Arizona Geological Society

Fall 1998 Field Trip

Phoenix Metro Area,

Maricopa County, Arizona

Leader:

Bob Leighty

Saturday October 10, 1998

Arizona Geological Society
P. O. Box 40952, Tucson Arizona, USA

THIS PAGE

INTENTIONALLY BLANK

CONTENTS

INTRODUCTION

Welcome to the Fall 1998 Arizona Geological Society Field Trip. I hope this will be an interesting and informative trip for everyone. The ultimate goal of this trip is to describe and discuss a range of topics that pertain to the varied physiography and geology of the Phoenix region. For those who are not familiar with the geology of the Phoenix metropolitan area, the trip should provide informative overview of the geologic setting. The trip should also provide a basis for more detailed discussion about topics relevant to the various areas we will visit. The trip consists of five stops between South Mountain and the Cave Creek area (Figure 1), with the last being optional if time permits. Discussion at each stop will be guided (but not limited to) the field guide. Material will also be covered on the bus between stops. Some of the topics will involve Tertiary evolution of tectonism and sedimentation, as well as description of various Proterozoic rocks and structures. Special thanks to Steve Reynolds for providing helpful material and to Steve Richard for organizing transportation.

Enjoy the day!

Bob Leighty

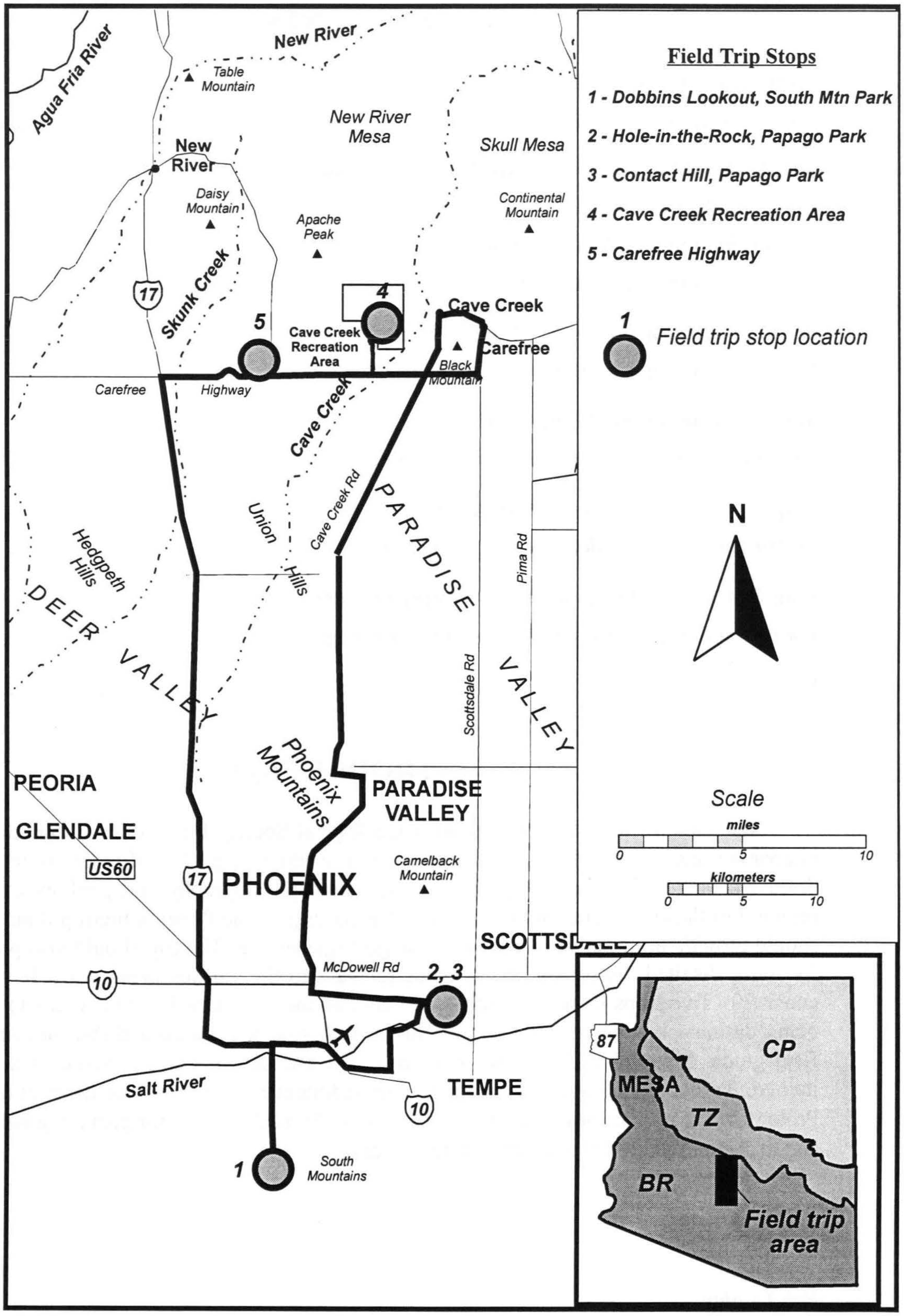


Figure 1. Generalized location map for the various field trip stops.. Inset map shows the location of the study area relative to the three physiographic provinces in Arizona: the Basin and Range (BR), Transition Zone (TZ), and Colorado Plateau (CP).

ROAD LOG

🚌 ***South Phoenix to South Mountain Park.*** *From the parking area, drive south on Central Avenue to South Mountain Park, the world's largest municipal park. Start road mileage at the Ranger station (second gate).*

0.0 Park Ranger station. Follow the signs to Dobbins Lookout (Figures 2 and 3). Alluvial valley to the south parallels the road. Brown- to tan-weathering Tertiary granodiorite exposed here. Continue west. Quaternary surficial deposits cover much of the valley floor.

1.0 Bear left as road turns south. Early Proterozoic Estrella Gneiss forms the ridge ahead. As the road begins the upward grade, outcrops of Estrella Gneiss become more common. The Early Proterozoic Estrella Gneiss consists of tonalite, tonalitic gneiss, and amphibolite gneiss (Reynolds, 1985).

1.5 San Juan Road milepost 2.0. Good view to the northeast of downtown Phoenix, Squaw Peak, Camelback Mountain, the Papago Buttes, McDowell Mountains, etc.

1.9 San Juan Road milepost 2.5. Estrella Gneiss is well exposed here.

2.3 Contact between Estrella Gneiss and the Middle Tertiary Telegraph Pass Granite. Small turnout on left. Several Middle Tertiary felsic dikes strike through this area.

2.8 San Juan Road milepost 3.5. Approaching hairpin turn. Telegraph Pass affords a good view of some of the southern foothills of South Mountain.

3.1 Intrusive contact between the Telegraph Pass Granite and South Mountain Granodiorite.

3.3 San Juan Road milepost 4.0. NNW-striking Middle Tertiary microdiorite dikes intrude South Mountain Granodiorite. The paleomagnetic orientation of these intermediate to mafic rocks have been used to determine the amount of rotation experienced by the dikes since emplacement.

3.5 The view to the southwest includes the San Juan Valley, bordered on the northwest by Alta Ridge. The rugged Sierra Estrella mountain range is further southwest.

4.5 Turn left at road intersection for the Dobbins lookout.

5.0 Park for Stop 1. "Droppers" are available here if needed.

STOP 1 - DOBBINS LOOKOUT, SOUTH MOUNTAIN PARK

✔ The purpose of this stop is three-fold: 1) to introduce the physiographic layout of the Phoenix area, 2) to briefly review regional geologic history, and 3) to describe the South Mountain metamorphic core complex and its significance. Depending on time constraints, we will spend 45 minutes to one hour here.

Physiography of the Phoenix area

Arizona is divided into three physiographic/geologic provinces: the Colorado Plateau, the Transition Zone, and the Basin and Range. The terrain in this part of the Basin and Range is generally characterized by NW-trending mountain ranges that are separated by alluvial valleys. The mountains of the Basin and Range consist of fault-bounded and highly eroded rocks of Proterozoic to Cenozoic age. The valleys are commonly filled with Cenozoic volcanic, sedimentary, and alluvial deposits, with normal faults typically buried beneath the alluvium.

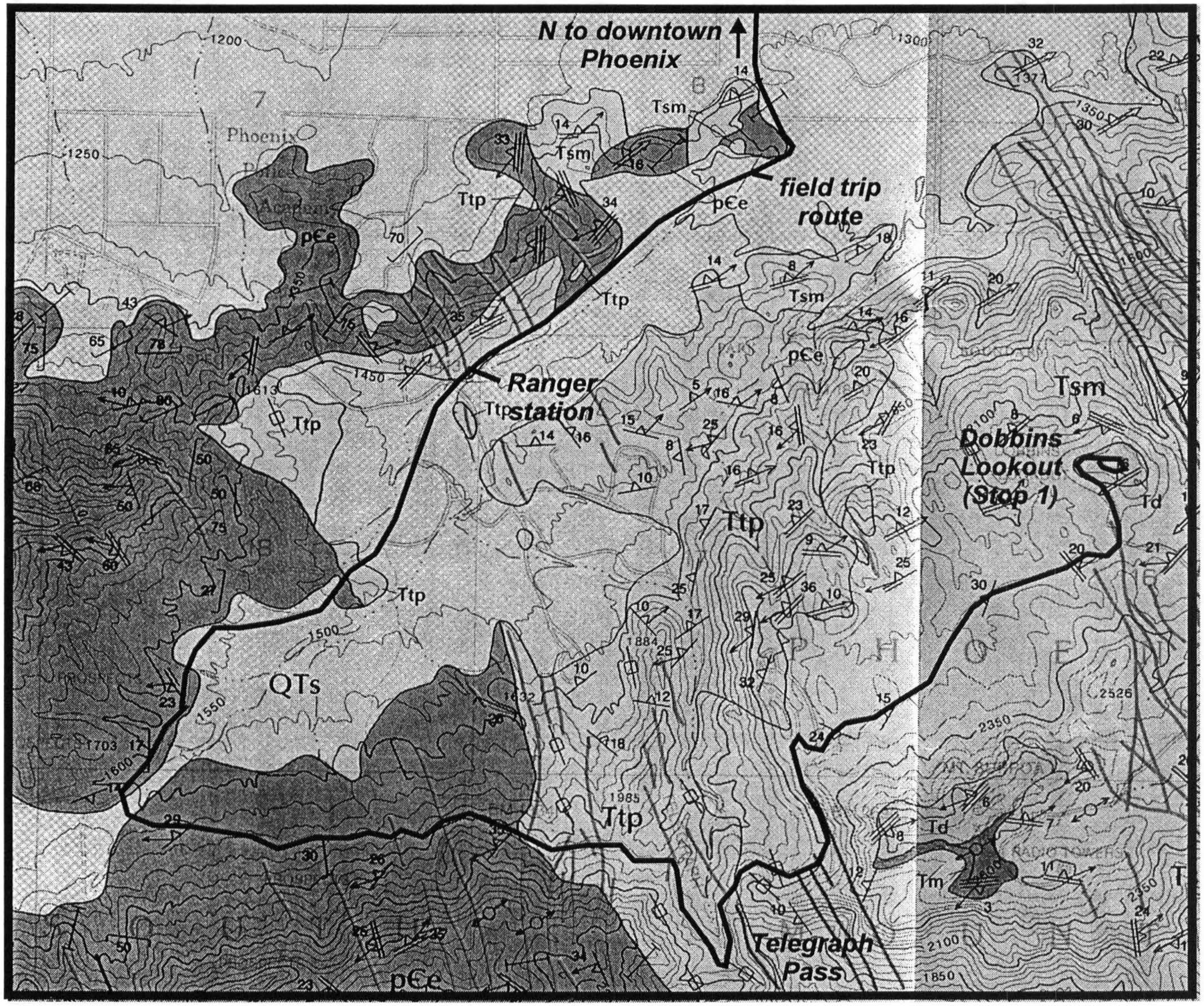
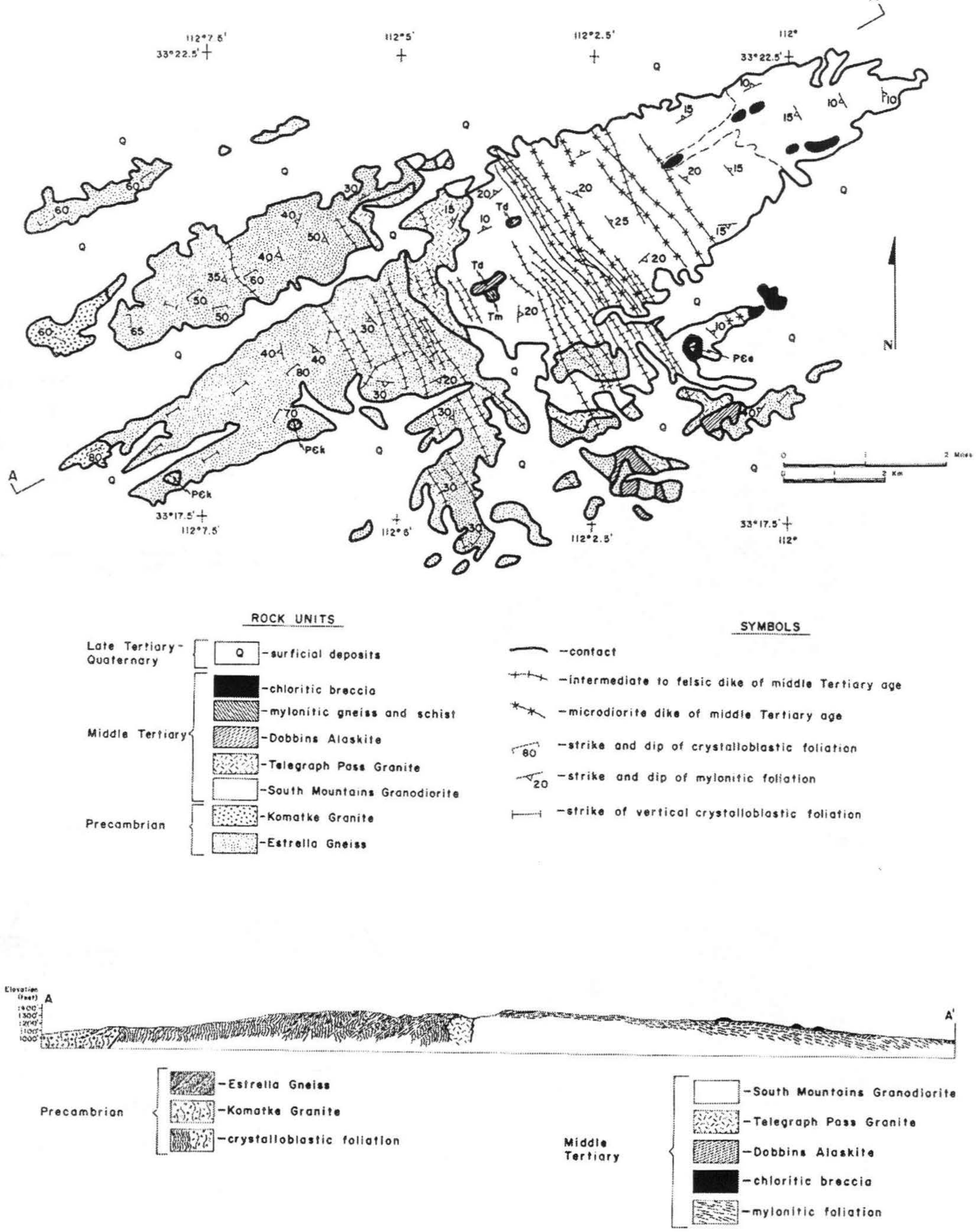


Figure 2. Field trip route through South Mountain Park. Map base from Reynolds (1985).



8

Figure 3. Generalized geologic map and cross section of the South Mountains. Taken from Reynolds (1985).

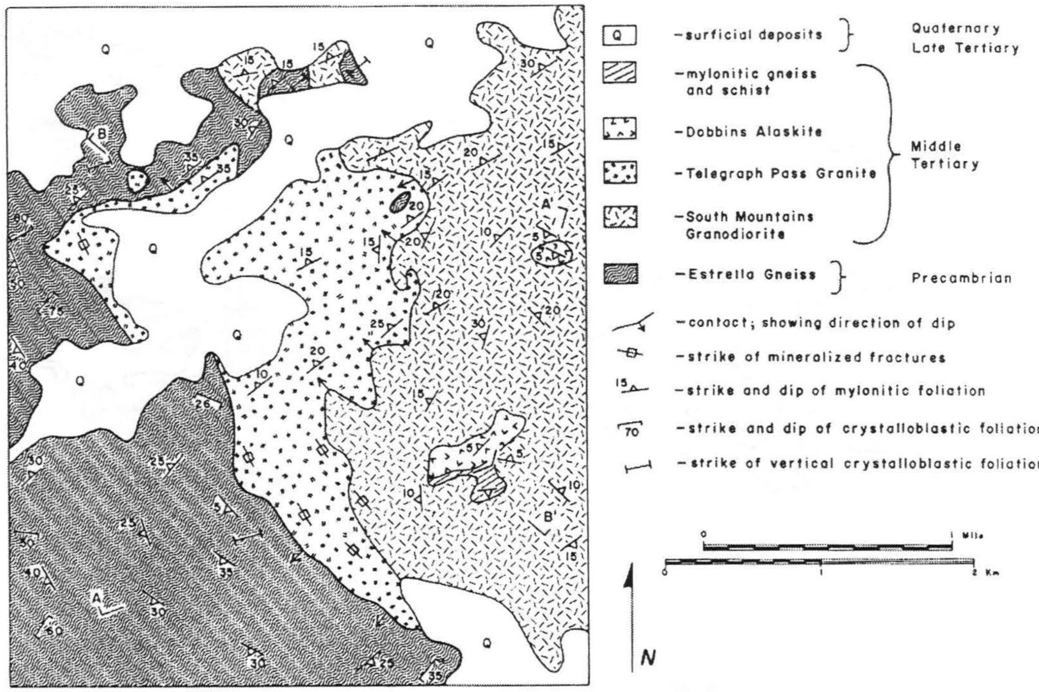


Figure 7. Generalized geologic map of Telegraph Pass and vicinity.

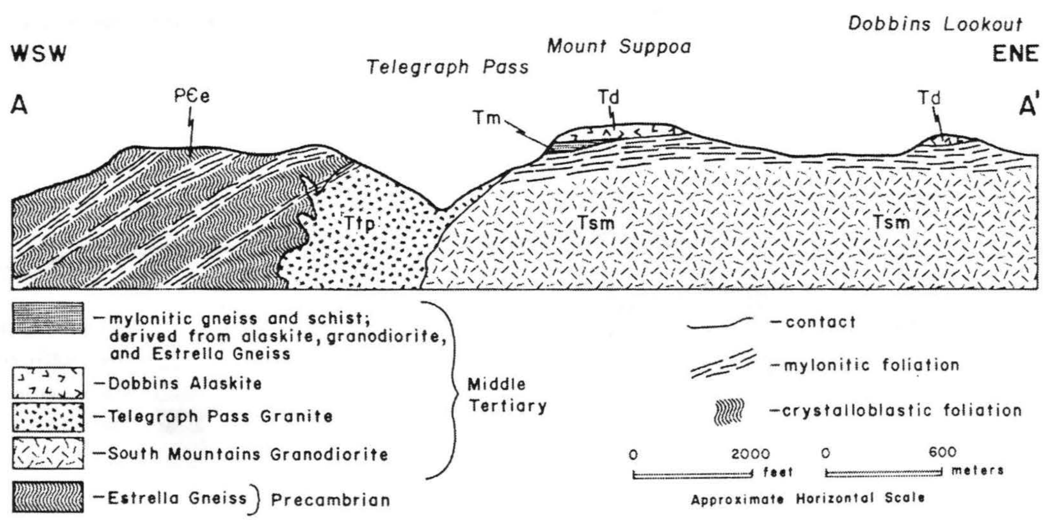


Figure 8. Schematic cross section of Telegraph Pass, Mount Suppoa, and Dobbins Lookout.

9

Figure 3 (continued). Additional geologic maps and cross sections for the central South Mountains area. Taken from Reynolds (1985).

Phoenix area

The Phoenix area is located within the northeastern Basin and Range in central Arizona. The geology of this area is dominated by a mid-Tertiary metamorphic core complex uplift and Middle to Late Tertiary fault-block ranges. Various landmarks that are visible from this location include (Figure 4): radio towers (S10W), Sierra Estrella (S20W to S70W), White Tank Mountains (N65W), Wickenburg (N45W), Bradshaw Mountains (N15W), Central Phoenix (N05W); Squaw Peak, New River Mountains, and New River Mesa (N10E); Camelback Mountain, Pinnacle Peak, and Kentuck Mountain (N25E); Papago Park and central McDowell Mountains (N35E to N45E); Bell Butte and Tempe Butte (N55E); Red Mountain and Four Peaks (N60E); Goldfield Mountains (N70E); Superstition Mountains (N80E).

South Mountains. The South Mountains are an ENE-trending mountain range, containing Early Proterozoic amphibolite-grade metamorphic rocks that have been exhumed by Middle Tertiary detachment faulting. The western South Mountains consist of two strongly deformed, upper amphibolite facies Proterozoic rocks units: the Estrella Gneiss and the Komatke Granite (Reynolds, 1985). The Estrella Gneiss consists of tonalite, tonalitic gneiss, and amphibolite gneiss, whereas the Komatke Granite is a coarse- to medium-grained granodiorite to granite that intrudes the Estrella Gneiss in the westernmost South Mountains (Reynolds, 1985; Reynolds and DeWitt, 1991). The eastern part of the range consists largely of the Middle Tertiary South Mountains granodiorite and Telegraph Pass.

Sierra Estrella. The rugged, NW-trending Sierra Estrella are composed of Early Proterozoic amphibolite-grade metamorphic rocks and lesser Middle Proterozoic granite.

Phoenix Basin. Located to the west of downtown Phoenix, this large, deep Miocene basin formed during the Middle to Late Tertiary. From well log and geophysical data, the depth of the basin is over 10,000 feet. The area is entirely covered by Quaternary surficial deposits.

Salt, Gila, Agua Fria, and Verde Rivers. The major drainage systems of the Phoenix area.

White Tank Mountains. The White Tank Mountains, located <40 km west of Phoenix, contain Proterozoic crystalline rocks intruded by several Cretaceous-Tertiary plutons that have been overprinted by Tertiary mylonites on the eastern edge of the range (Rehrig and Reynolds, 1980; Brittingham, 1985; Reynolds, 1988; Reynolds and DeWitt, 1991). Structural features, similar to those present in the South Mountains, include gently-dipping mylonitic fabrics with an east-northeast-trending lineation, top-to-the-east-northeast sense of shear, and chloritic-breccia-style brittle structures (Spencer and Reynolds, 1989). A detachment fault is locally preserved and an east-northeast-dipping detachment fault, correlative with the South Mountains detachment fault, is inferred to project from over the range toward the northeast, below the Lake Pleasant and New River areas (Spencer and Reynolds, 1989; Kruger et al., in press).

Hieroglyphic Mountains. A significant volume of Early Miocene intermediate to felsic volcanic rocks was erupted across the Hieroglyphic Mountains area (Ward, 1977; Satkin, 1981; Capps et al., 1986; Kortemeier et al., 1986).

Phoenix Mountains. A relatively small NW-trending range consisting almost entirely of Early Proterozoic metamorphic rocks. Includes Squaw Peak, North Mountain, Shaw Butte.

Camelback Mountain. A distinctive Scottsdale landmark with Middle Tertiary fanglomerate (Camels Head Formation) representing the camel's head and Early Proterozoic granite (Camelback granite) forming the hump of the prone camel.

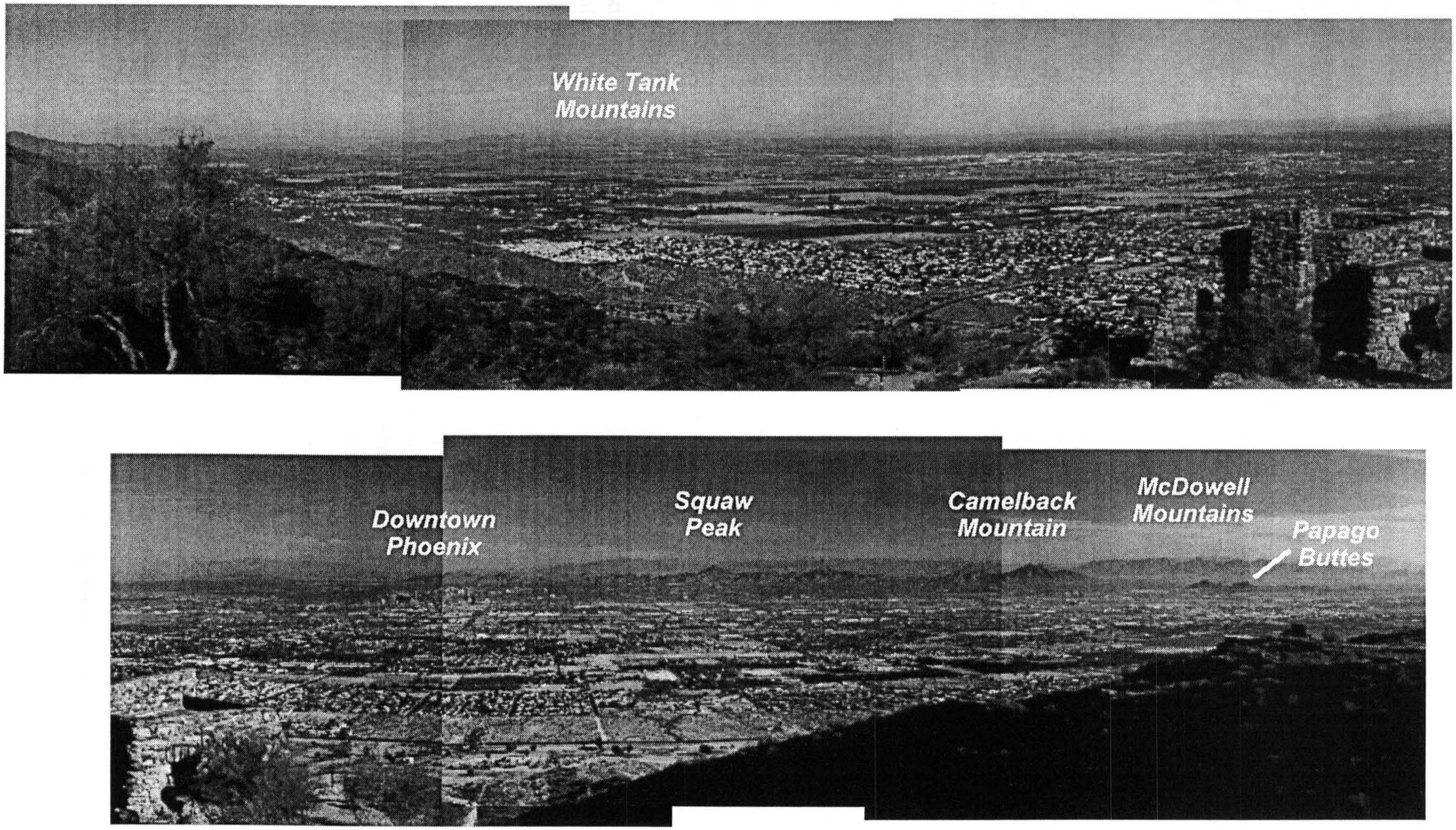


Figure 4. View to the north from Dobbins Lookout across the Phoenix metropolitan area.

North Phoenix area. A large amount of Middle Tertiary crustal extension and rotational faulting greatly affected the Phoenix area Basin and Range and, together with the later high-angle normal faulting of the Basin and Range disturbance, was largely responsible for creating the present physiography of the region. Many of the ranges are underlain predominantly by Proterozoic rocks, including the Phoenix Mountains, Union Hills, and North Union Hills. Many of the tilted, fault-block ranges in the Phoenix area contain Oligocene to Early Miocene rocks (e.g., pre-volcanic fanglomerate, Chalk Canyon formation) and Middle Miocene mesa-capping basaltic flows (e.g., Hickey Formation). Isolated Late Miocene basin-fill clastic sediments are also locally exposed near bedrock ranges. Although voluminous ash-flow-related volcanism occurred across the region during the Middle Tertiary, significant exposures of rocks representing this volcanism are not exposed in this area.

Southern Transition Zone. A relatively unextended area bordering the Basin and Range on the north that includes Proterozoic metamorphic and plutonic rocks of the Early Proterozoic Yavapai and Tonto Basin Supergroups, as well as a variety of Tertiary volcanic and sedimentary rocks. The rugged Bradshaw Mountains and New River Mountains each represent Proterozoic terranes having rocks of different age, metamorphic grade, and deformational fabric. Several broad mesas (e.g., New River Mesa, Skull Mesa) at the southern boundary contain interbedded sequences of Oligocene to Miocene volcanic and sedimentary strata.

McDowell Mountains. A NW-trending range northeast of Phoenix largely underlain by Early Proterozoic metamorphic rocks (i.e., Alder Group) and Middle Proterozoic plutonic rocks. Pinnacle Peak is a distinctive landmark at the northern end.

Tempe area buttes. Small, tilted fault-block remnants (Papago Buttes, Tempe Butte, and Bell Butte) that include well exposed Middle Tertiary sedimentary rocks and altered andesitic lavas.

Superstition Mountains. The Superstition and Goldfield Mountains, located on the boundary between the Basin and Range and Transition Zone east of Phoenix are one of several areas in Arizona dominated by extensive Middle Tertiary felsic ash-flow tuffs and related rocks (Nealey and Sheridan, 1989). Large amounts of rhyolite, rhyodacite, and latite ash-flow tuffs and lava flows, with lesser basaltic rocks and fluvial sediments, overlie basement consisting of various Proterozoic granitoid rocks, Early Proterozoic Pinal Schist, and minor Middle Proterozoic Apache Group sedimentary rocks (Ferguson and Skotnicki, 1996).

Two billion years of Arizona geology

Early Proterozoic

A diverse assemblage of Early Proterozoic (1765 to 1625 Ma) metavolcanic, metasedimentary, and intrusive rocks, comprise the crystalline basement in central Arizona. These rocks largely represent magmatic and deformational processes related to subduction and the formation of continental crust. Early Proterozoic rocks in central Arizona can be broadly divided into two provinces: 1) an older (1800-1700 Ma) northwestern province comprised of supracrustal rocks of the Yavapai Supergroup and batholithic intrusives (Karlstrom et al., 1987), and 2) a younger (1740-1625 Ma) southeastern province largely consisting of rocks of supracrustal rocks of the Tonto Basin Supergroup and Diamond Rim Intrusive Suite (Conway and Wrucke, 1986; Karlstrom and others, 1987). The nature of the boundary between these two provinces is controversial, but has generally been accepted to correlate with the northeast-trending Moore Gulch fault zone. Rocks of the northwestern "Yavapai" province have been interpreted as island arc volcanic rocks and associated calc-alkaline batholiths, whereas rocks of the southeastern "Mazatzal" province have continental affinities and have structural and metamorphic histories representative of more shallow crustal levels (Anderson, 1978, 1986; Condie, 1986; Vance, 1986; Karlstrom et al, 1987). Both provinces include major north- and northeast-trending shear zones (e.g., Shylock fault zone, Moore Gulch fault zone) that may either be discrete zones of high strain within terranes or tectonic sutures between distinctive terranes (Karlstrom and Bowring, 1988).

Middle Proterozoic

Large volumes of Middle Proterozoic granitoid intrusives were emplaced into the Arizona crust between 1485 and 1380 Ma (Silver and others, 1977; Anderson, 1989), after the significant deformational events of the Early Proterozoic. These granites represent the southwestern extent of an extensive belt of similar batholiths that extend from the mid-continent region across the southern Rocky Mountains to the Mojave Desert (Anderson, 1983; Dickinson, 1989). Examples include the granite at the southern end of the Sierra Estrella Mountains, the large porphyritic granite between Cave Creek and the Mazatzal Mountains, and possibly the granite of Pyramid Peak in the north Phoenix area.

Also following Early Proterozoic tectonism and magmatism was the deposition of several kilometers of Middle Proterozoic shallow-marine and coastal-plain sedimentary strata over a continental platform built upon the Early Proterozoic basement. Rocks of this age are absent in the Phoenix area, but are represented by the Grand Canyon Supergroup (Elston and McKee, 1982) and the Apache Group (Shride, 1967), in northern and central Arizona.

Paleozoic and Mesozoic

Several hundred million years elapsed between deposition of the youngest preserved Proterozoic strata (the Chuar Group in the Grand Canyon) and the onset of Paleozoic sedimentation. The widespread structural concordance of Middle Proterozoic and Middle Cambrian strata is dramatic evidence that a remarkably stable continental platform had existed in Arizona since the Late Proterozoic (Dickinson, 1989). During much of the Paleozoic, a shallow sea covered the southwestern margin of the North American craton, resulting in clastic and carbonate sedimentation (>1 km thick) over much of Arizona. Pre-Pennsylvanian Paleozoic strata of Arizona were deposited in shelf seas and related environments that fringed and covered this continental basement platform, but disconformities within this sequence indicate that platform sedimentation was discontinuous, marked by repetitive transgression and regression of marine waters (Dickinson, 1989).The sedimentary rocks (e.g., Tapeats Sandstone, Martin Formation, Redwall Limestone, Supai Group, Kaibab Limestone, etc.) representing Paleozoic continental-margin sedimentation are exposed along the Transition Zone-CP boundary, but are absent in central Arizona, due to either erosion or non-deposition.

Late Mesozoic/Early Tertiary tectonism

Widespread magmatism, compressional deformation, and crustal thickening of the Laramide Orogeny occurred across much of Arizona between the Middle to Late Cretaceous and the earliest Tertiary. Laramide magmatism and deformation were most intense in southern Arizona, starting at ~75 Ma with subduction-related magmatism and ending by ~50 Ma with the intrusion of leucocratic peraluminous granites (Shafiqullah et al., 1980; Haxel et al., 1984). Plutons associated with this magmatism formed the widespread porphyry copper deposits in Arizona between 72 and 54 Ma (Shafiqullah et al., 1980).

Early to Middle Tertiary erosion and sedimentation

The crustal thickening that occurred during the Laramide Orogeny led to widespread Eocene uplift and erosion. Much of the Laramide volcanic cover in Arizona was removed by subsequent Eocene erosion during a 10-30 million year period of tectonic and magmatic quiescence (i.e., the Eocene volcanic gap) following the Laramide Orogeny (Shafiqullah et al., 1980; Spencer and Reynolds, 1989). The resulting Eocene erosion surface, a regionally extensive low-relief surface probably below 1000 meters in elevation (Epis and Chapin, 1975), has been recognized across western North America (Schmitt, 1933; Epis and Chapin, 1975). Southern and central Arizona were part of this regional erosion surface, but were also a source area for fluvial sediments that were deposited to the northeast onto the CP (Peirce et al., 1979; Potochnik, 1989). The "Rim gravels" are constrained as Eocene to Oligocene, in that they contain clasts of 54 Ma Laramide volcanics and contain a 37 Ma rhyolite tuff (Potochnik, 1989).

Early to Middle Tertiary sediments were largely fanglomerates and arkosic redbeds that were deposited across much of the region before the initiation of significant Late Oligocene volcanism. Examples of these pre-volcanic clastic sediments include the Sil Murk Formation in the eastern Gila Bend Mountains (Heindl and Armstrong, 1963; Scarborough and Wilt, 1979; Shafiqullah et al., 1980), the Camels Head Formation in the Phoenix area (Cordy, 1978; Peters, 1979; Scarborough and Wilt, 1979), the Whitetail Conglomerate (Pederson, 1969; Krieger et al., 1979), the basal Pantano Formation (Brennan, 1962; Finnell, 1970; Shafiqullah et al., 1978), and the Cave Creek-Bloody Basin fanglomerates of the Transition Zone (Gomez, 1978; Elston, 1984; Jagiello, 1987; Leighty, 1997).

Middle Tertiary extension, magmatism, and sedimentation

Following the Early Tertiary tectonic quiescence, significant extension and magmatism occurred during the Middle Tertiary (Late Oligocene and Early Miocene), and has been referred to as the "mid-Tertiary orogeny" (Damon, 1964). The Middle Tertiary extension and magmatism in Arizona may have been broadly related to the evolving plate-tectonic setting of the continental margin of western North America (Atwater, 1970), and more specifically to changes in plate motions and geometries compounded by overriding of the progressively thinner and hotter subducted Farallon plate (Coney and Reynolds, 1977; Coney, 1978; Damon, 1979; Pilger and Henyey, 1969).

Extension. Over much of the Arizona Basin and Range, Middle Tertiary tectonism was dominantly characterized by ENE-WSW-directed extension and subsequent fault-block rotation, typically related to the development of metamorphic core complexes (Crittenden et al., 1980; Davis et al., 1980; Wernicke, 1981). Movement on low-angle normal faults (i.e., detachment faults) was responsible for the large-magnitude crustal extension and fault-block rotation in the Basin and Range (Spencer and Reynolds, 1989). Across the central and western Arizona Basin and Range, initiation of extension-related tilting occurred before or during felsic volcanism and before the end of Middle Miocene basaltic volcanism (Spencer et al., 1995). Extension generally ended before 17 Ma, except in a northwest-trending belt adjacent to the relatively unextended Transition Zone (Spencer et al., 1995). The Transition Zone and Colorado Plateau did not experience significant extensional deformation during this time, at least at the shallow crustal levels now exposed. However, the reversal of regional drainage and formation of the Mogollon Rim was a likely effect of middle to lower crustal deflation in response to metamorphic core complex extension in the adjacent Basin and Range (Spencer and Reynolds, 1989).

Magmatism. Much of the Arizona BR was covered by large amounts of volcanic rocks (i.e., felsic to intermediate domes, lava flows, and ash-flow tuffs) during the Middle Tertiary (30-15 Ma) as magmatism migrated from east to west across southern New Mexico and Arizona (Coney and Reynolds, 1977; Shafiqullah et al., 1978; Dickinson, 1979; Shafiqullah et al., 1980; Damon et al., 1981; Lipman, 1981; Seager et al., 1984; Reynolds et al., 1986; Damon, 1989; Dickinson, 1989; Nealey and Sheridan, 1989; Spencer and Reynolds, 1989). Voluminous rhyolitic ash-flow tuffs were erupted in southwestern New Mexico between 40-30 Ma (Elston, 1976; Deal et al., 1978), and continued into southern Arizona between 30-20 Ma, as represented by rocks in the Chiricahua, Galiuro, Superstition-Superior, Castle Dome, and Kofa Mountains; Bikerman, 1968; Eastwood, 1970; Stuckless and Sheridan, 1971; Suneson, 1976; Shafiqullah et al., 1978; Sheridan, 1978; Krieger, 1979; Gutmann, 1982; Latta, 1983; Grubensky and Bagby, 1990; Skotnicki and Ferguson, 1996). By the Early Miocene, the locus of magmatism had moved out of southeastern Arizona and into western Arizona, southeastern California, and coastal Sonora.

Although large amounts of Middle Tertiary ash-flow-related volcanism occurred across the Arizona Basin and Range, more localized alkaline volcanism occurred across the Transition Zone and Colorado Plateau during this time. Late Oligocene (30-25 Ma) diatremes and alkaline rocks were erupted across the Navajo volcanic province of the northeastern Arizona Colorado Plateau. In central Arizona, Late Oligocene to Early Miocene (27.3-18.9 Ma) latites, trachyandesites, and trachytes were erupted in the Sullivan Buttes, New River-Camp Creek, and Cordes areas. Many of these rocks are inclusion-bearing and host crustal and mantle xenoliths.

Basaltic volcanism across the Basin and Range was relatively minor in comparison to the widespread felsic-intermediate volcanism, with the exception of alkaline basalts of the Chalk Canyon Formation exposed across the Basin and Range-Transition Zone boundary. Eruption of relatively small volumes basaltic rocks generally preceded the larger volume felsic-intermediate eruptions. Early and Middle Miocene basaltic volcanism and sedimentation are largely represented by the Chalk Canyon formation and correlative rocks alkaline basalts, fluvial-lacustrine sediments, and tuffs that are exposed across the Basin and Range-Transition Zone in central Arizona. Lower and upper members of the Chalk Canyon formation are distinctive, with the lower member consisting mainly of alkaline basalts and crystal tuffs, whereas the upper member is largely composed of fluvial-lacustrine deposits and subordinate basaltic rocks. Others areas with similar rocks include the Hieroglyphic Mountains (Garfias Wash basalts), Superstition Mountains (Apache Lake basalts), and Bighorn-Belmont Mountains (Deadhorse Formation).

The Middle Miocene tectonic transition

A tectonic and magmatic transition occurred during the Middle Miocene in which the processes characteristic of the mid-Tertiary orogeny waned and those of the Basin and Range Disturbance waxed (Damon and Mauger, 1966; Lipman et al., 1972; Elston, 1976; Coney and Reynolds, 1977; Shafiqullah et al., 1980; Damon et al., 1984; Spencer and Reynolds, 1989). The change from convergent to transform processes at the plate margin is the likely cause for the tectonic and magmatic transition. Late Oligocene and Early Miocene large-magnitude extension and fault-block rotation, along with felsic to intermediate dominated volcanism, were replaced by Middle Miocene low-magnitude extension along high-angle normal faults (Basin and Range Disturbance) and dominantly basaltic volcanism. The timing of the change in the tectonism is constrained in many places by the ages of lava flows situated above and below angular unconformities created across the region (Eberly and Stanley, 1978; Shafiqullah et al., 1980). In the Phoenix area, Middle-Tertiary-style fault-block rotation overlapped in time with the regional, high-angle normal faulting of the Late Miocene Basin and Range disturbance.

Basin-and-Range Disturbance. This period of extension can be characterized by graben subsidence along high-angle normal faults, largely without major crustal block rotation. It began in the Arizona Basin and Range ~15 Ma and ended ~8 Ma. Basin subsidence was probably not simultaneous, but mostly occurred before 8 Ma when differential vertical movement essentially ceased, pediments formed, and basins filled (Shafiqullah et al., 1980). Newly created basins filled with undeformed fluvial and lacustrine deposits and basaltic rocks that were deposited over tilted beds deformed by earlier mid-Tertiary normal faulting. Subsidence also disrupted the Early Miocene drainage and created internal drainage leading to accumulation of fluvial, lacustrine, and evaporate deposits in some basins (Shafiqullah et al., 1980). Similar elevations of pediment gravel layers suggest that basin subsidence occurred with little or no change in the absolute elevation of the surrounding ranges (Peirce, 1976a; Peirce et al., 1979).

Hickey Formation volcanism. Basaltic volcanism during the Middle to Late Miocene was widespread across the Basin and Range and Transition Zone region. Felsic to intermediate volcanism was much less common across the region, occurring locally in western and central Arizona. Basaltic rocks and fluvial sediments of the Middle Miocene Hickey Formation basaltic flows (16.2-13.4 Ma) cap many of the mesas of the southern Transition Zone (e.g., New River Mesa, Skull Mesa, Wild Burro Mesa, Squaw Creek Mesa) and fault-block ranges in the Phoenix area (i.e., Shaw Butte, the Deem and Hedgpeth Hills, and the Rifle Range). The Hickey Formation in these areas typically lacks a significant sedimentary component. Distinction between Early and Middle Miocene basalts in many areas has not been made, but many of the rocks across the Arizona Basin and Range are probably correlative with the Hickey Formation.

Late Miocene to Pliocene sedimentation

The Late Miocene and Pliocene was a time of pedimentation and denudation across much of the Arizona Basin and Range. However, deposition of basin-fill material occurred in several areas across the Transition Zone and northeasternmost Basin and Range. The Carefree basin represents a small depositional basin of probable Late Miocene age that is situated along the Basin and Range -southern Transition Zone boundary. Similar Late Miocene sedimentation also occurred in the lower Verde River area around the Bartlett and Horseshoe Reservoirs.

Quaternary sedimentation

Quaternary surficial deposits cover much of the Phoenix area, and include Pleistocene to Holocene alluvial fan, channel, and terrace units (Demsey, 1988; Pearthree et al., 1997). Piedmont deposits were shed onto the broad plains that slope gently down from mountain ranges toward basin floors. These deposits are generally poorly sorted, containing particles that range in size from silt or clay to cobbles or boulders. Piedmont deposits grade or interfinger downslope into finer-grained deposits. The older alluvial deposits are predominantly exposed marginal to the various bedrock ranges in the area. These sediments are typically extensively eroded, leaving rounded ridges between modern channels. Late Pleistocene and Holocene alluvium is exposed either as fairly narrow bands along washes or as broad thin, basin-covering veneers. Riverine sediments include active channels and one or more terrace levels that record former, higher positions of the stream channels. These deposits are differentiated from piedmont deposits by their diverse lithologic composition, clast rounding, and landform morphology. In the Phoenix area, these deposits are mainly related to the development of the Salt River, Gila, Agua Fria, and Cave Creek drainage systems. River terraces are also commonly elongate landforms that mimic the general trend of the modern rivers.

South Mountain Metamorphic Core Complex

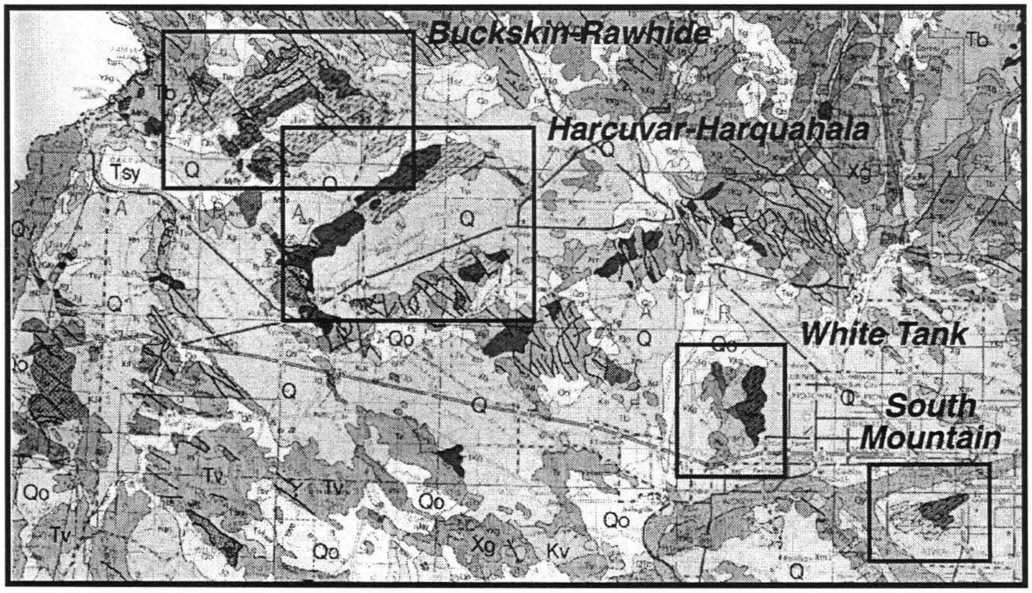
The South Mountains metamorphic core complex is a major tectonic feature in the Phoenix area. A large amount of Middle Tertiary crustal extension and rotational faulting greatly affected this area, together with the later high-angle normal faulting of the Basin and Range disturbance, was largely responsible for creating the present physiography of the region. Metamorphic core complexes have also been recognized in other highly extended parts of Arizona (Figure 5; Buckskin-Rawhide, Harcuvar, Harquahala, Picacho, Tortolita, Catalina, and Rincon Mountains). The origin and evolution of metamorphic core complexes have been the topic of many studies (Coney, 1973; Davis and Coney, 1979; Coney, 1980; Crittenden and others, 1980; Davis, 1980; Wernicke, 1981; Reynolds, 1982; Davis, 1983; Davis and others, 1983; Lister and Davis, 1983; Reynolds, 1985; Reynolds and Lister, 1987; Spencer and Reynolds, 1989).

Metamorphic core complexes possess a central terrane of metamorphic, plutonic, and mylonitic rocks overlain by a marginal zone of brittle deformation and detachment faulting (Figure 6). The crystalline lower plate rocks are typically accompanied by highly faulted and extended upper-plate rocks above the detachment fault. Lower-plate rocks of the South Mountains metamorphic core complex are exposed in the South Mountains, whereas the tilted fault-block ranges to the north represent the upper plate. Large magnitude extension occurs along a low-angle normal fault (detachment fault), with brittle features being formed by normal slip at upper crustal levels and mylonitic fabrics being formed at deeper levels within or slightly below the ductile-brittle transition. With progressive normal shear along the detachment zone, lower plate rocks become successively more shallow relative to the upper plate, therefore becoming increasingly brittle with time. Thus, rocks representing deeper crustal levels (amphibolite facies) have been exhumed at South Mountain by Tertiary detachment faulting, in contrast to the upper crustal rocks (greenschist facies) exposed in ranges above the detachment fault to the north.

In many core complexes, Middle Tertiary magmatism is represented by mid-crustal plutons, but the apparent lack of large Middle Tertiary plutons in other core complexes (e.g., Harcuvar and Harquahala Mountains) indicates that such plutons do not underlie the entire region, but were generally localized sources of magma and heat (Shafiqullah et al., 1978, 1980; Keith et al., 1980; Rehrig, 1982; Reynolds, 1985; Spencer and Reynolds, 1989). Large magnitude extension was not associated with areas of greatest magmatism, and rapid cooling and exhumation of core complexes typically postdated local magmatism (Spencer et al., 1995). However, the long duration and amount of Basin and Range extension adjacent to the Transition Zone are consistent with a mechanism of the gravitational potential energy of the thicker Transition Zone crust causing collapse to the southwest (Spencer et al., 1995).

In the South Mountains, Middle Tertiary granodioritic rocks are overprinted by a gently inclined mylonitic foliation, that contains a conspicuous lineation generally consistent in trend over the entire mountain range (Spencer and Reynolds, 1989). The lower-plate mylonitic rocks display a top-to-the-east-northeast sense of shear that matches the east-northeast transport direction of upper-plate rocks above the detachment fault. These gently dipping mylonitic fabrics have been dated by U-Th-Pb, Rb-Sr, and K-Ar methods at 25 to 20 Ma (Reynolds and Rehrig, 1980; Reynolds, 1985; Reynolds et al., 1986; Spencer and Reynolds, 1989). Fission-track cooling ages on apatite average 18-17 Ma (Fitzgerald et al., 1994). The South Mountain detachment fault projects in the subsurface to the northeast beneath the tilted, upper plate fault-blocks and is visible on seismic reflection profiles (Frost and Okaya, 1986; Spencer and Reynolds, 1989). Thus, active core complex extension occurred during the Early Miocene, but upper plate rotational faulting lasted into the Middle Miocene (<15.4-13.4 Ma Ma), possibly overlapping in time and space with the regional Basin and Range disturbance.

a)



b)

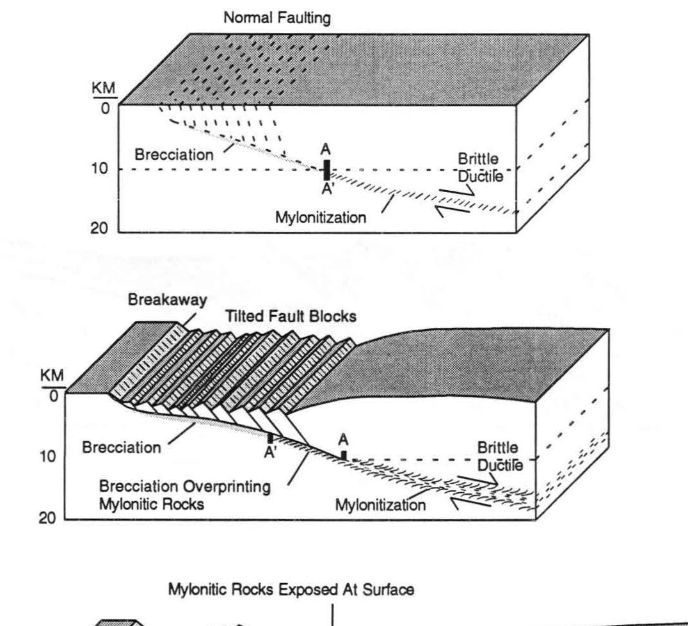


Figure 5. Metamorphic core complexes in central and western Arizona. a) Distribution of metamorphic core complexes in central and western Arizona. Upper-plate tilt-block domains not included. b) Evolution of a typical core complex (Reynolds and others, 1988).

a)

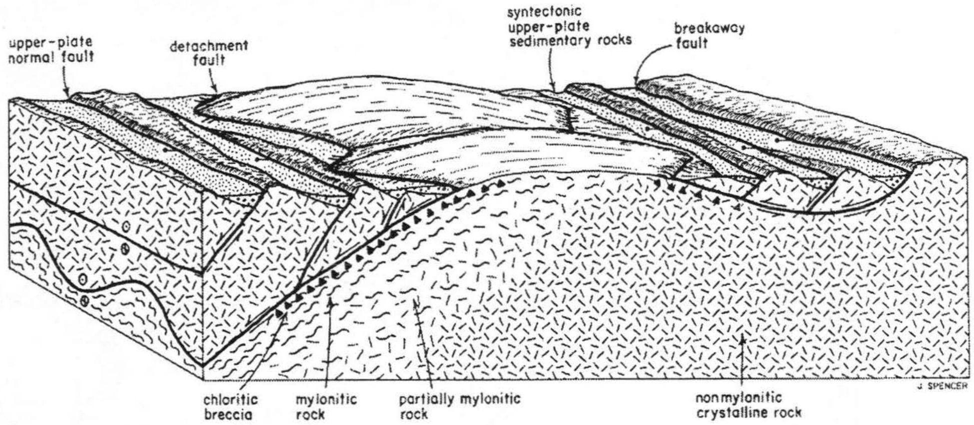


Figure 6. Idealized block diagram of a metamorphic core complex.

b)

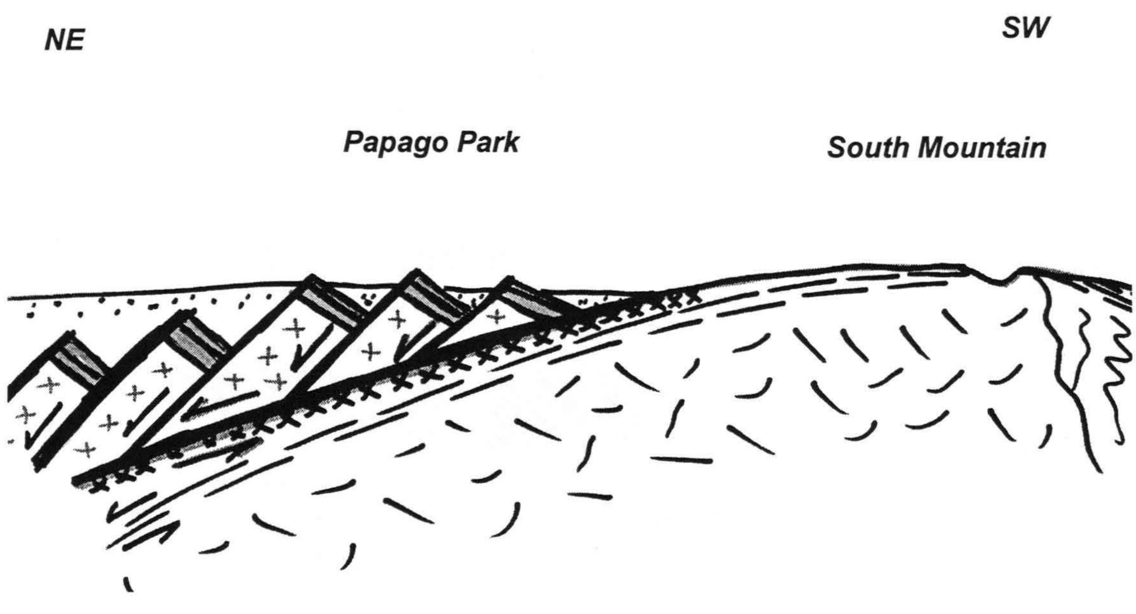


Figure 6. Cross section of a metamorphic core complex. a)Idealized block diagram (from Spener and Reynolds, 1989). b) NE-SW cross section of the northeastern part of the South Mountains metamorphic core complex. Taken from the field notes of Steve Reynolds.

South Mountain to Papago Park*. Proceed to the park exit and continue to Papago Park for the next two stops.*

5.2 Turn right at the junction with the summit road.

5.7 Subhorizontal mylonitic foliation is displayed in the summit area (9-12:00). See Figure 3.

6.1 Holbert Lookout. The road begins the serious downgrade here. View to the west includes the Sierra Estrella, San Juan Valley, and Alta Ridge. Thin microdiorite dikes intrude the South Mountains Granodiorite on left. Other steeply E-dipping mafic dikes are straight ahead.

7.5 Turnout on right. Contact between the Telegraph Pass Granite and Estrella Gneiss.

9.8 Ranger station.

10.2 View to the ENE over Tempe Butte, Red Mountain, and Four Peaks.

10.8 View to the north down Central Avenue, across a broad pediment slope, and toward the downtown Phoenix area.

12.2 Western Canal.

15.0 Salt River. Channel includes moderately- to well-sorted, well rounded sand and gravel clasts.

15.4 Light at frontage road light. Turn right onto 7th Street.

15.9 Pass through the light and enter I-17 southbound.

18.6 Salt River. View of South Mountain and the Sierra Estrellas to the S and W.

21.0 Exit (#153) for AZ143/48th Street (Hohokam Expressway). Stay in left lane. View of Bell Butte at 12:00. Turn left (N) onto AZ143. View of the Camels Head (12:00) and Squaw Peak (11:00).

21.8 University Drive. View of Tempe Butte to the east, Papago Buttes (1:00), and Camelback Mountain (12:00). Stay right.

22.4 Salt River.

22.5 Exit (#3) for AZ202 (Red Mountain Freeway) towards Mesa; stay right and take next exit for Priest Drive.

23.6 Turn left (N) at light onto Priest Drive. At Van Buren Street, Priest Drive becomes Galvin Parkway.

24.8 Turn right at the Papago Park/Zoo light.

24.9 Take the first left. Follow the road around to picnic area #8, at the base of "Hole-in-the-Rock".

STOP 2 - "HOLE-IN-THE-ROCK", PAPAGO PARK

✔ The main purpose of this stop is to briefly (20-30 minutes) observe the unconformity between the Tertiary breccias of the Camels Head Formation and Proterozoic Camelback Granite. Take Hole-in-the-Rock Trail to east.

"Hole-in-the-Rock" is one of many small, erosional remnants of upper plate fault blocks in the Tempe area (Figure 7). In Papago Park, a thick sequence of SW-dipping fanglomerates, locally containing large boulders of Proterozoic granite and metarhyolite, grade upward into the fine-grained Tempe Butte redbeds (Figure 8). These fanglomerates likely represent mudflows or debris flows. At the western end of Camelback Mountain, laminated, reddish, granite-derived grus deposits are overlain by a massive mudflow and debris flow sequence (collectively referred to as the Camels Head Formation), and are lithologically similar to the sediments at Papago Park and Mt. McDowell (Cordy, 1978; Scarborough and Wilt, 1979; Skotnicki, 1995).

At "Hole-in-the-Rock", Proterozoic granite underlies the parking area, with the Tertiary breccia rotated to the SW along a NE-dipping fault (Figure 9). The breccia here is a reddish brown, poorly sorted, massive to very crudely bedded breccia and arkosic breccia. Subangular to angular Proterozoic granite and metarhyolite clasts (1 cm to 5 m diameter) are locally crudely imbricated. The reddish, fine-grained basal sediments are not brecciated and represent an unconformable depositional contact that dips steeply to W (Figure 9). The underlying Camelback Granite to the east is coarse-grained to porphyritic, with large (up to 2 cm) K-feldspar crystals. This unit is variably foliated, and locally contains xenoliths of metarhyolite and fine-grained mafic rock.

The "Hole-in-the-Rock" breccia represents the Barnes Butte Member of the Camels Head Formation (Pewe et al., 1986), which is part of the lower part of a stratigraphic sequence that has the SW-dipping reddish mudstones at Tempe Butte at the top (Figure 8). At Tempe Butte, the younger SW-dipping, laminated reddish siltstones are overlain by 17.6 Ma andesitic flows (Scarborough and Wilt, 1979). These beds include pink to red, poorly to moderately sorted, pebbly arkosic sandstone with less abundant tan to purple siltstone, poorly sorted volcanic arenite, and thin tuff. Median grain size decreases upwards, abundant sedimentary structures. These redbeds may represent fluvial deposition on a floodplain, delta, or marginal playa (Peters, 1979; Scarborough and Wilt, 1979). A deformed fine-grained, quartz + feldspar bed is interbedded with the red beds and likely represents a reworked airfall tuff that was deposited on the floodplain after an eruption from one of several coeval silicic volcanic centers (e.g., Superstition, Hieroglyphic Mountains, etc.).

The andesitic rock capping Tempe Butte is a variably porphyritic trachyandesite, with hornblende, plagioclase, and clinopyroxene phenocrysts (Leighty, 1997). Similar trachyandesitic rocks are present at Bell Butte, a very small erosional remnant roughly 5 km north of the east end of South Mountain. Quartz inclusions and granitic xenoliths are common in rocks at both locations.

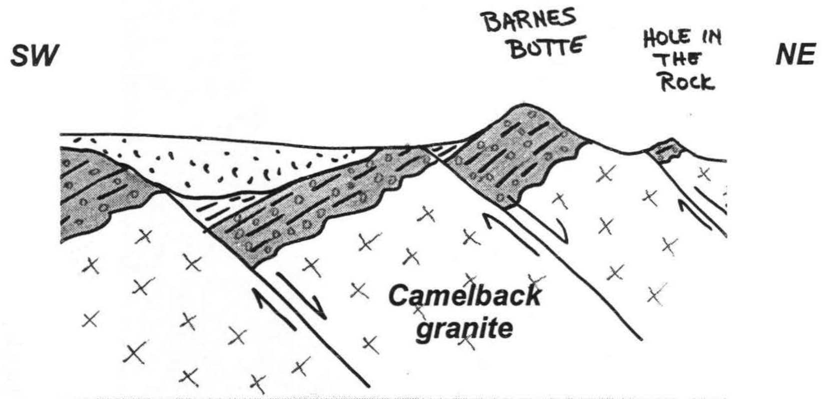
*"**Hole-in-the-Rock" to "Contact Hill", Papago Park.** Return to the Zoo entrance at Galvin Parkway.*

24.9 At the light, cross Galvin Parkway (W), and bear right toward Elliot Ramada. Park at/near the ramada.

STOP 3 - "CONTACT HILL", PAPAGO PARK

✔ The purpose of this stop is to 1) look at debris flow deposits and landslide blocks of the Camels Head Formation and 2) describe the relations between core complex extension and syn-tectonic sedimentation. We will eat lunch here. If the ramada is crowded, feel free to bring lunch on the short hike. Watch your step on the rocks.

a)



b)

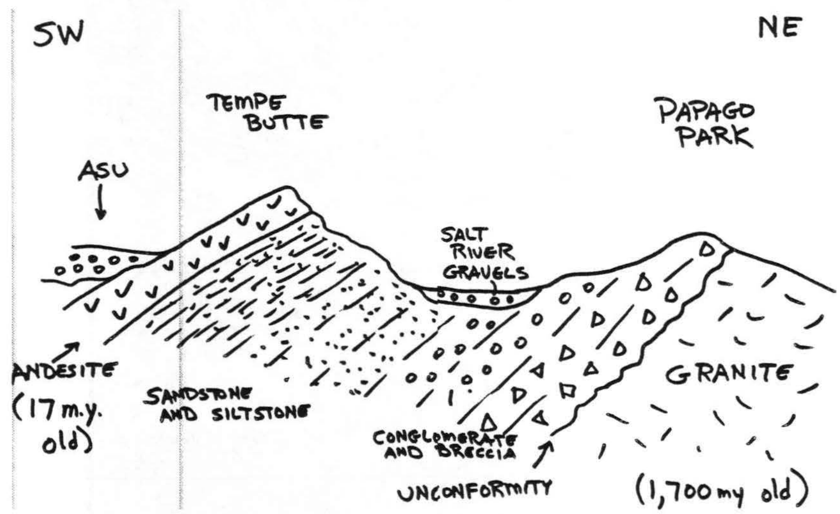


Figure 7. Cross section of the Tempe Butte and Papago Park areas. Taken from the field notes of Steve Reynolds. a) Barnes Butte and "Hole-in-the-Rock" area. b) Tempe Butte to Papago Park.

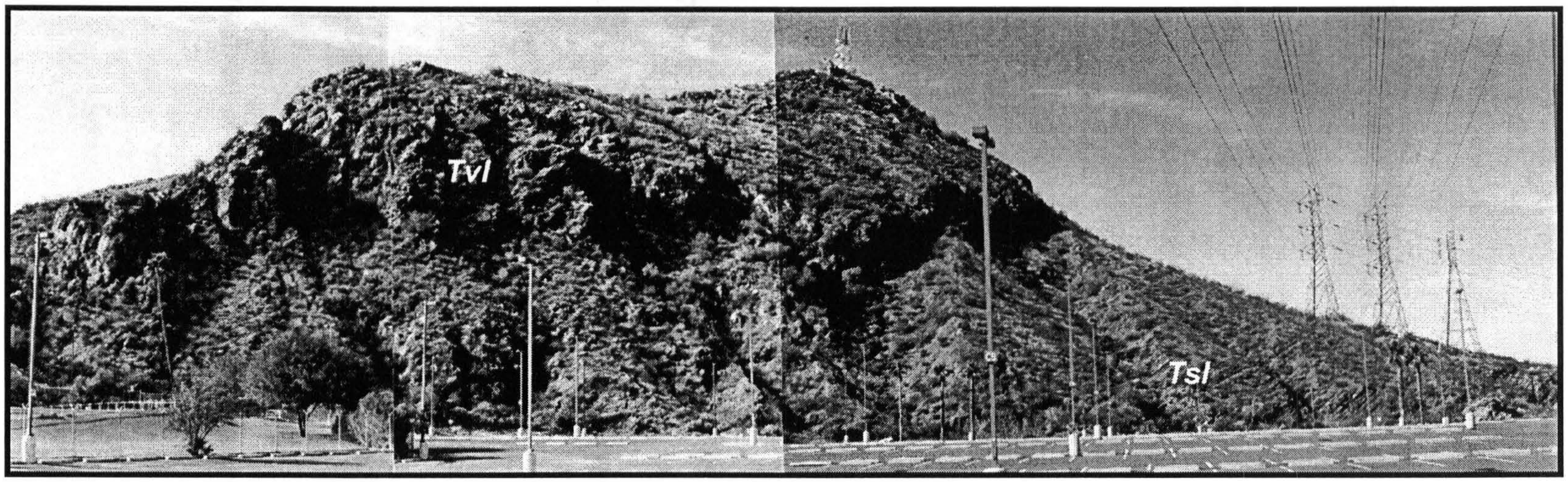
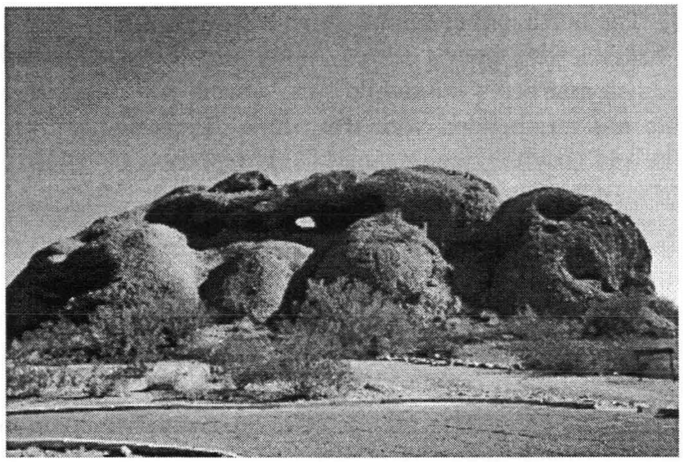
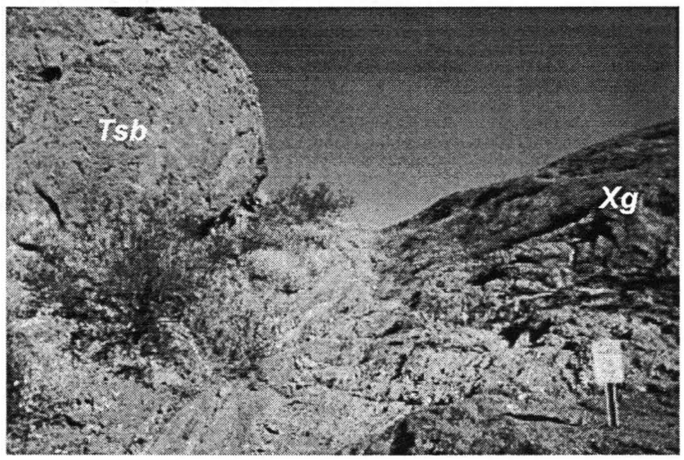


Figure 8. Middle Tertiary sedimentary and volcanic rocks at Tempe Butte.

a)



b)



c)

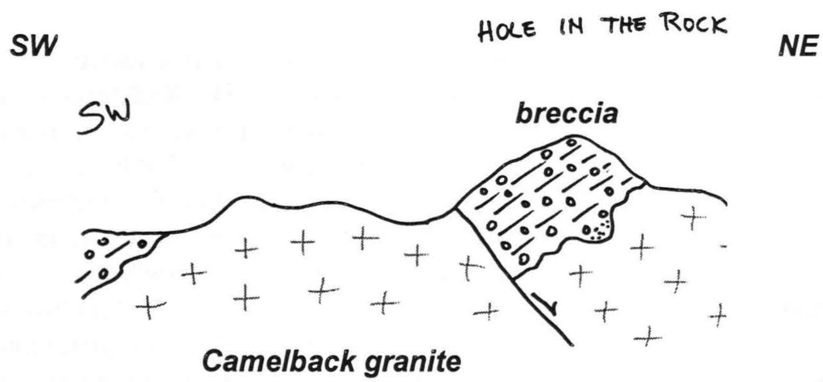


Figure 9. "Hole-in-the-Rock" area. a) View to the east from parking loop. b) View to the north of the basal contact of the SW-dipping breccia and the Early ProterozoicCamelback granite. c) Sketch cross section from the field notes of Steve Reynolds.

"Contact Hill" to the west includes massively bedded debris flows and landslide blocks (Figure 10). The north end of the hill is underlain by debris flows. The granitic debris flows are massively bedded, very poorly sorted, W-dipping deposits, with large granite blocks in a fine-grained, reddish matrix. In the saddle area, breccia with large blocks of granite and fine-grained metarhyolite are interbedded with the debris flows. Farther south, large areas of brecciated metarhyolite and granite (megabreccia) likely represent landslide blocks encased in debris flows. Enclaves of metarhyolite are also exposed within the granite.

During the Middle Tertiary across the Basin and Range and parts of the Transition Zone, clastic sediments accumulated in developing structural basins. The coarse-grained and poorly sorted nature of these deposits suggests relatively short transport distances in areas of considerable relief. These basin-marginal deposits contrast with the finer-grained fluvial-lacustrine clastic sediments, carbonates, and evaporites that may have been more distal deposits. Also, contemporaneous plutonism related to the South Mountain metamorphic core complex was probably occurring at depths of 8-12 km.

Papago Park to the Cave Creek Recreation Area. *This part of the trip will involve roughly 1 hour of driving and will include drive-by descriptions of several area (e.g., the Phoenix Mountains, Union Hills, Paradise Valley, and Carefree-Cave Creek areas).*

26.3 Follow the road to the west from the Elliot Ramada. In this area, Middle Pleistocene surficial deposits cover the pediment that likely fringes most of the Papago Buttes area.

27.5 Papago Park Golf Course. View S and W of the South Mountains and Sierra Estrella.

28.0 Turn left at the light onto 52nd Street.

28.2 Turn right onto westbound AZ202 (Red Mountain Freeway). Exit onto northbound AZ51 (Squaw Peak Parkway).

28.5 View of Camels Head Formation on Camelback Mountain at 3:00. Squaw Peak at 2:00.

31.5 Stay right and enter AZ51 northbound (exit#1).

33.1 View to NW of Squaw Peak and Shaw Butte.

Phoenix Mountains area

The northwest-trending Phoenix Mountains contain a variety of Proterozoic and Tertiary rocks (Shank, 1973; Thorpe, 1980; Anderson, 1989b; Karlstrom et al., 1990; Reynolds and DeWitt, 1991). The Squaw Peak area contains a sequence of metarhyolite, quartzite, and heterogeneous metasedimentary and metavolcanic rocks that have been correlated with rocks of the Tonto Basin Supergroup, including the Alder Group (Anderson, 1989a; Reynolds and DeWitt, 1991; Jones, 1996) and the Mazatzal and Red Rock Groups (Karlstrom et al., 1990). Two types of Tertiary volcanic rocks are present in the Shaw Butte area in the western part of the Phoenix Mountains, including: 1) Early Miocene (20.5-19.2 Ma) alkaline basalts, and 2) Middle Miocene subalkaline basalts. The textural, mineralogical, and geochemical differences between these two units are significant. The alkaline rocks are porphyritic-microcrystalline biotite-bearing olivine + clinopyroxene hawaiites, correlative with similar alkaline basalts of the Chalk Canyon Formation in the Transition Zone. A very thin remnant of Middle Miocene intergranular, plagioclase-phyric, olivine-subalkali basalt caps Shaw Butte and is probably equivalent to the Hickey Formation (15.4 Ma) rocks exposed in the Rifle Range roughly 25 km to the north.

38.4 Dreamy Draw Park to east.

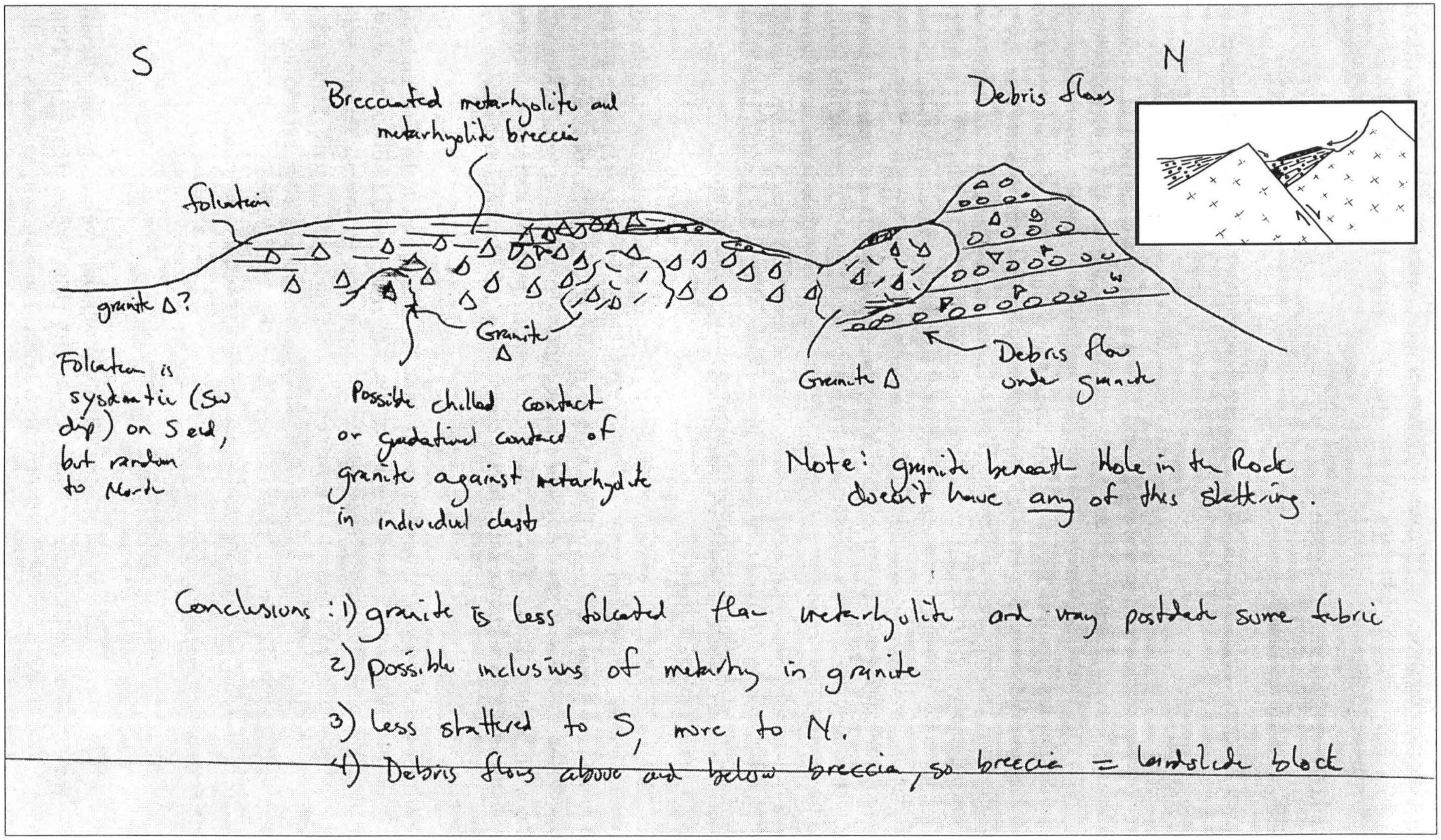


Figure 10. Contact Hill (Stop 3). Sketch from the field notes of Steve Reynolds (10/21/95). Inset diagram shows origin of landslide blocks.

38.9 Large roadcut on the NW side of road. Foliation in these heterogeneous pelitic rocks is NE-dipping here. Get in right lane to exit on 32nd Street (exit#8). The McDowell Mountains are at 12:00.

40.2 Turn right (N) at light onto 32nd Street.

42.6 Turn left on Greenway Road.

43.3 Greenway Parkway curves to north. View to the southwest (9:00) of Lookout Mountain.

Lookout Mountain

Middle Tertiary conglomeratic sediments and basaltic lavas are exposed at Lookout Mountain. The conglomeratic sediments are poorly exposed beneath an apron of colluvium, talus, and Middle Pleistocene sediments. This crudely bedded pre-volcanic conglomerate is similar to the clastic deposits that typically form the base of the Chalk Canyon formation sequence and may correlate with other Middle Tertiary clastic deposits in the Phoenix area. Early Miocene basaltic lavas and breccias cap Lookout Mountain and are likely equivalent to basaltic lavas of the lower member of the Chalk Canyon formation. Basaltic rocks of the lower member (23-20 Ma) are generally dark gray, densely microcrystalline olivine ± clinopyroxene ± biotite basalts of alkaline composition. Although the Lookout Mountain Tertiary sequence dips ~20° to the NNE, there is little direct evidence of major Tertiary fault structures in the area. It is likely that the Union Hills structural block was formed by movement along one or more normal faults, now covered by post-faulting sediments. Quaternary alluvial deposits overlie many deep basins in the area (e.g., Paradise Valley Basin, Luke Basin), where water wells typically do not intersect bedrock. Gravity data suggests that the area underlain by Deer Valley is not a significant basin, but a very large gravity gradient corresponds to the trend of the Paradise Valley.

43.7 Turn right onto Cave Creek Road.

46.0 Buffalo Ridge area. Early to Middle Proterozoic, coarse-grained, relatively unfoliated, porphyritic biotite granite in the roadcuts. This unit is also exposed at the northwesternmost end of the Union Hills and is correlative with granitic rocks exposed to the west in the Biscuit Flat and Hedgpeth Hills Quadrangles that have been informally referred to as the granite of Pyramid Peak. This granite is possibly correlative with the large, Middle Proterozoic granite batholith exposed north of the McDowell Mountains.

47.0 CAP Canal.

47.5 Deer Valley Road. Cave Creek Road now angles to the NE. Basalt to basaltic andesite rocks, likely correlative with the Hickey Formation, cap several small hills to the west. These lavas are characteristically intergranular to porphyritic in overall texture, with altered olivine phenocrysts present in a framework of plagioclase crystals. Similarities with other lavas in the region suggest that these lavas are probably subalkaline in chemistry (olivine-subalkali basalt and basaltic andesite), but hornblende is locally present that may indicate a more silicic composition (e.g., basaltic andesite to andesite).

48.4 Pinnacle Peak Road. Cave Buttes Dam at 9:30.

Union Hills

The Union Hills area includes small ranges and hills, piedmonts with coalescing alluvial fans, whereas broad alluvial plains cover Paradise Valley and Deer Valley. The Union Hills contains a diverse assemblage of Early Proterozoic rock types. The metamorphic rocks of the

Union Hills area are dominantly highly foliated metavolcanic rocks (greenschist facies or lower), with minor psammitic to pelitic metasedimentary rocks. Granitic to dioritic intrusive bodies are also present. These rocks have been described as part of the Union Hills Group, an assemblage of dominantly of mafic to intermediate volcanic rocks and related sediments (1740 to 1720 Ma) that are exposed across the region, from the Union Hills and Cave Creek areas to the Mazatzal Mountains and Sierra Ancha to the northeast (Anderson, 1989b; Reynolds and DeWitt, 1991).

The Union Hills contains a well-preserved sequence of highly foliated, greenschist facies metavolcanic rocks, including thick sequences of basaltic andesite to andesite lavas are interbedded with thinner dacite, rhyolite, iron formation, intermediate to felsic tuff, and breccia. The dominant lithologies in the Union Hills are meta-andesite and metabasalt. These rocks are typically fine- to medium-grained, aphyric to subporphyritic lavas that commonly have plagioclase phenocrysts in a fine-grained chloritic groundmass. Original amphibole and pyroxene have been altered to biotite. Olivine phenocrysts are absent from most lavas, except for those in the southeasternmost part of the Union Hills. The lava flows can be mesoscopically heterogeneous, with chilled margins, microdioritic cores, and vesicular flow tops. Andesitic or basaltic pillow-shaped masses are locally exposed that are 30-60 cm in diameter and have vesicular rinds and hyaloclastic haloes. Lavas with these pillow structures signify subaqueous eruption, and can often be used to define stratigraphic orientation. The pillow lava exposures scattered across the Union Hills generally indicate stratigraphic top to the northwest. All of these units are laterally interbedded with variably thick sequences of andesitic graywacke. Very fine-grained ferruginous chert/iron formation is also present. These sedimentary rocks were likely deposited in a relatively deep submarine environment proximal to the volcanic center. Overall, the metasedimentary rocks and ferruginous chert, along with the metavolcanic rocks, are equivalent to rocks of the Union Hills Group of Anderson (1989b). Similar fine-grained metasedimentary and phyllitic rocks are exposed to the northeast in the Cave Creek area.

49.2 Cave Buttes berm. Panorama of New River Mesa (11:00), Black Mountain (12:00), Skull Mesa (11:30), McDowell Mountains at 2:00-3:00, Pinnacle Peak (2:00), granite pediment (1:00-2:00), Kentuck Mountain (1:00), Black Mountain at 12:00. Entering the Paradise Valley area.

Paradise Valley

The Paradise Valley is a large, Late tertiary basin that is at least 6000 feet deep in this area. Below roughly 5000 feet of basin-fill deposits is a lacustrine sequence containing cherty limestones overlying 330 feet of Early Miocene (22 Ma) basalt and 500 feet of redbeds similar to those present in the Tempe area (Peirce and Scurlock, 1972; Eberly and Stanley, 1978; Scarborough and Wilt, 1979; Shafiqullah et al., 1980). This basalt-sediment sequence correlates with similar Early Miocene rocks in the New River Mesa and Cave Creek areas to the north. The presence of these rocks across the northern Phoenix area suggests that deposition of Late Oligocene and Early Miocene redbeds, fluvial and lacustrine sediments, and basaltic lavas was widespread across the southern Transition Zone and northeastern Basin and Range, occurring prior to or during significant pre-Middle-Tertiary extension.

55.7 At the light, turn left (E) onto AZ74 (Carefree Highway).

57.4 Good view to the NW of the N-trending meta-argillite/granite contact that bisects Black Mountain. The fine-grained Alder Group pelitic rocks in the area may have recrystallized into meta-argillite due to proximity of the granite batholith. Although no mineral growth was observed in the meta-argillite near the summit, abundant hornblende and biotite are present in locally schistose pelitic rocks adjacent to the granite contact at the north end of Black Mountain. This represent the western margin of a large Middle Proterozoic (1422 Ma) granite batholith exposed between the Verde River and the Mazatzal Mountains to the east (C. Isaacson, unpub. data; Leighty et al. 1997; Skotnicki and Leighty, 1997).

57.7 At the light, turn left (N) onto Tom Darlington Drive. Large granite boulders are exposed here.

Carefree area

Granite and pediment. In this area, the relatively low relief alluvial plain gives way to an extensive pediment surface, broken only by a few isolated granite knobs and hills of Tertiary rhyolite and tuff to the east of Scottsdale Road (Figure 11). Unfoliated, coarse-grained Middle Proterozoic granite and granitic pediment forms the basement between Black Mountain and the McDowell Mountains (Péwé et al., 1985; Kenny, 1986; Doorn and Péwé, 1991; Leighty et al., 1997; Skotnicki et al., 1997). The granite weathers into large spheroidal boulders and erodes easily into grus that mantles the granitic bedrock. A variable thickness of grus mantles much of the low-relief pediment surface. These deposits are formed by the in situ weathering of the granite, and result in a subdued, rounded, and moderately dissected surface.

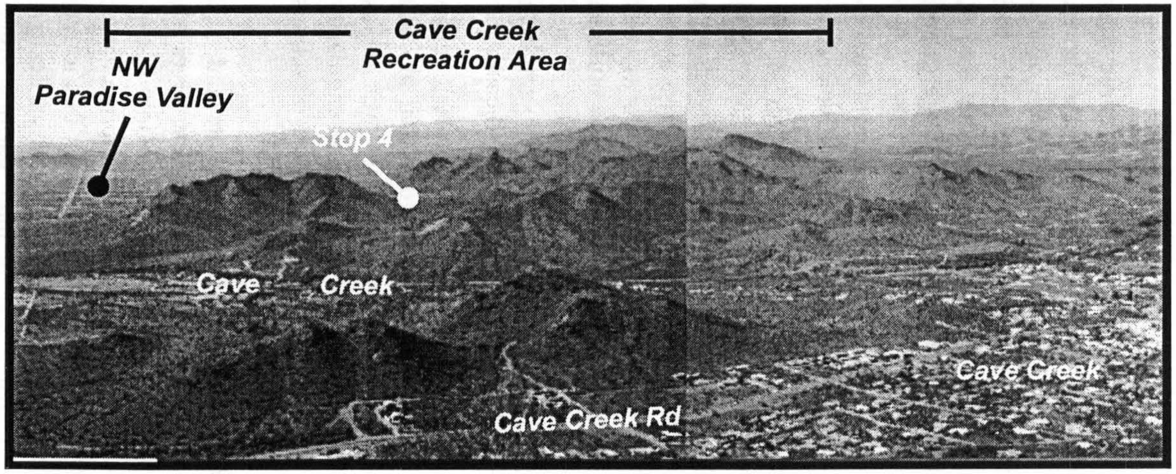
Radon. Radon, a colorless, odorless gas, is a product of the radioactive decay of uranium. Radon produced in the ground as part of the uranium decay series can escape into overlying homes and other buildings, and can result in elevated radiation exposure, and associated risk of cancer, to human lungs. Areas with higher uranium concentrations present greater risk of elevated indoor radon levels (Spencer, 1992).

Uranium is present in all geologic materials, generally in concentrations of 1 to 10 parts per million (ppm). Uranium levels in the Carefree granite, measured *in situ* with a gamma-ray spectrometer, vary from 1 to 13 ppm (Harris, 1997). Most measurements revealed levels of 6 ppm or less, which is considered normal. The high variability of uranium levels is possibly due to different amounts of leaching of uranium from weathered granite at or near the surface. The occurrence of local elevated uranium concentrations, plus the generally permeable character of weathered granite which allows radon to leak out of the ground (Peake and Schumann, 1991), indicate that elevated radon levels in homes built on this granite are probably more likely than on most other geologic materials in the Phoenix metropolitan area.

A thin, WNW-trending discontinuous belt of Early to Middle Miocene calcareous sedimentary rocks (Chalk Canyon formation ≈ White Eagle Mine formation) is present from Carefree to New River (Scarborough and Wilt, 1979; Doorn and Péwé, 1991; Leighty, 1997). These rocks contain anomalous uranium levels in many areas (Duncan and Spencer, 1993): a single measurement of 50 ppm uranium reported by Harris (1997) If near the surface, these rocks can be a significant potential radon hazard in the Cave Creek area.

58.7 Big Brownie Hill and Little Brownie Hill (4:00) are outliers of Tertiary rocks on the granite pediment. The view to the north includes Continental Mountain (12:00), with Skull Mesa to its left.

59.6 Intersection with Cave Creek Road. The view to the north includes Lone Mountain (1:00), Continental Mountain (11:00), and Skull Mesa (10:00). Turn left (W) onto Cave Creek Road.



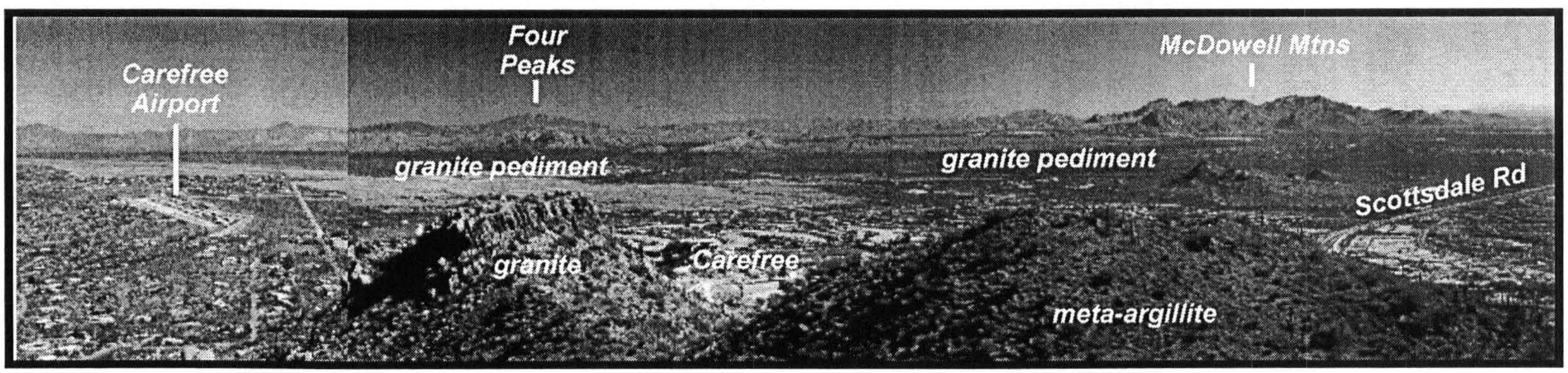


Figure 11. Views from the summit of Black Mountain. a) View west toward the Cave Creek Recreation Area. Hills in middleground are part of the metavolcanic-dominated assemblage The town of Cave Creek is at right. b) View to the east of the Carefree area, showing the granite/meta-argillite contact, the granite pediment, and the McDowell Mountains to the southeast.

Basin and Range - Southern Transition Zone boundary

The area north of Carefree and Cave Creek straddles the physiographic and structural boundary between the Basin and Range and Transition Zone in central Arizona (Figure 12). The mountainous area to the northeast represents the southern boundary of the Transition Zone. The Tertiary volcanic and sedimentary sequence include Early to Middle Tertiary pre-volcanic fanglomerate, Late Oligocene/Early Miocene trachyandesite and trachyte, Early Miocene Chalk Canyon Formation alkaline basalt, tuffaceous sediment, and felsic tuff, multiple subalkaline flows of the Middle Miocene Hickey Formation, and Late Miocene Carefree Basin-related sediment.

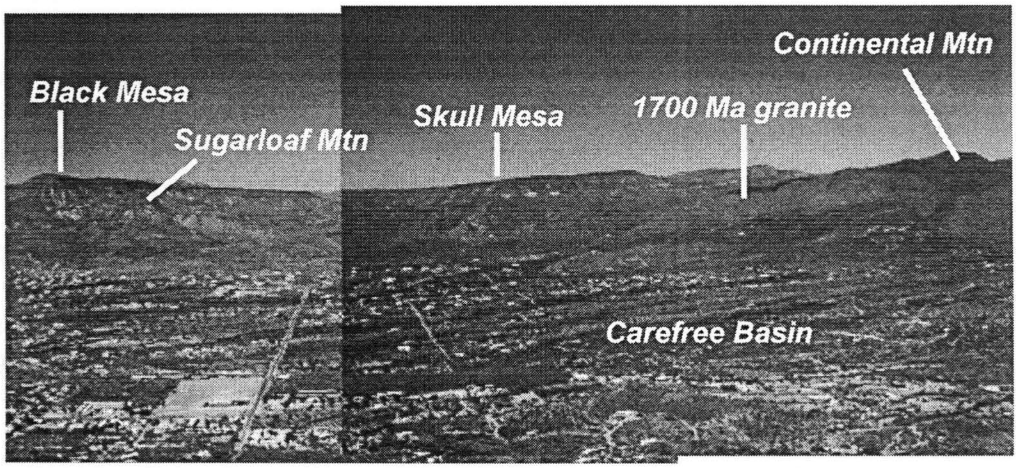
Proterozoic rocks. This area contains a diverse assemblage of Proterozoic rock types. The Early Proterozoic rocks are part of the "Mazatzal province" that includes the Proterozoic terrain southeast of the Moore Gulch fault zone (Conway et al., 1987). The rocks of this terrane are correlative with the rocks of the Tonto Basin Supergroup, consisting of mafic to intermediate volcanic rocks of the Union Hills Group, felsic volcanic rocks of the Red Rock Group, metasedimentary rocks of the Alder and Mazatzal Groups, and several large granitic batholiths (Anderson and Guilbert, 1979; Karlstrom et al., 1987; Maynard, 1986; Maynard, 1989; Anderson, 1989b; Conway and Silver, 1989). Middle Proterozoic granitoid rocks of the Cave Creek quadrangle are part of a larger, regionally extensive granitic batholithic assemblage.

The Early Proterozoic metamorphic rocks (greenschist facies or lower) of the Cave Creek area can be subdivided into two broad sequences that include (1) a highly foliated, lithologically diverse metavolcanic and metasedimentary assemblage in the northwestern part of the quadrangle, and (2) a less foliated, dominantly metasedimentary assemblage in the central and northeastern parts of the quadrangle. Early Proterozoic dioritic to granodioritic plutonic bodies are also present within the northwestern assemblage. In adjacent areas to the north and northwest of the Cave Creek quadrangle, the 1700 Ma rocks of the New River Felsic Complex underlie much of the New River Mountains (Maynard, 1986; Anderson, 1989b). The southern portions of the 1700 Ma Verde River granite batholith are present to the north and northeast.

Pre-volcanic fanglomerate. A reddish-orange fanglomerate is locally present between the Cave Creek and Bloody Basin and represents the oldest post-Laramide rock unit in central Arizona. The lack of Tertiary volcanic clasts suggests that the fanglomerate was deposited before significant volcanism in the area, and the large clast size, poor sorting, and angularity of many of the clasts suggest that the clasts experienced minimal transport. Paleoflow directions commonly indicate local control, with some NE-directed flow (Ferguson et al., 1998).

Middle Tertiary felsic to intermediate volcanic rocks. Trachyandesite and trachyte domes and flows are exposed in several places across the STZ, including the New River Mesa, Gavilan Peak, Cline Creek, Elephant Mountain, Sugarloaf Mountain, Orizaba Mine, Camp Creek, and Grapevine Wash areas. Alkaline plugs and associated short flows of intermediate composition (trachyandesites and trachytes) predate all other Tertiary volcanic rocks of the region and the initiation of significant Tertiary magmatism in central Arizona. The trachyandesites (latites and benmoreites) and trachytes are typically porphyritic and include various combinations of clinopyroxene, biotite, and hornblende phenocrysts in a densely microcrystalline groundmass. Glomerocrysts of these minerals are common and xenoliths of badly altered wall rock are found locally. No mantle-derived nodules have been observed in these rocks, although crustal xenoliths are locally abundant (e.g., the Camp Creek latite). The precise ages of many of these rocks are not known, but may correlate with similar Late Oligocene rocks (26.5 to 22.0 Ma) to the west.

a)



b)

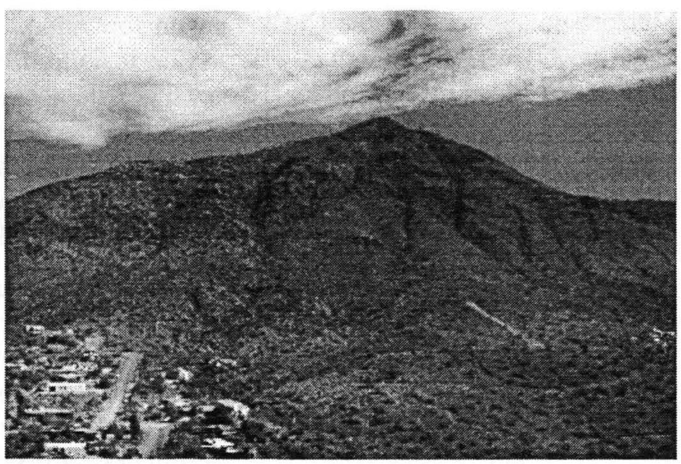


Figure 12. Cave Creek area. a) View north across the Carefree Basin toward the southern Transition Zone. b) Dark, resistant meta-argillite at Black Mountain. View to the east.

Chalk Canyon formation. Interbedded basalts, felsic tuffs, and fluvial lacustrine sediments of the Early Miocene Chalk Canyon Formation are well-exposed across this area. The basaltic rocks of the lower member are typically porphyritic olivine-phyric lavas that commonly contain modal biotite, and are probably alkaline basalts. These basalts are interbedded with several lithic and crystal-rich tuffs. The lowest exposed basalt flow at Sugarloaf Mountain is a 21.3 Ma alkali basalt that overlies sediment containing an oreodont fossil, the oldest known mammal in Arizona (Lindsay and Lundin, 1972). The upper member is dominated by fluvial-lacustrine sediments.

At Lone Mountain, the White Eagle Mine area is important because it constrains (at least locally) the nature of the contact between the Chalk Canyon formation and Hickey Formation. The youngest dated Chalk Canyon formation lower member basaltic rocks are 20 Ma, leaving the age relations of the upper member ill-defined (<20Ma). In most places, the Hickey Formation basaltic rocks disconformably overlie Chalk Canyon Formation lacustrine sediments, and paleosols are common at this horizon. These relations suggest a hiatus of indeterminate length between the final deposition of Chalk Canyon Formation lakebed sediments and the earliest eruption of Hickey Formation basaltic rocks. However, the lowest basalt in the White Eagle Mine section (15.4 Ma) underlies a thin sequence of lakebed sediments, and therefore represent a conformable relationship between the uppermost lacustrine sediments of the Chalk Canyon Formation and the lowest Hickey Formation basaltic rocks.

Hickey Formation. Widespread Middle Miocene Hickey Formation basalts cap many of the mesas in this area and represent the youngest products of Tertiary volcanism in the southern Transition Zone. Hickey Formation sheet lavas may have extended across the much of the northern Phoenix area, where the dated lavas range from 16.2 to 13.4 Ma. The cliff-forming Middle Miocene (14.8-14.7 Ma) Hickey Formation basaltic flows that cap Skull Mesa and New River Mesa unconformably overlie the Chalk Canyon formation. These lava flows have been referred to as the New River Mesa basalt (Gomez, 1978; Jagiello, 1987), but simply represent the southern Transition Zone equivalent of the Hickey Formation (Anderson and Creasey, 1958; McKee and Anderson, 1971; Eberly and Stanley, 1978; Gomez and Elston, 1978; Elston, 1984). The maximum exposed thickness occurs at Black Mesa, where as many as eight flows are present. These rocks also have characteristic intergranular textures, with clinopyroxene and altered olivine phenocrysts within a framework of plagioclase crystals.

Carefree Basin. The Carefree Basin is a small, WNW-trending structural basin of probable Late Miocene age, located between Black Mountain and the Proterozoic basement terrane to the north. The thickness of basin-fill deposits (the Carefree Formation) is roughly 2,000 ft in the eastern part of the basin, but is less in the western part of the basin (Doorn and Péwé, 1991). Thus, the Carefree Basin is less deep than nearby basins in the Basin and Range, such as the Paradise Valley and Phoenix Basins, which are typically greater than 9,000 feet deep.

Late Miocene to Pliocene basin-fill sediments are exposed in the Carefree Basin area north of the towns of Cave Creek and Carefree (Doorn and Pewe, 1991; Leighty et al., 1997). The basin-fill sediments included in the Carefree Formation are subdivided into five members composed of material derived from different local sources. The basin-fill deposits consist of interbedded, moderately to poorly sorted sandstones and conglomerates, containing heterolithic subrounded to angular clasts. Sandstone and basalt-rich conglomerate and grade upward and laterally into fine-grained siltstone representing playa deposits. Lower basin-fill sediments are tilted, but become more horizontal upward in the section. Although most of the members of the Carefree Formation have low discharge rates (0-50 g.p.m.), the Grapevine Member, which underlies much of the basin, has the highest permeability in the Carefree Formation and produces up to 1,600 g.p.m. Doorn and Péwé (1991).

Late Miocene extension

Middle to Late Miocene tectonism and coeval fluvial sedimentation, are responsible for much of the physiographic and geologic characteristics of the modern Basin and Range-Transition Zone boundary. This extension may have been related to one or more tectonic phases, including waning core complex extension, block faulting of the Basin and Range Disturbance, or an even younger extensional event (Menges and Pearthree, 1989; Leighty and Reynolds, 1996).

The Late Tertiary structural development of the Basin and Range-Transition Zone boundary involved two major of W- to NW-trending groups of normal faults (Figure 13). The SW-dipping strata along the northeastern margin of the Carefree Basin were rotated along a NE-dipping normal faults, whereas the Carefree Basin and the NE-dipping tilt-blocks of the Basin and Range were formed by movement along SW-dipping normal faults. Although the two main faults representing each set are covered by post-faulting sediments and are not exposed at the surface, the locations of the faults in the subsurface can be constrained from geometrical relationships and well log data (Doorn and Péwé, 1991). Each of these large faults probably exists beneath the northeastern boundary of the Carefree Basin, less than 1 kilometer southwest of exposed tilted Tertiary strata. These faults may be related to the Carefree fault system, located in the Wildcat Hill quadrangle to the east (Skotnicki and others, 1997).

Northeast-dipping faults. The southwest tilting of the homoclinal strata of the high mesas to the north can be observed between New River Mesa and Carefree. The gently N-dipping Tertiary strata of New River Mesa changes gradually to slightly a SW-dipping at its southern extremity. Larger southwesterly dips (~15°) occur at Elephant Mountain. Excellent exposures are present in the Lone Mountain and White Eagle Mine areas (see cross sections B-B' and D-D'), where the SW-dipping Tertiary rocks are cut by several secondary faults having relatively small displacements. These faults were probably related to a larger, NE-dipping, somewhat listric fault that is buried beneath younger sedimentary cover. This fault (informally referred to here as the Lone Mountain fault) is probably listric to account for the 20-40° rotation of Tertiary strata. This fault may have projected beneath the high mesas to the north, and was possibly synthetic to the NE-dipping South Mountain-White Tank detachment fault system associated with metamorphic core complex development in the nearby Basin and Range. If so, this implies that core-complex-related extension occurred after 13.4 Ma (late Middle Miocene).

Southwest-dipping faults. The large, NE-dipping tilt-blocks in the Basin and Range, between Phoenix and the high mesas of the Transition Zone, formed with movement along large, SW-dipping normal faults. Development of the Carefree Basin likely occurred in response to this faulting, which may or may not have directly followed the extension involving the NE-dipping normal faults. Although it is possible that the Carefree Basin formed before the movement along the NE-dipping normal faults, various considerations make this scenario less plausible. A large, southwest-side-down normal fault (informally referred to here as the Carefree Basin fault) was likely the master structure bounding the northeast side of the asymmetric, Carefree Basin half-graben. Another large, SW-dipping normal fault may bound the southwestern side of the bedrock block containing the granitic pediment, Black Mountain, the Cave Creek Recreation Area, and Apache Peak; this fault may be buried beneath the alluvial cover.

59.8 Carefree Basin sediments are exposed in the roadcut. Note Verde Granite to N. Good vista.

60.2 Passing Circle-K. S-dipping strata of Black Mesa are visible to the west.

60.9 Schoolhouse Road. Excellent view to the north. The Plio-Pleistocene Elephant Mountain terrace to the NW is the highest and oldest Cave Creek-related terrace.

Cave Creek

Cave Creek is a moderately large drainage that heads in the Transition Zone to the north. It is capable of generating large floods, and its principal tributaries generate smaller, but still significant, floods. During the late Pliocene, Cave Creek may have initially drained to the west along a strike valley between the main scarp of the high mesas and the first Basin and Range tilt-block. This drainage is represented by the highest Cave Creek terrace (the Little Elephant terrace of Gorey, 1990; Doorn and Péwé, 1991). Deposition of the Carefree Formation covered much of the lower bedrock surfaces in the area, and the highest level of basin-fill deposition may have formed a topographic barrier to the flow of Cave Creek to the southeast. Flow of Cave Creek subsequently was diverted to the south, where the drainage eventually cut through the basin-fill sediments and into the Proterozoic bedrock. Further downcutting by Cave Creek likely resulted in the removal of unconsolidated sediments from the upper parts of the basin-fill deposits, exposing the moderately consolidated fanglomerates and underlying volcanic and basement rocks.

62.0 Blue Ridge Drive.

Western Black Mountain area

The largely of clastic metasedimentary rocks (i.e., Alder Group) contrast with the primarily of metavolcanic and related metavolcaniclastic deposits (i.e., Union Hills Group) in western Black Mountain area. Dark purplish gray to dark maroon, relatively homogeneous pelitic rocks are exposed on the northwestern flanks of Black Mountain to the SE. These rocks may correlate with the Alder Group, which typically consists of purple slate, siltstone, and graywacke, with lesser rhyolitic tuff, psammite, chert, metaconglomerate, and limestone. The low hills to SW contain a complexly interbedded and compositionally diverse sequence that are different than those exposed at Black Mountain to the east of Cave Creek Road (see Figure 12). The contact is sharp, dips to the west at ~45° and may represent either an angular unconformity or a discrete, pre-foliation Early Proterozoic fault. The NW-younging direction inferred from the meta-argillite at Black Mountain and phyllitic metasedimentary rocks west of Cave Creek rules out the possibility that this contact is an angular unconformity because older rocks would overlie younger rocks. This contact may be structural, representing a fault forming before development of the NNE-trending regional foliation since there is no significant difference in foliation orientations across the boundary. This contact may represent a rotated, west-vergent thrust fault that placed Union Hills Group rocks over younger Alder Group rocks.

63.2 New River Road at bottom of the alluvial fan. The contrast between alluvium dominated by darker metamorphic clasts and lighter granite is well defined.

63.8 At light, turn right (W) onto AZ74 (Carefree Highway).

65.6 Cave Creek. Several Cave Creek terrace levels are present in this area.

66.5 Turn right (N) onto 32nd Street. (Cave Creek Parkway).

Apache Peak is composed of a thick sequence of porphyritic basalts with interbedded crystal tuffs and tuffaceous sediments (Jagiello, 1987).

68.1 Entrance gate to the Cave Creek Recreation Area. Early Proterozoic andesitic tuffs and pelitic sediments are exposed in this area. Follow the road around to its termination at the picnic areas.

69.1 Turn left (N) on Tonalite Drive. Turn immediately right (E) and park. Bathrooms and picnic areas are available here.

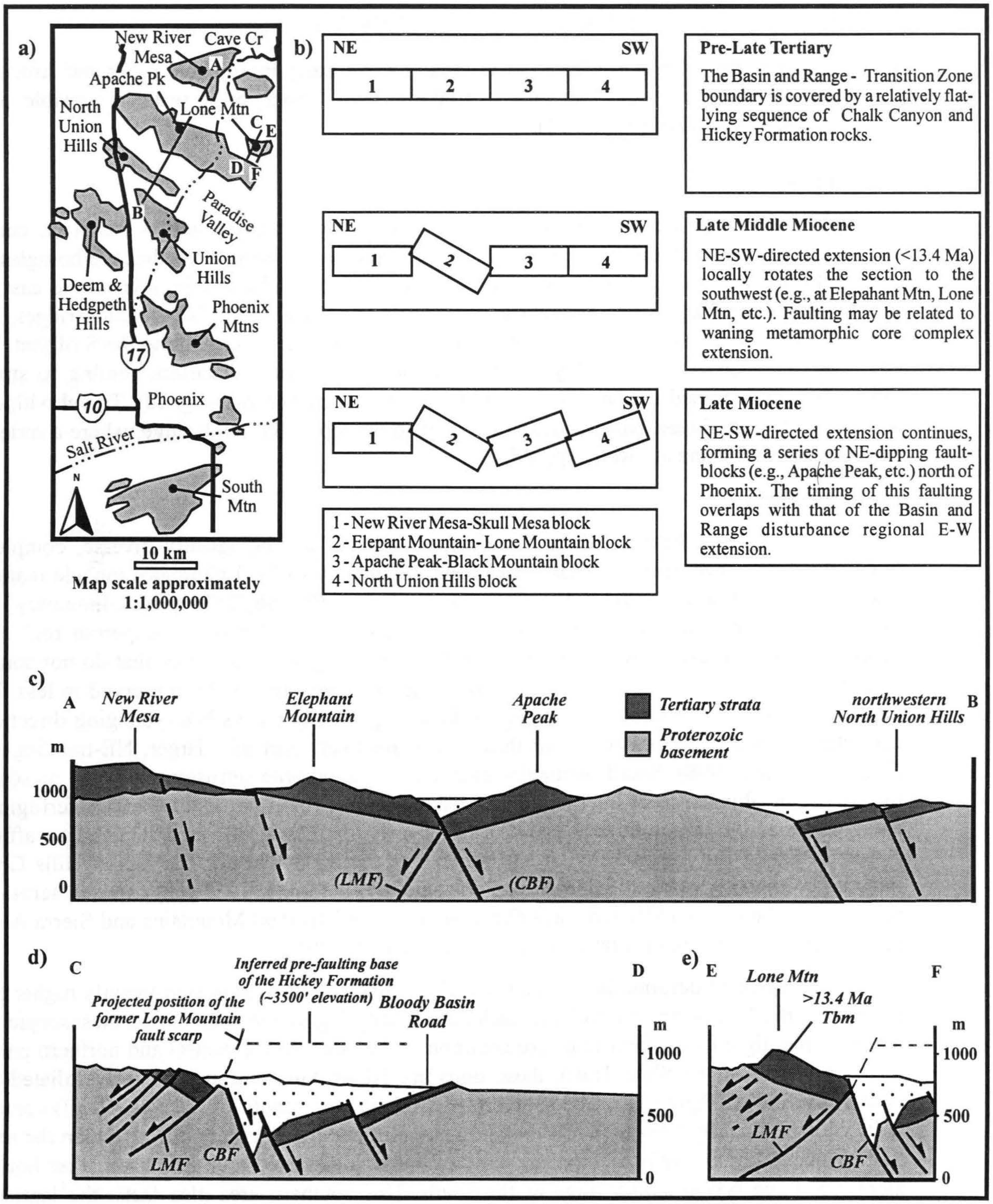


Figure 1.3 Structural evolution of the southern Transition Zone - northern Basin and Range boundary. a) Location map (modified from Reynolds and Grubensky (1993) with cross section locations. b) Block diagrams describing the sequence of Late Tertiary extension. c) Simplified geologic cross section from New River Mesa to northwestern Union Hills Modified from Jagiello (1987) and Leighty (unpub. mapping). d) Simplified geologic cross section of part of the Carefree Basin. Modified from Leighty et al. (1997). LMF = Lone Mountain fault, CBF = Carefree Basin fault. e) Simplified geologic cross section of the Lone Mountain area. Modified from Leighty et al. (1997). The scale of all cross sections is 1:100,000 with no vertical exaggeration.

STOP 4. CAVE CREEK RECREATION AREA

✔ The goal of this stop is to take a closer look at some Early Proterozoic rocks and structures while stretching our legs. This hike will take at least 1 hour; bring water if possible. Start east on the Slate Trail (Figure 14).

Slate Trail

Initially, the trail crosses a Middle Pleistocene alluvial surface with a desert pavement. Note the clast compositions as we go east; they give clues as to what the bedrock lithologies are locally. Continue east on Slate Trail, passing Jasper trail. Black Mountain is visible to east. To the N, intermediate and felsic metavolcanic rocks form several large, NE-trending ridges. The next hill to the E contains ferruginous metasedimentary rocks, with phyllite to the S of that. The trail eventually crosses into highly foliated, pelitic rocks. Exit trail before coming to stream (where two large armed saguaros and a milky quartz outcrop become aligned). Travel with care across the small drainage, past the quartz outcrop, to the top of the small ridge, where a series of folded felsic tuff layers are well exposed.

Local Geology

The area from here to Black Mountain consists of a lithologically diverse, complexly interbedded sequence of metavolcanic and metasedimentary rocks. Lithologies include mafic to intermediate volcanic rocks, felsic lava flows and tuffs, phyllitic metasedimentary and metavolcanic rocks, hematitic sediments, ferruginous chert, and massive jasperoid rock. The metasedimentary rocks in this area are generally very fine-grained phyllites that do not contain well-preserved sedimentary structures. However, graded beds are locally preserved in less fine-grained metasedimentary rocks. Bedding in the area generally shows NW-younging directions, consistent with the interpretation that these rocks are likely part of a larger, NE-trending fold (Ferguson et al., 1998). Small, lenticular diorite and granodiorite intrusions are also present in this area. The abundance of intermediate to felsic volcanic rocks and related rocks, ferruginous chert, and massive jasperoid rock and dioritic intrusive bodies in this area suggests an affinity closer to that of the Union Hills Group rather than the Alder Group. The Union Hills Group includes dominantly mafic to intermediate volcanic rocks (1740 to 1720 Ma) exposed across the region from the Union Hills and Cave Creek areas to the Mazatzal Mountains and Sierra Ancha to the northeast (Anderson, 1989b; Reynolds and DeWitt, 1991).

The degree of deformation in the Cave Creek Recreation Area is significantly higher than in areas to the NE, north of Carefree. Rocks are locally highly crenulated, and mesoscopic and macroscopic, tight to isoclinal folds are common in this area. In the central and northern part of the park (north of the Slate Trail), these units are NE-striking and are intensely foliated and isoclinally folded (Figure 10). The southern part of the park (south of the Slate Trail) contains units with dominantly NW- to WNW-trending strike orientations that are different than the rocks to their north. For example, an elongate body of massive jasperoid rock forms a marker horizon along the large NW-trending ridge to the south. This southern area also lacks the lenticular metavolcanic and dioritic intrusive rocks that are abundant to the north. The lithologic and orientation differences between the northern and southern parts of the Cave Creek Recreation Area may result from: 1) a W-trending, pre-foliation fault or 2) a large, W-trending fold.

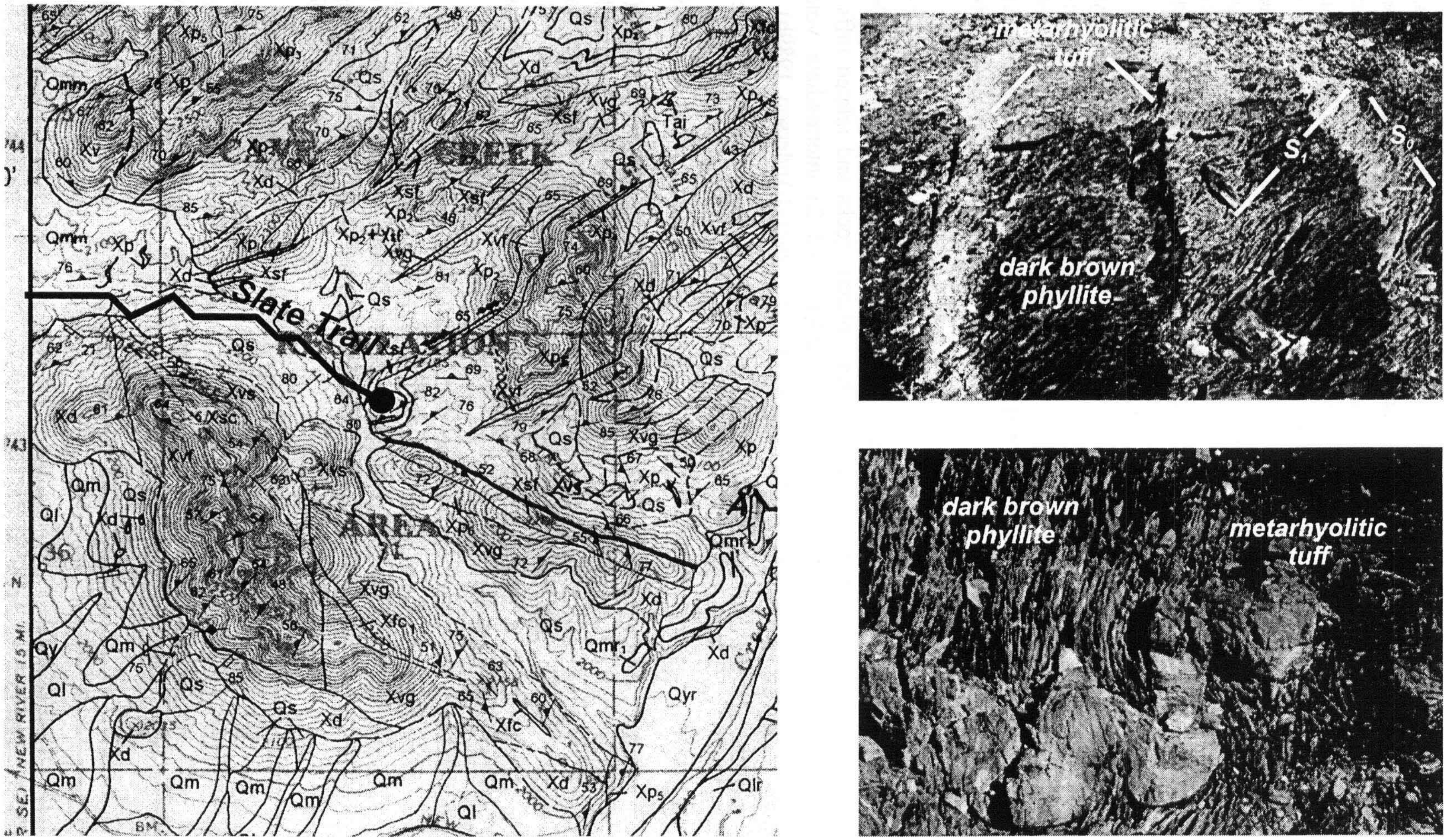


Figure 14. Cave Creek Recreation Area (Stop4). a) 1:24,000 scale geologic map from Leighty et al. (1997) showing traverse to fold hill. b) Bedding-cleavage relationships. Lighter beds are felsic tuff layers interbedded in the darker phyllite. c) Shortened tuff bed in fold hinge area.

Regional stratigraphy: the Tonto Basin Supergroup and related rocks

The Cave Creek Recreation Area includes Early Proterozoic metavolcanic, metasedimentary, and intrusive rocks that are part of an Early Proterozoic terrane ("the Mazatzal Province") that contains rocks having similar age, metamorphic grade, and deformational fabrics, largely correlative with the Tonto Basin Supergroup and Diamond Rim Intrusive Suite (1740 to 1680 Ma; Anderson and Guilbert, 1979; Maynard, 1986; Karlstrom et al., 1987; Anderson, 1989a,b; Conway and Silver, 1989). The metamorphic rocks of this terrane are distinctly different in lithology, petrology, chemistry, and geologic setting than the rocks of the Yavapai Supergroup (1800 to 1740 Ma), exposed to the north of the Moore Gulch fault zone in the Transition Zone (Anderson, 1968b; Karlstrom and Bowring, 1988; Anderson, 1989b).

The Tonto Basin Supergroup was probably formed between 1740 and 1700 Ma, deformed largely between 1700 and 1650 Ma, and intruded by pre-1700-Ma granite and hypabyssal rocks (Anderson, 1989a,b; Conway and Silver, 1989; DeWitt, 1989; Karlstrom et al., 1990; Reynolds and DeWitt, 1991). Although the stratigraphy and nomenclature are still somewhat controversial, the Tonto Basin Supergroup includes four major groups (from oldest to youngest): Union Hills Group, Alder Group, Red Rock Group, and Mazatzal Group (Anderson, 1989a,b; Conway and Silver, 1989; Reynolds and DeWitt, 1991).

Union Hills Group. The Union Hills Group (1740-1720 Ma) is the oldest unit of the Tonto Basin Supergroup, but is distinctly younger than the Yavapai Supergroup. The Union Hills Group includes: 1) mafic, intermediate, and felsic volcanic rocks and related tuffs that were deposited in proximity to submarine volcanic centers, and 2) intermediate volcanic and volcaniclastic rocks deposited distally from major volcanic centers (Anderson, 1989b).

Alder Group. The Alder Group (1720-1710 Ma) is composed largely of clastic metasedimentary rocks (e.g., purple shale, quartzite) and felsic volcanic rocks. Alder Group volcanism may have occurred largely in shallow seas (Gastil, 1958; Conway, 1976; Conway and Silver, 1989).

Red Rock Group. The Red Rock Group is a thick sequence of felsic extrusive rocks (i.e., alkali rhyolite ash-flow tuffs) overlying the Alder Group in the Tonto Basin and Mazatzal Mountains (Ludwig, 1974; Conway, 1976; Wrucke and Conway, 1987). Felsic magmatism was broadly contemporaneous with quartz arenite deposition in the upper part of the Alder and Mazatzal Groups. The Red Rock Group was probably deposited subaerially (Gastil, 1958; Conway, 1976; Conway and Silver, 1989).

Mazatzal Group. Relatively mature quartzite and other siliciclastic rocks of the Mazatzal Group (Wilson, 1939; Anderson and Wirth, 1981; Anderson, 1986) are the youngest part of the Tonto Basin Supergroup. This thick sequence of quartz arenite is fundamentally of continent-margin character and was deposited in fluvial and shallow-marine environments (Krieger, 1965; Trevena, 1979; Anderson and Wirth, 1981; Conway et al., 1981; Conway and Silver, 1984).

Intrusive rocks. Plutonism in the area was slightly different than that which occurred northwest of the Moore Gulch fault zone. Except for plutons coeval with the Union Hills Group volcanism, pre-1720-Ma plutonic rocks are effectively absent. The earliest major batholiths are voluminous 1710 to1700 Ma granites (e.g., Verde River granite, Payson granite) that were coeval with ignimbrites of the younger felsic complexes.

Deformation. The Yavapai Orogeny (1700-1690 Ma) involved crustal shortening, thickening, and uplift which generated the N- to NE-striking subvertical foliation that is the dominant fabric in central Arizona (Karlstrom and Bowring, 1991). Regional deformation related to the Mazatzal Orogeny (1675-1625 Ma) is generally characterized by NW-vergent folding and thrusting.

🚌 ***Cave Creek Recreation Area to North Union Hills.*** *Head south on 32^{nd} Street to its intersection with the Carefree Highway.*

71.7 Intersection of 32^{nd} Street and the Carefree Highway. The view ahead includes the McDowell Mountains (SE), Squaw Peak (S), and the North Union Hills (SW).

75.5 7^{th} Avenue

75.6 Pull-off after guardrail before curve in road.

Stop 5 - Overview (if time permits)

✔ The goal of this stop is to briefly synthesize the Tertiary geologic evolution the area.

Eocene to Oligocene

- Pre-volcanic deposition of fanglomerate and arkosic redbeds.

Late Oligocene and Early Miocene

- Localized eruption of trachyandesite and trachyte domes and flows across the Transition Zone. Some of these units contain crust (and possibly upper mantle) xenoliths.
- Large magnitude, ENE-WSW extension in the Basin and Range involved low-angle detachment faulting. The Transition Zone experienced minor upper crustal extension, but significant volumes of lower crust were removed with the southwest-directed collapse of the thick Basin and Range crust (Spencer and Reynolds, 1989).
- Subduction-related, dominantly felsic ash-flow volcanism occurred across the Basin and Range, whereas basaltic volcanism, represented by the alkaline lavas of the Chalk Canyon formation, occurred across southern Transition Zone.

Middle and Late Miocene

- Across the northern Basin and Range, waning NE-SW-directed, rotational faulting directly preceded or overlapped with the E-W regional extension of the Basin and Range disturbance.
- Hickey Formation volcanism resulted from the interaction of relatively hot, convecting asthenosphere, through the sublithospheric slab window, with the base of the lithospheric mantle (Leighty, 1997). Melting progressed into the lithospheric mantle, occurring mostly within the thermal boundary layer above the convecting asthenosphere (Leighty, 1997). This period of thermal erosion of the lithospheric mantle may have been responsible for much of the present lithospheric geometry under the Transition Zone (Leighty, 1997).
- The thinned lower crust and lithospheric mantle under the Transition Zone allowed the relatively thick, buoyant Colorado Plateau crust to dominate the stress field (Leighty, 1997). Late Miocene and younger NE-SW extension propagated across the Transition Zone, culminating with the development of several large structural basins (Leighty, 1997).

Pliocene

- Minor, buoyancy-related NE-SW-directed extension continued to affect the southwestern Colorado Plateau margin.
- The scattered basaltic magmatism in the Basin and Range was dominantly alkaline and asthenosphere-derived.

North Union Hills to south Phoenix. Continue west to I-17.

76.1 Outcrop of reddish, altered felsic rock (Proterozoic). This unit has elevated U concentrations and may be a potential radon hazard (Harris et al., 1998).

76.4 Pyramid Peak at 12:00.

76.5 Early to Middle Proterozoic granite (near future intersection of 19th Avenue).

77.9 Skunk Creek. To the northwest, the small, northeast-dipping Rifle Range contains poorly exposed Early Miocene tuffaceous sandstones, olivine + clinopyroxene basalts, and cherty dolomite (Scarborough and Wilt, 1979; Jagiello, 1987). The mesa-capping 15.4 Ma Hickey plagioclase + olivine basaltic lavas overlie the Chalk Canyon formation carbonates with a slight angular unconformity (Scarborough and Wilt, 1979; Jagiello, 1987).

78.5 Cross I-17. Turn left onto I-17 southbound. Biscuit Flat and Pyramid Peak are to the southwest. The main Proterozoic units in the Biscuit Flat area are a mafic plutonic complex that consists predominantly of tonalite, diorite, and gabbro and an unfoliated, coarse-grained, porphyritic biotite granite (the granite of Pyramid Peak; Reynolds and DeWitt, 1991; Leighty and Huckleberry, 1998). Much of the Biscuit Flat area to the north and west of Pyramid Peak is a low-relief grus-covered pediment surface developed upon coarse-grained Proterozoic granite.

80.6 At 10:00, coarse-grained granite is quarried for use as decorative yard rock.

82.1 CAP canal. Tertiary rocks in the Deem Hills to the west are gently NE-dipping and contain trachyte, andesite, basalt, poorly exposed fluvial-lacustrine beds, and a thin layer of Middle Miocene olivine subalkali basalt. (Jagiello, 1987; Leighty, 1997). The andesite contains sieved andesine and distinctive resorbed quartz inclusions with clinopyroxene reaction coronas (Leighty, 1997). The sedimentary rocks are correlative with the Chalk Canyon formation and include conglomeratic sandstone and thin carbonate and calcareous sandstone (Jagiello, 1987).

83.3 Skunk Creek.

84.3 Happy Valley Road. Immediately west of the highway, the andesitic lavas of Adobe Mountain are largely buried by desert-varnished andesitic talus. These dark gray, porphyritic lavas contain glassy plagioclase phenocrysts and resorbed quartz inclusions. In the Hedgpeth Hills Quadrangle to the west, similar andesite overlies the basalt-tuff sequence and Hickey Formation basaltic rocks (e.g., Ludden Mountain, Hedgpeth Hills), but also underlies the conglomeratic and tuffaceous units (e.g., Deem Hills).

86.7 Loop AZ101. The Hedgpeth Hills to the west are a small, NE-dipping range similar to the Deem Hills. However, this range lacks fluvial-lacustrine sediments and the andesite unit overlies the Hickey basaltic lavas.

102.8 Durango Curve. View of the South Mountains (12:00) and the Sierra Estrella (2:00).

104.2 Exit (#196) for 7th Avenue/Central Avenue. Proceed south on central to parking area. Total mileage is roughly 107 miles.

END OF ROAD LOG

REFERENCES

Anderson, C.A., and Creasey, S.C., 1958, Geology and ore deposits of the Jerome area, Yavapai County, Arizona: U.S. Geological Survey Professional Paper 308, 185 p., 9 sheets, scale 1:24,000.

Anderson, P., and Guilbert, J.M., 1979, The Precambrian massive-sulfide deposits of Arizona, a distinct metallogenic epoch and province, in Ridge, J.D., ed., Papers on mineral deposits of western North America (IAGOD Fifth Quadrennial Symposium Proceedings, V. 2): Nevada Bureau of Mines and Geology Report 33, p. 39-48.

Anderson, P., and Wirth, K.R., 1981, Uranium potential in Precambrian conglomerates of the central Arizona arch: U.S. Department of Energy Report GJBX-33(81), 576 p.

Anderson, C.A., 1968b, Metamorphosed Precambrian silicic volcanic rocks in central Arizona, in Coats, R.R., and others, eds., Studies in volcanology; a memoir in honor of Howel Williams: Geological Society of America Memoir 116, p. 9-44.

Anderson, P., 1978, The island arc nature of Precambrian volcanic belts in Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 156.

Anderson, J.L., 1983, Proterozoic anorogenic granite plutonism of North America, in Medaris, L.G., Jr., Byers, C.W., Mickelson, D.M., and Shanks, W.C., eds., Proterozoic geology: Selected papers from an International Proterozoic Symposium: Geological Society of America Memoir 161, p. 133-154.

Anderson, P., 1986, Summary of the Proterozoic plate tectonic evolution of Arizona from 1900 to 1600 Ma, in Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 5-11.

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., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 57-147.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, no. 12, p. 3513-3536.

Brennan, D.J., 1962, Tertiary sedimentary rocks and structures of the Cienega Gap area, Pima County, Arizona, in Heindl, L.A., ed., Cenozoic geology of Arizona - a symposium: Arizona Geological Society Digest, v. 5, p. 45-57.

Brittingham, P.L., 1985, Structural geology of a portion of the White Tank Mountains, central Arizona: Tempe, Arizona State University, M.S. thesis, 106 p.

Capps, R.C., Reynolds, S.J., Kortemeier, C.P., and Scott, E.A., 1986, Geologic map of the northeastern Hieroglyphic Mountains, central Arizona: Arizona Bureau of Geology and Mineral Technology Open-File Report 86-10, 16 p., 1sheet, scale 1:24,000.

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.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403-406.

Coney, P.J., 1973, Plate tectonics of marginal foreland thrust-fold belts: Geology, v. 1, p. 131-134.

Coney, P.J., 1978, The plate tectonic setting of southeastern Arizona, in Callender, J.F., Wilt, J.C., and Clemons, R.E., eds., Land of Cochise, southeastern Arizona: New Mexico Geological Society 29th Field Conference Guidebook, p. 285-290.

Coney, P.J., 1980, Cordilleran metamorphic core complexes: An overview, in Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 7-31.

Conway, C.M., and Silver, L.T., 1984, Extent and implications of silicic alkalic magmatism and quartz arenite sedimentation in the Proterozoic of central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 4, p. 219.

Conway, C.M., and Silver, L.T., 1989, Early Proterozoic rocks (1710-1615 Ma) in central to southeastern Arizona, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 165-186.

Conway, C.M., and Wrucke, C.T., 1986, Proterozoic geology of the Sierra Ancha-Tonto Basin-Mazatzal Mountains area, road log and field trip guide, in Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 227-247.

Conway, C.M., Silver, L.T., Wrucke, C.T., and Ludwig, K.R., 1981, Proterozoic Mazatzal quartzite of central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 2, p. 50.

Conway, C.M., Karlstrom, K.E., Silver, L.T., and Wrucke, C.T., 1987, Tectonic and magmatic contrasts across a two-province Proterozoic boundary in central Arizona, in Davis, G.H., and VandenDolder, E.M., eds., Geologic diversity of Arizona and its margins: Excursions to choice areas; Field-trip guidebook, 100th Annual Meeting, The Geological Society of America, Phoenix, Arizona, October 26-29, 1987: Arizona Bureau of Geology and Mineral Technology Special Paper 5, p. 158-175.

Conway, C.M., 1976, Petrology, structure, and evolution of a Precambrian volcanic and plutonic complex, Tonto Basin, Gila County, AZ: Pasadena, California Institute of Technology, Ph.D. dissertation, 460 p.

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.

Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., 1980, Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, 490 p.

Damon, P.E., and Mauger, R.L., 1966, Epeirogeny-orogeny viewed from the Basin and Range Province: American Institute of Mining, Metallurgical, and Petroleum Engineers, Society of Mining Engineers, Transactions, v. 235, p. 99-112.

Damon, P.E., Shafiqullah, M., and Clark, K.F., 1981, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera, in Dickinson, W.R., and Payne, W.D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 137-154.

Damon, P.E., Lynch, D.J., and Shafiqullah, M., 1984, Cenozoic landscape development in the Basin and Range province of Arizona, in Smiley, T.L., Nations, J.D., Pewe, T.L., and Schafer, J.P., eds., Landscapes of Arizona - The geological story: Lanham, Md., University Press of America, p. 175-206.

Damon, P.E., 1964, Correlation and chronology of ore deposits and volcanic rocks, Annual Progress Report No. COO-689-42, Contract AT(11-1)-689 to Research Division, U.S. Atomic Energy Commission: Tucson, University of Arizona, Geochronology Laboratories, 102 p.

Damon, P.E., 1979, Continental uplift at convergent boundaries: Tectonophysics, v. 61, p. 307-319.

Damon, P.E., 1989, Evidence for origin of the rhyolite-andesite-doreite series by crustal melting during the mid-Tertiary orogeny in southeastern Arizona, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 575-584.

Davis, G.H., and Coney, P.J., 1979, Geologic development of the Cordilleran metamorphic core complexes: Geology, v. 7, no. 3, p. 120-124.

Davis, G.A., Anderson, J.L., Frost, E.G., and Shackelford, T.J., 1980, Mylonitization and detachment faulting in the Whipple-Bucksin-Rawhide Mountains terrane, southeastern California and western Arizona, in Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds.,Cordilleran metamorphic core complexes: Geol. Society of America Memoir 153, p. 79-129.

Davis, G.A., Lister, G.S., and Reynolds, S.J., 1983, Interpretation of Cordilleran core complexes as evolving crustal shear zones in an extending orogen [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 311.

Davis, G.A., 1980, Problems of intraplate extensional tectonics, western United States, in Continental tectonics: Washington, D.C., National Academy of Sciences, Studies in Geophysics, p. 84-95.

Davis, G.H., 1983, Shear-zone model for the origin of metamorphic core complexes: Geology, v. 11, no. 6, p. 342-347.

Deal, E.G., Elston, W.E., Erb, E.E., Peterson, S.L., Reiter, D.E., Damon, P.E., and Shafiqullah, M., 1978, Cenozoic volcanic geology of the Basin and Range province in Hidalgo County, southwestern New Mexico, in Callender, J.F., and others, eds., Land of Cochise, southeastern Arizona: New Mexico Geological Society 29th Field Conference Guidebook, p. 219-229.

Demsey, K.A., 1988, Geologic map of Quaternary and Upper Tertiary alluvium in the Phoenix North 30' x 60' quadrangle, Arizona (revised August 1990): Arizona Geological Survey Open-File Report 88-17, 1 sheet, scale 1:100,000.

DeWitt, E., 1989, Geochemistry and tectonic polarity of Early Proterozoic (1700-1750-Ma) plutonic rocks, 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., 1979, Cenozoic plate setting of the Cordilleran region in the United States, *in* Armentrout, J.M., Cole, M.R., and TerBest, Harry, Jr., eds., Cenozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 3, p. 1-13.

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.

Doorn, P.L., and Péwé, T.L., 1991, Geologic and gravimetric investigations of the Carefree Basin, Maricopa County, Arizona: Arizona Geological Survey Special Paper 8, 187 p., 10 sheets, scales 1:24,000 and 1:48,000. Eberly and Stanley, 1978

Elston, D.P., and McKee, E.H., 1982, Age and correlation of the late Proterozoic Grand Canyon disturbance, northern Arizona: Geological Society of America Bulletin, v. 93, no. 8, p. 681-699.

Elston, W.E., 1976, Tectonic significance of mid-Tertiary volcanism in the Basin and Range province - A critical review with special reference to New Mexico, in Elston, W.E., and Northrop, S.A., eds., Cenozoic volcanism in southwestern New Mexico: New Mexico Geological Society Special Publication 5, p. 93-102.

Elston, D.P., 1984, Polarity of river-flood silt in Stanton's Cave, Marble Canyon, Arizona, in Euler, R.C., ed., The archaeology, geology, and paleobiology of Stanton's Cave, Grand Canyon National Park, Arizona: Grand Canyon Natural History Association Monograph No. 6, p. 107-112.

Epis, R.C., and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains, in Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 45-74.

Ferguson, C. A., Gilbert, W. G., and Leighty, R. S., 1998, Geologic map of the New River Mesa quadrangle, Maricopa County, Arizona: Arizona Geological Survey Open-File Report 98-12, 1:24,000 scale geologic map and text.

Finnell, T.L., 1970, Pantano Formation, in Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1968: U.S. Geological Survey Bulletin 1294-A, p. A35-A36.

Fitzgerald, P.G., Reynolds, S.J., Stump, E., Foster, D.A., and Gleadow, A.J.W., 1994, Thermochronologic evidence for timing of denudation and rate of crustal extension of the South Mountains metamorphic core complex and Sierra Estrella, Arizona, Nuclear Tracks and Radiation Measurement, v. 21, p. 555-563.

Frost, E.G., and Okaya, D.A., 1986, Seismic-reflection view of the South Mountains, Arizona, detachment fault and its deeper crustal structure [abs.]: Geological Society of America Abstracts with Programs, v. 18, no. 2, p. 107.

Gastil, R.G., 1958, Older Precambrian rocks of the Diamond Butte quadrangle, Gila County, Arizona: Geological Society of America Bulletin, v. 59, no. 12, p. 1495-1513.

Gomez, E., and Elston, D.P., 1978, Oligocene and Miocence development of the mountain-desert region boundary, Cave Creek, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 107.

Gomez, E., 1978, Geology of the south-central part of the New River Mesa Quadrangle, Cave Creek area, Maricopa County, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 144 p., map, scale 1:12,000.

Gorey, T.L., 1990, The geology and terraces of Cave Creek, Arizona: Tempe, Arizona State University, unpublished M.S. thesis, 95 p.

Harris, R.C., 1997, Uranium distribution in the Cave Creek-Carefree area, central Arizona: Arizona Geological Survey Open-File Report 97-6, 11 p., scale 1:100,000.

Haxel, G.B., Tosdal, R.M., May, D.J., and Wright, J.E., 1984, Latest Cretaceous and early Tertiary orogenesis in south-central Arizona; thrust faulting, regional metamorphism, and granitic plutonism: Geological Society of America Bulletin, v. 95, no. 6, p. 631-653.

Heindl, L.A., and Armstrong, C.A., 1963, Geology and ground-water conditions in the Gila Bend Indian Reservation, Maricopa County, Arizona: U.S. Geological Survey Water-Supply Paper 1647-A, p. A1-A48.

Jagiello, K.J., 1987, Structural evolution of the Phoenix basin, Arizona: Tempe, Arizona State University, M.S. thesis, 156 p.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, no. 5, 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, v. 19, p. 1-10.

Karlstrom, K.E., 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., 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, Geological Society of America, Cordilleran section, 86th Annual Meeting, Tucson Ariz., March 14-16, 1990, Field-Trip Guidebook: Arizona Geological Survey Special Paper 7, p. 114-123.

Keith, Stanley B., Reynolds, S.J., Damon, P.E., Shafiqullah, M., Livingston, D.E., and Pushkar, P.D., 1980, Evidence for multiple intrusion and deformation within the Santa Catalina-Rincon-Tortolita crystalline complex, southeastern Arizona, in Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 217-267.

Kenny, R., 1986, Reconnaissance environmental geology of the Tonto Foothills, Scottsdale, Arizona: Tempe, Arizona State University, M.S. Thesis, 158 p., 4 sheets, scale 1:24,000.

Kortemeier, C.P., Jorgensen, M., and Sheridan, M.F., 1986, Volcanic geology of the Castle Hot Springs area, in Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 473-477.

Krieger, M.H., Johnson, M.G., and Bigsby, P.R., 1979, Mineral resources of the Aravaipa Canyon Instant Study Area, Pinal and Graham Counties, Arizona: U.S. Geological Survey Open-File Report 79-0291, 183 p., 1 sheet, scale 1:24,000.

Krieger, M.H., 1965, Geology of the Prescott and Paulden quadrangles: U.S. Geological Survey Professional Paper 467, 127 p., 5 sheets, scales 1:48,000 and 1:96,000.

Leighty, R. S. and Huckleberry, G., 1998, Geologic map of the Hedgpeth Hills quadrangle, Maricopa County, Arizona: Arizona Geological Survey Open-File Report 98-18, 1:24,000 scale geologic map and text.

Leighty, R. S. and Huckleberry, G., 1998, Geologic map of the Biscuit Flat quadrangle, Maricopa County, Arizona: Arizona Geological Survey Open-File Report 98-19, 1:24,000 scale geologic map and text.

Leighty, R.S. and Reynolds, S.J., 1996, Dynamics of Neogene faulting across the Colorado Plateau-Basin and Range boundary in central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. A451.

Leighty, R.S., Skotnicki, S.J., and Pearthree, P., 1997, Geology of the Cave Creek quadrangle, Maricopa County, Arizona: Arizona Geological Survey Open-File Report 97-1, 1 sheet, 1:24,000.

Leighty, R.S., 1997, Evolution of tectonism and magmatism across the Basin and Range-Colorado Plateau boundary, central Arizona: Tempe, Arizona State University, unpublished Ph.D. dissertation, 1019 p.

Lindsay, E.H., and Lundin, R.F., 1972, An Oligocene oreodont (Mammalia: Artiodactyla) from central Arizona: Journal of Paleontology, v. 46, p. 115-119.

Lipman, P.W., Prostka, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States; I. Early and middle Cenozoic: Royal Society of London, Philosophical Transactions, series A, v. 271, p. 217-248.

Lipman, P.W., 1981, Volcano-tectonic setting of Tertiary ore deposits, southern Rocky Mountains, in Dickinson, W.R., and Payne, W.D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 199-213.

Lister, G.S., and Davis, G.A., 1983, Development of mylonitic rocks in an intracrustal laminar flow zone, Whipple Mountains, S.E. California [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 310.

Ludwig, K.R., 1974, Precambrian geology of the central Mazatzal Mountains, Arizona (part I) and lead isotope heterogeneity in Precambrian igneous feldspars (part II): Pasadena, California Institute of Technology, Ph.D. dissertation, 218 p.

Maynard, S.R., 1986, Precambrian geology and mineralization of the southwestern part of the New River Mountains, Maricopa and Yavapai Counties, Arizona: Albuquerque, University of New Mexico, M.S. thesis, 155 p.

Maynard, S.R., 1989, Geologic map and cross-sections of the southwestern part of the New River Mountains, Arizona: Arizona Geological Survey Contributed Map CM-89-E, 2 sheets, scale 1:12,000.

McKee, E.H., and Anderson, C.A., 1971, Age and chemistry of Tertiary volcanic rocks in north-central Arizona and relation of the rocks to the Colorado Plateaus: Geological Society of America Bulletin, v. 82, no. 10, p. 2767-2782.

Menges, C.M., and Pearthree, P.A., 1989, Late Cenozoic tectonism in Arizona and its impact on regional landscape evolution, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 649-680.

Nealey, L.D., and Sheridan, M.F., 1989, Post-Laramide volcanic rocks of Arizona and northern Sonora, Mexico, and their inclusions, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 609-647.

Peake, R.T., and Schumann, R.R., 1991, Regional radon characterizations, *in* Gunderson, L.C.S., and Wanty, R.B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 175.

Pedersen, E.P., 1969, Sedimentology and stratigraphy of basin-fill sediments of the Payson Basin, Gila County, Arizona: Tempe, Arizona State University, M.S. thesis, 136 p., 1 sheet, scale 1:32,000.

Peirce, H.W., and Scurlock, J.R., 1972, Arizona well information: Arizona Bureau of Mines Bulletin 185, 195 p.

Peirce, H.W., Damon, P.E., and Shafiqullah, M., 1979, An Oligocene(?) Colorado Plateau edge in Arizona: Tectonophysics, v. 61, no. 1, p. 1-24.

Peirce, H.W., 1976, Elements of Paleozoic tectonics in Arizona, in Wilt, J.C., and Jenney, J.P., eds., Tectonic digest: Arizona Geological Society Digest, v. 10, p. 37-57

Peters, D., 1979, The sedimentologic history of the sandstones of Tempe Butte, Arizona: Tempe, Arizona State University, M.S. thesis, 197 p.

County, Arizona, in Péwé, T.L., Wellendorf, C.S., and Bales, J.T., Environmental geology of the Tempe quadrangle, Maricopa County, Arizona: Arizona Bureau of Geology and Mineral Technology Geologic Investigation Series Map GI-2-A, 1 sheet, scale 1:24,000.

Péwé, T.L., and Kenny, R., and Bales, J., 1985, Reconnaissance environmental geology of the Tonto foothills, Scottsdale, Maricopa County, Arizona: Arizona Geological Survey Contributed Map CM-94-F, scale 1:24,000, 4 sheets.

Pilger, R.H., Jr., and Henyey, T.L., 1969, Mutual constraints on Neogene volcanism in coastal California and the continental borderland, Pacific-North American Plate interaction, and the development of the San Andreas fault system: Tectonophysics.

Potochnik, A.R., 1989, Depositional style and tectonic implications of the Mogollon Rim formation (Eocene), east-central Arizona, in Anderson, O.J., Lucas, S.G., Love, D.W., and Cather, S.M., eds., Southeastern Colorado Plateau: New Mexico Geological Society 40th Field Conference Guidebook, p. 107-118.

Rehrig, W.A., and Reynolds, S.J., 1980, Geologic and geochronlogic reconnaissance of a northwest-trending zone of metamorphic core complexes in southern and western Arizona, in Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 131-157.

Rehrig, W.A., 1982, Metamorphic core complexes of the southwestern United States - an updated analysis, in Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada - Anderson-Hamilton Volume: San Diego, Cordilleran Publishers, p. 551-559.

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, v.19, p. 237-250.

Reynolds, S.J., and Lister, G.S., 1987, Structural aspects of fluid-rock interactions in detachment zones: Geology, v. 15, no. 4, p. 362-366.

Reynolds, S.J., and Rehrig, W.A., 1980, Mid-Tertiary plutonism and mylonitization, South Mountains, central Arizona, in Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 159-175.

Reynolds, S.J., Spencer, J.E., Richard, S.M., and Laubach, S.E., 1986, Mesozoic structures in west-central Arizona, in Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 35-51.

Reynolds, S.J., 1982, Geology and geochronology of the South Mountains, central Arizona: Tucson, University of Arizona, Ph.D. dissertation, 220 p., 1 sheet, scale 1:24,000.

Reynolds, S.J., 1985, Geology of the South Mountains, central Arizona: Arizona Bureau of Geology and Mineral Technology Bulletin 195, 61 p., 1 sheet, scale 1:24,000.

Reynolds, S.J., 1988, Geologic map of Arizona: Arizona Geological Survey Map M-26, 1 sheet, scale 1:1,000,000.

Satkin, R.L., 1981, A geothermal resource evaluation at Castle Hot Spring, Arizona: Tempe, Arizona State University, M.S. thesis, 147 p., 3 sheets.

Scarborough, R.B., and Wilt, J.C., 1979, A study of uranium favorability of Cenozoic sedimentary rocks, Basin and Range province, Arizona - Part I - General geology and chronology of pre-late Miocene Cenozoic sedimentary rocks: Arizona Bureau of Geology and Mineral Technology Open-File Report 79-01, 101 p.

Schmitt, H.A., 1933, Summary of the geological and metallogenic history of Arizona and New Mexico, in Finch, J.W., and others, eds., Ore deposits of the western states (Lindgren Volume): American Institute of Mining and Metallurgical Engineers, p. 316-326.

Seager, W.R., Shafiqullah, M., Hawley, J.W., and Marvin, R.F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, no. 1, p. 87-99.

Shafiqullah, M., Damon, P.E., Lynch, D.J., Kuck, P.H., and Rehrig, W.A., 1978, Mid-Tertiary magmatism in southeastern Arizona, in Callender, J.F., Wilt, J.C., Clemons, R.E., and James, H.L., eds., Land of Cochise, southeastern Arizona: New Mexico Geological Society 29th Field Conference Guidebook, p. 231-241.

Shafiqullah, M., 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, v. 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.

Shride, A.F., 1967, Younger Precambrian geology in southern Arizona: U.S. Geological Survey Professional Paper 566, 89 p.

Silver, L.T., Bickford, M.E., Van Schmus, W.R., Anderson, J.L., Anderson, T.H., and Medaris, L.G., Jr., 1977, The 1.4 - 1.5 b.y. transcontinental anorogenic plutonic perforation of North America [abs.]: Geological Society of America Abstracts with Programs, v. 9, no. 7, p. 1176-1177.

Skotnicki, S.J., Leighty, R.S., and Pearthree, P., 1997, Geology of the Wildcat Hill quadrangle, Maricopa County, Arizona: Arizona Geological Survey Open-File Report 97-2, scale 1:24,000

Skotnicki, S.J., and Ferguson, C.A., 1995, Geologic map of the Goldfield quadrangle and northern Superstition Mountains SW quadrangles, Maricopa and Pinal Counties, Arizona: Arizona Geological Survey Open-File Report 95-9.

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, v. 17, p. 539-574.

Spencer, J.E., Richard, S.M., Reynolds, S.J., Miller, R.J., Shafiqullah, M., Gilbert, W.G., and Grubensky, M.J., 1995, Spatial and temporal relationships between mid-Tertiary magmatism and extension in southwestern Arizona, Journal of Geophysical Research, v. 100, p. 10321-10351.

Spencer, J. E., 1992, Radon gas: A geologic hazard in Arizona: Arizona Geological Survey, Down-to-Earth Series, no. 2, 17 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.

Trevena, A.S., 1979, Studies in sandstone petrology: Origin of the Precambrian Mazatzal Quartzite and provenance of detrital feldspar: Salt Lake City, University of Utah, Ph.D. dissertation, 390 p.

Vance, R.K., 1986, Geochemistry and tectonic setting of the Yavapai Supergroup, west central Arizona: [Ph.D. thesis], New Mexico Institute of Mining and Technology.Ward, 1977

Wernicke, B.P., 1981, Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen: Nature, v. 291, no. 5817, p. 645-648.

Wilson, E.D., 1939, Pre-Cambrian Mazatzal revolution in central Arizona: Geological Society of America Bulletin, v. 50, no. 7, p. 1113-1163.

Wrucke, C.T., and Conway, C.M., 1987, Geologic map of the Mazatzal Wilderness and contiguous Roadless Area, Gila, Maricopa, and Yavapai Counties, Arizona: U.S. Geological Survey Open-File Report 87-0664, 22 p., 1 sheet, scale 1:48,000.