GEOLOGIC MAP OF THE CAVE CREEK QUADRANGLE, MARICOPA COUNTY, ARIZONA

by
Robert S. Leighty, Steven J. Skotnicki, and Philip A. Pearthree

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416 W. Congress, Suite 100, Tucson, AZ 85701

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INTRODUCTION

The Cave Creek quadrangle is located along the northernmost fringe of the Phoenix metropolitan area, and is bordered by the Paradise Valley to the south and high-standing mesas to the north. Given its location, the Cave Creek area is becoming increasingly urbanized and is undergoing rapid population growth. Thus, the knowledge of the distribution and character of bedrock and surficial deposits is important to make informed decisions concerning management of the land and its resources. Geologic mapping of the Cave Creek quadrangle is related to other previous and ongoing mapping projects of urban fringe areas located to the north and northeast of the Phoenix metropolitan area (figure 1).

Access for most parts of the Cave Creek quadrangle is excellent (figure 2). Numerous paved roads (e.g., Scottsdale Road, Cave Creek Road, Carefree Highway) and well-maintained dirt roads make much of the quadrangle highly accessible. Access within the Cave Creek Recreation area is limited to the established trail system, unless permission from the park rangers is obtained. Building construction is active across the area, and several large, gated housing developments restrict the access to previously accessible areas; permission is required to enter several of these developments (e.g., Desert Mountain).

Geologic mapping of bedrock in the quadrangle was based on field mapping, whereas surficial mapping was based upon both field observations and interpretation of aerial photographs. A series of black-and-white, 1:48,000-scale aerial photographs (dated 9-17-92) and color, 1:24,000-scale aerial photographs (dated 11-5-79 and 6-11-88) were obtained from the Tonto National Forest office in Phoenix. This study is contiguous with geologic mapping recently completed in the Wildcat Hill quadrangle to the east (Skotnicki and others, 1997). This project was funded by the Environmental Protection Agency through the State Indoor Radon Grant Program, Grant #K1009544-07-0, the U.S. Geological Survey through the STATEMAP Program, Agreement # 1434-HQ-96-AG-01474, and the Arizona Geological Survey.

PREVIOUS STUDIES

Initial geologic investigation in the Cave Creek area was related to the geology and mining potential of the Phoenix mine, roughly 1 kilometer north of the map area along Cave Creek (Ricketts, 1887). A more detailed analysis of the general geology and mining potential of the northern and western parts of the area was performed by Lewis (1920). Most of the study of Proterozoic rocks and structures has concentrated in areas adjacent to the Cave Creek quadrangle, including the northern Phoenix, New River, New River Mountains, and Bradshaw Mountains areas (Maynard, 1986, 1989; Reynolds and DeWitt, 1991; Bryant, 1994; DeWitt, unpublished mapping; Reynolds, unpublished mapping). Anderson (1989b) summarized the Early Proterozoic geology of the region, including rocks of the Cave Creek area. Other geologic studies of adjacent areas to the west and northwest of the quadrangle have emphasized the Tertiary rocks and structures (Gomez, 1978; Gomez and Elston, 1978; Jagiello, 1987; Leighty and others, 1995; Leighty, 1996; Leighty, 1997). Various aspects of the geology, geophysics, and hydrologic characteristics of the Cave Creek quadrangle have been studied by several workers (Péwé, 1982; Kenny, 1986; Péwé and others 1986; Gorey, 1988, 1990; Doorn and Péwé, 1991; Pearthree, 1992).

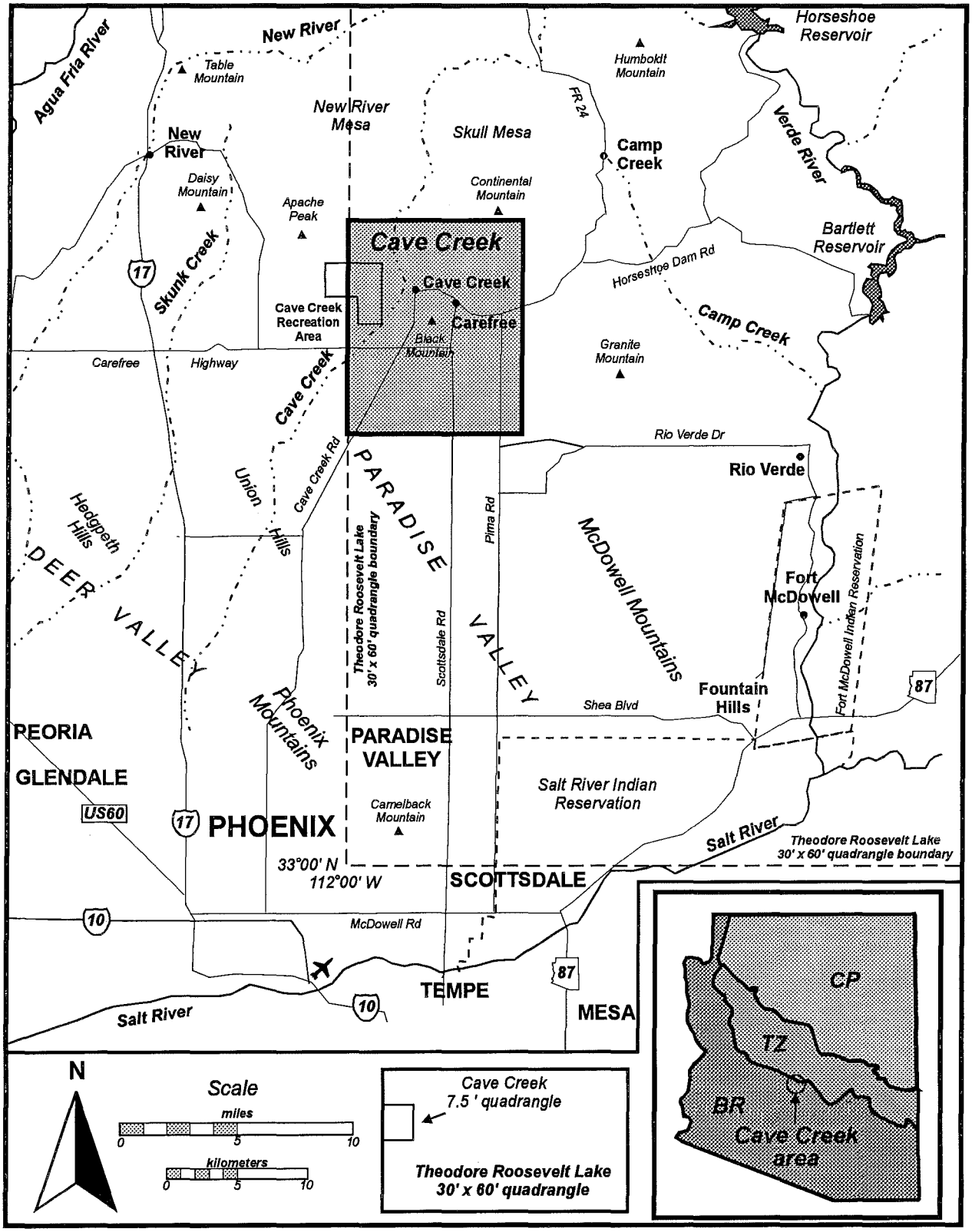

Figure 1. Location of the Cave Creek quadrangle in the Phoenix region. Inset map shows the location of the study area relative to the three physiographic provinces in Arizona: the Basin and Range (BR), Transition Zone (TZ), and Colorado Plateau (CP).

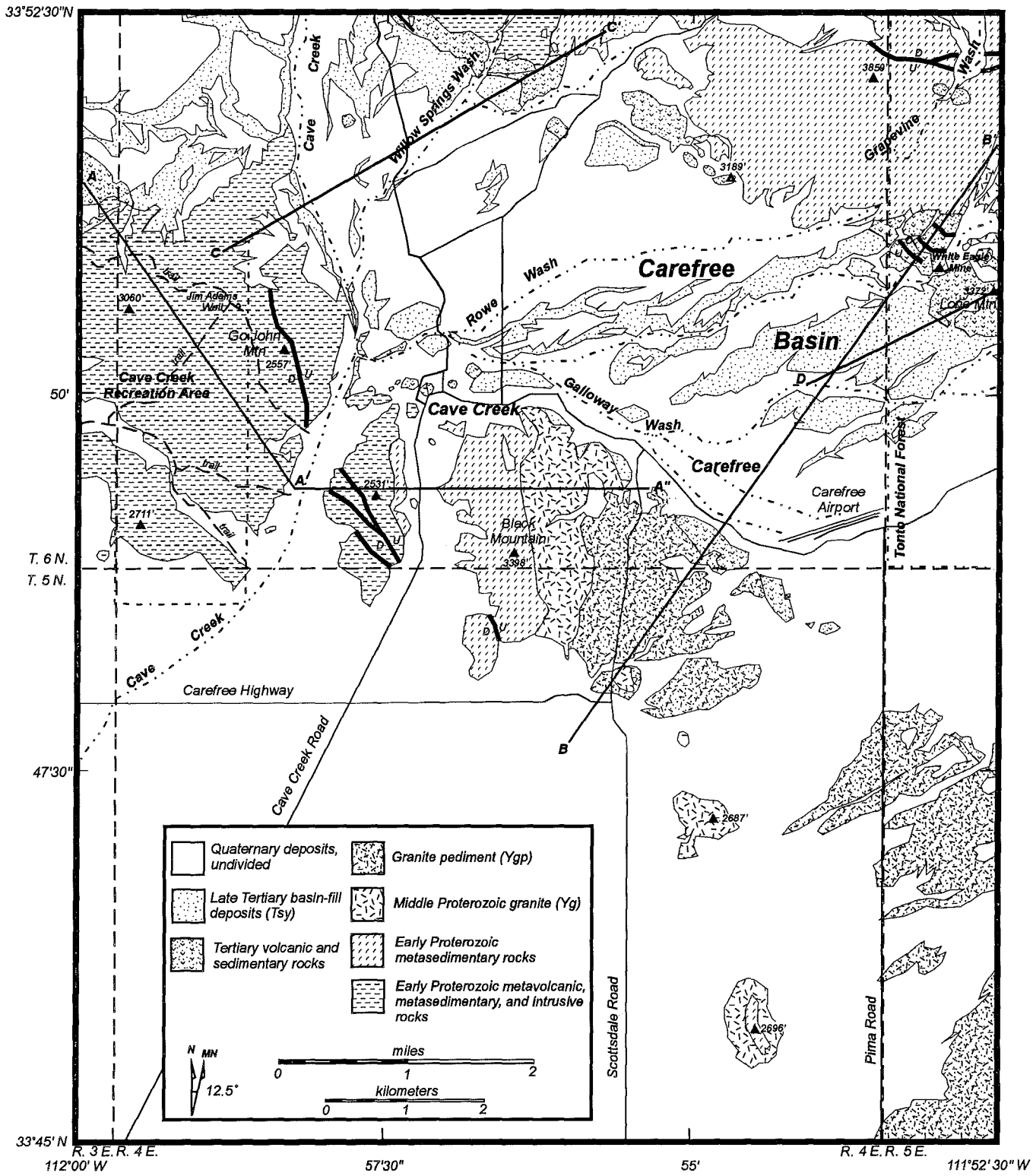

Figure 2. Generalized location diagram for the Cave Creek quadrangle.

A number of geophysical and hydrogeologic studies have been conducted in the area, largely related to the geometry and hydrologic characteristics of the Carefree Basin and adjacent areas. The geometry of the Carefree Basin has been interpreted in several geophysical studies incorporating gravity, magnetic, and electrical resistivity methods (Theile, 1958; Koenen, 1973; Sumner and others, 1974; Bernier and others, 1979; Wagner, 1979; Doorn and Péwé, 1991). The hydrologic characteristics of the Carefree Basin and related deposits have been studied by numerous workers (Nemecek and Briggs, 1975; Bernier and others, 1979; Manera, 1982; Bernier, 1986, 1988, 1989; Doorn and Péwé, 1991). The uranium potential of the Tertiary sediments of the region was described by Scarborough and Wilt (1979), including the deposits located in the White Eagle Mine area north of Carefree that are considered to be a potential radon hazard (Duncan and Spencer, 1993; Harris, 1997).

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The Cave Creek quadrangle straddles the physiographic and structural boundary between the Basin and Range and Transition Zone in central Arizona (see figure 1). Although the mountains north of the Cave Creek quadrangle are within the Transition Zone, most of the Cave Creek quadrangle lies within the Basin and Range province, where the terrain is generally characterized by north- and NW-trending mountain ranges that are separated by wide valleys. The mountains of the Basin and Range consist of fault-bounded and highly eroded rocks of Proterozoic to Cenozoic age, and the valleys are commonly filled with Cenozoic volcanic, lacustrine, and alluvial deposits. The terrain of the Transition Zone consists of rugged mountains, primarily composed of Proterozoic metamorphic and igneous rocks, minor erosional remnants of Paleozoic sedimentary rocks, and a scattered, relatively thin cover of Tertiary volcanic and sedimentary rocks.

The southern half of the Cave Creek quadrangle is largely a low relief alluvial plain and pediment surface, broken only by a few isolated granite knobs to the east of Scottsdale Road (see figure 2). The Carefree Basin area, extending from Cave Creek to past Lone Mountain, has more topographic relief. Recent building development has been the most active in these areas. Several streams drain the Cave Creek-Carefree area (e.g., Rowe Wash, Galloway Wash, Willow Springs Wash). Cave Creek, located in the western and northwestern part of the quadrangle, is the largest stream in the area and flows south from its headwaters to the north in the Transition Zone. The mountainous northeastern part of the quadrangle, and the rugged mesas farther north, represent the southern boundary of the Transition Zone. Another moderate relief area exists to the southwest of the communities of Carefree and Cave Creek where a series of ridges and hills extend westward from Black Mountain to the Cave Creek Recreation Area.

The Cave Creek quadrangle contains a diverse suite of geologic units ranging in age from Early Proterozoic to Latest Cenozoic (figure 3). Proterozoic rocks include sequences of Early Proterozoic metavolcanic, metasedimentary, and intrusive rocks, as well as part of a large Middle Proterozoic granite batholith. Cenozoic rocks include Late Oligocene to Miocene intermediate and felsic flows and intrusions, Early Miocene alkaline basalt, conglomerate, tuffaceous sediment, and felsic tuff, subalkaline basaltic lavas, Late Miocene basin-fill sediment, and Plio-Pleistocene to Holocene river terraces and alluvium.

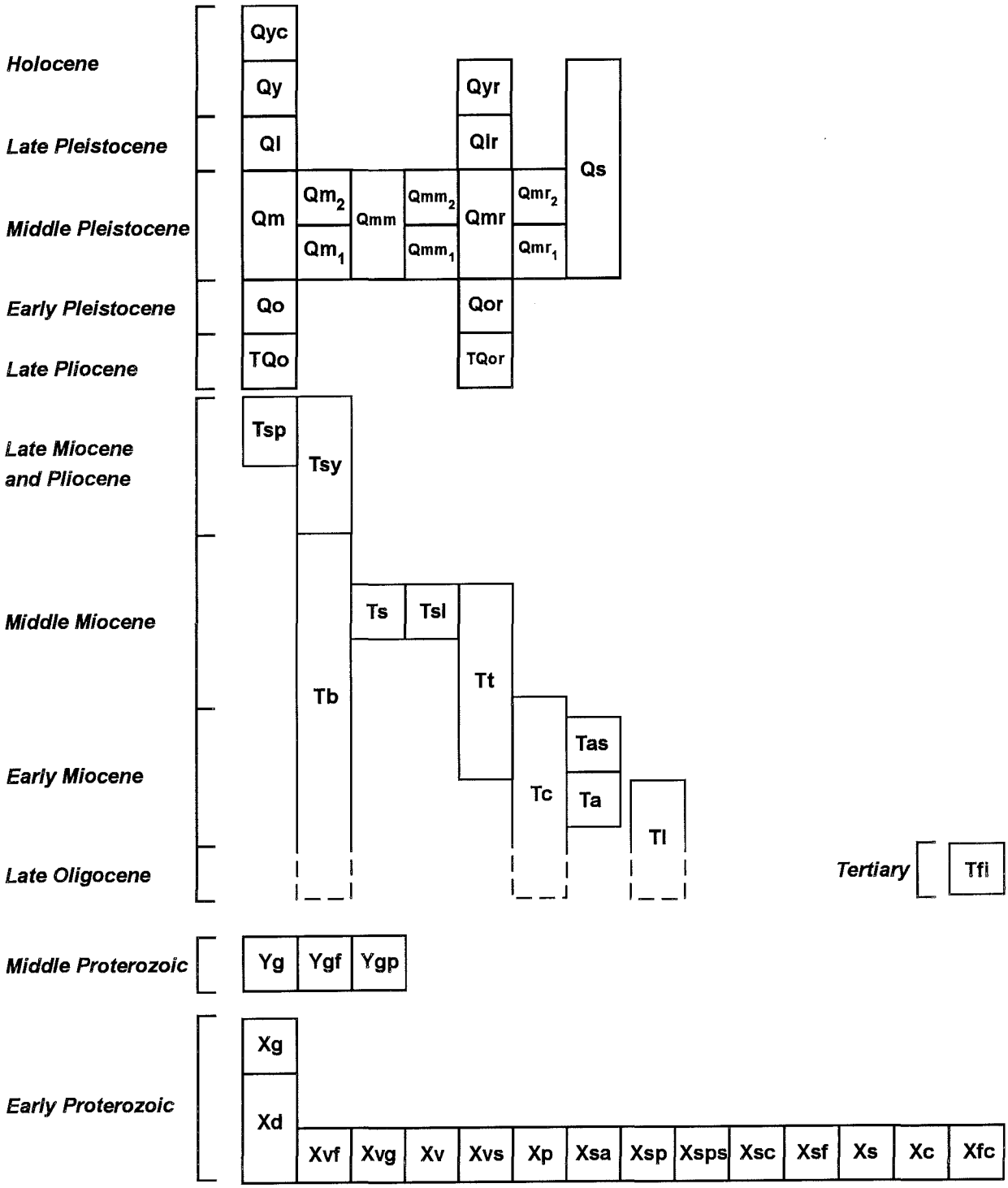

Figure 3. Correlation of map units for the Cave Creek quadrangle.

PROTEROZOIC ROCKS

The Cave Creek quadrangle contains a diverse assemblage of Proterozoic rock types. The Early Proterozoic rocks are correlative with the rocks of the Tonto Basin Supergroup, which consists 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 and others, 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 (figure 4a). 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). These rocks are not present in the Cave Creek quadrangle. The southern portions of the 1700 Ma Verde River granite batholith are present to the north and northeast of the quadrangle. Two granitic dikes intrude the metasedimentary rocks at the northern boundary of the quadrangle (section 10, T. 6 N., R. 4 E.); these dikes are related to a larger mass of Verde Granite in the nearby Continental Mountain area to the north.

Metavolcanic-dominated Northwestern Assemblage

The northwestern part of the Cave Creek quadrangle, from Black Mountain to the quadrangle boundary, consists of a lithologically diverse, complexly interbedded sequence of metavolcanic and metasedimentary rocks (figure 4a; see cross section A-A'-A''). Some of the units include mafic to intermediate volcanic rocks (Xvg, Xv), felsic lava flows and tuffs (Xvf), phyllitic metasedimentary and metavolcanic rocks (Xp), hematitic sediments (Xsf), ferruginous chert (Xfc), and massive jasperoid rock (Xfc_1).

The Early Proterozoic terrane between Cave Creek Road (section 33, T. 6 N., R. 4 E.) and the area north of the Cave Creek Recreation Area (section 24, T. 6 N., R. 4 E.) consists of a diverse belt of NE-trending rock types. The hills between Black Mountain and Cave Creek contain a complicated sequence of interbedded ferruginous chert, phyllite, and felsic to mafic volcanic rocks. Between Cave Creek and Go John Mountain, bedrock exposures are dominated by phyllite, with lenticular dioritic intrusions and thin tuff beds. Northwest of Go John Mountain, the phyllitic rocks contain abundant hematite and dark red to purple chert or jasper. The western part of the Cave Creek Recreation Area includes abundant intermediate and felsic metavolcanic rocks that form several large, NE-trending ridges. The metasedimentary rocks of the northwestern assemblage are generally very fine-grained phyllites that do not contain well-preserved sedimentary structures. However, graded beds are present in less fine-grained, metasedimentary rocks (e.g., Xp_2, Xp_5). The southern part of the Cave Creek Recreation Area (section 31, T. 6 N., R. 4 E.) contains units having dominantly NW- to WNW-trending strike orientations that are

different than the rocks to their north. For example, a large, elongate body of massive jasperoid rock forms a marker horizon that extends along the large NW-trending ridge in the southwestern half of section 31. This southern area also lacks the lenticular metavolcanic and dioritic intrusive bodies that are abundant to the north.

Small, lenticular diorite and granodiorite intrusions are present in the sequence west of Cave Creek. The best exposures of these rocks are present between Go John Mountain and the southern boundary of the Cave Creek Recreational area. These foliated intrusive bodies have been interpreted to be roughly 1710 to 1720 Ma in age (Anderson, 1989b). Significant contact metamorphic effects in adjacent rocks were not observed.

Metasedimentary-dominated Northeastern Assemblage

The Early Proterozoic rocks of the central and northeastern part of the Cave Creek quadrangle are almost exclusively metasedimentary in composition (see figure 4a). In the central part of the quadrangle, excellent exposures of dark gray to maroon phyllite (Xp_1) and meta-argillite (Xsa) are present along the northern and western sides of Black Mountain. The resistant meta-argillite forms much of the higher portions of Black Mountain, and phyllite underlies the lower western and northern slopes. Minor tuff is exposed at the southernmost end of Black Mountain. Bedding is typically steeply W- or NW-dipping, generally concordant with foliation.

In the northeast part of the quadrangle, metasedimentary rocks are well-exposed and display abundant primary sedimentary structures. For example, the southeastern slopes of Continental Mountain (located just north of the quadrangle) in sections 12 and 7, T. 6 N., R. 4-5 E. are composed of dark, relatively unfoliated slates that display well-defined bedding features (e.g., ripple marks, cross beds, etc.). Another well-exposed sequence of pelitic and psammitic rocks are exposed between Willow Springs Wash and Grapevine Wash (sections 11, 12, 13, 14, 24, T. 6 N., R. 4 E; sections 7 and 18, T. 6 N., R. 5 E.); the dark gray pelite unit (Xsp_1) may be equivalent to similar rocks exposed at Black Mountain to the southwest. A belt of interbedded pelitic (Xsp), psammitic (Xsps), and cherty rocks (Xc) is also well-exposed north of Grapevine Wash. This sequence may coarsen slightly to the southeast, with finer-grained pelitic rocks to the northwest grading into more psammitic rocks to the southeast. Metaconglomerate is locally within the psammite unit that is exposed along the NE-trending ridge to the north of Grapevine Wash. The cherty units in this area may represent silicified tuff beds, and many thin beds are laterally continuous for over a kilometer. Bedding orientations are somewhat variable in the northeastern part of the quadrangle, but generally dip in a westerly direction. Southeast of Grapevine Wash, bedding ranges from very steeply NW-dipping to vertical, and many of the E-dipping metasedimentary beds in the area north of Lone Mountain are overturned.

There are several examples of contact metamorphism in the metasedimentary rocks adjacent to the Middle Proterozoic granite. A N-trending meta-argillite-granite contact bisects Black Mountain, where the meta-argillite is juxtaposed against the western margin of the granite. The meta-argillite may have resulted from the recrystallization of the fine-grained pelitic rocks in the area. 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. Near the granite contact east of Grapevine Wash, the pelitic rocks are locally schistose and contain abundant muscovite (up to 1 cm) and biotite (up to 5 mm).

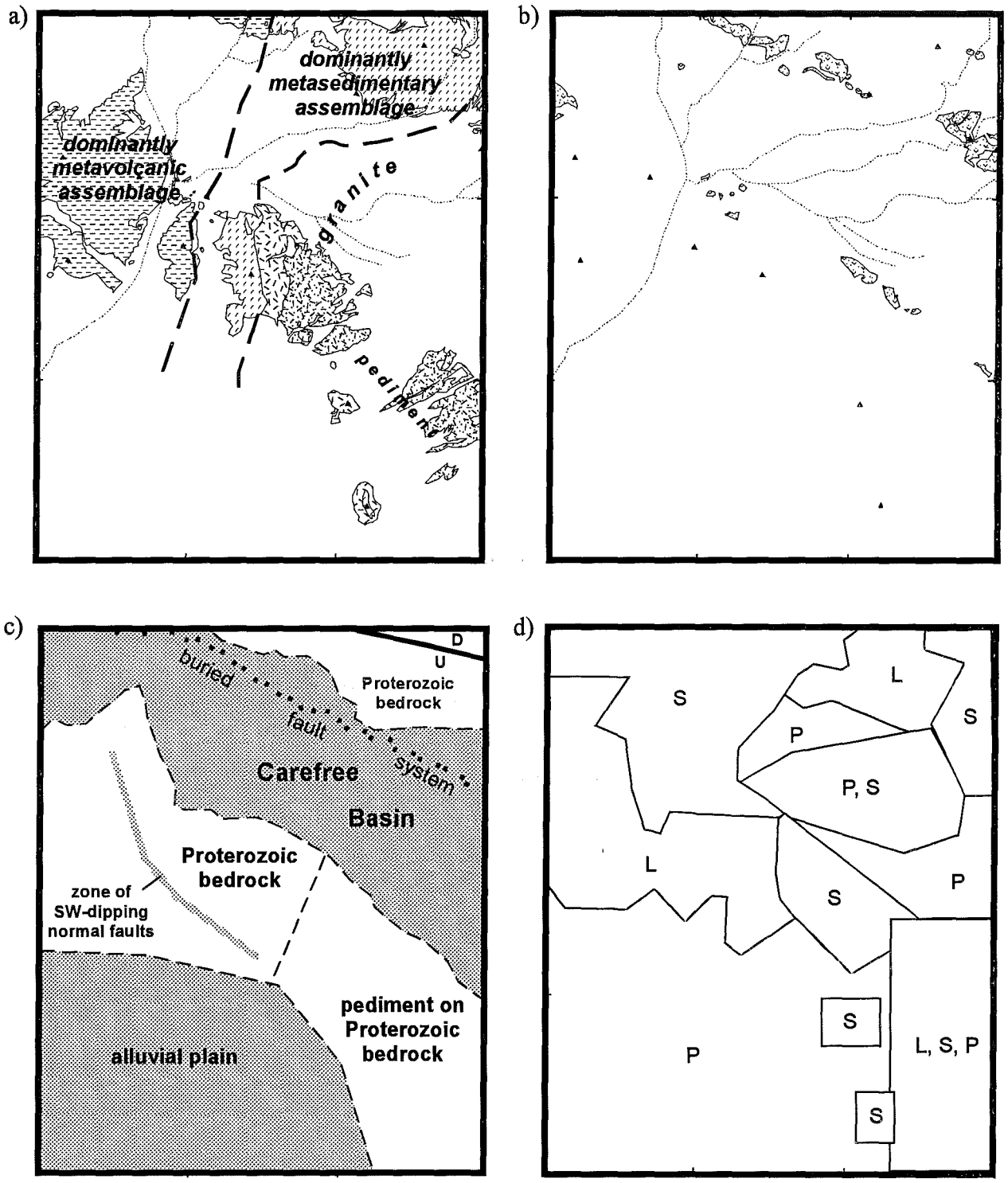

Figure 4. Distribution of various geologic units and features in the Cave Creek quadrangle. a) Early and Middle Proterozoic rocks. b) Late Oligocene to Middle Miocene volcanic and sedimentary rocks. c) Tertiary structural features. d) Mapping coverage; L = Leighty, S = Skotnicki, P = Pearthree.

Early Proterozoic Stratigraphic Relations

The northwestern and northeastern lithologic assemblages in the Cave Creek quadrangle may be equivalent to rocks of the Union Hills Group and the Alder Group, respectively (Anderson, 1989b). The primary distinction between these two Groups in the Cave Creek region is that the Union Hills Group is composed primarily of volcanic and related volcaniclastic deposits, whereas the Alder Group consists largely of clastic sediments and reworked volcanic material.

The abundance of intermediate to felsic volcanic rocks and related rocks, ferruginous chert, and massive jasperoid rock and dioritic intrusive bodies in the northwestern assemblage 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 type locality consists of a well-preserved suite of basaltic andesite to andesite flows and graywackes exposed in the Union Hills (Anderson, 1989b). In the Cave Creek region, three formations are included in the Union Hills Group: the North Union Hills, Cramm Mountain, and Grays Gulch Formations; these units are probably equivalent to the Mount Ord Formation and East Verde River Formation in the Mazatzal Mountains area (Anderson, 1989b). If correlative with the Union Hills Group, the northwestern metavolcanic-dominated assemblage may also represent complex lithologic facies changes within the Union Hills Group, possibly between the distal edges of the North Union Hills and Cramm Mountain Formations.

The dominantly metasedimentary rocks of the northeastern assemblage may be part of the Alder Group, a regionally extensive, dominantly metasedimentary, 1710 to 1720 Ma sequence of rocks in central Arizona (Wilson, 1939; Conway and Wrucke, 1986; Anderson, 1989b; Conway and Silver, 1989). The Alder Group typically consists of purple slate, siltstone, and graywacke, with lesser rhyolitic tuff, psammite, chert, metaconglomerate, and limestone. In the Cave Creek area, these rocks have been referred to as a facies equivalent of the Rackensack Canyon Formation of the Alder Group (Anderson, 1989b).

Between the Phoenix metropolitan area and the Transition Zone north of Cave Creek, the pelitic rocks of the Alder Group have been interpreted to disconformably overlie rocks of the Union Hills Group, suggesting an overall younging of stratigraphy to the southeast (Anderson, 1989b; Reynolds and DeWitt, 1991). In the Cave Creek quadrangle, if the dominantly metavolcanic northwestern assemblage represents the older Union Hills Group and the dominantly metasedimentary northeastern assemblage represents the Alder Group, then the overall younging direction (to the east) agrees with previous interpretations of the regional SE-younging of Proterozoic units (Anderson, 1989b).

However, this regional SE-younging stratigraphic interpretation may have some problems. Stratigraphic orientation of various Early Proterozoic rocks was determined using various primary sedimentary structures (i.e., graded beds, cross beds, ripple marks, etc.) that were correlated with the orientation of bedding or unit boundaries. Although the degree of deformation and the fine-grained nature of many of the metasedimentary rocks in the northwestern assemblage may complicate stratigraphic interpretation, available bedding structures in strata from both the northwestern and northeastern assemblages display orientations that are steeply NW-dipping to vertical, suggesting a general younging to the northwest. Hypothetically, if the younging direction

in these rocks was in the opposite direction (to the southeast, as assumed by regional stratigraphic relations), then most of observed bedding in the quadrangle would represent overturned strata. A more comprehensive analysis of sedimentary structures and fold relationships needs to be done to rectify this contradiction between regional and local stratigraphic interpretations.

Early Proterozoic Structural Relations

The primary foliation across the quadrangle is typically N- to NE-trending, consistent with the orientation of the main foliation in rocks of similar age in other parts of the region (e.g., Mazatzal Mountains, Phoenix Mountains, Gila Bend Mountains). This primary foliation is best expressed in the phyllitic rocks and is typically parallel or slightly discordant to bedding. The degree of deformation is significantly higher in the western part of the quadrangle, with local areas that are highly crenulated and complexly folded.

Mesoscopic and macroscopic tight to isoclinal folds are common in the area west of Cave Creek. In the Cave Creek Recreation Area, a repetition of map units (i.e., Xvf, Xsc, Xvg) and a well-exposed, folded metavolcanic tuff (near the junction of the Slate and Jasper trails) are evidence of a large, W-trending fold. The previously mentioned 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 and (2) the large, W-trending fold. Foliation trends are similar in both areas. Folded diorite and metasedimentary rocks are also present in the western Go John Mountain area. Deformation is generally less severe in the northeastern part of the quadrangle, although overturned bedding is locally present.

Based solely on the bedding relationships, the Early Proterozoic rocks in the Cave Creek quadrangle show NW-younging directions that conflict with the regional interpretation of SE-younging of the Union Hills Group and Alder Group stratigraphy. However, an alternative explanation for the lack of SE-facing bedding may involve the removal of the SE-facing limbs from most folds during isoclinal folding, leaving only the NW-facing limb preserved. This deformation may be consistent with the presence of overturned bedding north of Lone Mountain, but implies SE-vergent shortening, whereas the deformation related to the Mazatzal Orogeny (1675-1625 Ma) is generally characterized by NW-vergent folding and thrusting (Wilson, 1939).

To the west of Black Mountain (section 33, T. 6 N., R. 4 E.), complexly interbedded and compositionally diverse rocks (Xfc, Xp, Xp_5, Xvf, Xvg; i.e., Union Hills Group) are juxtaposed against relatively homogeneous pelitic rocks (Xp_1; i.e., Alder Group). The contact is sharp, dips to the west at approximately 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. However, a similar structure has not been identified in the northern part of the quadrangle (section 10, T. 6 N., R. 4 E.).

Middle Proterozoic Granite

An unfoliated, coarse-grained Middle Proterozoic granite and granitic pediment forms the basement in the eastern part of the quadrangle (see figure 4a). A spectacular pediment surface is developed on this granite between the towns of Carefree and Camp Creek and the McDowell Mountains to the south (Péwé and others, 1985; Kenny, 1986; Doorn and Péwé, 1991; Skotnicki and others, 1997). The granite weathers into large spheroidal boulders and erodes easily into grus that mantles the granitic bedrock. A few isolated granite knobs and hills of Tertiary rhyolite and tuff protrude above this pediment surface.

Mineralization

Throughout the Cave Creek quadrangle, small man-made pits are surrounded by tailings containing variable amounts of quartz, hematite, malachite, and chrysocolla. West of Go John Mountain, the chert interbedded with the phyllitic metasedimentary rocks contains abundant hematite, both as very fine-grained crystals disseminated throughout the rock and as sheets of specular hematite crystals coating fracture surfaces. Northeast of Go John Mountain, a very deep near-vertical shaft is present along the contact between platy metasiltstone and a resistant, dark reddish-purple quartz-hematite band. Hematite coatings are present on fracture surfaces in the mine tailings pile, but no other mineralization was observed. On the south side of the NW-trending hill in section 14, T. 6 N., R. 4 E., several inclined adits follow two 4-cm-thick white quartz-hematite veins; the veins are unfoliated and cross-cut the primary foliation. Near Grapevine Wash, in the northeast corner of section 18, T. 6 N., R. 5 E., a near-vertical shaft at least 20 feet deep (partially filled) contains fractures having traces of chrysocolla, malachite, and hematite.

LATE OLIGOCENE AND EARLY MIOCENE ROCKS

During the middle Tertiary, voluminous ash-flow-related volcanism occurred across the Arizona Basin and Range. In central Arizona, silicic volcanism across the Transition Zone was generally more potassic in composition and more localized in extent. Late Oligocene to Early Miocene (27.3-17.7 Ma) andesite, trachyandesite, and trachyte were erupted in the Sullivan Buttes, Cordes, New River, and Camp Creek areas (Krieger, 1965; McKee and Anderson, 1971; Tyner, 1979, 1984; Esperança, 1984; Esperança and Holloway, 1986; Jagiello, 1987; Esperança and others, 1988; Leighty, 1997). Many of these rocks are inclusion-bearing and host important crustal and mantle xenoliths.

Early Miocene basaltic volcanism across the Basin and Range was volumetrically minor in comparison to the widespread felsic-intermediate volcanism. Eruption of relatively small volumes of basaltic rocks generally preceded the larger volume felsic-intermediate eruptions. Across the southern part of the Transition Zone, alkaline basalts were interbedded with tuffs and fluvial-lacustrine sediments, together comprising the Chalk Canyon Formation. To the north of the Cave Creek quadrangle, a thick Chalk Canyon Formation section forms the steep slopes beneath a series of resistant, Middle Miocene Hickey Formation basaltic flows capping New River Mesa and Skull Mesa. In the Basin and Range to the south of these high-standing mesas, several small, tilted, fault-block ranges contain the same rock units as the homoclinally dipping basaltic and sedimentary sequence underlying New River Mesa (see figure 4b).

Felsic to Intermediate Volcanic Rocks

Several relatively small occurrences of intermediate and silicic volcanic rocks are present in the Cave Creek quadrangle. In the northern part of the quadrangle, fine-grained hornblende andesite lavas (22.2 Ma, Doorn and Péwé, 1991) are exposed to the east of Cave Creek (sections 9, 15, 16, 17, T. 6 N., R. 4 E.). This andesite is underlain by thin basaltic flows. The andesite pinches out to the east and is overlain and replaced by a sedimentary breccia composed exclusively of andesite clasts. Associated mudflow deposits are typically present in paleotopographic low areas proximal to the andesitic plugs (Gomez, 1978; this study). Small hornblende andesite intrusions are also present in the Go John Mountain area west of Cave Creek (section 29, T. 6 N., R. 4 E.). A well-exposed felsic plug/breccia pipe is present along Grapevine Wash (section 18, T. 6 N., R. 5 E.), roughly 5 km north of Carefree. The exact age relations of the Go John and Grapevine Wash volcanic rocks are unknown. The Grapevine Wash intrusion may be related to the felsic dikes and lithic tuffs exposed to the southeast, between Carefree and Granite Mountain (Kenny, 1986; Skotnicki and others, 1997). Limited exposures of latite are present in the small hills south of the Carefree airport. This unit contains abundant crustal xenoliths and xenocrysts (e.g., basalt, granite, garnet, green pyroxene, brown amphibole); no mantle-derived nodules have been observed in these rocks.

Andesite, trachyandesite, and trachyte domes and flows are also exposed in several areas adjacent to the Cave Creek quadrangle, including western New River (26.5 Ma), New River Mesa, Gavilan Peak (22.0 Ma), Cline Creek, Elephant Mountain, Sugarloaf Mountain, and Camp Creek (Gomez, 1978; Esperança, 1984; Jagiello, 1987; Leighty, 1997). These rocks typically predate most of the other Tertiary volcanic rocks of the region and represent the initial phase of middle Tertiary volcanism. Although the Early Miocene basalts and tuffs of the Chalk Canyon Formation typically overlie the trachyandesites and trachytes, several units are interbedded with rocks that are probably equivalent to the lower member of the Chalk Canyon formation (Early Miocene).

Chalk Canyon Formation

The Chalk Canyon Formation is a sequence of Early Miocene alkaline basalts, fluvial-lacustrine sediments, and felsic tuffs that overlie the heterogeneous Proterozoic basement across the Basin and Range and southern Transition Zone. The Chalk Canyon Formation was informally named by Gomez (1978) for exposures north of the Cave Creek quadrangle, in Chalk Canyon on the western side of Skull Mesa. Lithologic sequences within the Chalk Canyon Formation are distinctive and have been recognized at locations across the region (e.g., eastern Lake Pleasant, north Phoenix, New River, Black Canyon City, Cave Creek, etc.). An unconformity within the formation allows it to be subdivided into lower and upper members. The lower member consists mainly of alkaline basalts and crystal tuffs, and has a maximum thickness of slightly more than 200 m in the Skull Mesa and eastern New River Mesa areas, but is thinner to the south. The basaltic rocks of the lower member are typically porphyritic olivine-phyric lavas that commonly contain modal biotite, and have alkaline compositions. These basalts are interbedded with several lithic and crystal-rich tuffs. One of the lowest exposed alkaline basalt flows east of Sugarloaf Mountain is a 21.3 Ma alkali basalt that overlies a lithic tuff containing an oreodont fossil, the oldest known mammal in Arizona (Lindsay and Lundin, 1972; Leighty, 1997). The upper member of the Chalk

Canyon Formation is largely composed of fluvial-lacustrine deposits and subordinate basaltic rocks, and is approximately 100-150 m thick. It is typically overlain by multiple basalt flows of the Middle Miocene Hickey Formation (16.2-13.4 Ma) that cap many of the mesas of the region (e.g., New River Mesa, Skull Mesa, Wild Burro Mesa, Squaw Creek Mesa).

Several exposures of the Chalk Canyon Formation are present in the Cave Creek-Carefree area, largely in the northwestern (section 24, T. 6 N., R. 3 E.) and north-central part of the quadrangle (sections 14-15, T. 6 N., R. 4 E.). The section 24 sequence contains interbedded pumice-rich tuff, tuffaceous sediments, and basalt. The basalt is probably alkaline in composition, with olivine and clinopyroxene phenocrysts. The southern half of section 14 contains olivine-phyric basalt, very fine-grained vitric tuff, and pumice-rich tuff. However, the best Chalk Canyon Formation exposures are located in the Lone Mountain and White Eagle Mine areas (see the inset map and cross sections B-B' and D-D'). The oldest Tertiary rocks are moderately consolidated pre-volcanic conglomerate composed of platy, gray clasts of metasiltstone and rounded boulders of granite. This conglomerate is also exposed in the low hills around Carefree and on the north and east sides of Lone Mountain. North of the White Eagle Mine, the conglomerate is interbedded with a very light gray to white lithic-rich tuff; however, the conglomerate is overlain by basalt in most other exposures. Also present beneath the basal basalt is a locally silicified lithic tuff that forms a small ledge several meters thick.

At the White Eagle Mine, the uppermost Chalk Canyon Formation basalt (15.4 Ma) is overlain by a lacustrine sequence of thinly bedded mudstone, fine-grained sandstone, marl, and minor tuff, that are correlative with the Chalk Canyon Formation (referred to as the White Eagle Mine Formation by Doorn and Péwé, 1991). Abundant soft-sediment deformation features (e.g., flare structures) are present, with stem and root fossils also exposed (Doorn and Péwé, 1991; this study). The white carbonaceous mudstone and siliceous to dolomitic limestone have been quarried. The lacustrine sediments are overlain by a sequence of 13.4 Ma Hickey Formation basalts (Doorn and Péwé, 1991).

The White Eagle Mine sequence provides age constraints for the upper member of the Chalk Canyon Formation and the age of the lacustrine sequence. Aside from the White Eagle Mine area, the only dated Chalk Canyon Formation basaltic rocks (23-20 Ma) are part of the lower member, leaving the age relations of the upper member ill-defined. Regionally, the top of the lacustrine unit typically forms the boundary between the two formations, and in most other areas across the region, the basaltic rocks of the Hickey Formation overlie the Chalk Canyon Formation sequence with slight angular unconformity, with paleosols commonly present 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. The 15.4 Ma basalt in the White Eagle Mine section (15.4 Ma) not only represents the youngest (and only) age for the upper member of the Chalk Canyon Formation, but with the overlying 13.4 Ma Hickey Formation basalt, brackets the timing of lacustrine deposition as Middle Miocene. Also, the upper member of the Chalk Canyon Formation is likely of late Early to Middle Miocene age, possibly significantly younger than the lower member. Thus, Chalk Canyon Formation lacustrine sedimentation and basaltic eruptions occurred simultaneously with eruption of Hickey Formation basaltic rocks (16.2-13.4 Ma) across the Basin and Range-Transition Zone boundary during the Middle Miocene.

MIDDLE MIOCENE ROCKS

Basaltic volcanism during the Middle Miocene was widespread across the Basin and Range and Transition Zone and is represented by subalkaline lavas of the Hickey Formation and correlative rocks (Anderson and Creasey, 1958; McKee and Anderson, 1971; Eberly and Stanley, 1978; Gomez, 1978; Elston, 1984; Jagiello, 1987; Leighty and Glascock, 1994; Leighty, 1997). Basaltic rocks with similar petrography and geochemistry are exposed atop several fault-block remnants in the Phoenix area (e.g., Shaw Butte, Deem Hills, Hedgpeth Hills, Carefree Highway range). To the north of the Cave Creek quadrangle, a series of cliff-forming Hickey Formation basaltic flows (14.8-14.7 Ma) cap Skull Mesa and New River Mesa. These lavas 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 (Leighty, 1997). The maximum exposed thickness of these basalts is 120-180 meters between Skull Mesa and New River Mesa. A paleosol (2-5 meters thick) typically separates these lavas from the underlying Chalk Canyon Formation, with thin sediment and soil horizons also separating individual Hickey Formation flow units.

Exposures of Hickey Formation basaltic rocks are limited to isolated exposures along the northern and southern edges of the Carefree Basin. At Lone Mountain, the tilted 13.4 Ma basaltic rocks of the Hickey Formation are overlain by basin-fill deposits (Tsy) that fan upward into subhorizontally bedded strata. No significant differences were observed between the 13.4 Ma Hickey Formation lava and the 15.4 Ma Chalk Canyon Formation lava; however, the texture and mineralogy of these basalts are quite different from the dense, dark gray, olivine-phyric basaltic rocks north of Grapevine Wash (section 14, T. 6 N., R. 4 E).

LATE MIOCENE AND PLIOCENE ROCKS AND STRUCTURES

Late Miocene to Pliocene tectonism, and coeval fluvial sedimentation, are responsible for much of the physiographic and geologic characteristics of the Cave Creek quadrangle, with NE-SW extension helping to produce the modern Basin and Range-Transition Zone boundary. This extension may have been related to one or more tectonic phases, including waning metamorphic core complex extension, block faulting of the Basin and Range Disturbance, or an even younger extensional event (Menges and Pearthree, 1989; Leighty and others, 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. 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. Figure 4c shows the inferred locations of these buried structures. These faults may be related to the Carefree fault system, located in the Wildcat Hill quadrangle to the east (Pearthree and Scarborough, 1984; 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, 1 km north of the northwestern part of the quadrangle boundary. In the Cave Creek quadrangle, several WNW-trending, variably SW-dipping Tertiary exposures display similar relationships (sections 9, 15, and 16, T. 6. N, R. 4 E.). 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).

Hickey Formation sheet lavas probably extended across the Cave Creek quadrangle, and likely had a very slight regional dip to the south. Given the present elevation of the base of the Hickey Formation on Skull Mesa (4000-4200 feet) and a 1° dip to the south, the elevation of this contact in the Lone Mountain area may have been at an elevation of roughly 3500-3700 feet (see cross sections B-B' and D-D'). This requires a minimum of 1500 feet of displacement along the Lone Mountain fault to restore the tilted Tertiary sequence back to its initial, nearly horizontal position.

As much as a kilometer of apparent right-lateral offset may exist between the belt of Early Proterozoic rocks at Go John Mountain and those along the northern boundary of the quadrangle. The apparent right-lateral offset may have been produced by NE-side down movement along a NE-dipping normal fault (i.e., the Lone Mountain fault). However, Cenozoic sedimentary deposits cover the area between the two Early Proterozoic sequences, making determination of the amount of throw on the main NE-dipping structure rather speculative. Given an overall dip of 60° to the northwest for the Proterozoic sequence, a 0.5 kilometer right-lateral displacement, and a dip of 45° to 60° on the Lone Mountain fault, calculated NE-side-down displacement ranges from 3200 to 4000 feet. This displacement decreases with (1) decreasing dip of the Proterozoic sequence, (2) decreasing right-lateral offset, and (3) increasing dip on the Lone Mountain fault. Several other WNW-trending faults show similar right-lateral offset of basement rocks in the northeasternmost part of the quadrangle (section 18, T. 6 N., R. 5 E.), and further to the northeast.

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 (see cross sections B-B', C-C', and D-D'). Given the 3500-3700 foot elevation of the initial Chalk Canyon Formation-Hickey Formation datum, roughly 2500 to 3000 feet of SW-side-down displacement may have occurred on the Carefree Basin fault. Secondary synthetic faults are probably also present. 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 in the southern part of the quadrangle.

Several small southwest-dipping normal faults are present in the Proterozoic terrane between southern Black Mountain and Go John Mountain. The small normal fault at the Mormon Girl Mine (section 4, T. 6 N., R. 4 E.) exposes highly brecciated hanging wall rocks that contain limited chrysocolla mineralization on and near the fault plane. No fault striae were observed on the fault surface. Other small mineralized faults and veins are present to the north of the Mormon Girl Mine. Similar NW-trending normal faults with unknown displacement are present in the hills between Cave Creek and Black Mountain. Several other steeply SW-dipping, NW- to N-trending faults are present between Cave Creek Road and Go John Mountain that may be related to the Mormon Girl Mine fault.

The 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 in the northern part of the quadrangle (see figure 2). This basin has been the focus of many previous geologic and geophysical studies, with the work of Doorn and Péwé (1991) serving as a compilation of available data. The thickness of basin-fill deposits (the Carefree Formation) is roughly 2,000 ft in the eastern part of the basin (Doorn and Péwé, 1991). The depth to the base of the Carefree Formation is much shallower in the western part of the basin, except between Rowe Wash and Willow Springs Wash (sections 21 and 22, T. 6 N., R. 4 E.), where the basin is roughly 1,100 feet thick (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.

From well-log and gravity data, the Carefree Basin is underlain by irregular, fault-related basement topography (see cross sections B-B', C-C', and D-D'). Beneath the basin-fill deposits, a thin Tertiary sequence overlies Proterozoic metamorphic rocks in the west and the coarse-grained Middle Proterozoic granite in the east. The weathered upper portion of the coarse-grained Middle Proterozoic granite may locally be more than 500 ft thick (Doorn and Péwé, 1991).

The basin-fill sediments included in the Carefree Formation (Tsy) were described and subdivided by Doorn and Péwé (1991) into five moderately consolidated members composed of material derived from different local sources. The Grapevine Member is the thickest and most widespread member and is present in the eastern and southern parts of the Carefree Basin. This member was largely derived from the Middle Proterozoic granite that underlies the eastern part of the basin. The Sombrero Member is a fanglomerate characterized by Tertiary basalt and Proterozoic pelitic rocks from the Lone Mountain area, and overlies the Grapevine Member.

Perhaps due to the composition of its clasts, the sediments of the Sombrero Member form distinctive, NE-trending ridges, whereas the other members of the Carefree Formation are much less resistant and form low-relief surfaces. The Naked Girl Canyon Member is also fanglomeratic, characterized by Tertiary basaltic and andesitic clasts, with a clay-rich playa facies that grades laterally into the Sombrero and Galloway Members. The Galloway Member is present in the southwestern part of the basin, and is dominantly composed Proterozoic metamorphic and Tertiary basalt clasts. This member grades laterally into the Church Member, a Proterozoic meta-argillite-rich fanglomerate, present at the northern base of Black Mountain, which grades laterally into the Grapevine Member to the east.

The groundwater discharge potential of various lithologies in and around the Carefree Basin is summarized in Doorn and Péwé (1991). Tertiary basalts and related rocks, as well as Proterozoic basement rocks, produce water at low discharge rates (e.g., 2-5 gallons per minute), but locally produce up to 30 gallons per minute (g.p.m.) in areas where the bedrock is more fractured. The weathered granite zone beneath the basin may yield up to 600 g.p.m. Groundwater discharge from members of the Carefree Formation is summarized in Doorn and Péwé (1991), Table 3. 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 and transmissivity in the Carefree Formation and produces up to 1,600 g.p.m.

PLIO-QUATERNARY GEOLOGY

The alluvial landforms of the Cave Creek quadrangle record the recent geologic evolution of the area. Several terrace levels related to the development of the Cave Creek main drainage are present in the northwestern part of the quadrangle. 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 (TQor; the Little Elephant terrace of Gorey, 1990; Doorn and Péwé, 1991); very old alluvial fan sediments (TQo) grade laterally into this unit from the northwest. Basin-fill deposits (i.e., 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.

Quaternary alluvium deposited by tributaries of Cave Creek (e.g., Qo, Qm, Qmm, Ql, and Qy) covers most of the Carefree Basin and the southern half of the quadrangle. Alluvium in the southeastern part of the Carefree Basin and southern part of the quadrangle is composed of largely granitic sand and gravel, with some basalt clasts. In these areas, Quaternary alluvial deposits form thin, discontinuous mantles over basin-fill deposits or weathered granite pediment. Alluvium estimated to be of middle Pleistocene age (Qm) is predominant in these areas; typically, middle Pleistocene alluvium has been extensively eroded, leaving rounded ridges between modern channels. Most late Pleistocene and Holocene alluvium (Ql and Qy) is restricted to fairly narrow bands along washes.

The easternmost part of the quadrangle contains small portions of the extensive pediment surface developed in the northern part of the McDowell Mountains (see figure 4a; the Pinnacle Peak pediment of Doorn and Péwé, 1991). In situ weathering of the coarse-grained Middle Proterozoic granitic basement rocks across this pediment surface has resulted in a veneer of arkosic sediment (Ygp) of variably thickness. Quaternary alluvium in the central Carefree Basin contains a much greater percentage of metamorphic gravel clasts than the deposits to the south. Deposits and alluvial surfaces dominated by these metamorphic clasts are more resistant to erosion than the finer gravels derived primarily from weathered granite. This accounts in part for preservation of older Quaternary deposits (Qo) and much better preservation of planar alluvial surfaces associated with middle Pleistocene deposits (Qmm) compared with areas farther south.

GEOLOGIC HAZARDS

A variety of potential geologic hazards exist in the study area. The primary geologic hazards that may affect this area are soil problems, flooding, debris flows, and rockfalls. Radon, a radioactive gas that is a decay product of uranium, is also a potential hazard because the granitic rocks that underlie the eastern part of the quadrangle have elevated uranium concentrations in some areas. The geologic hazards of a larger area that includes most of the Cave Creek quadrangle have been mapped and considered in detail by Kenny (1986). The general character of these hazards and the areas that may be affected by them are summarized below.

Flooding

Flooding is probably the most serious geologic hazard of the Cave Creek quadrangle. Potential flood hazards consist of inundation and erosion along Cave Creek and its larger tributaries, and flash-flooding associated with the smaller tributary streams that flow across the piedmonts of the area.

Cave Creek is a moderately large drainage that heads in the Transition Zone north of the Cave Creek quadrangle. Its drainage area is about 80 mi^2 at the northern edge of the quadrangle and about 130 mi^2 at the southwestern edge of the quadrangle. Thus, it is capable of generating large floods; the flood with a 1 percent chance of being exceeded annually (the 100-year flood) has been estimated at about 23,000 cubic feet per second (cfs) to 36,000 cfs (Kenny, 1986). The principal tributaries of Cave Creek that cross the Carefree Basin can generate smaller, but still significant, 100-year floods ranging from about 6,000 cfs to 18,000 cfs (Kenny, 1986). Such large floods involve deep, high-velocity flow in channels, inundation of overbank areas, and may cause substantial bank erosion along the channels. Areas mapped as Qyc are likely to be affected by deep, high velocity flow during floods. Adjacent areas mapped as Qy are likely to be subject to shallower inundation, and local bank erosion. Areas near these large streams covered by older deposits (Ql, Qlr, and older) generally are not subject to inundation, but they may be affected by lateral stream erosion.

Flood hazards associated with smaller tributaries may be subdivided into (1) localized flooding along well-defined drainages, where there is substantial topographic confinement of the wash; and (2) widespread inundation in areas of minimal topographic confinement (i.e., active alluvial fans). Delineation of flood-prone areas along well-defined drainages is fairly straightforward, and these hazards may be mitigated by avoiding building in or immediately adjacent to washes. Floods leave behind physical evidence of their occurrence in the form of deposits. Therefore, the extent of young

deposits on piedmonts is an accurate indicator of areas that have been flooded in the past few thousand years. These are the areas that are most likely to experience flooding in the future. Following this logic, the extent of potentially flood-prone areas on a piedmont may be evaluated based on the extent of young deposits (Qy).

The washes that flow across piedmonts of the Cave Creek quadrangle have small drainage basins that head on the low-relief bedrock pediment. The extent of Holocene deposits, including active channels and low terraces, that are associated with these washes is fairly limited. This geologic evidence indicates that the extent of potentially flood-prone areas on piedmonts of this quadrangle is also of limited extent. Although topographic relief along the washes typically is a few meters or less, this relief evidently is sufficient to contain the largest floods that are generated on the washes, and we have found no geologic evidence of alluvial-fan flooding. Holocene deposits are somewhat more extensive along several of the washes, however, indicating that flood inundation is more widespread or channel locations have shifted during the Holocene.

Soil/substrate Problems

Several types of soil/substrate problems may be encountered in the Cave Creek quadrangle. Soil compaction or expansion upon wetting or loading may be an important geologic hazard in limited portions of the quadrangle. Soil instability has caused extensive damage to buildings in Arizona (Christenson and others, 1978; Péwé and Kenny, 1989). Changes in soil volume beneath structures may cause damage ranging from nuisance cracks to serious structural damage. Deposits that are susceptible to compaction are typically relatively fine-grained, young sediments. Deposits in the area that are candidates for compaction are the fine-grained terrace deposits of Qy, Qyr, and Ql. Clay-rich soils associated with the well-preserved early and middle Pleistocene alluvial fans (Qo, Qmm, and locally, Qm) may have some potential for shrinking and swelling during dry and wet periods, respectively. However, clay-rich horizons associated with these surfaces are generally less than 1 m thick, so their shrink-swell potential is probably limited.

The presence of cemented caliche (petrocalcic soil horizons) or shallow bedrock may impact construction excavation and leaching potential. Calcium carbonate accumulates in soils in this desert environment over thousands to hundreds of thousands of years. Typically, the soils associated with middle Pleistocene alluvium (Qm and Qmm) in this area have significant accumulations of calcium carbonate, but strongly cemented carbonate soil horizons are not common. Petrocalcic horizons are common in early Pleistocene alluvium (Qo), and are found in some middle Pleistocene alluvium (Qm and Qmm) and thin hillslope deposits (Qs) (Kenny, 1986). Progressively less carbonate accumulation is associated with increasingly younger surfaces, such that Ql and younger deposits have weak carbonate accumulations. Some of the map area is composed of granitic pediment or very thin mantles of alluvial deposits (typically a few meters or less thick) over pediment. These deposits are typically poorly indurated and are composed of granitic grus and much sand- and silt-sized material shed from the granite bedrock and do not pose a serious obstacle to excavation. The weathered bedrock typically found beneath the alluvial deposits generally is highly weathered and fairly easy to excavate, but construction may be affected if more resistant bedrock is encountered in the near subsurface (Kenny, 1986).

Rockfalls and Debris Flows

Rockfalls, small landslides, and debris flows are potential hazards on and immediately adjacent to steep slopes. The mass movement of material on steep slopes is typically triggered by intense or prolonged periods of precipitation (Christenson and others, 1978). Debris flows are viscous slurries of sediment and water that can transport large boulders substantial distances downslope. In southern and central Arizona, nearly all of the documented historical debris flows have been restricted to mountain slopes and valleys. Rockfalls and landslides are potential hazards below bedrock cliffs and where bedrock outcrops exist at or near the top of steep mountain hillslopes. The existence of large boulders near the base of a steep slope should be considered evidence of potential rockfall hazard in most cases.

Potential rockfall hazards in the Cave Creek quadrangle are greatest on or near the toes of slopes of bedrock hills and low mountains formed on granitic rocks (Yg). Rockfall hazard exists in these areas because of the combination of steep slopes and large rock masses exposed on the slopes, and boulders strewn near the bases of these slopes are clear evidence of past rockfalls (Kenny, 1986). Smaller-scale rock falls and slides of groups of smaller rocks may occur on steep hillslopes formed on Precambrian metamorphic rocks or basin-fill deposits (Kenny, 1986). Debris flows may be a hazard along the steep upper reaches of the streams that drain the hills and mountains of the quadrangle. They are typically generated by mass movements on hillslopes or within steep stream valleys. Larger debris flows in some environments may continue downslope out of the mountains and impact piedmont areas. In this environment, however, it is more likely that debris flows will impact only hillslopes and channels within steep-walled mountain valleys.

Radon

Uranium is present in all geologic materials, generally in concentrations of 1 to 10 parts per million (ppm). When a uranium atom undergoes radioactive decay it begins a long string of decays through a series of isotopes that make up the uranium decay series. Radioactive decay ends at stable lead-206. Radon, a colorless, odorless gas, is a member of the uranium decay series. 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).

The coarse-grained granite (Yg) underlies much of the adjacent (to the east) Wildcat Hill quadrangle, and generally forms gentle slopes and low hills that are not an impediment to construction of new homes or other buildings. This granite extends into the eastern part of the Cave Creek quadrangle where it forms a low-relief pediment over much of its exposed area. Uranium levels in this 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, but uranium was measured at 7 ppm at one point along Pima Road in the southeastern part of the Cave Creek quadrangle, which is slightly anomalous. 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, west-northwest trending belt of irregular and discontinuous outcrops of calcareous sedimentary rocks (Tsl) in the northern part of the Cave Creek Quadrangle, named the White Eagle Mine Formation by Doorn and Péwé (1991), contains anomalous uranium levels in many areas (Duncan and Spencer, 1993). A single measurement of 50 ppm uranium reported by Harris (1997) for these rocks is higher than previously reported measurements of this map unit within the Cave Creek Quadrangle but is lower than uranium levels measured nearby to the northwest. Rocks of this unit are a significant potential radon hazard in the Cave Creek area.

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UNIT DESCRIPTIONS

Pliocene to Quaternary piedmont deposits

Qs **Colluvium, undivided (< 750 ka)** - Unconsolidated to moderately consolidated colluvial deposits on hillslopes. Typically fairly coarse, subangular to angular, very poorly sorted, weakly bedded, steeply sloping deposits. Deposits probably range in age from Holocene to middle Pleistocene.

Qy **Holocene alluvium (< 10 ka)** - Unconsolidated, poorly sorted sand, gravel and boulder deposits confined to the modern drainages (e.g., Willow Springs Wash, Rowe Wash, Galloway Wash, and many small tributaries). Larger clasts consist of Proterozoic metamorphic clasts and Tertiary basalt; smaller clasts commonly are subangular granitic grus. Characterized by stratified, poorly to moderately sorted sand, gravel, and cobbles; frequently mantled by sandy loam sediment. The single channels commonly diverge into braided channels, which converge again downstream. Alluvial surfaces exhibit bar-and-swale topography, with the ridges typically being more vegetated. Soil development is weak, with only slight texturally or structurally modified B horizons and slight calcification (Stage I). Some of the older Qy soils may contain weakly developed argillic horizons. Because surface soils are not indurated with clay or calcium carbonate, Qy surfaces have relatively high permeability and porosity.

Ql **Late Pleistocene alluvium (10 to 250 ka)** - Moderately sorted, clast-supported sandstones and conglomerates containing abundant granitic or metamorphic gravel clasts in a tan to brown sand and silt matrix. Ql surfaces are moderately incised by stream channels, but still contain constructional, relatively flat, interfluvial surfaces. Ql soils typically have moderately clay-rich, tan to red-brown argillic horizons; these soils contain moderate amounts of pedogenic clay and some calcium carbonate, resulting in relatively low infiltration rates. Thus, these surfaces favor plants that draw moisture from near the surface. Ql soils typically have Stage II calcium carbonate development.

Qm **Middle Pleistocene granitic alluvium (250 to 750 ka)** - Sandy to loamy, tan-colored sandstones and minor conglomerates containing dominantly of granitic gravel clasts, with minor to locally abundant volcanic gravel clasts. Qm surfaces have typically been eroded into shallow valleys and low ridges; original depositional surfaces may be preserved along ridge crests. Deposits are moderately consolidated and locally indurated by carbonate. Argillic horizons moderately developed where alluvial surfaces are well -preserved; on the eroded valley slopes, argillic horizons are weak due to erosion. This unit is predominant across the southern part of the quadrangle and in the southeastern Carefree Basin, where the streams drain the granitic pediment to the east. The Qm unit locally consists of an older member (Qm_1) and a younger member (Qm_2).

Qmm Middle Pleistocene metamorphic alluvium (250 to 750 ka) - Sandy to loamy, tan- to brown-colored conglomerates containing dominantly of metamorphic gravel clasts, with minor to locally abundant volcanic gravel clasts. Qmm surfaces are cut by shallow to moderately deep gullies, but away from the gullies are planar, laterally extensive, and relatively uneroded. Deposits are moderately consolidated and locally indurated by carbonate. Reddish-brown argillic horizons typically moderately developed to well developed in interfluvial areas. Probably similar in age to Qm, but metamorphic clasts typically are larger and more resistant to erosion than granitic gravels. Thus, Qmm alluvial surfaces tend to be much better preserved than Qm surfaces, and soil development is substantially stronger. This unit covers much of the Carefree Basin area where the surrounding bedrock is composed dominantly of Early Proterozoic metamorphic rocks. The Qmm unit locally consists of an older member (Qmm_1) and a younger member (Qmm_2).

Qo Early Pleistocene alluvial fan deposits (750 ka to 1.6 Ma) - Sandy to loamy, brown-colored conglomerates containing dominantly of metamorphic gravel clasts, with minor to volcanic gravel clasts. These deposits are moderately consolidated and commonly are indurated by soil carbonate. Deposits are deeply dissected by the larger drainages of the Carefree Basin, as well as by tributaries that head on Qo surfaces. Reddish-brown argillic horizons are moderately developed to well developed on planar, relatively well-preserved alluvial surface remnants. Cemented petrocalcic are commonly exposed on side slopes below ridge crests. This unit is almost entirely restricted to the Carefree Basin area, primarily between Rowe Wash and Galloway Wash.

TQo Pliocene to Early Pleistocene alluvial fan deposits (1 to 3 Ma) - Very old alluvial fan deposits that are graded to the highest preserved terrace (TQor) of the ancestral Cave Creek drainage in the northwesternmost corner of the quadrangle. Deposits are sandy with abundant basalt cobbles and boulders. Soils are brown and clay-rich. Cemented petrocalcic horizons are typically exposed in shallow gullies.

Quaternary River Deposits

Qyc Active channel deposits - Deposits in the active channels of Cave Creek and its principal tributaries in the Carefree Basin. Gravel clasts range in size up to boulders, with Cave Creek alluvium typically being coarser that tributary alluvium. Clasts are subrounded to well-rounded and lithologies vary substantially.

Qyr Holocene river terrace deposits (0 to 10 ka) - Unconsolidated, moderately to poorly sorted, subrounded to rounded sand- and gravel-sized clasts in a sandy to silty matrix. Landforms typically are low terraces, but also include minor channels. Equivalent to the Hidden View terrace of Doorn and Péwé (1991).

Qlr **Late Pleistocene river terrace deposits (10 to 250 ka)** - Intermediate, moderately old terrace deposits of Cave Creek. Unconsolidated, moderately to poorly sorted, subrounded to rounded sand- and gravel-sized clasts in a sandy to silty matrix. Moderate soil clay accumulation and carbonate development, but no cementation. Equivalent to the Cahava Ranch terrace of Doorn and Péwé (1991).

Qmr **Middle Pleistocene river terrace deposits (400 to 750 ka)** - High, old terrace deposits of Cave Creek. Unconsolidated, moderately to poorly sorted, subrounded to rounded sand- and gravel-sized clasts in a sandy to silty matrix. Clay-rich soil with a well-developed caliche horizon. Locally consists of an older member (Qmr_1) and a younger member (Qmr_2). This unit is roughly equivalent to the Mesquite Tank terrace of Doorn and Péwé (1991) and the Mesa terrace of the Salt and Verde rivers (Péwé, 1978).

Qor **Early Pleistocene river terrace deposits (750 ka to 1.6 Ma)** - Old terrace remnant of Cave Creek. Map unit includes only one poorly preserved terrace remnant that is a few meters higher than adjacent Qmr_1 terraces but well below the TQor terrace. Deposits are weakly consolidated, moderately to poorly sorted, subrounded to rounded sand- to boulder-sized clasts in a sandy to silty matrix. Soil development is weak because the original depositional surface has been removed by erosion.

TQor **Pliocene to Early Pleistocene river terrace deposits (1 to 3 Ma)** - Very old terrace of Cave Creek located roughly 100 m above the modern stream channel. Unconsolidated to moderately consolidated, moderately to poorly sorted, subrounded to rounded sand- to boulder-sized clasts in a sandy to silty matrix. Characterized by a strongly developed, several meter-thick petrocalcic horizon; chocolate brown, clay-rich argillic horizon exists where planar depositional surface is well-preserved. This terrace was named the Little Elephant terrace by Doorn and Péwé (1991), and it is equivalent to the Sawik terrace of the Salt and Verde rivers (Péwé, 1978; Skotnicki, 1995).

Oligocene to Pliocene rocks

Tsp **Playa deposits (Late Miocene to Pliocene)** - Light tan, fine-grained siltstone exposed in washes north of the town of Cave Creek (section 21, T. 6 N., R. 4 E.). Generally massive to crudely bedded. Forms crumbly exposures. The unit grades downward into sandstone and basalt-rich conglomerate, and grades laterally into basin-fill conglomerate (Tsy) within a distance of 50 feet.

Tsy **Younger basin-fill deposits (Late Miocene to Pliocene)** - Interbedded moderately to poorly sorted sandstones and conglomerates. Subrounded to angular clasts of Proterozoic metamorphic rocks, and Tertiary volcanic and sedimentary rocks; clast type and relative abundance varies with locality. Clast sizes range from sand to boulders in a grussy, carbonate-rich matrix. Sandstone and basalt-rich conglomerate grades upward and laterally into fine-grained siltstone representing playa deposits. Clast compositions and relative abundances are variable, and are largely dependent on the composition of nearby bedrock.

This unit is equivalent to the Carefree Formation of Doorn and Péwé (1991) and is typically covered by Quaternary deposits, but is exposed along stream drainages. Lower basin-fill sediments are tilted, but become more horizontal upward in the section (sections 15 and 16, T. 6 N., R. 4 E.; sections 19 and 30, T. 6 N., R. 5 E.). A considerable age difference may exist between the lowest beds and the uppermost, untilted post-faulting beds. The SW-trending ridges between Carefree and Lone Mountain are underlain by fanglomeratic sediments that are particularly rich in basaltic and metamorphic clasts (equivalent to the Sombrero Member of the Carefree Formation of Doorn and Péwé, 1991).

Ts **Conglomeratic sediments, undivided (Miocene)** - Typically poorly exposed conglomeratic sandstone. In section 24, T. 6 N., R. 3 E., a sequence of conglomeratic sediment is present between the porphyritic olivine + clinopyroxene basalt of the Chalk Canyon Formation and the brownish-gray, intergranular basalt of the Hickey Formation (just west of the quadrangle boundary).

Tsl **Lacustrine deposits (Middle Miocene)** - Light gray to tan and white fine-grained sedimentary deposits composed of thinly bedded light gray to tan mudstone, calcareous mudstone (marl), minor fine-grained sandstone, and white dolomitic limestone. Tan-colored claystones are more abundant upward. Soft-sediment deformation features are abundant; flare structures of the upper part of the unit intrude the overlying basalt. Minor thin (<5 cm thick) tuff bed is present within 3 meters of the top of the unit. Doorn and Péwé (1991) described plant stem and root fossils. Excellent exposures are present in the Lone Mountain and White Eagle Mine areas (section 19, T. 6 N., R. 5 E.). Equivalent to the upper member of the Chalk Canyon Formation (Gomez, 1978; Leighty, 1997) and the White Eagle Mine Formation of Doorn and Péwé (1991).

Tb **Basalt, undivided (Early to Middle Miocene)** - Basaltic lavas correlative with the Early Miocene Chalk Canyon Formation and the Middle to Late Miocene Hickey Formation. Most exposures are probably equivalent to the Chalk Canyon Formation. The basaltic flows locally contain minor scoria and basalt-related breccia. This unit forms dark, resistant hills. In the Lone Mountain and White Eagle Mine area, the Chalk Canyon Formation lavas are porphyritic, with subhedral olivine phenocrysts (10%, 1-4 mm diameter, altered to iddingsite) in a dark gray, fine-grained groundmass. This unit contains several different flow units, with the flow directly below the lacustrine sediments (Tsl) at the White Eagle Mine representing the youngest dated basaltic rock in the Chalk Canyon Formation (15.4 ± 0.4 Ma, Doorn and Péwé, 1991). To the northwest, in sections 14 and 15, T. 6 N., R. 4 E., very dark gray, very dense, porphyritic olivine basalt flows are interbedded with tuffs and tuffaceous sediments. In section 24, T. 6 N., R. 3. E., amygdaloidal, olivine + clinopyroxene basaltic rocks are also interbedded with tuffs.

The lava flows above Chalk Canyon Formation tuffs and lacustrine sediments are correlative to lavas of the Middle and Late Miocene Hickey Formation (Leighty, 1997) and have also been referred to as the New River Mesa Basalt (Gomez, 1978; Jagiello,

1987). These rocks also have characteristic intergranular textures, with clinopyroxene and altered olivine phenocrysts within a framework of plagioclase crystals. Columnar jointing and zones of vesicles ("pipe" vesicles) are common in outcrop, and the vesicles are typically open, 1-2 cm in diameter, and may be rimmed with calcite. These basaltic andesites (Leighty, 1997) are generally different in outcrop color (dark grayish brown) than the underlying Chalk Canyon Formation alkaline basaltic flows (dark gray to bluish gray).

Isolated erosional remnants are present across the quadrangle. In section 24, T. 6 N., R. 3 E. (just off the western edge of the quadrangle), a tilted remnant of Hickey Formation basalt overlies basaltic rocks and tuffs of the Chalk Canyon Formation. This Hickey Formation lava is fine-grained, with olivine and pyroxene phenocrysts in an intergranular groundmass. The olivine phenocrysts are moderately altered, and pyroxene is dark brown in color. This rock is moderately vesicular, typically having flattened, open vesicles (1-15 mm long), with smaller vesicles commonly filled with calcite. Between sections 14 and 23, T. 6 N., R. 4 E., a thin remnant of scoriaceous basalt contains abundant plagioclase, with minor olivine and pyroxene phenocrysts. In the Lone Mountain and White Eagle Mine area, southwest-dipping Hickey Formation basaltic lavas overlie the lacustrine sediments (Tsl), underlie the basin-fill sediments (Tsy), and cap much of Lone Mountain. This basalt has been dated at 13.4 ± 0.4 Ma (Doorn and Péwé, 1991), and is relatively dense, very fine-grained, with plagioclase, pyroxene, and olivine phenocrysts.

Tt **Tuff (Early Miocene)** - Light gray to white tuff and reworked pumice-rich, vitric, or lithic tuff. This unit typically crumbles easily, but is locally well-indurated and forms slopes to small ridges. In section 24, T. 6 N., R. 3 E., this unit is a massive, creamy tan colored, matrix-supported pumice-rich tuff and reworked tuff, and is interbedded with northeast-dipping olivine + clinopyroxene basalts. Rounded pumice fragments are much more abundant than lithic fragments. This pumice-rich tuff is baked an orange-red color within 1 m of the overlying basalt flow. The hill straddling the boundary between sections 14 and 23, T. 6 N., R. 4 E. contains largely light orange-tan, tuffaceous arkose and pumice-rich lithic tuff that overlie and are interbedded with very dark gray, porphyritic, olivine basalts. In section 15, T. 6 N., R. 4 E., the tuff dips steeply to the southwest, and is present between older andesitic conglomerate (Tas) and younger basin-fill sediments (Tsy). At Lone Mountain, a light gray to white lithic tuff contains gray pumice (up to 1 cm wide) and rare, anhedral to subhedral biotite, sanidine, and minor quartz (all <2 mm wide). The lowermost 5-8 meters is thinly bedded, with the base of the tuff having abundant basaltic clasts. The uppermost 15-20 meters is mostly massive to thickly bedded. The tuff is interbedded with conglomerate (Tc) and overlies the lowest basalt flow. This tuff unit is likely correlative with the Early Miocene tuffs in adjacent areas that belong to the lower member of the Chalk Canyon Formation.

A distinctive pale reddish brown vitric tuff underlies the basaltic rocks in section 14, T. 6 N., R. 4 E. This tuff lacks phenocrysts or pumice and breaks in a conchoidal fashion. This unit may represent an airfall tuff that was still relatively hot when deposited. From other exposures to the north and northeast of the quadrangle (east of

Sugarloaf Mountain and east of Quien Sabe Peak, respectively), this vitric tuff is typically present near the bottom of the Tertiary section and is highly similar to the one exposed along Cave Creek (east of Sugarloaf Mountain) that contains an oreodont fossil and is overlain by a 21.3 Ma alkaline basalt (Lindsay and Lundin, 1972; Gomez, 1978; Leighty, 1997).

Tc **Conglomerate (Early Miocene)** - Moderately consolidated conglomerate that contains abundant angular to subrounded, mostly pebble to cobble-size clasts derived from metasedimentary rocks (Xs). The matrix is rusty red, and grussy and contains no carbonate. This unit forms dark, rounded slopes and hills. At Lone Mountain, the unit grades eastward into deposits containing large, rounded boulders of coarse-grained granite (Yg) and smaller angular, fine-grained granite boulders and cobbles and minor Xs clast. Northwest of Lone Mountain, the unit contains interbedded sandstones containing light gray, low-density felsic volcanic clasts. This unit is interbedded with the tuffs and basalts that are correlative with the Chalk Canyon Formation. Much of the lower part of this unit may be Late Oligocene in age, significantly predating basaltic volcanism. This unit is similar to other basal, prevolcanic conglomerates in the Chalk Canyon Formation (Gomez, 1978; Jagiello, 1987; Leighty, 1997).

Tas **Andesitic conglomerate (Early Miocene)** - Volcanic-derived conglomerate containing entirely angular andesite (Ta) clasts, from sand-sized to about 15 cm diameter, in a fine-grained tan sandy carbonate-rich matrix. Bedding is locally exposed. In section 15, T. 6 N., R. 4 E, this unit overlies 22.2 Ma andesite flows, and the lower part of the unit is interbedded with thin olivine basalt flows. This conglomerate is overlain by tuffaceous sediments.

Tai **Intrusive hornblende andesite (Early Miocene?)** - Medium to dark gray rock containing 1-4 mm rectangular hornblende phenocrysts in a light gray, fine-grained groundmass. Forms small, irregular intrusions southwest of Go John Mountain.

Ta **Andesite (Early Miocene)** - Contains tabular black phenocrysts of black hornblende or pyroxene (<2% 1-2 mm long) and smaller, clear plagioclase crystals in a tan to brown aphanitic matrix. The unit is typically brecciated and massive; crude bedding can be discerned only from a distance. The unit overlies Proterozoic metamorphic rocks and forms resistant hills in the north-central part of the map area. The exposure in section 17, T. 6 N., R. 4 E. has been dated at 22.2 ± 0.4 Ma (Doorn and Péwé, 1991), similar in age to other Middle Tertiary intermediate and felsic volcanic rocks in the region.

Tf **Latite (Late Oligocene to Early Miocene)** - Contains abundant fine-grained phenocrysts (20-50%, <1 mm diameter) of subhedral to euhedral plagioclase, biotite, and minor olivine in a fine-grained pinkish-tan matrix. The biotite crystals are slightly altered to hematite and are preferentially oriented into parallel planes forming a trachytic fabric. Contains subangular to subrounded xenoliths (up to 5 cm in diameter) and xenocrysts of basalt, granite, coarse-grained brown biotite, coarse-grained brown amphibole, red garnet, green pyroxene, and feldspar. This unit underlies basaltic rocks in section 35,

T. 6 N., R. 4 E., and may be correlative to similar middle Tertiary silicic to intermediate volcanic rocks in the region, some containing crustal inclusions (e.g., western New River, Elephant Mountain, Camp Creek).

Tfi **Felsic intrusive rock (Tertiary)** - Aphyric lava and breccia containing very small crystals (<1 mm diameter) of biotite and feldspar. Forms an oval-shaped intrusion along Grapevine Wash (section 18, T. 6 N., R. 5 E.), where light tan outcrops are locally brecciated, vitric, and flow-banded. This intrusion is probably a rhyolitic feeder conduit that may be related to felsic dikes exposed to the southeast in the Wildcat Hill quadrangle (Skotnicki and others, 1997). Age relations are unknown.

TXd **Diorite (Tertiary or Proterozoic)** - Fine-grained diorite that contains light gray plagioclase, subhedral biotite, and a completely altered to a light orange mineral (possibly pyroxene or hornblende). The small exposure in section 19, T. 6 N., R. 4 E. is very crumbly in outcrop. Probably equivalent to Xd.

Middle Proterozoic rocks

Yg(p) **Pediment deposit on coarse-grained granite (Middle Proterozoic)** - A layer of grus of variable thickness that mantles much of the low-relief pediment surface formed on granitic bedrock (Yg). These deposits are formed by the in situ weathering of the granite, and result in a subdued, rounded, and moderately dissected surface.

Yg **Coarse-grained granite (Middle Proterozoic)** - Unfoliated, coarse-grained granite with abundant phenocrysts of light gray to pink subhedral potassium feldspar (2-4 cm long), light gray plagioclase (2-8 mm diameter), clear gray quartz (2-8 mm diameter), and subhedral black biotite. Biotite occurs in thin books and is generally fresh or slightly altered to hematite and locally chlorite(?). Near the contact with the Proterozoic metamorphic rocks biotite, plagioclase and quartz are locally fine-grained, but the K-feldspar phenocrysts generally are not. Contact metamorphic effects are well-exposed in the meta-argillite at the northern end of Black Mountain (section 34, T. 6 N., R. 4 E.). Jointing is widely spaced. This unit generally weathers into spheroidal boulders and easily erodes into a grussy deposit (Ygp) that mantles the granitic bedrock. This granite is likely correlative with other undeformed granitic plutons in Arizona (~1430 Ma; Anderson, 1989). Specifically, this granite may be the westernmost exposure of a large granitic batholith exposed between the Verde River and the Mazatzal Mountains to the east (Skotnicki and Leighty, 1997)

Ygf **Fine-grained granite (Middle Proterozoic)** - Medium- to fine-grained equigranular granite composed of subhedral light tan potassium feldspar, plagioclase, clear gray quartz, and biotite. Generally weathers slightly darker than the main coarse-grained granite and erodes into smaller, angular blocks instead of spheroidal boulders. Contacts with the coarse-grained granite are typically sharp. The rock forms lenticular dike-like bodies within the coarse-grained granite on the east side of Black Mountain.

Early Proterozoic plutonic rocks

Xg **Granite (Early Proterozoic)** - Foliated, medium-grained leucocratic granite that is probably equivalent to the granite of the Verde River batholith (1700 Ma). This unit occurs as two SW-trending dikes in section 10, T. 6 N., R. 4 E., and are related to a large granitic mass exposed to the north of the quadrangle at Continental Mountain.

Xd **Diorite to granodiorite (Early Proterozoic)** - Foliated medium- to fine-grained diorite to granodiorite. The dioritic phases contain phenocrysts (1-4 mm) of subhedral light gray orthoclase, tabular black crystals that may have formerly been hornblende, but are now completely altered to fine-grained biotite, plagioclase, and minor clear quartz. This unit is typically moderately weathered and oxidized. These rocks form lenticular intrusive bodies subparallel to the strike of primary foliation (sections 29, 30, and 32, T. 6 N., R. 4 E.). Forms light-gray green resistant ridges, typically with poorly expressed foliation. Breaks along fractures into angular cobble-sized blocks. Excellent exposures are present along the Go John trail 0.6 km south of Go John Mountain. This unit is equivalent to the Go John Diorite of Doorn and Péwé and Doorn (1991). A granodioritic phase of this unit (section 36, T. 6 N., R. 3 E.) may be equivalent to the granodioritic phases described by Anderson (1989b). This rock contains plagioclase (<2 mm diameter), quartz, potassium feldspar, and a fine-grained an olive-green matrix. The granodiorite is massive, but generally poorly exposed with crudely-developed foliation and jointing.

Early Proterozoic metavolcanic rocks

Xv **Metavolcanic rocks, undivided (Early Proterozoic)** - A complex assemblage of rocks of probable volcanic origin that may include flows, tuffs, and related volcaniclastic sediments. A sequence of light-colored, creamy grayish white silicic beds with medium to dark grayish green phyllites and schistose rocks may represent interbedded felsic to mafic metavolcanic rocks. The felsic beds are thin and generally very fine-grained. Fissile, dark green to tan, slaty rocks locally contain phenocrysts of light gray feldspar and clumps of fine-grained biotite. This unit forms slopes and is generally less-resistant than the neighboring felsic volcanic rocks (Xvf).

Xvf **Felsic metavolcanic rocks (Early Proterozoic)** - Resistant, light gray felsic lavas and tuffs. Typically silicified. Where porphyritic, this rock contains slightly deformed relict phenocrysts (all <3 mm) of light gray to pink feldspar, quartz, and altered biotite or dark gray magnetite in a fine-grained quartz-sericite matrix. Primary flow textures are locally exposed. However, this rock is commonly aphyric and lacks significant crystal content. Less-resistant portions typically exhibit better foliation than more massive parts of the unit and are more fissile, darker gray rocks with stretched white spots of sericite (up to 1 cm long) that may be relict pumice. In more strongly foliated regions, xenoliths of fine-grained chlorite (probably altered siltstone) suggest these areas may

by metamorphosed tuffaceous rocks. Thin tuff or reworked tuff beds, typically <30 cm wide, are highly deformed in the nose of a fold in section 31, T. 6 N., R. 4 E.

Xvg **Mafic to intermediate metavolcanic rocks (Early Proterozoic)** - Massive, fine-grained, relatively homogeneous greenstone, with lesser amounts of more foliated, slaty rock. Plagioclase phenocrysts are locally present in a very fine-grained, chloritic groundmass. Protolith may have been basaltic, dacitic, or andesitic lavas, with lesser amounts of tuff and reworked lava or tuff. Ridges weathers in a blocky or platy fashion. Exposed in the area between Black Mountain and the northwestern boundary of the Cave Creek Recreation Area. More schistose, dark green intermediate to mafic volcanic rocks are interbedded with felsic volcanic beds in the southern portion of the small hills between Cave Creek and Black Mountain. A top-to-the-left (north) shear sense is locally displayed in the schistose metavolcanic rocks in this area. Generally exposed in lenticular, NE-trending bodies (except in the southeastern ¼ of section 31, T.6.N., R.4.E).

Xvs **Interbedded metavolcanic and metasedimentary rocks (Early Proterozoic)** - Where the metavolcanic component is more abundant (e.g., section 24, T. 6 N., R. 3 E., sections 19 and 30, T. 6 N., R. 4 E.), this unit consists of green to tan fissile, slaty rocks. Fragments of feldspar and lighter-colored spots of sericite (pumice?) are present in a fine-grained, greenish phyllitic matrix. Where the metasedimentary component is dominant (section 4, T. 5 N., R. 4 E.), thin, phyllitic, pelitic to psammitic rocks are interbedded with creamy white-colored tuff beds.

Early Proterozoic metasedimentary rocks

Xs **Metasedimentary rocks, undivided (Early Proterozoic)** - A less foliated metasedimentary equivalent to the phyllite unit (Xp_1). Typically composed of pelitic to psammitic rocks that are locally conglomeratic. Where foliation is poorly developed, cross beds and ripple marks show younging directions oriented dominantly to the northwest. Between Lone Mountain and Grapevine Wash, bedding in this unit is overturned to the east and southeast.

Xsa **Meta-argillite (Early Proterozoic)** - A massive, very fine-grained, medium to dark gray ridge-forming metasedimentary unit with relatively homogeneous internal fabric. Cleavage is poorly developed and the micaceous minerals are randomly oriented. This unit is locally conglomeratic, with interbedded conglomerate and sandstone. Milky vein quartz is present in minor amounts. Weathers to a dark brown color and commonly shows some degree of desert varnish. This unit underlies the higher portions of Black Mountain.

The protolith for this unit was likely a fine-grained sedimentary rock (e.g., mudstone or shale). Bedding structures are rare, but include laminated bedding and cross beds. Well exposed graded bedding is present south of the Mormon Girl Mine (section 4, T. 5 N., R. 4 E.), and although bedding is typically laminar, crude cross

bedding is locally present. Based on these sedimentary structures, younging directions are dominantly to the west to northwest. The recrystallization of the sedimentary protolith was likely related to the emplacement of the large Middle Proterozoic granite. Near the granite contact at the north end of Black Mountain (section 34, T. 6 N., R. 4 E.), the meta-argillite is more coarse-grained and schistose in texture, with a local biotite and hornblende porphyroblasts. Small, coarse-grained potassium feldspar-rich veins are also present.

Xsp **Pelite (Early Proterozoic)** - Medium to dark gray, fine-grained clastic metasedimentary rock exposed in the northeast part of the quadrangle. This unit contains more massive silicic or cherty lenses (Xc) that break into angular fragments rather than thin plates; where possible, these cherty lenses were mapped separately. Metamorphism grades from a biotite-muscovite (possibly sillimanite) schist near the contact with Middle Proterozoic granite (Yg) to phyllite and slate away from the contact. Porphyroblast minerals vary with location and locally include abundant dark gray albite(?) up to 3 mm long, coarse-grained muscovite, biotite, and large subhedral hematite (after pyrite?) up to 2 cm wide. In the northeast corner of the map (section 7, T. 6 N., R. 5 E.), foliation is poorly developed, with well exposed bedding and primary sedimentary features (e.g., cross-beds, graded bedding, and rare ripple marks).

Xsp_1 **Dark purplish gray to dark maroon pelite (Early Proterozoic)** - Dark gray pelitic rocks located in the northeastern part of the quadrangle (sections 11, 12, 13, and 14, T. 6 N., R. 4 E.). This unit is the less foliated equivalent of the phyllite unit (Xp_1) exposed on the northwestern flanks of Black Mountain.

Xsps **Psammite (Early Proterozoic)** - Fine-grained medium to light gray meta-sandstone and minor meta-conglomerate. Contains subrounded grains of light and dark gray quartz, chalcedony, jasper, and feldspar, all in a medium gray silicic matrix. Very well-indurated and difficult to break. Also commonly more resistant than the pelites and forms ridges. Where conglomeratic the rock also contains subangular to rounded pelitic clasts up to about 4 cm long. Exposures are limited to the hills north of Grapevine Wash in the northeastern part of the quadrangle. This unit typically coarsens to the southeast (section 13, T. 6 N., R. 4 E., section 18, T. 6 N., R. 5 E.).

Xsc **Metaconglomerate (Early Proterozoic)** - Matrix-supported metaconglomerate, typically containing abundant subrounded felsic volcanic clasts. It may be a marker bed as it occurs along strike with the massive jasperoid unit (Xfc_1) on the northeastern slopes of the large NW-trending ridge in section 31, T.6 N., R.4 E. Near the quadrangle boundary in the Cave Creek Recreation Area (section 25, T.6.N. R. 3.E.), the conglomerate is relatively immature, possible representing a mafic or intermediate volcaniclastic protolith. Rounded basaltic to andesitic clasts with plagioclase phenocrysts are present in a fine-grained, well sorted, sandy matrix. Near the contact with the adjacent Xvf unit, rounded to subangular, largely matrix-supported felsic volcanic clasts are present in a very fine-grained matrix. Localized metaconglomerate lenses are mapped as part of other metasedimentary units (e.g., Xsps, Xs, etc.).

Xc **Chert (Early Proterozoic)** - Very fine-grained siliceous crystalline rocks. Resistant and breaks with conchoidal fracture. No bedding features observed. Generally exposed as thin (<5-10 m), but laterally continuous beds. Exposures are most common in the hills north of Grapevine Wash in the northeastern part of the quadrangle (section 13, T. 6 N., R.4 E.). Massive epidote-rich lenses are associated with this unit (probably a replaced felsic tuff) in the thick metasedimentary sequence in the northeastern part of the map (section 13, T. 6 N., R. 4 E., section 18, T. 6 N., R. 5 E.). The protolith may have been a siliceous chemical sediment or a silica-rich rock (i.e., a felsic tuff or quartz sandstone).

Xs_1 **Interbedded pelite and chert (Early Proterozoic)** - Finely interbedded laminated pelite and chert form the transition between rocks of either type. Exposures are limited to the hills north of Grapevine Wash in the northeastern part of the quadrangle (section 13, T. 6 N., R. 4 E.). Thin, light-colored, coarse- to fine-grained sand-mudstone sequences are present locally that fine upwards (to the northwest) from relatively sharp basal contacts.

Xs_2 **Interbedded pelite and psammite (Early Proterozoic)** - Fine- to medium-grained metasedimentary rocks that are gradational between rocks of either type. Exposures are limited to the hills north of Grapevine Wash in the northeastern part of the quadrangle (section 13, T. 6 N., R. 4 E.). Locally conglomeratic.

Xsf **Ferruginous metasedimentary rocks (Early Proterozoic)** - A very dark gray, well-bedded unit that is dominantly composed of fine-grained hematitic sediments. This unit is typically gradational with the tan phyllite unit (Xp_2), and is best exposed in a NE-trending belt southwest of Go John Mountain (section 30, T. 6 N., R. 4 E).

Xfc **Ferruginous chert (Early Proterozoic)** - Very fine-grained, dark red to purple to black lenses (typically <10 m wide). Forms resistant ridges. Sharp contact with surrounding rocks. Specular hematite is common along fractures. Quartz veins are abundant.

Xfc_1 **Massive jasperoid rock (Early Proterozoic)** - Moderate red to dusky red chert forms small lenses. The lenses are typically several centimeters thick, less than a few meters long, with tapered ends. These lenticular bodies have tension fractures that suggest bedding-parallel stretching. This rock may represent deep water replacement processes via iron- and silica-rich fluids in a reducing environment. A large, elongate mass is exposed along the southern ridge in section 31, T. 6 N, R. 4 E.

Early Proterozoic metamorphic rocks

Xp **Phyllite, undivided (Early Proterozoic)** - Moderately to highly foliated fine-grained metasedimentary and metavolcanic rocks. In areas of higher strain, the fine-grained nature of these rocks makes interpretation difficult. Minor amounts of carbonate rocks are locally present. Typically forms slopes and saddles.

Xp_1 **Black to dark gray to purple phyllite (Early Proterozoic)** - A dark maroon to purplish-gray, very fine-grained phyllite/slate. Exposures of "pencil" cleavage are present in the lower northwestern slopes of Black Mountain (section 33, T. 6 N., R. 4 E.) where bedding and foliation cross at high angles. Reddish oxidation spots are common. Bedding locally identifiable as light-colored laminations that have variable attitudes.

Xp_2 **Gray to tan phyllite (Early Proterozoic)** - Lithologically variable, very fine-grained tan phyllite, with abundant thin jasper-rich lenses. Locally interbedded with dark-colored hematitic sediments (Xsf). Probable protolith was a fine-grained sedimentary rock (siltstone) or volcaniclastic rock.

Xp_3 **Green phyllite (Early Proterozoic)** - Very fine-grained, medium- to dark green-colored phyllite. May be related to Xvg, but is commonly interbedded with thin pelitic beds and phyllite. Protolith may have been a mafic to intermediate lava or tuff.

Xp_4 **Light gray phyllite (Early Proterozoic)** - Very fine-grained, light-colored phyllite. Lithologically homogeneous, with minor interbedded tuff. Protolith may have been a siltstone or mudstone. Present in a NE-trending belt located west-southwest of Go John Mountain (sections 30 and 31, T. 6 N., R. 4 E.).

Xp_5 **Dark gray to dark brown phyllite/schist (Early Proterozoic)** - Dark-colored phyllitic to schistose rocks. Protolith may have been a mafic volcanic or volcaniclastic rock. In section 33, T. 6 N., R. 4 E., these rocks are highly crenulated, and contain plagioclase crystals (1-2 mm diameter) in a very fine-grained purplish-gray matrix. Locally ferruginous, with interbedded, lensoidal jasper (in the Cave Creek Recreation area between sections 25 and 30). This unit may have an andesite protolith, as interpreted from thermal infrared spectrographic data in section 31, T. 6 N., R. 4 E. (S. Reynolds, unpub. data).