

**GEOLOGIC FIELD GUIDE  
TO THE PHOENIX MOUNTAINS,  
CENTRAL ARIZONA**

by

**Julia K. Johnson and Stephen J. Reynolds**

**Guidebook for the Arizona Geological Society  
Spring Field Trip  
Saturday, April 20, 2002**



**Field Trip Leaders  
J. K Johnson and S. J. Reynolds**

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# Geologic field guide to the Phoenix Mountains, central Arizona

Julia K. Johnson and Stephen J. Reynolds  
Department of Geological Sciences  
Arizona State University  
Tempe, Arizona 85287

20 April 2002

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Dear Field Trip Participant,

Welcome to the Arizona Geological Society 2002 Spring Field Trip led by Steve Reynolds and Julia Johnson of Arizona State University. We will be looking at Proterozoic metasedimentary and metavolcanic rocks in the Dreamy Draw and Squaw Peak areas of the Phoenix Mountains. These areas are located in the Phoenix Mountains Preserve and Squaw Peak Recreation Area so we are encouraged to stay on trails and discouraged from banging on rocks. (Please leave your rock hammers in your vehicles.)

Dr. Stephen J. Reynolds is Professor of Geology at Arizona State University. After receiving his Ph.D. from the University of Arizona, Steve spent 10 years directing the geologic framework and mapping program at the Arizona Geological Survey. He has completed more than 100 published geologic maps, articles, and reports, including the 1988 *Geologic Map of Arizona* and AGS Digest 17, *Geologic Evolution of Arizona*. Since arriving at ASU, Steve and his students have mapped many of the mountain ranges around Phoenix and elsewhere in central and western Arizona. He is also coauthor of the widely used textbook *Structural Geology of Rocks and Regions*. At ASU, he is known for his innovative teaching methods and award-winning website, and has received numerous teaching awards.

Julia K. Johnson received her B.S. and M.S. degrees in geology from Arizona State University. For her M.S. thesis, she mapped all of the Phoenix Mountains, except for a previously mapped area around Squaw Peak. She compiled a geologic map of the entire Phoenix Mountains (planned to be released with the Arizona Geological Survey). She is a coauthor of *Observing and Interpreting Geology, a Laboratory Manual for Introduction to Geology*, along with Dr. Stephen Reynolds. She helped create various websites, including the Arizona Geology 3D site (<http://reynolds.asu.edu/azgeo3d>). She has worked in industry, taught geology classes at several community colleges, and is currently employed by the Department of Geological Sciences at ASU as a visualization and curriculum developer. Her geologic mapping in the Phoenix Mountains was supported by an AGS Courtright Scholarship and a USGS EDMAP contract.

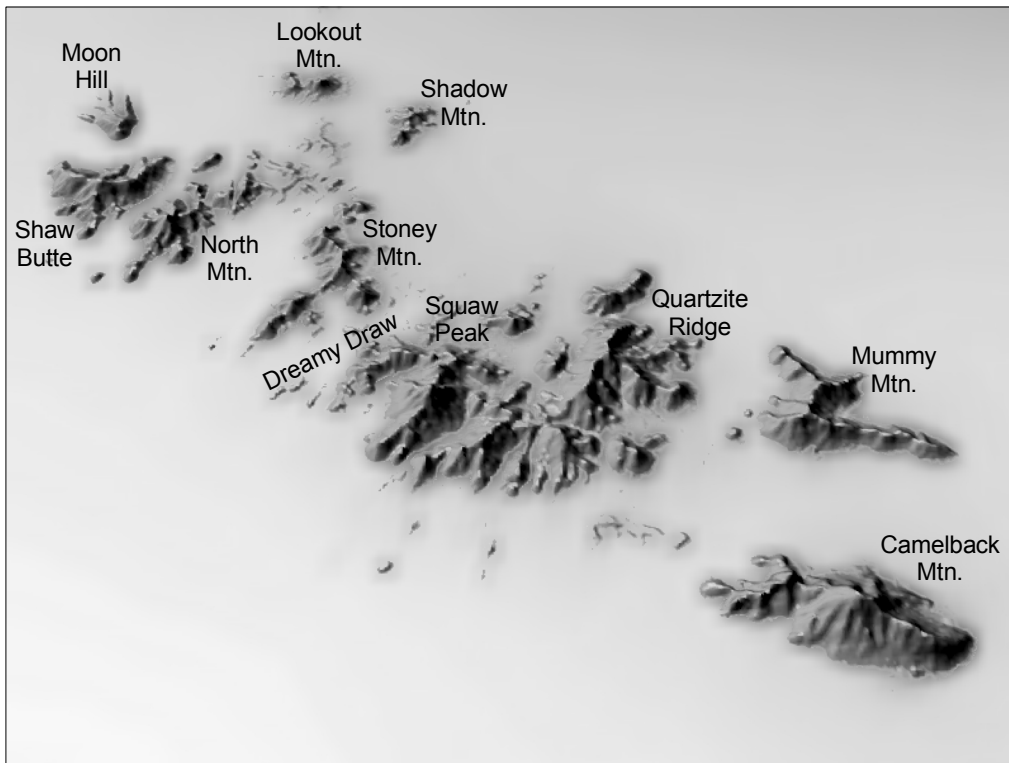
I would like to extend the appreciation of the Arizona Geological Society to Steve Reynolds and Julia Johnson for taking the time to prepare and lead this trip. Also, special thanks to Cori Hoag for her tireless assistance with logistical matters. Thank you for coming and enjoy the trip!

**Driving Directions:** Meeting location is Dreamy Draw Recreation Area. From Tucson, take I-10 to Phoenix. At the well-marked freeway interchange, proceed north on SR-51 (Squaw Peak Parkway). Take the Northern Avenue exit and turn right (east) on Northern into the Dreamy Draw Park parking area (~1/2 mile). If there is freeway construction, you may also continue on I-10 to I-17, take I-17 north to Northern Avenue, and proceed east on Northern until it ends at the park.

David Maher, VP Field Trips, Arizona Geological Society

**Overview:** The Phoenix Mountains are an isolated range within the rapidly expanding Phoenix metropolitan area of central Arizona (Fig. 1). The range contains two distinct sequences of Proterozoic rocks, separated by a north-northeast-trending fault or shear zone in the center of the range. The oldest Proterozoic rocks are greenstones exposed west of the fault, in the northwestern part of the range. These were originally intermediate volcanic and intrusive rocks interbedded with ferruginous quartzite and metasilstone. This sequence is interpreted as oceanic in origin and is correlated with the Union Hills Group. East of the fault, the rocks are more continental and include quartzite, phyllite, and rhyolite, repeated by several large folds. Rhyolite and quartzite, near Squaw Peak, have been correlated with the Red Rock Group and Mazatzal Group, respectively. The remaining rocks are more likely equivalent to the Alder Group. Proterozoic structures include northeast-striking, steeply southeast-dipping cleavage and several large, steeply plunging isoclinal folds at Squaw Peak and east of Squaw Peak. The Squaw Peak fault or shear zone juxtaposes dissimilar sequences near Squaw Peak.

In this trip we will examine various Proterozoic rocks and structures near Dreamy Draw Park, accessed from Northern Avenue and SR51 (Squaw Peak Parkway). In the morning, we will traverse a circuit along park trails northwest of Dreamy Draw Park and SR51. In this traverse, we will examine the transition from oceanic lithologies, including greenstones and ferruginous quartzites, to more continental ones, including phyllite and orthoquartzite. In the early afternoon, we will complete another circuit along park trails to the east toward Squaw Peak. This traverse will largely be across more continental lithologies, such as quartzites, conglomeratic quartzites, stretched-pebble conglomerates, and, time permitting, metarhyolites and related quartz-kyanite rocks.



**Figure 1. Three-dimensional perspective of the Phoenix Mountains, looking north.**

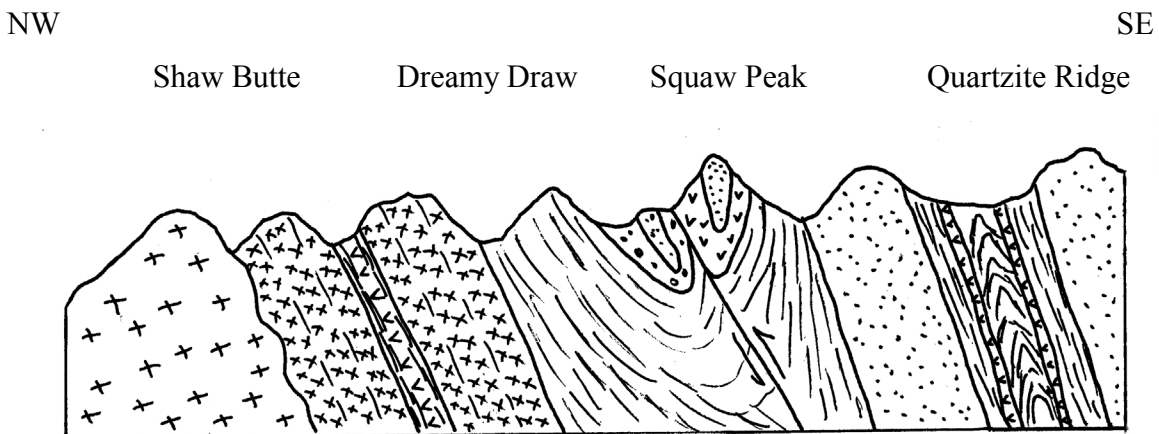
## Location and Physiography

The Phoenix Mountains include a main range, with 420 m (1,378 ft) of local relief, as well as two smaller ranges, several isolated peaks, and piedmonts of coalescing alluvial fans. The range is a northwest-trending, uplifted fault block that extends for about 12.8 km (8 miles) from Moon Hill in the northwest to Camelback Mountain in the southeast (Fig. 1). How the rock units are expressed in the northwest part of the range differs markedly from how they are expressed in the southeast. The dominant feature of the southeastern part of the range is the nearly vertical manner in which the rock layers cross the landscape. In contrast, flat-lying or very gently tilted layers of basalt cap isolated hills in the northwest.

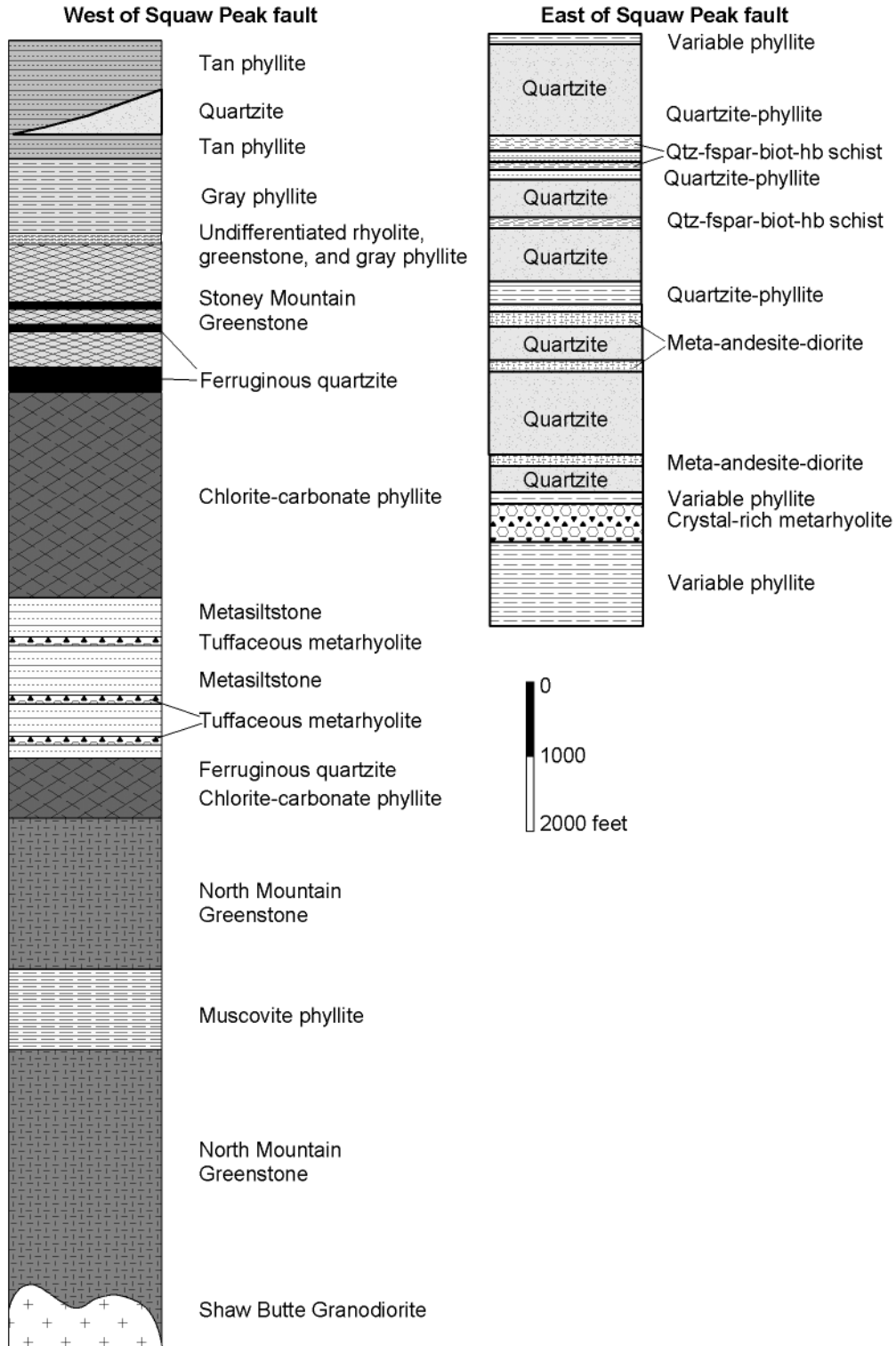
## Geology of the Phoenix Mountains

The northwest-trending Phoenix Mountains are composed of Proterozoic and Tertiary bedrock surrounded by Quaternary alluvium (see geologic map on last page of guidebook). The Proterozoic rocks are low-grade metavolcanic and metasedimentary rocks that mostly dip steeply to the southeast (Fig. 2) and strike approximately N30°E; they locally are intruded by diabase dikes. In the northwest portion of the range, the rocks are generally of submarine origin and contain greenstone intermixed with ferruginous quartzite, as well as meta-mudstone high in the stratigraphic sequence (Fig. 3). Rocks that are more continental, including abundant sandy quartzite, conglomeratic quartzite, tuffaceous phyllite, and metarhyolite dominate the southeast part of the range.

The Tertiary rocks include conglomerates and flat-lying or gently tilted basalt flows and basalt breccias. Tertiary basalt crops out in low hills at the far northwest end of the range. Basin-fill sediments are overlain by relatively flat-lying Quaternary surficial deposits that surround the range and were deposited nonconformably over all rock types in the area.



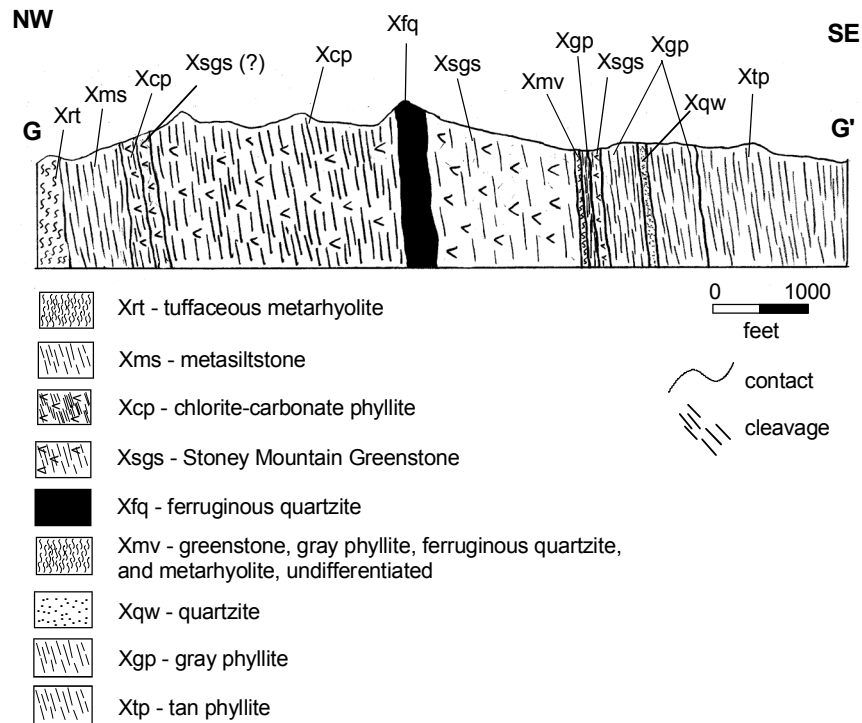
**Figure 2. Schematic cross section across the Phoenix Mountains (from Johnson, 2000).**



**Figure 3. Stratigraphic sections for areas west and east of the Squaw Peak fault (from Johnson, 2000). Highest parts of the section east of the fault, such as rhyolite and quartzite mapped by Jones (1996), are not shown.**

## Geology of the Dreamy Draw Area

The Dreamy Draw area straddles the Squaw Peak Parkway (SR51). It is composed mostly of gray and tan phyllite, but also includes a bed of metamorphosed pure quartz sandstone. This area may represent the transition from a more oceanic setting to a more continental setting, as evidenced by the discontinuation up section of ferruginous quartzite and greenstone and the first occurrence of a continental quartzite (Fig. 4).



**Figure 4. Cross section of Stoney Mountain North and Dreamy Draw (from Johnson, 2000). Dips are less steep than shown in this partially exaggerated section.**

## Geology of Squaw Peak Park

Squaw Peak Park includes Squaw Peak, the highest peak in the range, with an elevation of 782 m (2608 ft.) above sea level. Jones (1996) identified a large, northeast-striking reverse fault to the west of Squaw Peak (Fig. 2). North of Squaw Peak, this feature is more a shear zone than a discrete fault surface. Rock units on either side of the fault or shear zone cannot be correlated and commonly face in opposite directions. To the north and northwest, the rocks reflect a more oceanic to somewhat continental setting, including phyllite, greenschist, and conglomeratic quartzite. Rock units east of the fault consist of continental material, including cross-bedded quartzite, metarhyolite, and metamorphosed tuff breccia. A large northeast-plunging syncline at Squaw Peak (Jones, 1996) contains rocks that have been correlated to those of the Red Rock Group and Mazatzal Group.



## Rock Units

Proterozoic rocks in the Phoenix Mountains have been subdivided into a number of mappable units by Jones (1996), Johnson (2000), and Johnson, Reynolds, and Jones (in preparation), and many units have been assigned formal stratigraphic names (Fig. 3). Names and rock descriptions are included below for the main rock units and are summarized from Johnson (2000). Rock units are described from northwest to southeast, or from older to youngest.

### *Stoney Mountain Greenstone (Xsgs)*

This unit is a thick package of greenstones of variable composition intermixed with ferruginous quartzite. It is named the *Stoney Mountain Greenstone* for excellent exposures on Stoney Mountain. Down section it is in depositional contact with a large belt of ferruginous quartzite intermixed with greenstone; up section it is in contact with a mix of quartzite, gray phyllite, and metarhyolite that more or less define the transition across a mostly oceanic environment to a more continental one. In outcrop, these greenstones exhibit a distinctive green cast, usually accompanied by thick, dark bands of ferruginous quartzite. Textural variation is common throughout the unit, but can be divided into two broad components, each with a more or less gradational transition: a dacitic-andesitic component that contains most of the ferruginous quartzite, and an andesitic component.

The Stoney Mountain Greenstone unit is interpreted to be of submarine volcanic origin. The original composition of the volcanics probably varied between andesitic and dacitic, as suggested by the essentially green color of the unit and chloritic to biotitic matrix. The abundance of ferruginous quartzite throughout the unit, whose origin is probably related to submarine hot-spring activity, supports this interpretation.

It is unclear at the time if the tan color variation across the unit is due to initial composition, some kind of weathering phenomenon or, more likely, related to hydrothermal alteration in association with the ferruginous quartzite. Certainly, the unit is greener when there is less ferruginous quartzite.

### *Ferruginous Quartzite (Xfq)*

Ferruginous quartzite is widely exposed on ridges and hillsides in a thick zone interbedded with metavolcanic rocks, mostly andesitic to dacitic greenstones. The zone trends northeast through the Stoney Mountain North and Stoney Mountain South portion of the Phoenix Mountains. Individually recognizable beds are commonly from 5 to 10 m (16 to 33 ft) thick, and hundreds of meters in strike length. Small zones of isoclinal folding have produced thicker sequences along several ridges. From a distance, these layers can be identified as dark-colored bands tracing through hills of greenstone. A large, distinctive belt of ferruginous quartzite intermixed with greenstone traces across the landscape and has been mapped as a single unit. Individual beds that are more discontinuous have been mapped as separate units.

This unit consists of varying amounts of Fe-oxide, both magnetite and hematite, intermixed with layers and beds of banded chert or quartz producing a color range from red to dark gray. These beds of ferruginous quartzite are finely crystalline, homogenous, massive, and dense. Generally, the unit is highly resistant to weathering and creates

ridges that protrude out from the surrounding rock. Some areas, however, have been broken down into talus, and seldom do you find beds that track across washes. The talus is usually covered with abundant carbonate. The rocks are somewhat magnetic, but the degree of magnetism varies greatly. Alternating colors of dark rusty red with black to steel gray are probably due to minor oxidation of Fe-oxide minerals. A weak north-northeast cleavage is present throughout the exposures.

Some areas of the unit contain beautiful fold structures with interlimb angles that vary between tight isoclinal to open. The plunge of the hinge lines is mostly steep. Looking down the hinge, most folds are Z-shaped. Some folds have small amplitudes that make the bedding wavy across short distances. Generally, the folds are local and small scale, but some have wavelengths up to 1 m. These folds are commonly accompanied on their outer edge by quartz veins or chert beds.

These ferruginous quartzites are most likely to have been formed by the chemical precipitation of very fine-grained iron and silica in a submarine hot springs environment near a volcanic arc setting or upwelling of heated ocean water. It is difficult to determine if they formed near or distal from the extrusive center, but generally iron oxide and silicate facies are intermediate in distance. There are several stratigraphic intervals of ferruginous quartzite layers within the Phoenix Mountains, which suggests several cycles of hydrothermal activity.

*Greenstone, Gray Phyllite, Ferruginous Quartzite, Metarhyolite, Undifferentiated (Xmv)*

A low pass separating mountain peaks north of the Dreamy Draw area contains a narrow strip of bedrock with a mixed volcanic package consisting of four dominant lithologies too thin to be mapped separately. The stratigraphically lowest unit is gray phyllite, overlain by greenstone. Ferruginous quartzite, which is intermixed with the gray phyllite and greenstone is overlain by a tan, silicified, metarhyolite.

The thin gray phyllite is cleaved but nonbedded, and has a volcanic-lithic aspect. The overlying greenstone is comparable in composition to the andesitic greenstone in Stoney Mountain. Mixed with this gray phyllite and greenstone is a cherty ferruginous quartzite. The overlying metarhyolite is finely crystalline, tan, and composed mostly of quartz and mica.

*Quartzite (Xqw)*

The stratigraphically lowest quartzite in the section crops out just northwest of the Squaw Peak Parkway in the Dreamy Draw area. Low-relief hills, surrounded by alluvium, are composed of both quartzite and a volcanic-lithic gray phyllite. A few isolated knobs protruding through the alluvium are pure quartzite, much of which has been reduced to boulders. The soil surrounding these hills is reddish tan. A thin lens of quartzite on the northeast side of the hill, is isolated from the main outcrop.

This light gray-green to pale purple quartzite consists of nearly 98% quartz grains. The isolated lens of quartzite is more pinkish-orange and micaceous. Some opaque minerals, probably magnetite, are present and tend to be concentrated in dark laminae that define bedding and cross bedding. It is a mature quartzite, well sorted, medium to fine grained, with subtle bedding features. There are a few cross-bed sets, about 3 cm thick, that indicate that the top of the unit is to the southeast and the original flow was to

the northeast in present orientations. The cleavage is poorly developed throughout the unit. Several fractures are filled with quartz, some as large as 10 cm. The quartzite on the northeast side of the valley contains coarse sandstone with local grit.

The mature nature of this quartzite and the small cross-bed sets seem to suggest that this sandstone may have originally been beach sand. This quartzite, because of its pure nature, may represent onset of a more continental environment.

#### *Gray Phyllite (Xgp)*

This unit is northwest of the Squaw Peak Parkway at Dreamy Draw. It is in contact with a tan phyllite up section; down section it is in contact with a narrow greenstone belt. The contact between the gray and tan phyllite is gradational, but is defined mostly by a spotted, gray-white-black metaconglomerate marker unit with a volcanic-lithic aspect. A gray phyllite of nearly the same composition, but separated from the main body by a greenstone belt comes in contact with quartzite further down section. The entire unit is approximately 330 m thick, and the composition varies greatly. A prominent feature is the distinct compositional layering seen at outcrop scale. Cleavage changes direction throughout the unit, but generally both the layering and cleavage dip steeply and strike northeast.

Although this unit varies greatly in composition, some generalizations can be made about its characteristics. The unit is rhythmically bedded, alternating between thin sandy beds and gray phyllite. The sandy beds are not micaceous and do not have a strongly developed cleavage. The gray phyllite is mostly fine grained with well-developed cleavage. It locally contains large red jasper clasts derived from ferruginous quartzite, quartz clasts, and fine-grained white clasts, possibly representing original pumice or tuffaceous material. Some intervals contain metasandstone that contains quartz eyes approximately 1 mm to 2 mm in diameter. High in the interval is a mix of gray, conglomeratic phyllite, gritty quartzite, and brown carbonate phyllite.

The diverse nature of this unit suggests that several events were taking place at the same time. The gray phyllite is commonly very fine grained and homogeneous; at other intervals it contains a mix of possible pumice and other reworked volcanic rock or tuff. The mixed phyllite could have been a mudstone deposited during ongoing volcanism. The more homogeneous intervals could be a mudstone deposited during periods of quiescence. The sandy intervals that are interbedded with the phyllite suggest that a river may have been nearby at the same time that volcanism was taking place, depositing sandy material, siltstone, and mudstone. The dark gray nature of the phyllite implies that the mudstone and siltstone may have been deposited in an environment reduced in oxygen, that is, under water.

As an alternative to a sedimentary origin, the phyllite may have originated as an air-fall tuff, as indicated by the thin, continuous, fine-grained, and pure nature of the phyllite. Also, the rhythmic nature of the bedding could be the result of a turbidite sequence rather than a surficial sedimentary deposit. It is possible, however, that the phyllite is the result of both sedimentary and volcanic processes.

### *Tan Phyllite (Xtp)*

This unit is immediately northwest of the Squaw Peak Parkway in the Dreamy Draw area. It is the unit that makes up the large roadcut that thousands of commuters drive past each day. It is in contact down section with gray phyllite, and up section with a unit described by Jones (1996) as a chlorite-feldspar-carbonate-biotite phyllite. The contact between the tan and gray phyllite is clearly gradational. A prominent feature is the distinct compositional layering seen at outcrop scale. Cleavage changes direction throughout the unit, but generally both the layering and cleavage dip steeply and strike northeast. A correlative rock, called variable schist by Jones (1996), is exposed on the east side of the Dreamy Draw syncline.

This unit is a light gray to tan phyllite with approximately 50% of it composed of coarse grains and fragments in a finer, micaceous matrix. The grains are mostly sandy quartz, 1 mm to 2 mm in diameter. The rock has a volcanic-lithic aspect with white fragments several centimeters long, possibly pumice or tuff, throughout the unit. A fine-grained white mica marker unit, about 1 m wide, contains zones of flattened and sheared, lenticular quartz grains with evidence of S-C fabric. The unit is rich in brown carbonate, which contributes to the weathered, rounded appearance of the outcrop.

The presence of sandy quartz material throughout the unit suggests a sedimentary origin for this rock. The variation in the composition of the matrix indicates that quartz deposition was accompanied by the deposition or reworking of intermediate to felsic volcanoclastic material. Although it was suggested above that this unit may be correlated with a variable schist described by Jones (1996) in the Dreamy Draw syncline, this particular tan phyllite is much more volcanic-lithic and lacks the interbedded quartzites described in that unit.

### *Rock Units East of the Squaw Peak Parkway*

South and east of the Squaw Peak Parkway the rocks become more quartzose and more clearly continental in origin. The ramadas at Dreamy Draw Park are located within a gray phyllite unit that overlies the tan phyllite described above. This section includes thin beds of alternating dark gray metasilstone and lighter gray to cream-colored metasandstones. The environment of these rocks are presumably similar to the tan and gray phyllite described above.

The gray phyllite is overlain by a thick section of conglomeratic quartzite. This rock is composed of fine to coarse quartz grains with thin laminae of dark, opaque minerals. The laminae define superbly preserved cross beds that provide evidence for stratigraphic tops. Within this sequence is a strongly deformed stretched-pebble conglomerate that contains clasts of various lithologies, including jasper.

Within the conglomeratic quartzite are several thin layers of greenstone and greenish phyllite. Some layers contain white spots interpreted to be deformed feldspar phenocrysts, whereas others contain dark spots interpreted to be altered mafic minerals. It is unknown if all of these are intrusive or some could be extrusive rocks that are part of this section.

Overlying the conglomeratic quartzite and greenstones is a more pure quartzite. This unit locally contains cross beds defined by opaque grains along laminae. These cross

beds are upright in the lower exposures of the unit but become upside down near the top exposures of the unit, clearly indicating that a large fold closure occurs within the quartzite. Further to the east the rock sequence is similar to that exposed below the quartzite and is consistent with this large fold repeating the section.

## **Structural Geology**

At least three deformational episodes are represented by structures of the Phoenix Mountains. The older Proterozoic event produced low-grade, greenschist-facies metamorphic rocks with steeply dipping bedding and cleavage, with folds, shear zones, and other structures. A mid-Tertiary extension event produced steeply tilted red beds at Camelback Mountain and vicinity. The steep tilt of the red beds, as well as their inconsistent bedding attitude, imply movement along a previously unrecognized fault, the Paradise Valley fault, which separates the main range of the Phoenix Mountains from Camelback Mountain. The third event occurred during the Basin and Range disturbance when high-angle faulting uplifted the Phoenix Mountains, or downdropped the surrounding basins, producing the landscape we see today. The character, orientation, and age of structures formed during each episode of deformation are discussed in the following sections.

### *Proterozoic Structures*

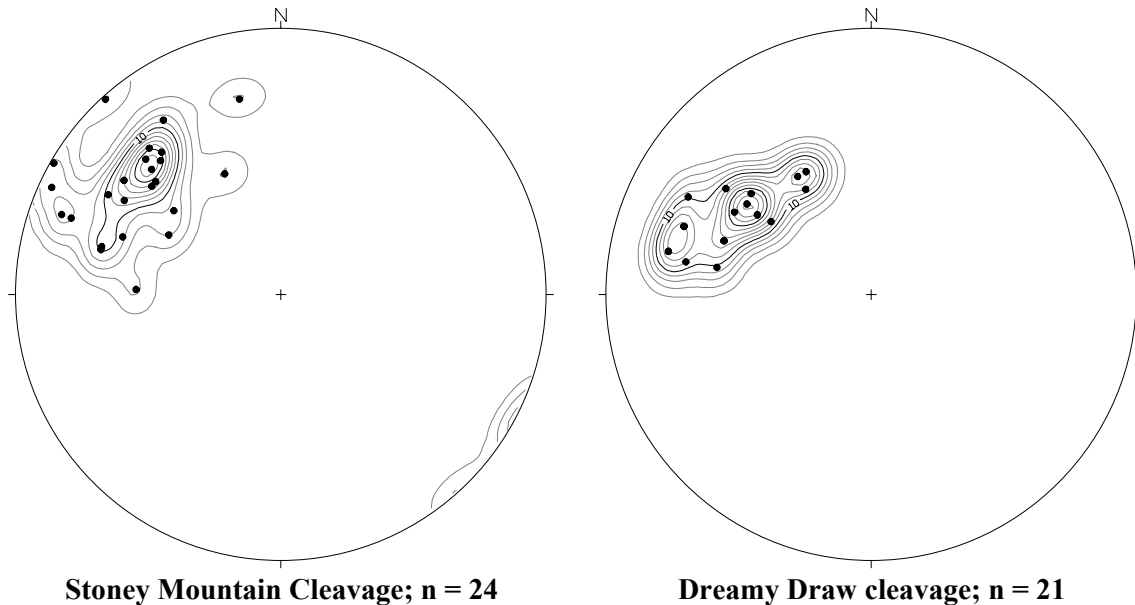
The Early Proterozoic Mazatzal orogeny (1675 Ma to 1650 Ma) controlled structural development of the Phoenix Mountains. This regional northwest-trending compressional event, probably related to subduction, produced steeply dipping, northeast-striking cleavage and isoclinal folds. It is estimated that approximately 12,000 m (36,000 ft) of Precambrian metamorphic rocks are exposed in the Phoenix Mountains, but internal strain and duplication of beds by faulting and folding have obscured the original thickness.

The orientation of bedding is determined on both large- and small-scale features. Large-scale indicators generally include lithologic contacts, whereas small-scale features include compositional variation within the rock unit, dark mineral laminations, graded bedding, tabular and tangential cross-bed sets, and rare scour features, ripple marks, and dune casts. Bedding is generally parallel to the northeast-striking cleavage found throughout the range. Locally, as in the hinges of folds, bedding cuts across the cleavage at a high angle.

The Proterozoic deformation produced well-developed cleavage that generally strikes northeast and dips steeply or moderately to the southeast. This planar fabric varies from slaty cleavage, to foliation, to schistosity. Deformation was accompanied by greenschist-facies metamorphism.

The cleavage is defined by the preferred orientation of mica grains, usually sericite or chlorite, segregated felsic and mafic minerals, and flattened quartz crystals. Cleavage is well developed in most volcanic and volcanic-sedimentary rocks and is developed to a lesser degree in quartzites. Cleavage has an average orientation of N30°E, 75°SE, but in general cleavage measurements are distributed between strikes of N-S and N70°E (Fig. 5). Lineations generally plunge down the dip of cleavage to the southeast and lie in the

plane of cleavage. Lineation is defined by the long axis of deformed and stretched clasts in clastic phyllites and by deformed phenocrysts or feldspar clasts in greenstones.



**Figure 5. Stereoplots of cleavage in areas near Dreamy Draw Park.**

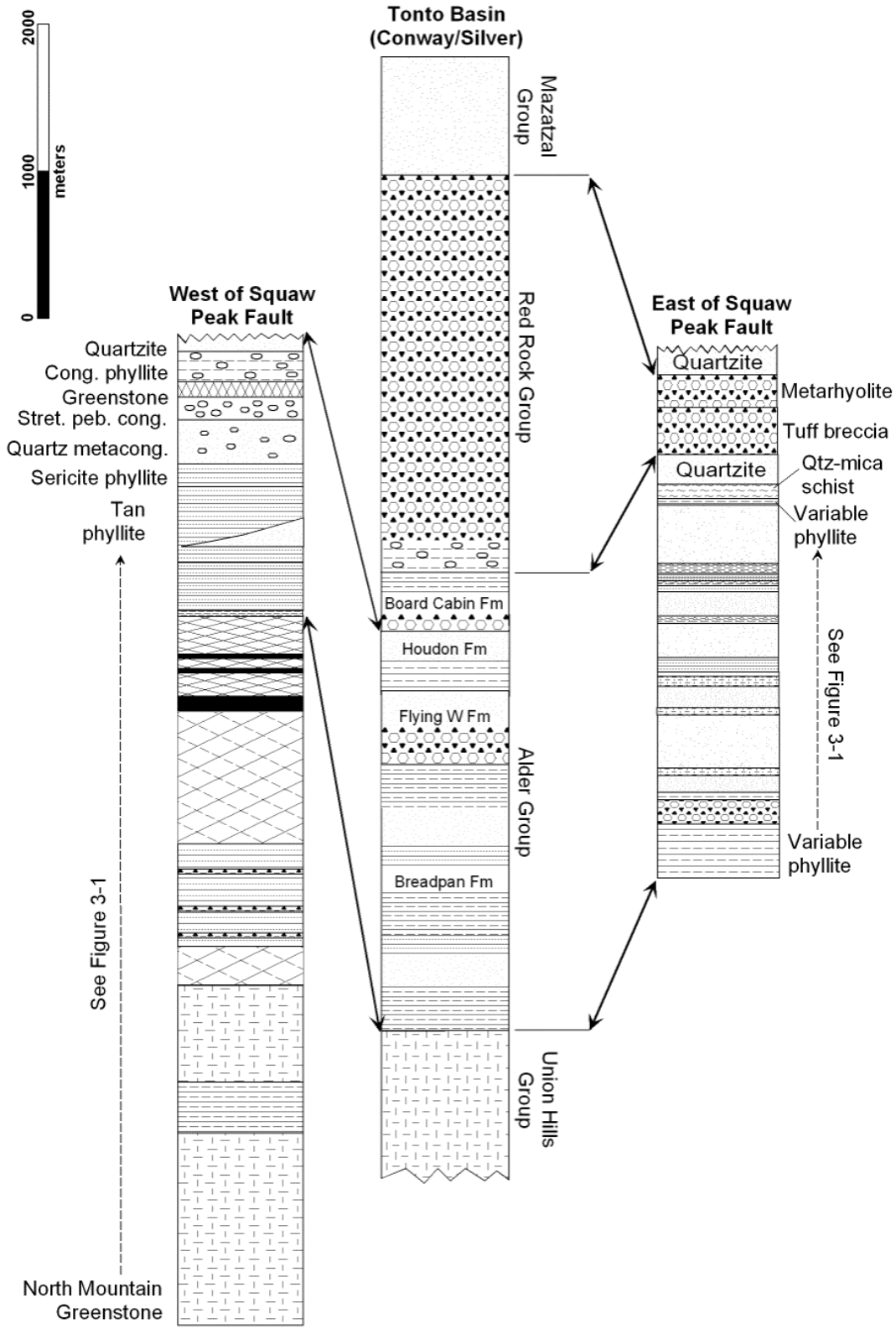
### **Regional Correlations**

A regional correlation of rock units in the Phoenix Mountains has not been well established because of a lack of geochronologic data; however, the rock types present and the overall sequence seem to correlate with rocks of the Mazatzal Province (Karlstrom and Bowring, 1991; Williams, 1991).

The Mazatzal region of the Arizona Transition Zone consists of four main units (Anderson, 1989): Union Hills Group, Alder Group, Red Rock Group, and Mazatzal Group (Fig. 6). The descriptions of these units in this paper are primarily those used by Anderson (1989a), but also incorporate observations made by Conway and Silver (1989), Karlstrom et al. (1987), and Karlstrom and Bowring (1988). The East Verde River Formation, which along with the Gibson Creek batholith is commonly used as an example of possible Yavapai correlative rocks located within the Mazatzal area, is included here as part of Anderson's Union Hills Group.

#### *Correlation of Rock Units*

The stratigraphically lowest unit in the Mazatzal Province is the Union Hills Group (Anderson, 1989a). This unit consists of basaltic andesite pillow lavas and vesicular flows, which grade upward to andesite and dacite flows and tuffs. Andesitic breccias and tuffs and large amounts of volcanoclastic graywacke are interstratified with the various flows and tuffs. The lower basaltic pillow lavas and flows in the Union Hills basalts commonly contain olivine phenocrysts, which are relatively common in lower Yavapai series basalts (Anderson, 1989a). Rhyodacite and local rhyolite lavas and tuffs are also present in some parts of the Union Hills Group.



**Figure 6. Correlation of Proterozoic units in the Phoenix Mountains with those in the Mazatzal Province (from Johnson, 2000).**

Plutonic rocks associated with the Union Hills Group are primarily diorite to granodiorite in composition. No radiometric dates have been published for most Union Hills volcanic or plutonic units, except for the Gibson Creek batholith, which has been dated at 1738 Ma, and is probably coeval or slightly older than the lowest Union Hills Group volcanics (Karlstrom et al., 1990). However, stratigraphic correlations, involving the Cherry Springs batholith, are interpreted by Anderson (1989a) as indicating that the Union Hills Group was deposited between 1740 and 1720 Ma.

Overall the rocks of the Union Hills Group are predominately calc-alkaline basalts, andesites, dacites, and rhyodacites. The Union Hills Group occurs over a large region from the Moore Gulch fault zone southeast to the Pinal schist block of the Mazatzal region (Conway and Silver, 1989; Anderson, 1989a). North Mountain in the Phoenix Mountains contains rocks very similar to Union Hills Group, including a sequence of andesites, dacites, andesitic tuffs, and local rhyolitic lavas and tuffs.

Overlying the Union Hills Group is the Alder Group volcanic and sedimentary sequence (Fig. 6). The basal unit of the Alder Group is disputed, but it probably consists of mafic to intermediate volcanics and graywackes similar to the Union Hills Group strata (Conway and Silver, 1989). Stratigraphically higher in the Alder Group, the sequence consists of distinctive Mn-rich purple slates interbedded with volcanoclastic impure quartzites and conglomerates. These in turn are overlain by a relatively thin layer of pillow basalts, minor limestone, bedded chert, iron formation, tuff, volcanic breccia, shale, and siltstone. Dikes and sills of diabase and andesite locally intrude the lower sequence of the Alder. The upper units of the Alder Formation become increasingly dominated by felsic volcanic flows, tuffs, and pyroclastics, and especially by cogenetic impure quartzite and conglomerates. Andesite porphyry, dacite, and rhyodacite with minor basalt are the primary volcanic rock types at the top of the Alder Group.

Some of the upper Alder Group rhyolites have been dated (Karlstrom et al., 1987). Age determinations for the youngest Alder rhyolite eruptions are generally about 1710-1700 Ma. The Alder Group is interpreted by Anderson (1989a) as a marine transgression from east to west. The Alder Group also marks a change from generally mafic and intermediate calc-alkaline volcanism to subalkaline or alkaline bimodal volcanism. The Dreamy Draw and the Quartzite Ridge areas of the Phoenix Mountains are thought to correlate with Alder Group rocks and contain a similar sequence of both volcanic and sedimentary rocks, including slates (phyllites) and quartzites.

Unconformably overlying the Alder Group across the region is the Red Rock Group (Fig. 6). It consists of subaqueous to subaerial rhyolitic ignimbrite ash-flow tuffs with minor basalt and sedimentary rock. Ignimbrite activity was apparently localized, with ash flows erupting at different times from different volcanic centers. Based on stratigraphic correlations, Anderson (1989a) suggests that ignimbrite activity progressively moved across the Mazatzal region from west to east. Plutonic rocks associated with the ignimbrite complexes are predominately subalkalic granites. Associated rhyolitic ash flows show the same chemical variation.

Radiometric ages have been obtained for several intrusive and extrusive units of the Red Rock Group (Karlstrom et al., 1987). These dates indicate that the main period of Red Rock Group igneous activity lasted from about 1710 to 1690 Ma with peak activity



at 1695 Ma. However, minor alkalic volcanism continued in the Mazatzal Province until 1675 Ma or later.

The geochemistry of the Red Rock ignimbrites has commonly been compared to the modern-day Yellowstone caldera, interpreted to be a continental hot spot (Karlstrom et al., 1987; Karlstrom and Bowring, 1988). Condie (1986) considered the trace-element composition of the Red Rock rhyolites to be more characteristic of continental margin arcs or associated back-arc basins than within-plate rifting, although continental rifting could not be ruled out based on trace-element data alone.

The Red Rock Group rhyolite is a dense, gray to red-brown, flow-banded rhyolite with relatively small locally corroded phenocrysts of quartz and plagioclase. Units in the upper part of the Red Rock Group tend to be more porphyritic, especially the Oxbow Mountain rhyolite at the top of the group (Conway and Silver, 1989). Significantly, the upper porphyritic units in the Tonto Basin area commonly display extensive kaolinization, sericitization, and finely divided hematite (Wilson, 1939). The Red Rock Group is probably represented in the Phoenix Mountains by the rhyolitic ignimbrite ash flow tuffs found in the core of a syncline at Squaw Peak. Rocks here are thought to be stratigraphically higher than the units to the east of Squaw Peak because of facing directions.

The Red Rock Group volcanics are in depositional contact with the overlying Mazatzal Group quartzites. The depositional surface is an erosional unconformity, under which the porphyritic Red Rock metarhyolite displays an extensive 30 m to 50 m highly oxidized alteration zone (Wilson, 1939). The Mazatzal Group is generally divided into three separate units (Anderson, 1989a): The Deadman Quartzite is the basal unit and consists of a basal conglomerate of rhyolite clasts in a quartzite matrix grading into a thinly bedded and cross-bedded quartzite with minor quartz pebble conglomerate and hematitic shale. Specular hematite is also common. Conformably overlying the Deadman Quartzite is the Maverick Shale, which is thinly bedded and ripple marked, and contains some quartz-jasper pebble conglomerates and micaceous alteration zones. The occurrence of the Maverick Shale is limited to the Mazatzal Mountain region. Conformably overlying the Maverick Shale is the Mazatzal Peak Quartzite. This unit is a red to purple, thick-bedded, cross-bedded, ripple-marked quartzite. The quartzite is medium grained and well sorted. Equivalents of the Mazatzal Group quartzites are probably quartzites in the core of the syncline at Squaw Peak in the Phoenix Mountains.

Paleocurrent data indicates a northern cratonic source region for the Mazatzal Group, with deposition occurring in a shallow-marine environment along a northeast-southwest trending coastline (Condie, 1982). Sediment thicknesses increase in a southeast direction and become intermixed with shallow-marine sediments (Conway and Silver, 1989).

In the Squaw Peak syncline, quartzite overlies metarhyolite. The quartzite-metarhyolite contact zone is characterized by a manganese-rich layer with Mn-andalusite, piemontite, Mn-chloritoid, spessartine garnet, and Zn-rich staurolite (Thorpe and Burt, 1978b). The Mn-rich layer is also interpreted as the result of lateritic weathering at high  $fO_2$  conditions. Triple point aluminosilicate assemblages are found in the metarhyolite and quartzite units. According to Karlstrom et al. (1990), the contact between the

quartzite and metarhyolite is a mylonitic shear zone with S-C fabrics and relative southward movement of the overlying quartzite, but this has not been verified.

### **Evolution of the Phoenix Mountains**

The Phoenix Mountains contain a unique geologic history in that the rocks record a depositional environment that changed over time from oceanic to continental. This package of rocks has been steeply tilted so that a traverse across the sequence is easily accomplished. The older, oceanic rocks are in the northwest part of the range, whereas younger, more continental rocks are to the southeast.

Proterozoic rock units in the Phoenix Mountains include Early Proterozoic metavolcanic, metasedimentary, and intrusive rocks. The Late Proterozoic history is unrecorded, except perhaps by the few diabase dikes. No rocks or structures record the Paleozoic and Mesozoic history, but rocks of such ages are interpreted to have been present. The geologic events during Tertiary include the eruption of magmas, deposition of sediments, and the formation of a metamorphic core complex and detachment fault that steeply tilted units near Camelback Mountain (Reynolds, 1985; Spencer and Reynolds, 1989). During the Basin and Range disturbance, the Phoenix Mountains were uplifted, or adjacent basins were downdropped, along steep north-south-trending normal faults (Scarborough and Peirce, 1978). Except for steep tilting recorded in Tertiary red beds near Camelback Mountain and gentle tilting of basalts in the northwest, the rest of the Phoenix Mountains do not seem to have been tilted significantly by either the mid-Tertiary event or the Basin and Range disturbance.

#### *Sequence of Events*

The depositional history of the Phoenix Mountains begins during Early Proterozoic, some 1700 million years ago. During this time the area was a submarine volcanic environment, located at the southern edge of the North American continent (Bennett and DePaolo, 1987; Anderson, 1989a; Wooden and DeWitt, 1991). Intense volcanic activity on the ocean floor, perhaps in island arcs, contributed a thick sequence of intermediate-composition volcanic material to the basin as well as iron-rich chert beds that formed in submarine hot-springs environments. Gradually, the ocean basin filled with volcanic material to such a degree that the once-deep ocean environment changed to a more shallow-marine setting, depositing shale and sandy-silty mudstone. This shallow marine environment evolved into a near-shore environment that deposited additional mudstone and sandstone in a shallow, shifting sea or a floodplain or a delta. Large volcanic eruptions spreading ash across the region were continuous throughout these depositional changes, bringing about the intercalated deposition of volcanic sediments with the shales, mudstones, and sandstones. Volcanism became more felsic with time, culminating in the rhyolites east of the Squaw Peak fault. The Shaw Butte Granodiorite was probably intruded sometime near the end of this depositional sequence, but prior to any deformation.

About 1650 Ma, these rocks were subjected to regional deformation during the Mazatzal orogeny, which is believed to be the last in a series of tectonic episodes that created northeast-trending mountain ranges across the southwest (Karlstrom and Bowring, 1991). The northeast-striking cleavage throughout the Phoenix Mountains, as

well as the folds and shear zones, are attributed to northwest-directed crustal shortening during this event (Karlstrom and Bowring, 1991).

Metamorphism occurred during deformation, as evidenced by the growth of metamorphic minerals parallel to cleavage rather than growing over it. Low-grade, greenschist-facies metamorphism is indicated by the presence of chlorite, actinolite, and epidote in the metavolcanic rocks, and by plagioclase, chlorite, muscovite, and biotite in the metasedimentary rocks. Kyanite and andalusite formed at this time, followed by retrograde pyrophyllite.

Greenschist-facies metamorphism suggests that at least 5 km to 10 km of additional material was either deposited on top of these units or was placed over the top tectonically and subsequently eroded off, perhaps during a middle Proterozoic uplift event (Dickinson, 1989).

Late Proterozoic time is represented only by diabase dikes, but Paleozoic and Mesozoic histories are not recorded in the rocks or structures of the Phoenix Mountains. Both Paleozoic and Mesozoic rocks are thought to have been deposited in the Phoenix area, but were eroded prior to mid-Tertiary (Dickinson, 1989). Where Paleozoic rocks are preserved, such as in the Superior or Payson areas, they are on average about a kilometer thick and are generally in contact with rocks that had been metamorphosed to greenschist facies at depth and then brought to the surface (Williams, 1991). Mesozoic rocks are thought to have been deposited in the area as well, but since they are no longer preserved, it is difficult to estimate their thickness. In western Arizona, however, the Mesozoic sequence is typically one to two kilometers thick (Reynolds et al., 1988). This implies that the thickness of both the Paleozoic and Mesozoic rock was not sufficient to bring about low-grade metamorphism in the Proterozoic rocks of the Phoenix Mountains and that they were metamorphosed prior to the end of Proterozoic.

The Paleozoic and Mesozoic sediments covering central and southern Arizona were subsequently eroded away. It is difficult to pinpoint an exact time for the uplift event that prompted this erosion, except to say that it was in part post-late Mesozoic and pre-mid-Tertiary (Reynolds et al., 1988). Timing for this event must be looked at on a regional scale to find evidence for when central and southern Arizona could have been uplifted. Based on the Mesozoic stratigraphy of the Colorado Plateau, no large conglomerate deposits exist to suggest that material was being shed onto the Plateau from southern and central Arizona during early and middle Mesozoic (Dickinson, 1989). There is also no evidence in the Phoenix Mountains to suggest that events of the Laramide orogeny, during late Mesozoic and early Tertiary, were significant enough to overprint Proterozoic metamorphic features. The first clear evidence of uplift is the Eocene-Oligocene Mogollon Rim Formation (rim gravels), which sits on the edge of the Colorado Plateau and contains clasts derived from Precambrian exposures in central Arizona (Peirce et al., 1979). This is the best evidence to support timing for uplift of central and southern Arizona, and may be the event that eroded away the Paleozoic and Mesozoic sediments.

After the Paleozoic and Mesozoic rock sequence was eroded, the Proterozoic rocks were covered with mid-Tertiary sediments and mafic volcanic material. Miocene volcanism in the Phoenix Mountains is distinctive in that it lacks the 15 Ma to 20 Ma ash flows and other silicic volcanics found throughout the rest of central Arizona, such as in

the Superstition Mountains (Shafiqullah et al., 1980). Only basaltic material was erupted in the Phoenix Mountains during mid-Tertiary and, assuming that the dates derived from basalts at Lookout Mountain are correct (~20 Ma), the Proterozoic rocks had to be exhumed by at least 20 Ma, prior to eruption of the basalts.

During mid-Tertiary extension, the crust was stretched as much as 50% to 100% (Hamilton and Meyers, 1966; Hamilton, 1969), producing tilted, fault-bounded blocks and deep Cenozoic sedimentary basins (Spencer and Reynolds, 1989). The South Mountains detachment fault affected the southeastern end of the Phoenix Mountains by tilting mid-Tertiary red beds and andesitic flows (Reynolds, 1985; Reynolds and Lister, 1987; Spencer and Reynolds, 1989). The Camels Head Formation, an alluvial fan deposit, and the Tempe Beds, a series of red sandstones and shales, may have been deposited concurrent with southwest-directed tilting, as evidenced by the existence of fanning dips (Reynolds, personal communication, 2000). The strike and dip of these units change dramatically from Hayden Butte across Papago Park to Camelback Mountain. The red beds exposed at Hayden Butte have a northwest strike and dip southwest. In Papago Park, the units strike north-northwest and dip southwest, and at the west end of Camelback Mountain they strike northeast and dip northwest. This change in strike is probably related to an east-west fault between Camelback Mountain and areas to the north (Johnson, 2000).

During the Late Tertiary Basin and Range disturbance, the Phoenix Mountains were either uplifted or the surrounding basins were down faulted along north-south-trending faults relative to the basins on either side (Menges and Pearthree, 1989). Scarborough and Peirce (1978) estimate that the Luke basin to the west shows a relative displacement of 2,400 m (8,000 ft) along a fault due to the Basin and Range disturbance, with more than 1,200 m (4,000 ft) of basin fill. The Paradise basin to the east shows a relative displacement of 2,100 m (7,000 ft) with more than 960 m (3,200 ft) of basin fill.

It is interesting to note that neither the mid-Tertiary extension period nor the Basin and Range disturbance had much effect on the overall tilting of Proterozoic units in the Phoenix Mountains. With the exception of red beds in the southeast part of the range, and the gently tilted late Tertiary volcanics to the northwest, there is little evidence to suggest the rest of the range was significantly tilting during either of these events.

Today, Quaternary surfaces are being developed and cover much of the surrounding area. These deposits include alluvial fans, channels, and terraces that range in age from Pleistocene to Holocene (Pearthree, 1991; Demsey, 1988, 1989).

### **Evolution of Proterozoic Lithosphere of Central Arizona**

Proterozoic rocks in central Arizona record the accretion and assembly of continental crust between 1800 and 1600 Ma. Much work has been done in recent years, in particular, the studies done by Anderson, DeWitt, Conway, Karlstrom, Bowring, and others in the Transition Zone of Arizona, to further the understanding of the evolution of the North America craton and the growth of continental masses throughout Earth's history. But terrane accretion and the subsequent tectonic history are not well understood, and many questions remain about the nature of accreted blocks. Debate continues as to whether or not these blocks were island arcs, continental arcs, or

microcontinents, or even whether the blocks exist. The sequence of events in the Phoenix Mountains and adjacent parts of central Arizona record the formation and evolution of continental crust in the region, and may contain some clues as to the accretionary mode during the Mazatzal orogeny.

The first event recorded in central Arizona is the formation of mafic to intermediate volcanic rocks and their intrusive equivalents. These rocks are represented by the greenstones in the northwestern Phoenix Mountains and their equivalents in other exposures of the Union Hills Group. During a period of volcanic quiescence at the end of this volcanic cycle, the area received an influx of pure quartz sandstones and then eventually evolved to the more clastic-dominated sequence of the Alder Group. This was followed by deposition of the Red Rock Group rhyolites and the Mazatzal Group quartzites. These supracrustal rocks were subsequently subjected to regional forces that caused regional shortening. The composition of granites intruded in the region during this time suggests that this deformation was related to subduction along a convergent plate boundary. Granites were probably intruded both before and during deformation, but the Shaw Butte Granodiorite, with its northeast cleavage and shear zones, suggests that it was intruded prior to deformation.

The Proterozoic greenstones found in the northwest area of the Phoenix Mountains were probably formed in a primitive continental-margin-arc setting. The presence of pure quartz sandstone in close proximity to Union Hills Group rocks, and the lack of deformation, suggests that the Union Hills Group was linked to a continent rather than being an isolated oceanic island arc. The abrupt evolution from mafic volcanics to felsic volcanics across the Union Hills Group-Alder Group boundary in a relatively short distance, suggests that the continental crust in this region was evolved enough to produce more silicic volcanics, but this evolution did not require collision or accretion, since no structures developed at this time.

### **Economic Geology**

There were primarily two minerals with economic significance mined from the Phoenix Mountains. The first is mercury, principally in the form of the mineral cinnabar, and the second is the mineral kyanite, an aluminosilicate used in porcelain manufacture. All of the commercial activity related to these commodities took place in the first half of the 20<sup>th</sup> century. The Phoenix Mountains are now within the confines of the City of Phoenix, essentially prohibiting any additional mineral development.

#### *Mercury (Hg)-Quicksilver*

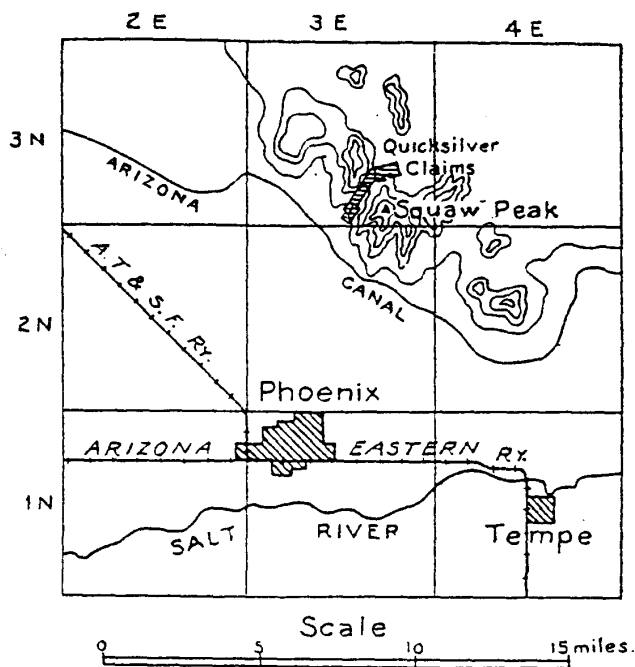
Mercury was discovered in the Phoenix Mountains in about 1900 with initial claims being filed in 1916 (Beckman and Kerns, 1965). It is present in the form of cinnabar and metacinnabar. Native mercury may also be present, but only as a very small fraction. Cinnabar generally occurs as an extremely fine crystalline substance within veins. Metacinnabar is less common than cinnabar and typically occurs in oxidation zones near neighboring mercury deposits.

In the Phoenix Mountains, cinnabar is present in veins found in quartz-sericite or chloritic phyllites. It is interpreted as having been deposited hydrothermally in joints, faults, or other openings in the host rocks, subsequent to metamorphism.

The general location of mercury claims and mines in the Phoenix Mountains is shown in Figure 7 (Lausen and Gardner, 1927). There is some inconsistency between the maps of claims shown in Lausen and Gardner's work versus that of Schrader in 1919. In general, the claims lie along the strike of the formations. These mines appear to have been eventually covered over by State Route 51, the Squaw Peak Parkway.

Schrader's 1919 review of the mercury mines reports the greatest activity at the Rico prospect, including shafts sunk to a depth of 60 feet. Lausen and Gardner (1927) report work continuing until at least 1927 on the Rico prospect with the main shaft at 112 feet and both drifting and cross cutting taking place. Beckman and Kerns (1965) state that the shafts probed to a depth of 245 feet with 500 feet of drifting. This represents considerable effort, and presents something of a mystery with respect to the apparent amount of metal extracted.

The neighboring Mercury Group's mining efforts paralleled the Rico prospect. According to Lausen and Gardner (1927), economic expansion would have been possible if these properties had joined together as one organization and had pursued their work with diligence and planning. But it seems production of mercury from the Phoenix Mountains/Dreamy Draw area was never a concerted effort.



**Figure 6. General location of mercury claims in the Phoenix Mountains (Lausen and Gardner, 1927).**

Lausen and Gardner (1927) indicate that "A few flasks of quicksilver were produced in a small retort built by Mr. Hughes." Earlier, Schrader (1919) indicated that the owners of the Mercury Group "...were planning to treat the ore during the winter of 1917-1918 in a reduction plant to be installed on their farm on the Paradise Valley slope three-fourths of a mile from the mine." No firm documentation of that or other mercury recovery equipment is noted in future references. Unless the ore was shipped elsewhere for processing, output must have been extremely small.

In other areas of the state, Tenney in 1928 reported that only the Mazatzal Mountains were being utilized for mercury production. In 1962, Wilson summarized in a table that \$1.2 million in mercury had been produced in Arizona from 1858 to 1961, noting that the Mazatzal mines produced most of it. Beckman and Kerns essentially state the same thing in 1965. An estimate that the Phoenix Mountain mines “had a production of less than 100 flasks” made by Bailey in 1969 succinctly summarizes the extent of the economic contribution of mercury mining from this region.

### *Kyanite*

Little information is available on the history of kyanite mining in the Phoenix Mountains. Schrader (1918) reported substantial kyanite (30% to 60%) in rocks associated with the Sealrock Claim No. 1 mercury prospect in 1918. He describes the country rock as “chiefly a micaceous, kyanite-quartz schist”, noting kyanite crystals of fairly substantial size. The trend line of the claims in this group run in a southwest to northeast trend up the southern side of Squaw Peak, passing to the east of its summit (Schrader, 1918). Lausen and Gardner (1927) also mention “cyanite” in their discussion of the Phoenix Mountain’s cinnabar mining.

The earliest identified reference to kyanite as a resource in the Phoenix Mountains was by F.W. Galbraith in 1941, while an earlier similar writing by Tenney in 1928 does not include it. Other sources support Schrader (1918) in recognizing Squaw Peak as the principal location for this mineral.

Actual extraction of kyanite on a production basis from the region was apparently quite limited. Wilson and Roseveare in 1949 discussed the economics of prospecting kyanite by stating, “...most of the deposits have not been regarded as of commercial size and grade.” Little else has been found to support production of this mineral at Squaw Peak or other parts of the Phoenix Mountains beyond this date. What mining was actually done is poorly documented. The only reference to a commercial recovery was the almost anecdotal comment by Wilson and Roseveare (1949):

“Several years ago Nels Anderson (Box 672, Peoria, AZ) shipped about 38 tons of kyanite from Squaw Peak, North of Phoenix.”

No particular location has been identified to date that would qualify as a kyanite mine per se, but the Schrader 1918 indication of Sealrock Group’s Claim No. 1 on the south side of Squaw Peak would be a very good place to start. There was also no indication of any separation or enrichment of the kyanite in the material that N. Anderson ostensibly transported from the area. Subsequent references mention the kyanite, but supply no additional data from a production standpoint (Wilson, 1962).

### *Other Mining Activities*

The Dreamy Draw area in the Phoenix Mountains contains a number of prospect pits, holes, etc. in the landscape that are likely the remainders of various exploration efforts, whether eventually supported by explicit claim or not.

There appears to have been some small-scale mining of industrial minerals in the Phoenix Mountains. A figure in Schrader (1918), regarding mercury-related activities, shows a slate quarry and a limestone quarry adjacent to the Rico and Jones-Husted

cinnabar claim, respectively. These are assumed to have been very modest operations. The quality and quantity of slate or limestone in the formations almost certainly represents an incidental resource. The “limestone quarry” was likely along hydrothermal calcite, rather than sedimentary limestone.

Only minimal development of minerals took place in the Phoenix Mountains. Neither of the two principal materials found were viable from a commercial standpoint. The mercury was not really sufficient to be a major source, or was under-capitalized to the extent that it essentially prohibited adequate recovery from the available deposits. Kyanite simply was not present in the quantity and quality necessary for it to be financially viable. The slate and limestone quarries were probably only local convenience operations.

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### **List of References** (from Johnson, 2000)

- Anderson, J.L., 1989, Proterozoic anorogenic granites of the Southwestern United States, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic Evolution of Arizona: Arizona Geological Society Digest 17*, p. 211-238.
- Anderson P., 1989a, Proterozoic plate tectonic evolution of Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic Evolution of Arizona: Arizona Geological Society Digest 17*, p. 17-55.
- Anderson, P., 1989b, Stratigraphic framework, volcanic-plutonic evolution, and vertical deformation of the Proterozoic volcanic belts of central Arizona, *in* Jenney, J.P. and Reynolds, S.J., eds., *Geological Evolution of Arizona: Arizona Geological Society Digest 17*, p. 57-147.
- Anthony, J.W., Williams, S.A., Bideaux, R.A., and Grant, R.W., 1995, *Mineralogy of Arizona*: Tucson, University of Arizona Press, 264 p.
- Aylor, J.G. Jr., 1973, *The geology of Mummy Mountain, Phoenix, Arizona*: Tempe, Arizona State University, M.S. thesis, 86 p.
- Bailey, E.H., 1969, Mercury, *in* *Mineral and water resources of Arizona*: Arizona Bureau of Mines Bulletin 180, p. 226-230.
- Beckman, R.T., and Kerns, W.H., 1965, Mercury in Arizona, *in* *Mercury potential of the United States*: U.S. Bureau of Mines Information Circular I.C. 8252, p. 60-74.



- Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the United States as determined by neodymium isotopic mapping, *in* Geological Society of America Bulletin 99 (5), p. 674-685.
- Bowring, S.A., and Karlstrom, K.E., 1990, Growth, stabilization and reactivation of Proterozoic lithosphere in the Southwestern United States: *Geology*, v. 18, p. 1203-1206.
- Cameron, D., 2000, Mineral resources of the Phoenix Mountains, personal communication.
- Chamberlain, K.R., 1998, Medicine Bow Orogeny: Timing of deformation and model of crustal structure produced during continent-arc collision, ca. 1.78 Ga, Southeastern Wyoming: *Rocky Mountain Geology*, v. 33, no. 2, p. 259-277.
- Condie, K.C., 1982, Plate-tectonics model for Proterozoic continental accretion in the southwestern United States: *Geology*, v. 10, p. 37-42.
- Condie, K.C., 1986, Geochemistry and tectonic setting of Early Proterozoic supracrustal rocks in the southwestern United States: *Journal of Geology*, v. 94, p. 845-864.
- Condie, K.C., 1992, Proterozoic terranes and continental accretion in Southwestern North America, *in* Condie, K.C., ed., *Proterozoic crustal evolution: New York, Elsevier, Developments in Precambrian Geology*, v. 10, p. 447-480.
- Conway, C.M., and Silver, L.T., 1989, Early Proterozoic rocks (1710-1615 Ma) in central to southwestern Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic Evolution of Arizona: Arizona Geological Society Digest 17*, p. 165-186.
- Cordy, G.E., 1978, Environmental geology of the Paradise Valley quadrangle, Maricopa County, Arizona: Part II: Tempe, Arizona State University, M.S. Thesis, 89 p., 9 sheets, scale 1:24,000.
- Davis, A.P., 1987, Irrigation Near Phoenix, Arizona: U.S. Geological Survey Water Supply Paper 2, p. 1-98.
- Demsey, K.A., 1988, Geologic map of Quaternary and Upper Tertiary alluvium in the Phoenix North 30' x 60' quadrangle, Arizona, Open File Report 88-17, Arizona Geological Survey, Tucson, Arizona, 1 sheet, scale 1:100,000.
- Demsey, K.A., 1989, Geologic map of Quaternary and Upper Tertiary alluvium in the Phoenix South 30' x 60' quadrangle, Arizona, Open File Report 88-17, Arizona Geological Survey, Tucson, Arizona, 1 sheet, scale 1:100,000.
- DeWitt, Ed, 1989, Geochemistry and tectonic polarity of Early Proterozoic (1700-1750 Ma) plutonic rocks of north-central Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic Evolution of Arizona: Arizona Geological Society Digest 17*, p. 149-163.
- Dickinson, W.R., 1989, Tectonic setting of Arizona through geologic time, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic Evolution of Arizona: Arizona Geological Society Digest 17*, p. 1-16.
- Galbraith, F.W., 1941, Minerals of Arizona: Arizona Bureau of Mines Bulletin 149, 83 p.

- Hamilton, W., 1969, Mesozoic California and the underflow of Pacific mantle: Geological Society of America Bulletin 80, p. 2409-2430.
- Hamilton, W., and Meyers, W.B., 1966, Cenozoic tectonics of the western United States: Review of Geophysics, v. 4, p. 509-549.
- Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., the geology of North America; an overview: Geological Society of America, The geology of North America, v. A, p. 447-512.
- Holloway, S.D., 1999, Proterozoic through quaternary geology of the Union Hills, North Phoenix, Arizona: Tempe, Arizona, M.S. Thesis, Arizona State University, 117 p.
- Hurlbut, C.S. Jr., and Klein, Cornelius, 1971, Manual of mineralogy (after James D. Dana): New York, John Wiley and Sons, 532 p.
- Johnson, J.K., 2000, Geology of the Phoenix Mountains, central Arizona: Tempe, Arizona, M.S. Thesis, Arizona State University, 140 p.
- Johnson, J.K., Reynolds, S.J., and Jones, D.A., in preparation, Geologic Map of the Phoenix Mountains, central Arizona: Arizona Geological Survey Map of some sort, scale 1:24,000.
- Jones, D.A., 1996, Proterozoic structural geology and stratigraphy of the Squaw Peak area, Phoenix Mountain, Arizona: Tempe, Arizona, M.S. Thesis, Arizona State University, 56 p.
- Karlstrom, K.E., and Bowring, S.A., and Conway, C.M., 1987, Tectonic significance of an Early Proterozoic two-province boundary in central Arizona: Geological Society of America bulletin, v. 99, no. 4, p. 529-538.
- Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561-576.
- Karlstrom, K.E., and Bowring, S.A., 1991, Styles and timing of Early Proterozoic deformation in Arizona: Constraints on tectonic models, *in* Karlstrom, K.E., ed., Proterozoic Geology and Ore Deposits of Arizona: Arizona Geological Society Digest 19, p. 1-10.
- Karlstrom, K.E., Doe, M.F., Wessels, R.L., Bowring, S.A., Dann, J.C., and Williams, M.L., 1990, Juxtaposition of Proterozoic crustal blocks; 1.65-1.60 Ga Mazatzal orogeny, *in* Gehrels, G.E. and Spencer, J.E., eds., Geologic excursions through the Sonoran Desert region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 114-123.
- Lausen, Carl, and Gardner, E.D., 1927, Quicksilver (Mercury) resources of Arizona: Arizona Bureau of Mines Bulletin 122, 112 p.
- Lee, W.T., 1905, Underground waters of Salt River Valley, Arizona: U.S. Geological Survey Water-Supply and Irrigation Paper No. 136, 196 p.

- Leighty, R.S., 1997, Neogene tectonism and magmatism across the Basin and Range – Colorado Plateau boundary, central Arizona, v. 1 and 2: Tempe, Arizona, PhD. Dissertation, Arizona State University, 1019 p.
- Maisano, M.D., and Malone, G.B., 1973, Petrology and provenance: Precambrian metamorphic sequence, Squaw Peak, Phoenix Arizona: (abs.) Arizona Academy of Science, v. 8, p. 41.
- McDonald, H.R., Wolcott, H.N., Bluhm, F.I., and Hem, J.D., 1947, Geology and groundwater resources of Paradise Valley, Maricopa County, Arizona: U.S. Geological Survey Mimeo Report, 34 p.
- Meinzer, O.E. and Ellis, A.J., 1915, Ground water in Paradise Valley, Arizona: U.S. Geological Society Water Supply Paper 375, p. 51-75.
- Menges, C.M., and Pearthree, P.A., 1989, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 649-680.
- Oppenheimer, J., and Sumner, J.S., 1980, Gravity modeling of the alluvial basins, southern Arizona: Tucson, Arizona, M.S. Thesis, University of Arizona, 1 sheet, scale 1:1,000,000.
- Peirce, H.W., Damon, P.E., and Shafiquallah, M., 1979, An Oligocene(?) Colorado Plateau edge in Arizona: Tectonophysics, v. 61, no. 1, p. 1-24.
- Pearthree, P.A., 1991, Geologic insights into flood hazards in piedmont areas of Arizona, Arizona Geology, v. 21 (4), p. 1-5.
- Reynolds, S.J., 1988, Geologic Map of Arizona, Arizona Geological Survey, Tucson, Arizona.
- Reynolds, S.J., 1985, Geology of the South Mountains, central Arizona, Arizona Bureau of Geology and Mineral Technology Bulletin 195, Tucson, Arizona.
- Reynolds, S.J., and DeWitt, E., 1991, Proterozoic geology of the Phoenix region, central Arizona, *in* Karlstrom, K.E., ed., Proterozoic Geology and Ore Deposits of Arizona: Arizona Geological Society Digest 19, p. 237-250.
- Reynolds, S.J., and Lister, G.S., 1987, Field guide to lower and upper plate rocks of the South Mountains detachment zone, Arizona, *in* Davis, G.H., and Van den Dolder, E.M., eds., Geologic diversity of Arizona and its margins: Excursions to choice areas: Arizona Bureau of Geology and Mineral Technology, Phoenix, p. 244-248.
- Scarborough, R.B., and Peirce, H.W., 1978, Late Cenozoic basins of Arizona, *in* Callender, J.F., Wilt, J.C., and Clemons, R.E., eds., Land of Cochise: New Mexico Geological Society 29th Field Conference Guidebook, p. 253-259.
- Schrader, F.C., 1918, Quicksilver deposits of the Phoenix Mountains, Arizona: U.S. Geological Survey Bulletin 690-D, p. 95-107.
- Schrader, F.C., 1919, Quicksilver deposits of the Phoenix Mountains, Arizona, *in* Contributions to economic geology (short papers and preliminary reports) 1918 - Part I--Metals and nonmetals except fuels: U.S. Geological Survey Bulletin 690, p. 95-109 [published separately as U.S. Geological Survey Bulletin 690-D, 1918].

- Shafiqullah, Muhammed, Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas, *in* Jenney, J.P., and Stone, Claudia, eds., *Studies in western Arizona: Arizona Geological Society Digest* 12, p. 201-260.
- Shank, D.C., 1973, *Environmental geology in the Phoenix Mountains, Maricopa County, Arizona: Tempe, Arizona State University, M.S. Thesis*, 40 p., 7 sheets, scale 1:15,000.
- Spencer, J.E., and Reynolds, S.J., 1989, Middle Tertiary tectonics of Arizona and adjacent areas, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic evolution of Arizona: Arizona Geological Society Digest* 17, p. 539-574.
- Tenney, J.B., 1928, *The mineral industries of Arizona: Arizona Bureau of Mines Bulletin* no. 125, 135 p.
- Thorpe, D.G., 1980, *Mineralogy and petrology of Precambrian metavolcanic rocks, Squaw Peak, Phoenix, Arizona: Tempe, Arizona State University, M.S. Thesis*, 96 p., 1 sheet, scale 1:5,000.
- Thorpe, D.G., and Burt, D.M., 1978a, Viridine, ottrellite, and piemontite from Squaw Peak, North Phoenix Mountains, Arizona: (abs.) *Geological Society of America Abstracts with Programs*, v. 10, p. 150.
- \_\_\_\_\_, 1978b, Precambrian metavolcanic rocks of the Squaw Peak area, Maricopa County, Arizona, *in* Burt, D.M., and Péwé, T.L., eds., *Guidebook to the geology of central Arizona; 74th Cordilleran Section Meeting, Geological Society of America, Arizona State University, Tempe, Arizona: Arizona Bureau of Geology and Mineral Technology Special Paper No. 2*, p. 101-106.
- \_\_\_\_\_, 1980, A unique chloritoid-staurolite schist from near Squaw Peak, Phoenix, Arizona, *in* Jenney, J.P., and Stone, C., eds., *Studies in western Arizona: Arizona Geological Society Digest*, v. 12, p. 193-200.
- Williams, M.L., 1991, Overview of Proterozoic metamorphism in Arizona, *in* Karlstrom, K.E., ed., *Proterozoic Geology and Ore Deposits of Arizona: Arizona Geological Society Digest* 19, p. 11-26.
- Wilson E.D., and Roseveare, G.H., 1949, *Arizona nonmetallics - A summary of past production and present operations – Second edition, revised: Arizona Bureau of Mines Bulletin* 155, 60 p.
- Wilson, E.D., 1939, *Bibliography of the geology and mineral resources of Arizona: Arizona Bureau of Mines Bulletin* 146, 164 p.
- Wilson, E.D., 1962, *A resume of the geology of Arizona: Arizona Bureau of Mines Bulletin* 171, 140 p.
- Wilson, E.D., Moore, R.T., and Peirce, H.W., 1957, *Geologic map of Maricopa County, Arizona: Arizona Bureau of Mines*, 1 sheet, scale 1:375,000.
- Wooden, J.L., and DeWitt, Ed, 1991, Pb isotopic evidence for the boundary between the Early Proterozoic Mojave and Central Arizona crustal provinces in Western Arizona,

*in* Karlstrom K.E., ed., Proterozoic Geology and Ore Deposits of Arizona: Arizona Geological Society Digest 19, p. 27-50.

## **NOTES**



Preliminary geologic map of the central part of the Phoenix Mountains, central Arizona (Julia K. Johnson, Stephen J. Reynolds, and David A. Jones, in preparation). Labels for the most important units visited on the field trip are listed in Figure 2.