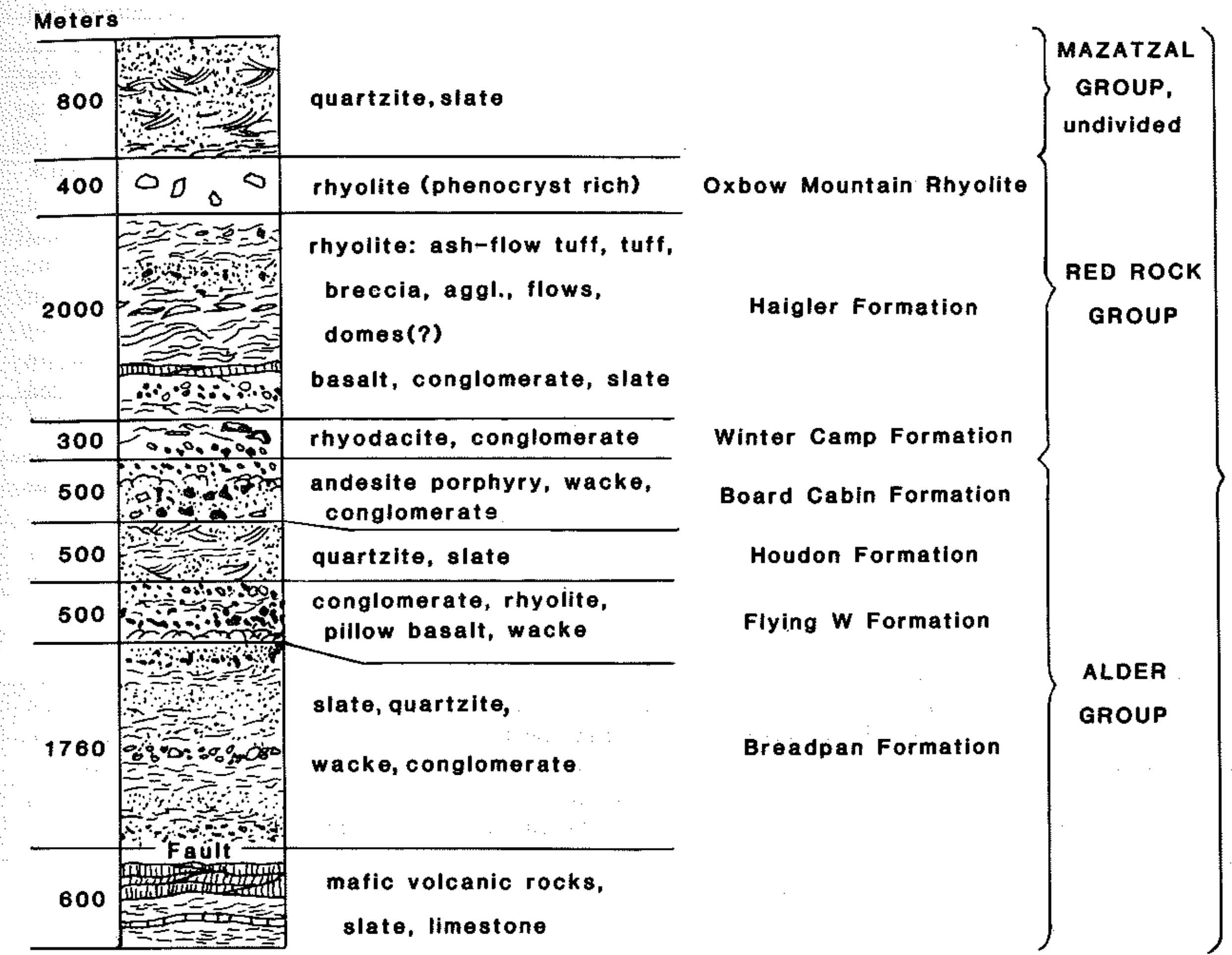


Figure 5. (continued)

central to southeastern Arizona in the interval 1675-1625 Ma, following deposition of the Tonto Basin Supergroup and the Pinal Schist. This is not precluded by evidence for polyphase deformation (Conway, 1976; Erickson, 1969; Condie and others, 1985; and Roller and Karlstrom, 1986), which may be interpreted as evidence of changing stress regime in a prolonged period of orogeny. The geologic units north of the Moore Gulch fault that are discussed in this paper, the Crazy Basin Quartz Monzonite and the Texas Gulch Formation, may have been affected by earlier events (Karlstrom and others, 1987).

In spite of past confusion in definition of the term "Mazatzal orogeny" (Silver, 1978), this long-familiar name (Wilson, 1939) is most appropriate for the singular, widespread post-1675-Ma event, the effects of which may be variable and extend beyond the region discussed here. In central to southeastern Arizona, including the type area in the Mazatzal Mountains, consistent 1710-1675-Ma ages for predeformation volcanic rocks and 1640-1615-Ma ages for late-tectonic to posttectonic plutonic rocks appear to bracket the orogeny between 1675 and about 1625 Ma (Silver, 1978).

We currently view the Mazatzal orogeny as being primarily deformation of a continent margin (or possibly continent interior) with principal compressive stress vectors oriented approximately southeast-northwest (in present coordinates). At present, we are unable to attribute the compression to a particular cause, e.g., plate interactions of some sort.

In the TBMM area, the effects of the orogeny are seen primarily as foreland thrusting and folding and development of a northeast-striking steep foliation. The supracrustal strata were thrust northwestward and folded to form generally shallow-plunging, northeast-trending fold axes and steep dipping axial surfaces (fig. 4; Wilson, 1939; Ludwig, 1974; Conway, 1976; Karlstrom and Puls, 1984; Karlstrom and Conway, 1986; Conway and others, 1987; Wrucke and Conway, 1987). The style of deformation in the

Tonto Basin Supergroup is to a considerable extent a function of competency. That the thick, massive units (i.e., quartzite and rhyolite) are high in the succession is also important. Incompetent, generally stratigraphically lower strata tend to be isoclinally folded, highly foliated, and penetratively deformed. Transposition features are common only locally. Competent, generally stratigraphically higher strata tend to be openly folded and weakly foliated. They are commonly devoid of salient deformation at outcrop scale. In places, the thick competent beds of the Red Rock and Mazatzal Groups may be decoupled, primarily on bedding-plane faults related to thrusting, from isoclinally folded underlying shaly rocks of the Alder Group.

Throughout the TBMM region, lineation expressed as mineral streaking, clast elongation, and amygdule elongation is largely subvertical in plunge and thus roughly normal to major fold axes. Minor folds in incompetent strata, presumably originally subhorizontal satellitic folds, are subhorizontal to subvertical. The variation in orientation may be due to variable strain rotation (Roller and Karlstrom, 1986).

Structural data are sparse for the Pinal Schist. The general structural grain is similar to that in the Tonto Basin Supergroup, and shallow-plunging major fold axes and steep lineations may predominate. In contrast, Silver (1955) postulated a major steep-plunging fold parallel to observed steep lineations and minor fold axes in the Johnny Lyon Hills.

Brittle deformation (open-space fault breccia) on some thrust and transcurrent faults and low-grade metamorphism in the TBMM region suggest relatively shallow crustal depths. However, the greenschist metamorphism documented in the Alder Group (Gastil, 1958; Ludwig, 1974; Conway, 1976) requires burial of at least 8 km (Turner, 1981) which suggests that either additional conformable strata above the Tonto Basin Supergroup or tectonically emplaced rocks have been eroded away.

A set of northeast- to north-trending, commonly arcuate, steep-dipping faults, widespread in central Arizona and best documented in the TBMM area (fig. 4; Conway, 1976), appears to postdate the folding and thrusting of the Mazatzal orogeny. It is uncertain whether these faults should be considered a final manifestation of the Mazatzal event or the result of a completely separate, possibly much later, Proterozoic event (Conway and others, 1982). These faults exhibit both normal offset and left-lateral offset and commonly have graben slices along north-trending segments. They may have formed in response to a regional left-lateral shear stress with faults distributed over a broad region in the crust.

The compressional deformation of the Mazatzal orogeny and the subsequent normal to transcurrent faulting were necessarily imposed on the continental substrate to the 1710-1675-Ma strata and associated hypabyssal rocks. This substrate, by our hypothesis, would include the Gibson Creek batholith, the East Verde River Formation, and probably the Yavapai Series and associated calc-alkaline batholiths (DeWitt, this volume). Structures of the Mazatzal orogeny should thus be found superimposed on any structures that developed during earlier tectonic assembly of the continental basement terrane. There are several possible examples of this. The East Verde River Formation may have been folded and eroded prior to deposition of upper parts of the undivided Red Rock Group and the Mazatzal Group in the northern Mazatzal Mountains and at Natural Bridge (fig. 4; Conway and others, 1987; Wrucke and Conway, 1987). Granodiorite clasts in probably 1700-Ma strata near Brooklyn Peak in the New River Mountains (see P. Anderson, this volume) were possibly derived from calc-alkaline granodiorite bodies to the north. We suggest this implies deep-seated erosion and hence deformation of the terrane consisting of the Yavapai Series and associated batholiths. Should the Texas Gulch Formation be equivalent in age to the Tonto Basin Supergroup (P. Anderson, this volume) its deformation but perhaps only part of the deformation of the unconformably underlying Yavapai Series rocks and Brady Butte Granodiorite could be attributed to the Mazatzal orogeny.

These cases are all controversial, particularly the latter. Karlstrom (see Karlstrom and Conway, 1986, and Karlstrom and others, 1987) argued that the deformation style and metamorphic grade of the Texas Gulch Formation are incompatible with deformation in the Mazatzal orogeny, and that the deformation occured between 1740 and 1700 Ma (F_1) and at 1700 (F_2).

CONCLUSIONS

1. The 1710-1675-Ma stratified rocks and associated hypabyssal rocks in central to southeastern Arizona were deposited in the Pinal basin, a basin or group of temporally related basins with shorelines to the north in central Arizona.

2. The thick graywacke-shale successions characterizing much of the Pinal Schist were deposited in southerly deep parts of the Pinal basin mostly by distal turbidity processes.

3. The thick quartz arenite sections, mostly in the Tonto Basin Supergroup, were deposited in northerly parts of the Pinal basin during intervals of extensive epeirogenic activity.

4. Sedimentary strata of the upper part of the Tonto Basin Supergroup constitute a fluvial (southeastward transport) to shallow-marine sequence deposited on the southern margin of an Early Proterozoic continental nucleus or in a major continental interior basin (rifted craton?).

5. The felsic magmatic suites of the Tonto Basin Supergroup and Diamond Rim Intrusive Suite are continental suites, probably derived by partial melting of continental crust. Locally abundant felsic volcanic rocks in the Pinal Schist are of similar origin. Felsic magmatism that produced these rocks was broadly contemporaneous with quartz arenite sedimentation.

6. The continental crustal substrate to the 1710-1675-Ma rocks may have been newly cratonized materials, including the Gibson Creek batholith, East Verde River Formation, Yavapai Series, and batholiths widespread in the Jerome-Prescott region.

7. Sedimentation and magmatism in the Pinal basin may have been terminated by the onset of the Mazatzal orogeny. This deformational episode resulted in northwest-directed thrusting and folding in the Tonto Basin-Mazatzal Mountains region and a regional fabric characterized by subvertical foliation and open to tight, northeast-trending, generally shallow-plunging major folds. This deformation appears to have occurred in the interval 1675-1625 Ma.

8. Syntectonic to posttectonic granitic bodies were emplaced throughout the orogen in the interval 1640-1615 Ma.

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