Geologic map of The Narrows 7½' Quadrangle and the southern part of the Rincon Peak 7½' Quadrangle, eastern Pima County, Arizona

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INTRODUCTION

The study area is located ~40 km southeast of downtown Tucson, and is bounded by the Rincon Mountains on the north, the Empire Mountains on the southwest, and the Whetstone Mountains on the southeast. The map area covers The Narrows 7 ½' Quadrangle and the southern half of the Rincon Peak 7 ½' Quadrangle. The area was mapped during October 2000 through April 2001 as part of a multiyear mapping program directed at producing complete geologic map coverage for the Phoenix-Tucson metropolitan corridor. A 1:24,000 scale map is the primary product of this study (Plate 1). This map consists almost entirely of new mapping but locally incorporates past mapping by Drewes (1977) and Finnell (1971, and unpublished mapping). The accompanying report describes rock units and other geologic features. This mapping was done under the joint State-Federal STATEMAP program, as specified in the National Geologic Mapping Act of 1992. Mapping was jointly funded by the Arizona Geological Survey and the U.S. Geological Survey under STATEMAP Program Contract #00HQAG0149.

The bedrock geology of the map area is dominated by several sets of rock units, as follows: (1) Variably mylonitic granitic and gneissic bedrock at the north flank of the map area forms the Rincon Mountains and the footwall of the Catalina detachment fault. The Catalina detachment fault is a Tertiary, moderately to gently southwest dipping normal fault that has tens of kilometers of top-to-the-southwest displacement (>27.5 km displacement estimated by Dickinson, 1991). (2) Complexly deformed Paleozoic carbonate and siliciclastic strata and Proterozoic granitoids and diabase are exposed at the southwestern foot of the Rincon Mountains and above the Catalina detachment fault. (3) The Oligo-Miocene Pantano Formation, which consists of variably tilted conglomerate, sandstone, mudstone, and andesitic lava flows. Farther to the southwest, the Empire Mountains consist of (4) structurally complex Proterozoic and Paleozoic rocks of diverse composition, and (5) a deformed, regionally southeast dipping sequence of siliciclastic sedimentary rocks of the lower Bisbee Group. In some extensive areas, Quaternary stream incision has uncovered unconsolidated to poorly consolidated clastic sedimentary deposits that are typically mantled by colluvium. These deposits are shown on plate 1 as Tertiary and Quaternary deposits, undivided.

Mineral deposits are of fairly minor importance in the map area, and are restricted largely to the Empire mineral district at the southwestern corner of the map area and the Rincon mineral district at the northwestern corner of the map area.

Previous mapping. The Narrows 7 ½' Quadrangle was mapped previously as part of a 1:48,000 scale map of the Empire Mountains 15' Quadrangle (Finnell, 1971). The Rincon Peak 7 ½' Quadrangle was mapped previously as part of a 1:48,000 scale map of the Rincon Valley 15' Quadrangle (Drewes, 1977), and the southwestern part of the quadrangle was partially mapped by Finnell (unpublished). Many topical studies, some including mapping, have been done as part of M.S. and Ph.D. thesis projects (Table 1).

Acknowledgments. We especially thank Bill Peachy for providing access to the Colossal Cave area, George Masek for providing access to the Empirita Ranch area, and Don Martin for providing access to his ranch land in the northern Empire Mountains. We also thank Ann Youberg for discussions that were helpful in understanding the Quaternary geology of the area, and Bill McIntosh and Lisa Peters for providing two $^{40}Ar/^{39}Ar$ dates of Tertiary tuffs.

TABLE 1: Empire Mountains and Cienega Gap area, relevant theses and dissertations

Acker, C.J., 1958, Geologic interpretations of a siliceous breccia in the Colossal Cave area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 50 p.

Alberding, H., 1938, Geology of the northern Empire Mountains, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 107 p.

Alexis, C.O., 1939, Geology of the Lead Mountain area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 60 p.

Balcer, R.A., 1984, Statigraphy and depositional history of the Pantano Formation (Oligocene-early Miocene), Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 107 p.

Bittson, A.G., 1976, Analysis of gravity data from the Cienega Creek area, Pima and Santa Cruz Counties, Arizona: Tucson, University of Arizona, M.S. thesis, 76 p., 5 sheets, scale 1:62,500.

Brennan, D.J., 1957, Geological reconnaissance of Cienega Gap, Pima County, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 53 p.

Butler, W.C., 1969, Upper Paleozoic stratigraphy of Total Wreck Ridge, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 138 p.

Feiss, J.W., 1929, Geology and ore deposits of Hiltano Camp, Arizona: Tucson, University of Arizona, M.S. thesis, 41 p.

Gillingham, T.E., 1936, Geology of the California mine area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 65 p.

Grimm, J.P., 1978, Cenozoic pisolitic limestones of Pima and Cochise Counties, Arizona: Tucson, University of Arizona, M.S. thesis, 71 p.

Janders, D.J., 1978, Comparative sedimentology, stratigraphy and economic potential of two Tertiary lacustrine deposits in Arizona: Tempe, Arizona State University, M.S. thesis.

Klute, M.A., 1991, Sedimentology, sandstone petrofacies, and tectonic setting of the late Mesozoic Bisbee Basin, southeastern Arizona: Tucson, University of Arizona, Ph.D. dissertation, 268 p.

Layton, D.W., 1957, Stratigraphy and structure of the southwestern foothills of the Rincon Mountains, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 87 p.

Marvin, T.C., 1942, Geology of the Hilton Ranch area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 60 p.

Mayuga, M.N., 1940, The geology of the Empire Peak area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 83 p.

Metz, R.A., 1963, The petrography of the Pantano Beds in the Cienega Gap area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 66 p.

Moore, R.A., 1960, Cretaceous stratigraphy of the southeast flank of the Empire Mountains, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 55 p.

Schafroth, D.W., 1965, Structure and stratigraphy of the Cretaceous rocks south of the Empire Mountains, Pima and Santa Cruz counties, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 135 p.

Sears, D.H., 1939, Geology of the Pantano Hill area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 48 p.

Sopp, G.P., 1940, Geology of the Montana mine area, Empire Mountains, Arizona: Tucson, University of Arizona, M.S. thesis, 63 p.

Trapp, R.A., 1987, Geochemistry of the Laramide igneous suite of the Santa Rita and Empire Mountains, southeastern Arizona: Tucson, University of Arizona, M.S. thesis, 95 p.

Weidner, M.I., 1957, Geology of the Beacon Hill-Colossal Cave area, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 34 p.

QUATERNARY GEOLOGY

Climate. Several weather stations surrounding the map area have operated during intervals over the past century. The current Tucson Weather Service Office at Tucson International Airport (WSO, about 15 miles west of the map area) has records from 1948 to the present, the weather station maintained at the Santa Rita Experimental Range Headquarters (ERH, about 15 miles southeast of the map area) has records from 1950 to present, and a weather station at Benson (BEN, about 10 miles east of the map area) was maintained from 1894-1975. Throughout this region, most of the annual precipitation (50-60%) falls during the summer monsoon from June to September. Much of the middle and late summer rainfall occurs as heavy thunderstorms when moist air sweeps northwards from the Gulf of California and the Gulf of Mexico. Occasional intense late summer to early fall precipitation occurs in this region as a result of incursions of moist air derived from dissipating tropical storms in the Pacific Ocean. All of the larger historical floods on Cienega Creek have occurred in the summer or early fall. Winter precipitation generally is caused by cyclonic storms originating in the Pacific. It is usually less intense and may be more prolonged, and therefore infiltrates into the soil more deeply than summer rainfall (summarized from Sellers and Hill, 1974). Freezing temperatures are common during most winters, but snow is uncommon and not persistent.

Climate records from the WSO at about 2500 ft asl and the BEN at 3500 ft asl are quite similar (Western Regional Climate Center, 2001). Average annual precipitation for the WSO is 11.6 in. and the average maximum temperature is 82.5° F, with an average high temperature of 99.1° F in July and 64.7° F in January. In Benson, the average annual precipitation is essentially the same (11.3 in. for a slightly different period), and the average maximum temperatures are about 2 degrees lower. Most of the map area is likely cooler and wetter than these two climate stations, however, because it is higher and closer to the mountains. Data from the ERH, located at about 4000 ft asl at the base of the Santa Rita Mountains may approximate the higher elevation parts of the map area. At ERH, the average annual precipitation is 22.2 in., nearly double the annual precipitation in the middle of the Tucson basin. The average annual maximum temperature at the ERH is 76.4° F, with average high temperatures of 91.6° F in July and 60.2° F in January. The average annual precipitation for ERH is probably a maximum for the map area because of its close proximity to the base of the Santa Rita Mountains.

Methodology. The surficial geology of the project area was mapped primarily using color aerial photos taken in 1979 and 1995. Photos from 1979 were provided by James Briscoe of JABA LLC, and the photos from 1995 were provided by the U.S. Forest Service. Unit boundaries were spot-checked in the field, and mapping was supplemented by observations of soils and stratigraphy. The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, stream terraces) evident on aerial photographs and in the field were used to differentiate their associated deposits by age. Surficial deposits of this quadrangle were then correlated with similar deposits in this region in order to roughly estimate their ages. Original mapping was done on aerial photos. These photos were orthorectified to a topographic base. Mapping was compiled in a GIS format and the final linework was generated from the digital data.

The physical characteristics of Quaternary alluvial surfaces (channels, floodplains, stream terraces, and alluvial fans) were used to differentiate their associated deposits by age. Alluvial surfaces of similar age have a distinctive appearance and soil characteristics because they have undergone similar post-depositional modifications. They are different from both younger and older surfaces. Terraces and alluvial fans that are less than a few thousand years old still retain clear evidence of the original depositional topography, such as of bars of gravel deposits, swales (troughlike depressions) where low flows passed between bars, and distributary channel networks, which are characteristic of active alluvial fans. Young alluvial surfaces have little rock varnish on surface clasts and have little soil development, and typically they are minimally dissected. Very old fan surfaces, in contrast, have been isolated from substantial fluvial deposition or reworking for hundreds of thousands of years. These surfaces are characterized by strongly developed soils with clay-rich argillic horizons and cemented calcium-carbonate horizons, well-developed tributary stream networks that are entrenched 10 m or more below the fan surface, and strongly developed varnish on surface rocks. The ages of alluvial surfaces in the southwestern United States may be roughly estimated based on these surface characteristics, especially soil development (Gile and others, 1981; Bull, 1991).

In this map, Quaternary surficial deposits are subdivided based on their source (axial valley stream and smaller tributary washes) and estimated age of deposits. Surface and soil characteristics were used to correlate alluvial deposits and to estimate their ages. Surface pits and exposures along cut banks were used to assess soil characteristics associated with deposits of different ages and from different sources. Soils and surfaces documented in the map area were generally correlated with soils and surfaces described in Quaternary mapping studies of adjacent areas conducted by Jackson (1989, 1990) and Pearthree and Youberg (2000). These correlations were also used to estimate the ages of surficial deposits in the map area.

Geologic/Geomorphic Framework

The Tucson metropolitan area is located along the eastern edge of the Sonoran Desert subprovince of the Basin and Range physiographic province. The Basin and Range province in Arizona is characterized by alluvial basins and intervening mountain ranges that formed as a result of normal faulting related to extension of the crust between about 30 and 6 Ma (Shafiqullah and others, 1980; Menges and Pearthree, 1989). The landscape of the Tucson area consists of alluvial basins between large, high mountain ranges to the east and small, low-lying mountain ranges to the west. The western part of the metropolitan area (Avra Valley and the west side of the Tucson Mountains) is typical of the undissected basins that are common throughout the Sonoran Desert subprovince. Mountain ranges are low and mountain fronts are deeply embayed, with few outlying bedrock knobs (inselbergs) that rise above the broad plains surrounding the mountain ranges. Upper piedmont areas typically are covered with Pleistocene deposits that are moderately dissected, but lower piedmont areas are undissected and covered by relatively fine-grained young deposits that grade downslope into axial valley deposits. The axial portions of valleys are typically occupied by unentrenched drainages with very broad floodplains. In stark contrast, the eastern, northern, and southern parts of the Tucson area have large, high mountain ranges and piedmont areas have been deeply dissected by erosion. In these areas, erosion has dominated landscape evolution at least through the Quaternary. Major periods of aggradation have punctuated the long-term trend toward downcutting along the major streams and their tributaries, resulting in the formation of terraces along these watercourses.

The highest levels of alluvial deposits (unit QTs ridgelines and sparse Qo surfaces) in the Cienega Gap area may have been graded approximately to the Tucson basin before it was significantly entrenched. They are probably approximately correlative with QT deposits mapped in the Catalina foothills on the north side of the Tucson basin (Klawon and others, 1999), Qo and QT deposits mapped in the Tucson Mountain foothills on the west side of the Tucson basin (Pearthree and Biggs, 1999), and other high remnant deposits throughout southeastern Arizona (Menges and McFadden, 1981). It is likely that in the late Pliocene to early Quaternary, the surfaces of the Cienega Gap area were fairly planar, undissected piedmonts that graded downslope to a large alluvial fan complex that emanates from this area westward across the Tucson basin.

During the past one to two million years, Cienega Creek and its tributaries have downcut substantially into the Quaternary and Tertiary deposits of Cienega Gap. The high ridges and deep valleys characteristic of much of the map area attest to the amount of stream erosion that has occurred since the highest levels of alluvium were deposited. Episodes of downcutting of Cienega Creek caused erosion of the toes of alluvial fans on both sides of the valley, and resulted in much of the stream downcutting in the piedmonts adjacent to the creek. The lower ends of tributary drainages are linked with the creek, so if Cienega Creek downcuts, the slopes of its tributary stream channels steepen and they tend to downcut as well. The ultimate cause of the downcutting by the larger streams in southeastern Arizona is not certain. It is may have occurred a delayed response of the integration of the Tucson basin streams into the larger regional drainage system. The oscillating climatic conditions of the Quaternary may have resulted in higher long-term erosion rates than during the Miocene and Pliocene (Peizhen and others, 2000). Alternatively, the downcutting may have been driven by some broad regional upwarping of southeastern Arizona, the cause of which is not known (Menges and Pearthree, 1989).

The fact that we observe suites of alluvial surfaces with similar characteristics and topographic relationships throughout southern Arizona implies that the factors that are controlling erosion and deposition in fluvial systems are regional in scope. Whether fluvial systems aggrade or degrade is a function of sediment supply and their ability to transport sediment. Most of the area within drainage systems consists of hillslopes, where sediment is generated from weathering of bedrock and in turn is weathered in place and/or transported downslope to the stream system. If hillslopes are stable, then weathering dominates and sediment supply to streams is relatively low. These conditions may have existed in this region during glacial intervals, when vegetation density on hillslopes was greater due to increased annual precipitation and/or decreased summer temperatures in this region. Hillslopes have probably been unstable during changes between glacial and interglacial conditions, as vegetation responded to changing climate and the character of precipitation and runoff varied in response to changes in the nature and frequency of thunderstorm activity (see Bull, 1991). As a result of these climate-induced changes, large fluxes of sediment may have been introduced into the fluvial systems, causing periods of aggradation on the piedmont. The fans and terraces of the Cienega Gap area likely record climate changes of this kind.

The most recent cycle of stream downcutting began in the late 1800's and is probably continuing at the present time. Historical photographs indicate that the floodplain of Cienega Creek at Pantano site (at the boundary between the Rincon Peak and The Narrows quadrangles) was unentrenched with no obvious channel in early 1880 (Myrick, 1975; Dobyns, 1981). Within 10 years, however, a large, deep channel had developed in this area, causing the railroad track to be relocated to higher ground. Remnants of the early historical floodplain in this area today are about 5 m above the modern channel and support a lush stand of mesquite trees. It is likely that arroyo development proceeded upstream rapidly in the subsequent large floods of the late 1800's and early 1900's. Currently, Cienega Creek is deeply entrenched below its historical floodplain throughout the map area. Tributary streams are also entrenched near their confluences with Cienega Creek, but entrenchment on even the largest tributaries tends to decrease quite rapidly upstream.

Geologic Hazards

This section summarizes the character and distribution of the principal geologic hazards that exist in Cienega Gap. This information is fairly general in nature. Detailed site-specific geologic, engineering, hydrologic, or soils investigations may be required to thoroughly assess potential hazards at particular locations. More specific information on soil properties may be obtained from the USDA Natural Resources Conservation Service, and information on mapped floodplain and flood-prone areas may be obtained from the Pima County Flood Control District.

Flood hazards. Hazards related to flooding in the Cienega Gap area may be subdivided into two broad categories. Along Cienega Creek and its major tributaries, flood hazards consist mainly of channel and floodplain inundation and lateral erosion of unprotected channel banks. The most widespread flood hazards in the map area are those associated with smaller tributary drainages on piedmonts, where the extent of flood-prone area varies with the size of the stream and local topographic confinement of floodwater. This latter category of flood hazard is particularly difficult to assess in areas where channel networks are distributary and topographic relief is low. These areas may be subject to alluvial fan flooding.

The largest floods on Cienega Creek have occurred in the middle to late summer or early fall (July through October). The only long-term stream gages that are useful for the study area are located downstream on Pantano Wash. The name Pantano Wash is used for the stream below the confluence of Cienega and Agua Verde creeks, so it is part of the same drainage as Cienega Creek. The closest gage (Pantano Wash near Vail) is about 4 miles west of the map area. Moderate to large floods on Pantano Wash occurred in 1941, 1958, 1959, 1963, 1964, 1981,and 1983. At the Pantano gage near Vail, the

38,000 cubic feet per second (cfs) discharge in August, 1958 is the peak of record (Pope and others, 1998; U.S. Geological Survey, 2001). In fact, the estimated peak discharge for this flood is 3 times larger than any other flood of the gage record. Prior to the gage record, sizable summer floods on Cienega Creek in the 1880's and 1891 began the development of the modern entrenched arroyo system (Dobyns, 1981). All of the sizable floods on Pantano Wash, and presumably Cienega Creek, have occurred in August, September, or early October. This suggests that exceptional summer monsoon storms and occasional dissipating tropical storms generate the floods on this small regional drainage.

The channels of Cienega Creek and Mescal Wash are entrenched one to as much as 8 meters below the floodplain of the middle 1800's. The capacity of the channels and low overbank areas is generally sufficient to convey flood discharges through this area without inundating areas former floodplain areas that are now terraces. Lateral bank erosion, however, is certainly a significant hazard as hundreds of feet of erosion may occur during floods (for example, Parker, 1995; Wood and others, 1999). The potential for serious bank erosion exists along extensive, unprotected banks formed in weakly consolidated Qyr deposits.

Smaller tributaries that drain the mountain ranges and the piedmonts are subject to flash floods. Floods on these drainages result from intense, localized thunderstorms that occur during the summer or early autumn, and stream stages typically rise and fall rapidly during floods. Flood hazards are relatively easy to manage where topographic relief contains floodwater to channels and adjacent low terraces. In these situations, the area that may be impacted by flooding is limited and should be easy to avoid. It is much more difficult to assess and manage flood hazards associated with alluvial fan flooding. This type of flooding occurs where topographic relief is minimal and floodwater can spread widely. In these areas, channels may or may not be well defined, and their positions may shift during floods, and inundation is likely to be widespread during floods.

Surficial geologic mapping provides important information about the extent of flood-prone areas on the piedmonts, and it is the best way to delineate areas that may be prone to alluvial fan flooding. Floods leave behind physical evidence of their occurrence in the form of deposits. Therefore, the extent of young deposits on piedmonts is a good 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 the piedmont varies with the extent of young deposits (units Qyc, Qy_2, Qy_1, and Qy). Active alluvial fans may be recognized by both distributary (downstream-branching) channel networks and laterally extensive young deposits between channels (see Pearthree and others, 1992).

Most of the modern drainages in the map area have tributary networks that are topographically confined by ridges of older deposits and bedrock. Along these drainages, flood hazards are restricted to active channels and adjacent low, young terraces (units Qyc and Qy_2). Portions of the slightly older and higher terraces that are mapped as unit Qy_1 may be subject to rare inundation in extreme floods. Lateral channel bank erosion may occur in young, weakly consolidated deposits. A few distributary drainage systems exist in the lower piedmont areas, especially north of Cienega Creek and Mescal Wash. Unconfined flow during floods occurs in many places along the margins of the floodplains of Cienega Creek, Mescal Wash, and Agua Verde Creek, where tributaries debouch from the topographically confined foothills onto the Qyr terrace.

Soil problems. Soils in the Tucson area present a number of problems to homeowners. Cracking of foundations, walls, driveways and swimming pools causes headaches and costs millions of dollars each year in repairs. Severe or recurring damage can lower the value of a house or commercial property. Leading in the list of potential soil properties that can cause structural failures are soils that shrink and swell when they are dry and wet. Properties of problem soils are generally related to the type and amount of clay, and to the conditions under which the clay originated. Clay minerals can form in-place by weathering of rocks, or by deposition from water or wind.

Potential soil problems in the map area consist of shrink-swell potential, low infiltration rates, and hard substrate. Shrink-swell problems may exist on clay-rich soils of unit Qm, Qmo, and Qo, although the gravel that is common in these deposits likely decreases the severity of unstable soil problems. May serious unstable soil problems may occur on the fine-grained member of the Davidson Canyon facies of the Pantano Formation (unit Tdf). Significant soil problems have occurred on outcrops of fine-grained beds of the Pantano Formation in the Catalina foothills on the north side of Tucson (Klawon and others, 1999). Excavation may be difficult and near-surface infiltration rates low on the oldest piedmont units (Qo, and QTs) due to the existence of carbonate- and silica-cemented hardpans (petrocalcic and duric horizons). Excavation and infiltration problems may be encountered on all surficial units in the uppermost piedmont areas because of the existence of bedrock at shallow depths.

Earthquake hazards. There has been very little historical seismic activity in southeastern Arizona with the exception of the Sonoran earthquake on May 3, 1887. This magnitude ~7 ¼ event, centered southeast of Douglas, Arizona, caused strong shaking and damage throughout southeastern Arizona. Later that year, at least two earthquakes were reported from observers on the railroad in the Pantano area (DuBois and others, 1982). Based on the fact that the maximum shaking reported for these events was in the map area, they were likely located in or near Cienega Gap. No subsequent seismic activity has been reported for this area.

The map area is in close proximity to the northern end of the Santa Rita fault zone, which extends along the Santa Rita Mountains for about 35 miles (60 km) from Tubac to Corona de Tucson (Pearthree and Calvo, 1987). Along the fault zone, a discontinuous zone of fault scarps offset Pleistocene alluvium. Scarps trend northeast to north-south and are 1 to 6 km west of the base of the Santa Rita Mountains. Scarps range up to about 5 m in height and have maximum slope angles up to about 10°. Surficial deposits as young as late Pleistocene are displaced but latest Pleistocene and Holocene deposits are not faulted, which brackets the age of youngest faulting between 10-20 ka and 75-130 ka. Quantitative analysis of fault scarp morphologies indicates that the youngest surface rupture occurred between about 60-130 ka. Fault displacement of late Pleistocene surfaces averages about 2 m, in contrast to 4 to 5 m of displacement of middle and early Pleistocene surfaces. Using surface displacement estimates and various estimates of surface rupture length, Pearthree and Calvo (1987) concluded that two paleoearthquakes of magnitude 6 ¾ to 7 ¼ occurred along the Santa Rita fault zone in the past 200 to 300 ka. Geophysical investigations on the northern part of the fault zone indicate that that part of the fault dips shallowly to the northwest (Johnson and Loy, 1992). This implies that the area of the seismogenic fault may be larger than previously suspected, and that it dips beneath the Tucson metropolitan area.

The evidence of low frequency Quaternary fault activity combined with the existence of broad bedrock pediments on the west side of the Santa Rita Mountains indicates that the long-term slip rate on the Santa Rita fault zone is very low. The very long recurrence intervals between surface ruptures and evidence for very low long-term slip rates are consistent with other Quaternary fault zones that have been studied in southeastern Arizona, southwestern New Mexico, and northern Sonora (Pearthree, 1986; Bull and Pearthree, 1988; Demsey and Pearthree, 1994; Pearthree, 1998). The fault activity that is observed in this region is either a late pulse of activity related to the Basin and Range disturbance or a new, weakly extensional tectonic regime that has developed in the middle to late Quaternary.

STRUCTURAL GEOLOGY

The Catalina detachment fault in the northern part of the study area separates mylonitic crystalline rocks of the Rincon Mountains from faulted and tilted Tertiary and older strata that make up most of the study area. The mylonitic crystalline rocks form the southern end of the Catalina metamorphic core complex (Drewes, 1977; Davis, 1980; Banks, 1980; Keith et al., 1980; Dickinson, 1991; Force, 1997). The Catalina detachment fault is a gently to moderately southwest-dipping normal fault with at least 27 km of displacement (Dickinson, 1991). This displacement uncovered the mid-crustal gneissic and granitic rocks that form the Rincon Mountains.

Rocks immediately below the Catalina detachment fault are generally highly fractured and altered so that mafic minerals are chloritized. Silicification is also common. Alteration and silicification typically affect footwall rocks for several to several tens of meters below the detachment fault. A silicified footwall ramp is very well exposed where Shaw Canyon crosses the detachment fault (NW¼, sec. 11, T. 16 S., R. 17 E.).

Most of the map area consists of rocks that are structurally above the Catalina detachment fault. Paleozoic and middle Proterozoic strata and middle Proterozoic diabase in the Colossal Cave area are complexly and multiply folded and faulted (e.g., Davis, 1975). Some strata are overturned. In the Empire Mountains, complex deformation affects all pre-Cenozoic rocks, although the severity of deformation varies greatly over the map area. Mesozoic and Paleozoic strata in the southern part of The Narrows 7 ½' Quadrangle form a northeast striking homocline, whereas farther northwest refolded folds have produced a complex map pattern.

Pre-Cretaceous uplift of rocks in the northern Empire Mountains is inferred to have caused erosional removal of all strata above Proterozoic granite that was then buried by the late Jurassic to early Cretaceous Glance conglomerate and younger strata (Bilodeau, 1979). This uplift event is not well understood. Finnell (1971) identified an east-west-striking belt of north-dipping thrust faults that displaced granitoids and Pinal Schist southward over Paleozoic and Mesozoic strata. Such thrust or reverse faulting would have caused uplift of the northern, hanging-wall block. Bilodeau (1979) and Bilodeau et al. (1987; see also Bilodeau, 2001) inferred that movement on south-dipping normal faults caused uplift of the northern, footwall block, and that later reverse faulting occurred along or near the normal fault zone, obscuring the older normal faults. We are not able to distinguish between either of these scenarios on the basis of mapping reported here (Plate 1). The area of concern is low relief, and contacts are generally concealed to a degree that does not allow ready determination of the nature or dip of the possible or known fault contacts. At one location (NE ¼, SW ¼, sec. 14, T. 17 S., R. 17 E.), a fault in this fault zone dips 45° to the northwest and places Proterozoic Pinal Schist over a sliver of Paleozoic carbonate that is bounded to the southeast by Proterozoic granite. This structural configuration indicates a complex structural history, possibly involving both normal and reverse faulting. Mapping of the adjacent Mt. Fagan 7 ½' quadrangle to the west suggests that latest faulting occurred on north-dipping reverse faults (Ferguson et al., 2001).

Much of the Tertiary strata in the map area are included in the Pantano Formation. The lower part of the Pantano Formation consists of faulted and tilted conglomerate, sandstone, siltstone, and clay, with interbedded porphyritic andesite that is ~27 Ma in age. The degree of tilting and faulting in the Pantano Formation dies out dramatically upward within the fine grained upper part of the Pantano Formation. The overlying breccia facies, as well as stratigraphically higher conglomerate of Agua Verde Creek and the unit of Wakefield Canyon are typically only slightly faulted and deformed. The conglomerate of Agua Verde Creek, which contains much debris that appears to have been derived from leucocratic and mylonitic granitoids in the Rincon Mountains, is horizontal in many areas but is inferred to have been deposited within alluvial fans that sloped several degrees to the southwest away from the Rincon Mountains. The unit of Wakefield Canyon unconformably overlies the lower Pantano Formation in one area (SW ¼, NE ¼, sec. 11, T. 17 S., R. 17 E.) and post-dates most of the faulting and tilting that affected the lower part of the Pantano Formation. However, a northeast-striking, northwest-facing monocline deforms strata of the unit of Wakefield Canyon, producing stratal dips of up to 50°. This monocline strikes southwestward toward the edge of exposures of the Cretaceous Willow Canyon member of the Bisbee Group, and it appears that the Bisbee Group rocks are uplifted by the monocline and juxtaposed with northwest-tilted strata of the unit of Wakefield Canyon. The contact between the two units is covered in most areas but is faulted at two exposures and depositional at one (Plate 1).

MINERAL DEPOSITS

Barite deposits in the Colossal Cave area consist of 1-3 m thick, irregular, elongate masses hosted by Mississippian Escabrosa Limestone (NE¼, NE¼, sec. 8, T. 16 S., R. 17 E.). Barite is massive, white, with no other identified hydrothermal minerals. Small prospect pits are located on some deposits.

A 30-cm-thick quartz-calcite-specular hematite vein is exposed in a prospect pit near Agua Verde Creek (NW¼, NE¼, sec. 17, T. 16 S., R. 17 E.; Vail 7 ½' Quadrangle).

Total Wreck Mine area

The Total Wreck Mine is located at the northeastern end of a northeast-striking, southeast-dipping ridge of upper Paleozoic strata (Butler, 1968). According to descriptions Alberding (1938) and Schrader (1915), summarized by Wilson (1951), mineralization occurs at the intersection between steep 'fissures' or 'faults' and favorable stratigraphic horizons in the Rainvalley Formation (referred to in the older published work as the Synder Hill Formation). Mineralization is associated with two steep, east-striking fissures, spaced about 30 meters apart, and a steep, northeast (030°) striking, down-to-the east fault. Mineralization occurs as replacements along bedding in the 'limestone', adjacent to the steep fault-fissures.

Observations made during our mapping support these observations. The mineralized area is located between two northwest-striking faults. The northern fault has been referred to as the Andrade fault (Wilson, 1951). It is a steep, northwest-striking fault that juxtaposes the Paleozoic strata to the southwest against strata of the Bisbee Formation to the northeast. The southern fault is parallel to the Andrade fault in the mine area, and has significantly less separation. The dip of the southern fault is not well constrained, but it is aligned with a WNW-striking, moderately north-dipping fault mapped in the Concha Limestone to the west of the mine area. This fault is characterized by a zone of silicified limestone 10-50 cm thick, with a sharp, relatively planar fault surface; the fault was traced a considerable distance in the Concha but could not be followed through to connect with the southern boundary of the mineralization. The southern fault appears to have been active between deposition of the Glance Conglomerate in the mine area and deposition of overlying reddish sandstones of the lower part of the Willow Canyon facies sandstone of the Bisbee Group. In the mine area, Concha Limestone is overlain by thin Rainvalley Formation, and a thin Glance Conglomerate interval. South of the southern boundary fault, the basal reddish sandstone of the Bisbee Group appears to be deposited directly on the Concha. At least one other minor, WNW to NW-striking, Glance-age fault cuts strata southwest of the mine area.

A small outcrop of a fine-grained, dark gray, dioritic(?) rock forms part of a dike that intrudes Glance conglomerate in the road on the southeast side of the mine area, and a similar dike intrudes Concha Limestone southwest of the mine area. These are probably outcrops of the diorite dikes reported in Wilson's (1951) summary. There is no obvious association between these dikes and the mineralization visible at the surface.

Based on the distribution of shafts and tunnels in the area, the mineralized horizons appear to occupy the lower part of the Rainvalley Formation, within about 10-20 m stratigraphically of the lower quartzite marker beds (see description of Rainvalley Formation). Reddish iron-oxide mineralization is commonly associated with shears and breccias in dolomite of the Rainvalley Formation. Black manganese oxide(?) and minor copper-oxide mineralization is present. Some spongy reddish hematitic(?) gossan material, with drusy quartz, minor malachite or chrysocolla, and stockwork after unidentified sulfide minerals, along with some skarn-like silicified carbonate rock was observed on the dump around the tunnel at UTM 538694 E, 3528893 N (zone 12).

ROCK UNITS

Quaternary and Late Tertiary map units

Piedmont Alluvium

Quaternary deposits cover portions of the piedmont areas between the Empire Mountains in the south and the Rincon Mountains in the north. This alluvium was deposited primarily by larger streams that head in the mountains; smaller streams that head on the piedmont have eroded deeply into older deposits and have reworked some of them. The lower margin of the piedmonts are defined by their intersection with stream terraces or channels of Cienega Creek, the largest drainage in the map area. Approximate age estimates for the various units are given in parentheses after the unit name. Abbreviations are ka, thousands of years before present, and Ma, millions of years before present.

Qyc **Active channel, bar, and low terrace deposits (Late Holocene)—** Deposits associated with active channels of larger tributary drainages composed of primarily of sand, pebbles, and cobbles. Channels are incised as much as several meters below adjacent Holocene terraces (unit Qy2). They generally consist of single, relatively large channels, but this unit includes some smaller branching channels in areas of channel expansions. Local relief within channels varies from minimal to more than 1 m. Vegetation generally consists of small bushes and grasses, although the channel banks are typically lined with trees including mesquite, acacia, and palo verde.

Qy2 **Deposits in channels, low terraces, and small alluvial fans (Late Holocene)—** Deposits in channels, low terraces, and small alluvial fans composed of cobbles, sand, silt and clay that have been recently deposited by modern drainages. Channels generally are incised less than 2 m below adjacent terraces and fans, but locally incision may be as much as 5 m. Channel morphologies generally consist of a single-thread channel or multi-threaded channels with gravel bars adjacent to low flow channels. Downstream-branching distributary channel patterns are associated with the few small active alluvial fans in the area. In these areas, channels typically are discontinuous, with small, well-defined channels alternating with broad expansion reach where channels are very small and poorly defined. Local relief varies from fairly smooth channel bottoms to the undulating bar-and-swale topography that is characteristic of coarser deposits. Locally near Cienega Creek channels are incised several meters below young terraces. Terrace surfaces typically have planar surfaces, but small channels are also common on terraces. Soil development associated with Qy2 deposits is minimal. Terrace and fan surfaces are brown, and on aerial photos they generally appear darker than surrounding areas, whereas sandy to gravelly channels appear light-colored on aerial photos. Vegetation density is variable. Channels typically have sparse, small vegetation. The densest vegetation in the map area is found along channel margins and on Qy2 terraces along channels. Along the larger washes, tree species include mesquite, palo verde, and acacia; smaller bushes and grass may also be quite dense. Smaller washes typically have palo verde, mesquite, large creosote and other bushes along them.

Qy1 **Deposits in low terraces and alluvial fans (Holocene)—**Deposits forming low terraces and alluvial fans found at scattered locations along drainages throughout the map area. Qy1 surfaces are slightly higher than adjacent Qy2 surfaces and generally are not subject to flood inundation. Surfaces are generally planar; local relief may be up to 1 m where gravel bars are present, but typically is much less. Qy1 surfaces typically are about 2 m above adjacent active channels, but may be higher. Surfaces typically are silty or sandy but locally have fine, unvarnished open gravel lags. Qy1 surfaces generally are lightly vegetated and appear somewhat lighter on aerial photos than Qy2 surfaces. Qy1 terrace surfaces support creosote and other small bushes, with some mesquite and palo verde trees along drainages. Qy1 soils typically are weakly developed, with some soil structure but little clay and stage I to II calcium carbonate accumulation

Qy **Young deposits, undifferentiated (Holocene)—**Unit Qy includes both Qy2 and Qy1 deposits. It is used where it was not possible, at a scale of 1:24000, to separately map Qy1 and Qy2 surfaces. Unit Qy is found along smaller incised drainages. Soil development consists of cambic horizons over weak to moderate (stage I to II) calcic horizons.

Qi3 **Younger intermediate terrace and relict fan deposits (Late Pleistocene)—** Deposits forming moderately dissected terraces and relict alluvial fans found in upper, middle and lower piedmont areas. Moderately to well- developed, slightly to moderately incised tributary drainage networks are typical on Qi3 surfaces. Active channels typically are incised a few meters below Qi3 surfaces. Qi3 fans and terraces are commonly lower in elevation than adjacent Qi2 and older surfaces, but the lower margins of Qi3 deposits lap out onto more dissected Qi2 surfaces in some places. Qi3 deposits consist of pebbles, cobbles, and finer-grained sediment. Qi3 surfaces commonly have loose, open lags of pebbles and cobbles; surface clasts exhibit weak rock varnish. Qi3 surfaces appear light orange to dark orange on color aerial photos, reflecting slight reddening of surface clasts and the surface soil horizon. Soils are moderately developed, with orange to reddish brown clay loam to light clay argillic horizons and stage II calcium carbonate accumulation. Vegetation includes grasses, small shrubs, mesquite, and palo verde.

Qi2 **Intermediate alluvial fan and terrace deposits (Middle Pleistocene)—**Deposits forming moderately dissected relict alluvial fans and terraces with strong soil development found throughout the map area. Qi2 surfaces are drained by well-developed, moderately to deeply incised tributary channel networks; channels are typically several meters below adjacent Qi2 surfaces. Well-preserved, planar Qi2 surfaces are smooth with scattered pebble and cobble lags; surface color is reddish brown rock varnish on surface clasts is typically orange or dark brown. More eroded, rounded Qi2 surfaces are characterized by scattered cobble lags with moderate to strong varnish, broad ridge-like topography and some carbonate litter on the surface. Well-preserved Qi2 surfaces have a distinctive dark red color on color aerial photos, reflecting reddening of the surface soil and surface clasts. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Underlying soil carbonate development is typically stage III, with abundant carbonate through at least 1 m of the soil profile; indurated petrocalcic horizons are rare. Qi2 surfaces generally support grasses, bursage, cholla, and small shrubs.

Qi **Intermediate alluvium, undifferentiated (Late to middle Pleistocene)—** Moderately dissected terraces and small alluvial fans found in valleys eroded into older deposits (unit QTs) and in the mountains. Deposits have orange to reddish brown surfaces with scattered pebble and cobble lags. Soils are reddened and are moderately to strongly developed. These deposits evidently partially filled valley bottoms, and may represent more than one period of aggradation.

Qi1 **Older intermediate alluvial fan deposits (Middle to early Pleistocene)—** Deposits forming moderately to deeply dissected relict alluvial fans with variable soil development. Qi1 surfaces are typically 5 to 10 m above adjacent active channels. Qi1 surfaces are drained by well- developed, deeply incised tributary channel networks. Well-preserved planar Qi1 surfaces are not common. Where they exist, they are smooth with pebble and cobble lags; rock varnish on surface clasts is typically orange to red. Well-preserved soils typically contain deep reddish brown, clay argillic horizons, with obvious clay skins and subangular blocky structure. Soil carbonate development is variable, but locally is quite strong. More eroded Qi1 surfaces are characterized by loose cobble lags with moderate to strong varnish, ridge- and-valley topography, and carbonate litter on the side slopes. On aerial photos, ridge crests on Qi1 surfaces are reddish brown, reflecting reddening of the surface soil and surface clasts, and eroded slopes are gray to white. Qi1 surfaces generally support bursage, ocotillo, and creosote.

Qo **Old alluvial fan deposits (Early Pleistocene)—** Deposits forming very old, dissected alluvial fan remnants capping high ridges. Qo deposits and fan surface remnants are found only in a few places in the map area. Qo deposits consist of cobbles, boulders, and sand and finer clasts. Surfaces are dark reddish brown in color, and strongly cemented calcic horizons are typical. Where surfaces are planar and well-preserved, reddish brown, clay argillic horizons are typical. Qo surfaces are dominated by grass, small shrubs, and ocotillo. Qo surfaces are near the highest levels of aggradation in the Cienega Gap, and are probably correlative with other high, remnant surfaces found at various locations throughout southern Arizona (Menges and McFadden, 1981).

QTs **Very old fan deposits forming eroded ridges (Early Pleistocene to Pliocene) —** Locally-derived, generally undeformed alluvial fan gravel and sand. These deposits form variably high eroded ridges and underly a variety of younger Quaternary deposits. These deposits filled in some erosional topography formed on a variety of older units

QTsc **Pantano Formation, conglomerate of Agua Verde Creek, unit of Wakefield Canyon, and mantling hillslope deposits, undivided (Quaternary to late Tertiary) —** Deposits of this unit include deeply dissected and highly eroded Tertiary alluvial fan and lacustrine deposits in areas where these Tertiary strata have not been divided from mantling colluvium. This map unit typically forms alternating eroded ridges and arroyos, with ridgecrests typically 5 to 30 meters above adjacent active channels that are part of deeply incised tributary channel networks. Even the highest surfaces atop QTsc ridges are rounded, and original highest capping fan surfaces are not preserved. QTsc deposits are dominated by gravel ranging from boulders to pebbles. Deposits are moderately indurated and are quite resistant to erosion because of the large clast size and carbonate cementation. Also included are areas where incision is moderate to slight and underlying Tertiary strata are fine grained and poorly resistant. In some of these areas, map unit QTsc has been outlined by aerial photograph analysis of low relief areas where a large amount of fine grained strata is apparent by its very light shades but a veneer of remobilized Pantano Formation and other Quaternary deposits is also apparent. Soils typically are cemented by carbonate accumulation on ridgecrests. Carbonate litter is common on ridgecrests and hillslopes. On aerial photos, QTsc surfaces are commonly gray to white. QTsc surfaces support creosote, mesquite, palo verde, ocotillo, and cholla.

Axial Stream Deposits

Sediment deposited by Cienega Creek cover a narrow strip that trends north-south through much of The Narrows 7 ½' Quadrangle, and trends northeast in the northwestern part of The Narrows and the southwestern part of the Rincon Peak 7 ½' Quadrangle. Deposits are a mix of gravel, sand and finer sediment; they include lithologies reflecting the relatively large and lithologically diverse drainage basin.

Qycr **River channel deposits (Late Holocene)—** River channel, bar, and low terrace deposits. Deposits are composed primarily of sand and gravel. Along Cienega Creek, modern channels are typically entrenched several meters below adjacent young terraces. The current entrenched channel configuration began to evolve with the development of arroyos in the late 1800's, and continued to evolve through this century. Channels have variable widths, but modern channels in much of the map area are relatively uniform within artificial dikes. Channels are extremely flood prone and are subject to deep, high velocity flow in moderate to large floods. Most modern channel banks are formed in weakly to moderately cohesive late Holocene alluvium and may be subject to severe lateral erosion during floods. Erosion is likely to be most severe on the outside banks of channel bends.

Qy3r **Low terrace and bar deposits (Late Holocene)—** Sand, gravel, silt and clay of low, variably vegetated bars and terraces.

Qy2r **Deposits underlying the historical floodplain (Late Holocene)—** Sand, silt, clay, with gravel beds and lenses. The terrace surface was the early historical floodplain of Cienega Creek. Contains weak buried dark, organic-rich soil horizons, and internal unconformities.

Qyr **Floodplain and terrace deposits, undifferentiated (Holocene)—**Deposits forming early historical floodplains and lower terraces flanking the main channel along Cienega Creek. Terrace surfaces are flat and uneroded, except immediately adjacent to channels. Qyr deposits consist of well-bedded, weakly to unconsolidated sand, silt, and clay. Soils are minimal to weakly developed, with some carbonate filaments and fine masses and weak soil structure in near surface horizons. Lower Qyr terraces and overbank areas may experience sheetflooding during large floods in areas where the main channel is not deeply entrenched. Higher areas of the historical floodplain are no longer subject to flood inundation as result of entrenchment of the main channel and tributary channels. Unprotected channel banks formed in Qyr deposits are very susceptible to lateral erosion.

Qi3r **Younger intermediate river terrace deposits (Late Pleistocene)—** Remnant river terrace deposits along Cienega Creek. These terraces are typically 5 to 10 m above the active channel. Qi3r deposits consist of cobbles, gravels and finer-grained sediment. Qi3r surfaces commonly have loose, open lags of cobbles and gravels; surface clasts exhibit weak rock varnish. Qi3r surfaces appear light orange color aerial photos, reflecting slight reddening of surface clasts and the surface soil horizon. Qi3r soils are moderately developed, with orange to reddish brown clay loam to light clay argillic horizons and stage II calcium carbonate accumulation. Vegetation on Qi3r terraces consists of scattered mesquite, prickly pear and creosote bushes.

Qi2r **Intermediate river terrace deposits (Middle Pleistocene)—** Remnant river terrace deposits along Cienega and Agua Verde creeks. These terraces are typically 10 to 15 m above the active channel. Qi2r deposits consist of cobbles, gravels and finer-grained sediment. Qi2r surfaces commonly have loose, open to moderately packed cobbles and gravel surface lags; surface clasts exhibit moderate rock varnish. Qi2r surfaces appear in orange color aerial photos, reflecting reddening of surface clasts and the surface soil horizon. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Underlying soil carbonate development is typically stage III, with abundant carbonate through at least 1 m of the soil profile. Dominant vegetation includes mesquite and prickly pear cactus with some creosote.

Qi1r **Older intermediate river terrace deposits (Middle to early Pleistocene)—** High remnant river terrace deposits along Cienega Creek. These terraces are typically 30 to 40 m above the active channel. Qi1r deposits consist primarily of cobbles, pebbles and finer-grained sediment. Qi1r surfaces commonly have open gravel surface lags. Qi1r surfaces appear red to reddish brown on color aerial photos, reflecting orange rock varnish on surface clasts and reddened soils. Soils typically contain reddish brown, clay-rich argillic horizons where surfaces are well preserved. Underlying soil carbonate development is typically stage III to IV, with abundant carbonate through at least 1 m of the soil profile; indurated petrocalcic horizons were not observed. Dominant vegetation includes mesquite and low shrubs, with some creosote.

Qor **Very high river terrace deposits (Early Pleistocene)—** Very high remnant river terrace deposits along Cienega Creek. The tops of these terraces are 40 to 60 m above the active channel of Cienega Creek. Qor deposits consist of cobbles, pebbles, and a few small boulders with sand and finer-grained sediment. Qor surfaces commonly have a loose cobble and pebble lag; surface clasts exhibit moderate to strong rock varnish. Qor surfaces appear dark reddish brown in color aerial photos, reflecting reddening of surface clasts and relatively clay-rich surface soil horizon with some dark organic material. Soils typically have brown to reddish brown clay argillic horizons over indurated stage IV carbonate horizons where surfaces are well preserved. In other places, argillic horizons have been removed by erosion. Dominant vegetation includes mesquite, prickly pear cactus and creosote.

Hillslope Deposits

Qtc **Hillslope colluvium and talus (Holocene and Pleistocene)—** Locally- derived deposits on moderately steep hillslopes in the Empire and Rincon mountains. Colluvium is extensive in the mountains and some dissected piedmont areas, but is mapped only where sufficiently thick and extensive as to obscure underlying bedrock. Deposits are very poorly sorted, ranging from clay to cobbles and boulders. Clasts typically are subangular to angular because they have not been transported very far. Bedding is weak and dips are quite steep, reflecting the steep depositional environment. Deposits are a few meters thick or less; thickest deposits are found at the bases of hillslopes. Some stable hillslopes are covered primarily with Pleistocene deposits, which are typically reddened and enriched in clay. Other more active hillslopes are covered with Holocene deposits, which have minimal soil development.

Other Quaternary to late Tertiary Deposits

d **Disturbed ground (<100 years) —** Areas where human activity has obscured the geologic nature of underlying material.

QTd **Diatomite? (Quaternary or late Neogene) —** Very light gray to white, poorly indurated, very-fine-grained sandstone, with sparse 1 mm gastropod fossils. Appears to be relict lacustrine deposit.

QTsc **Pantano Formation and mantling hillslope deposits, undivided (Neogene to Quaternary)—** Deeply dissected and highly eroded Neogene alluvial fan and lacustrine deposits in areas where these Tertiary strata have not been divided from mantling colluvium. This map unit typically forms alternating eroded ridges and arroyos, with ridgecrests typically 5 to 30 meters above adjacent active channels that are part of deeply incised tributary channel networks. Even the highest surfaces atop QTsc ridges are rounded, and original highest capping fan surfaces are not preserved. QTsc deposits are dominated by gravel ranging from boulders to pebbles. Deposits are moderately indurated and are quite resistant to erosion because of the large clast size and carbonate cementation. Also included are areas where incision is moderate to slight and underlying Neogene strata are fine grained and poorly resistant. In some of these areas, map unit QTsc has been outlined by aerial photograph analysis of low relief areas where a large amount of fine grained strata is apparent by its very light shades but a veneer of remobilized primarily Pantano Formation is also apparent. Soils typically are cemented by carbonate accumulation on ridgecrests. Carbonate litter is common on ridgecrests and hillslopes. On aerial photos, QTsc surfaces are commonly gray to white. QTsc surfaces support creosote, mesquite, palo verde, ocotillo, and cholla.

Cenozoic map units

Tqv **Hydrothermal silica and quartz — hematite breccia (Oligocene or early Miocene)**—Fine grained to cryptocrystalline, hydrothermal quartz, brecciated quartz, quartz-hematite breccia, and local milky quartz. Forms numerous, widely spaced veins and irregular masses. Silica is locally vuggy with fine drusy quartz lining vugs. Quartz-hematite breccia consists of angular fragments of gray, fine-grained to cryptocrystalline quartz with a brownish to reddish brown to brick red, siliceous and hematitic matrix. Limestone host for hydrothermal silica and quartz is locally preserved as sheets and irregular masses within silica. Silica locally displays layers and laminations on weathered surfaces that are interpreted as reflecting relict layering in replaced carbonates, siliceous carbonates, and silty and sandy strata. This unit includes rocks equivalent to the jasperoid breccia (unit Tsx) mapped in the adjacent Vail quadrangle (Richard et al., 2001).

Crushed hydrothermal quartz and re-silicified hydrothermal quartz forms a discontinuous, ~1-3 m thick sheet along a low-angle fault contact that places upper Paleozoic carbonates over Proterozoic rocks along the south side of Agua Verde Creek directly west of the Rincon Peak 7 ½' Quadrangle. Also, just west of “Agua Verde 2” (Castle on the hill) in the Rincon Peak 7 ½' Quadrangle, a fault zone contains silica replacement and open space filling quartz. Some quartz is shattered and re-cemented with silica (SW¼, NE¼, sec. 17, T. 16 S., R. 17 E.).

South and west of Colossal Cave (Richard et al., 2001) hydrothermal silicification affects conglomerate and sandstone of the Pantano Formation, which indicates that silicification is Oligocene or younger. Near Coyote Spring south of Agua Verde Creek, rock avalanche breccia was derived from silicified quartzite, so silicification is older than youngest conglomerates of the Pantano Formation. The hydrothermal quartz is thus interpreted to be

Oligocene or early Miocene. This age assignment is based on the interpretation that hydrothermal silicification in the area was due to a single extensive event, rather than to smaller events separated by millions of years.

x **Crushed rock (Tertiary?)** — Crushed rock in fault zones with uncertain and probably various protoliths. In Rincon Mountains rocks of this unit are typically silicified and have been subject to some alteration, including chloritization.

Conglomerate of Agua Verde Creek (Miocene)

Drewes (1977) mapped a conglomerate unit overlying the northeastern outcrops of Pantano Formation, and named it the Nogales Formation, presumably because it resembled a conglomerate of that name that underlies part of the city of Nogales, located about 80 km to the south (Simons, 1974). This unit is referred to here as the conglomerate of Aqua Verde Creek, based on the interpretation that it is a local unit that is unrelated to the Nogales Formation in the Nogales area. This name is informal and the unit is not associated with a type section or area (e.g., Hansen, 1991). The presence of mylonitic clasts is characteristic of this unit and indicates that the crystalline rocks below the Catalina detachment fault in the southern Rincon Mountains had been tectonically uncovered and were the source of mylonitic debris (e.g., Dickinson, 1991; Spencer, 2000). This unit includes minor exposures of conglomeratic sandstone and sandstone.

Tavc **Conglomerate** — Conglomerate with sparse to abundant clasts of leucocratic granite, leucocratic muscovite granite, and variably lineated, mylonitic and locally chloritic granitoids. Other types of clasts are typically sparse to absent. Granitoid clasts are inferred to have been derived from the Rincon Mountains. The appearance of these clasts in the stratigraphy marks the beginning of subaerial exposure of the mylonitic crystalline rocks and leucocratic granite that make up the Rincon Mountains.

Tavcs **Conglomeratic sandstone** — Pebbly conglomerate and sandstone distinguished by >50% content of sandstone and granule sandstone with pebbles less than 1 cm diameter. Exposures are found in the upper Mescal Wash drainage near the east edge of the map area, and contain pebbles derived from leucogranite and mylonitic granite (~60-90%) as well as Cretaceous Bisbee Group sandstone (~10-40%).

Tavs **Sandstone and sparse pebbly sandstone** — Where exposed along the south side of Agua Verde Creek, exposures contain pebbles derived from leucogranite and mylonitic leucogranite.

Unit of Wakefield Canyon (Miocene to Pliocene)

Sandstone and conglomerate in the southeastern part of the map area are here informally named the unit of Wakefield Canyon. This name is informal and the unit is not associated with a type section or area (Hansen, 1991). The fine-grained siltstone and claystone of the upper Pantano Formation grade southeastward across discontinuous exposures into sandstone and conglomerate that are generally coarser grained toward bedrock exposures on the northeast flank of the Empire Mountains and toward the west flank of the Whetstone Mountains. This sandstone and conglomerate of the unit of Wakefield Canyon probably represent distal alluvial fans either flanking or transgressing over the playa deposits of the upper Pantano Formation. Most of the unit of Wakefield Canyon is considered to be younger than the fine-grained strata of the upper Pantano Formation, and most of the Pantano Formation is considered to be older than the unit of Wakefield Canyon. Only the uppermost silty strata of the upper Pantano Formation are subhorizontal and are possibly correlative with the lowest stratigraphic levels of the unit of Wakefield Canyon.

Strata of the unit of Wakefield Canyon are generally gently dipping and poorly to moderately consolidated. Conglomerate near bedrock exposures on the west, south, and southeastern margins of the present lower Cienega Creek basin contain many clasts that resemble local bedrock. In eastern and southern exposures clasts of Cretaceous Bisbee Group sandstone and pale white to light gray quartz-biotite felsite are common. The felsite is suspected to have been derived from the southwestern Whetstone Mountains (Creasey, 1967). In northwestern exposures near I-10 at the northern end of the Empire Mountains, Rincon Valley granodiorite or similar granitoid is well represented in clast populations. Limestone clasts are locally abundant, porphyritic biotite granite clasts are locally present, and clasts derived from conglomerate in the Pennsylvanian Earp Formation are rare. In general clast types are diverse and are more angular and larger near bedrock exposed on the flanks of the basin as defined by the present outcrop distribution. Sedimentary rocks are finer grained toward the north where sandstone and siltstone are dominant. Along I-10 this unit overlies the Pantano Formation with a 10°-30° angular discordance. Strata are generally poorly exposed and form rounded slopes commonly mantled with colluvium. Excellent exposures are limited to the banks of numerous washes.

Twc **Conglomerate** — Lithologically diverse clasts commonly resemble exposed bedrock in the western Whetstone and eastern Empire Mountains. Generally poorly exposed, forming rounded slopes. Both plane bedded and channelized beds in the same localities are interpreted as alluvial fan deposits with channelized coarse deposits and planar overbank deposits. Clasts are typically 2 to 20 cm diameter, locally as large as 40 cm, rarely to 1 m.

Twsc **Sandy conglomerate** — Sandy pebble to cobble conglomerate, with less abundant sandstone. Generally tan to medium brown. Distinguished from conglomeratic sandstone (map unit Twcs) by >50% content of sandstone and granule sandstone with grains less than 1 cm diameter. Lenticular conglomerate beds 20 to 200 cm thick and 5 to 40 m long are locally common in wash bank exposures.

Twcs **Conglomeratic sandstone** — Primarily consists of strata that are dominantly sandstone but contain beds of pebble and cobble conglomerate with local boulders up to 30 cm diameter. Conglomerate commonly fills channels within finer grained beds. At one locality, channel-filling conglomerate lenses area 20 – 80 cm thick, 5 – 20 m across. Distinguished from conglomeratic sandstone (map unit Twsc) by <50% content of sandstone and granule sandstone with clasts less than 1 cm diameter. Locally includes sandy conglomerate and sandstone.

Twss **Sandstone** — Poorly sorted sandstone, silty sandstone, and pebbly sandstone, typically tan to pale brown and poorly to moderately consolidated. Locally includes siltstone, clay beds, and pebble-conglomerate beds. Locally, protruding sandy beds 5 to 20 cm thick alternate with 5 to 10 cm thick, recess-forming silty beds.

Pantano Formation (Oligocene to early Miocene)

The Pantano Formation was first described in detail by Brennan (1957, 1962), who designated and studied a type section along U.S. Highway 80 (now Interstate 10; see also Metz, 1963). Finnell (1970) identified several faults in Brennan's type section, described a revised stratigraphy consisting of five units, and elevated the formation name to formal status according to USGS guidelines. The lowest three of Finnell's five units are dominantly conglomeratic, the fourth consists of porphyritic andesite, and the fifth consists of conglomeratic sandstone grading upward into sandstone, siltstone, gypsiferous claystone, and breccia. Balcer (1984) mapped much of the Pantano Formation and re-defined its stratigraphy. He divided the breccia from Finnell's unit five to create a sixth, and highest, unit of breccia, and emphasized the calcareous and fine grained character of unit two. The combined thickness of Balcer's six units is 1277 m. In the mapping reported in this study, the distribution of sedimentary facies was found to be more complex than the layered sequence of units 1 through 4 defined by Finnell (1970). This study did not outline units 1 through 4 of Finnell (1970), but map units include coarse-grained strata, fine-grained strata, and volcanic rocks. In some areas, a division is also made between strata that underlie and strata that overlie the andesitic volcanic rocks.

The upper part of the Pantano Formation is overlain by, or grades laterally into, sandy and conglomeratic units in the northeastern and southeastern parts of the map area (the conglomerate of Agua

Verde Creek and the unit of Wakefield Canyon, respectively).

Breccia facies, Pantano Formation (Oligocene to early Miocene)

Breccia units are largely monolithologic and are interpreted as catastrophic rock avalanche deposits (e.g., Shreve, 1968; Kreiger, 1977; Yarnold and Lombard, 1989). Locally includes debris flows, mudflows, and coarse conglomerate.

Txc **Breccia derived from Paleozoic carbonate rocks** — A breccia composed of sub-angular to angular limestone clasts ranging in size from pebbles to boulders (many boulders in excess of 20 m in diameter are present locally). Rare clasts of siliclastic rocks are locally present. The unit occurs as a sheet like deposit in the north where it overlies gently dipping strata of the Pantano Formation, but to the south, a narrow outcrop band of this unit crosses I-10 that may be conformable with underling conglomerate and pebbly sandstone of the upper Pantano Formation.

Txm **Breccia derived from various rock types** — Mixed clast assemblages forming breccias and, possibly, massive conglomerate of possible debris-flow origin.

Txsc **Breccia derived from silty carbonate and siltstone of Paleozoic age** —Possible protoliths include Cambrian Abrigo Shale, Devonian Martin Formation, and Pennsylvanian-Permian Earp Formation.

Txq **Breccia derived from Cambrian Bolsa Quartzite** — At one location (northeast of Coyote Spring adjacent to Agua Verde Creek, i.e., SW¼, NW¼, sec. 22, T. 16 S., R. 17 E.), clasts consist of pale gray, angular quartzite fragments are surrounded by brownish red hematite-quartz matrix that looks like hydrothermal quartz. It is strongly suspected that this matrix material was produced by the extensive silica flooding that occurred in the Colossal Cave area, and that by the time this breccia was mobilized and transported, the hydrothermal silicification had ended and silica deposits were being shed from high relief areas into the Pantano basin. Lack of silicification in host conglomerate suggests that silicification did not occur after the breccia had been deposited on, and buried by, the conglomerate.

Txg **Breccia derived from granite or granodiorite of map unit YXg** — Contains typically 5 to 50 cm fragments of biotite granitoid, medium grained, non-porphyritic, with chalky white plagioclase. Locally, 10-20% of fragments were derived from Cambrian Bolsa Quartzite (railroad cut, NE¼, sec. 27, T. 16 S., R. 17 E.). Base of breccia sheet concordantly overlies siltstone and sandstone and minor conglomerate at well exposed contact in railroad cut (SW¼, sec. 22, T. 16 S., R. 17 E.) and discordantly overlies such strata at another nearby location (SE¼, NW¼, sec. 22, T. 16 S., R. 17 E.), possibly because of a disruptive catastrophic emplacement process.

Clastic sedimentary strata, Pantano Formation (Oligocene to early Miocene)

Tpf **Fine-grained siltstone and claystone** — Siltstone, silty clay, and clay, with local gypsum beds up to several cm thick. Color of clay is variable, and includes pale yellow, pale green, tan, and brown. Locally includes sandstone and sparse pebble conglomerate.

Tps **Sandstone and silty sandstone**

Tpc **Coarse-grained sandstone and conglomerate, undivided —** Massive to moderately well bedded, poorly sorted, pebble to boulder conglomerate. Locally includes sandstone and granule to pebbly sandstone. Clasts are mostly 3-30 cm and are locally as large as 2 m. Most clasts are subrounded, most others are subangular. Colors are highly variable, and include tan, brown, and pale gray to greenish gray. Clasts compositions vary greatly over the area of exposure. Near Cienega Creek this unit contains abundant clasts of Bisbee Group sandstone and pale gray to whitish gray biotite quartz porphyry. Granitic clasts and clasts of limestone and quartzite are absent or rare in most areas to the south and west, but are abundant in northern exposures near the Rincon Mountains. The absence of mylonitic clasts distinguishes this unit from the overlying conglomerate of Agua Verde Creek.

Adjacent to the Catalina detachment fault, and north of Agua Verde Creek, the conglomerate consists of poorly bedded, poorly sorted, medium to dark brown fanglomerate with subangular to angular clasts, mostly 1-10 cm, primarily of Paleozoic carbonate rock units with less abundant Mesozoic and Tertiary sandstone and granitoids. Volcanic and mylonitic rocks were not seen in the clast suite. Paleozoic carbonate clasts are more abundant to the west where the conglomerate is adjacent to the extensive exposures of Paleozoic carbonate rocks. Granitoid clasts are absent in some areas, abundant in others, and locally form up to 100% of clasts in what are possibly rock avalanche breccias. The high degree of heterogeneity of this clast suite, its massive to poorly bedded and poorly sorted character, the presence of rock avalanche breccias, and the absence of leucogranitic and mylonitic debris derived from the lower plate, indicate that the conglomerate was deposited in alluvial fans adjacent to relief probably produced by normal faulting within the upper plate of the Catalina detachment fault (see also Dickinson, 1991).

An unconformity within silty sandstone in this unit, on the south side of Pantano Road (SE¼, SE¼, sec. 20, T. 16 S., R. 17 E.) indicates that deformation occurred during deposition.

Interbedded andesite of map unit Ta and tuff, both on the adjacent Vail Quadrangle (Richard et al, 2001), were dated by the K-Ar method at 24.9 ± 5.2 Ma (2σ uncertainty [95% confidence interval]) and 29.5 ± 1.8 Ma (2σ), respectively. These dates indicate that at least some of this conglomerate is Oligocene in age (Shafiqullah et al., 1978).

Tpcc **Coarse-grained sandstone and conglomerate, limestone clasts only**

Tpcg **Coarse-grained sandstone and conglomerate, granite clasts only**

Tpu **Upper Pantano Formation, undivided** — A heterolithic assemblage of medium- to thick-bedded sandstone, pebbly sandstone, and pebble-cobble-boulder conglomerate, with intervals of thin- to medium-bedded sandstone and mudstone. Clasts, which range from rounded to subangular, consist chiefly of Bisbee Group sandstone and mudstone along with a distinctive coarse-grained, crystal-rich quartz porphyry. Minor volcanic clasts are also present. The base of the unit in many areas is defined as the top a distinctive crystal-rich, coarse-grained andesite lava (map unit **Ta**). In areas where this lava is absent or concealed, abundant clasts of the lava are common near the base of the unit. A sequence of one or two nonwelded felsic tuffs occur near the base in the easterly adjacent The Narrows 7 ½' Quadrangle, typically within a sequence of mudstone and thin-bedded to laminated sandstone. Also, in the easterly adjacent The Narrows 7 ½' Quadrangle, a distinctive, limestone boulder-megaclast breccia sheet appears to be interbedded with conglomerate near the top of this unit.

Tpfu **Fine-grained siltstone and claystone, upper Pantano Formation** —Siltstone, silty clay, and clay, with local gypsum beds up to several cm thick. Color of clay is variable, and includes pale yellow, pale green, tan, and brown. Locally includes sandstone and sparse pebble conglomerate. At top of unit near contact with overlying conglomerate of Agua Verde Creek, unit consists of sandstone, typically pale reddish brown, with sparse, poorly sorted pebble-conglomerate beds with clasts as big as 10 cm of leucogranite and other granitoids.

Tpcu **Coarse-grained sandstone and conglomerate, upper Pantano Formation —** Massive to thick bedded, poorly sorted, pebble to boulder conglomerate. Locally includes sandstone and granule to pebbly sandstone. Clasts are mostly 3-30 cm and are locally as large as 2 m. Many smaller clasts are subangular, most others are subrounded. Colors are highly variable, and include tan, brown, and pale gray to greenish gray. Clasts compositions vary greatly over the area of exposure.

Tpl **Lower Pantano Formation, undivided** — Rocks assigned to the lower Pantano Formation are stratigraphically above the porphyritic andesite lava flows.

Tpfl **Fine-grained siltstone and claystone, lower Pantano Formation** — Siltstone, silty clay, and clay.

Tpcl **Coarse-grained sandstone and conglomerate, lower Pantano Formation —** Massive to moderately well bedded, poorly sorted, pebble to boulder conglomerate.

Volcanic Rocks associated with the Pantano Formation (Oligocene to early Miocene)

Tt **Tuff (Late Oligocene)—**A sequence of one or two, discontinuous, nonwelded, moderately crystal-rich rhyolitic tuffs less than 10 meters thick. These are interbedded with fine-grained strata near the base of the upper Pantano Formation. A sample of this tuff unit yielded an $^{40}Ar/^{39}Ar$ date from sanidine of 26.42 ± 0.02 Ma (W.C. McIntosh, written communication, 2002). Also includes tuff at base of Tertiary section in Wakefield Canyon area along the east edge of the map area. A sample of this tuff unit from the adjacent Mescal 7 ½' Quadrangle (Skotnicki, 2001) yielded an $^{40}Ar/^{39}Ar$ date from sanidine of 26.54 ± 0.083 Ma (W.C. McIntosh, written communication, 1997). Overlying sediments resemble Pantano Formation and are tentatively correlated with it. Two exposures of this tuff, interbedded with Pantano Formation at the foot of the Rincon Mountains south of Charlies Tank, were mapped by Finnell (unpublished mapping provided by Brenda Houser, USGS) and were not examined by the authors of this report.

Tas **Andesitic volcaniclastic rocks (Late Oligocene)—**Massive to crudely bedded, volcanic lithic conglomerate, agglomerate, and/or breccia and coarse sandstone that is typically so massive and indurated that it is locally difficult to distinguish from lava flows of map unit Ta. At one locality (NE¼, SE¼, sec. 28, T. 16 S., R. 17 E.) this unit contained clasts of Mesozoic(?) sandstone and volcanic rocks and aphyric andesite. Locally includes thin- to medium-bedded volcaniclastic sandstone and pebbly sandstone mixed with greenish mafic pyroclastic beds.

Ta **Porphyritic andesite lava flows (Late Oligocene)—**Porphyritic, crystal-rich, andesite lava flows. Contains conspicuous plagioclase phenocrysts up to 3 cm diameter in a medium to dark gray aphanitic matrix. Phenocrysts make up 20 to 40% of the rock. Locally near top of unit includes crystal poor to aphyric andesite lava flows (adjacent part of the Vail 7 ½' Quadrangle).

Distinctive appearance of this rock has resulted in the informal name "turkey track porphyry" (e.g., Cooper, 1961). Cooper (1961) recognized the regional character of this distinctive rock, and identified some petrographic features, including the composition of plagioclase ($An_{52±6}$), the general lack of zoning in plagioclase phenocrysts except oscillatory zoning, and the presence of small amounts of hypersthene and augite. (Cooper did not report petrographic information for andesite samples from the study area.) Although it has been proposed that this rock unit, present in many areas in southeastern Arizona, was derived from a single magma body, this has not been rigorously demonstrated. Two samples that were analyzed contained 55.5 and 52.5% SiO_2 (Cooper, 1961). Mielke (1964) determined that the average K_2O and Na_2O content of 19 samples from widely scattered localities was 3.04% and 3.50%, respectively.

A sample of this unit, from near the railroad bridge over Cienega Creek 2 km west of the map area, yielded a K-Ar date of 24.9 ± 5.2 Ma (2σ uncertainty [95% confidence interval]), and a sample from the northeastern Rincon Mountains (Mineta Ridge) yielded an age of 26.9

± 4.8 Ma (2σ uncertainty [95% confidence interval]; Shafiqullah et al., 1978). A sample from the Del Bac Hills, south of the Tucson Mountains and west of the map area, yielded dates of 26.3 ± 1.6 Ma (plagioclase), 27.3 ± 1.6 Ma (HF-leached plagioclase(?)) and 26.9 ± 1.6 Ma (groundmass without magnetic fraction) (Percious, 1968; 2σ uncertainty [95% confidence interval] for all). The age of this rock unit is estimated to be 26 to 27 Ma.

Tr **Rhyolitic tuff (Early Oligocene)**—Pale gray to whitish gray, crystal-rich, densely welded, rhyolitic tuff beneath Pantano Formation, with phenocrysts of quartz, plagioclase, sanidine, and biotite.

This tuff was dated at 33.01 ± 0.38 Ma (weighted mean of six single-crystal $^{40}Ar/^{39}Ar$ sanidine dates from unpublished report by Lisa Peters, New Mexico Bureau of Mines and Mineral Resources [1999], sample 5-6-98-1; 2σ uncertainty). Previously determined dates are as follows: 33.6 ± 5.4 Ma (K-Ar biotite), and 37.6 ± 2.2 Ma (K-Ar sanidine; both by Damon and Bikerman, 1964, given as recalculated by Reynolds et al., 1986), and 34.4 ± 1.6 Ma (K-Ar biotite; Dickinson and Shafiqullah, 1989; 2σ uncertainty [95% confidence interval] given for all dates).

<u>Conglomerate beneath pre-Pantano tuff</u>

Tc **Conglomerate (Tertiary) —** This unit consists of a single exposure of red, thin- to medium-bedded pebbly sandstone to sandy pebble coarse-grained that underlies the welded rhyolite ash-flow tuff of map unit **Tr**. This exposure is located along Interstate 10.

Tertiary or Cretaceous igneous map units

TKf **Felsite (Tertiary or Cretaceous)** —White to very light gray felsite that contains 2-3%, 1-3 mm quartz, and sparse, tiny (≤1mm) chloritized biotite grains. Forms several dikes and sills in the southern part of the map area.

TKm **Mafic hypabyssal intrusive rock (Tertiary or Cretaceous) —** Dark green finely crystalline mafic dikes typically intrude the upper portion of the Empire Mountains stock (Ke).

TKgm **Muscovite granitoid (Tertiary or Cretaceous)** — Generally fine- to medium-grained, leucocratic felsic granitoids. Locally extreme fracturing, lithification, and chloritic alteration of mafic minerals, are common within several tens of meters of the detachment fault. At greater distances from the detachment fault, alteration and brecciation are less well developed and a lineated mylonitic fabric, characteristic of metamorphic core complexes, is commonly visible (e.g., Davis, 1980; Davis and Lister, 1988). The fabric is generally fairly weak and rarely is developed on sparse lithologic layering within the granitoids.

Ke **Empire Mountains stock (Upper Cretaceous)—**The upper part of this pluton is a medium-grained granodiorite containing 10-30% biotite and hornblende. Within its core, the pluton is medium-grained to coarse-grained, contains less than 10% mafic minerals, and appears to be slightly more felsic. Marvin et al. (1973) dated the stock at 71.9 $\pm$ 2.5 Ma (K/Ar biotite).

Mesozoic map units

<u>Bisbee Group (lower Cretaceous to upper Jurassic)</u>

The late Jurassic to middle Cretaceous Bisbee Group of southeastern Arizona and adjacent parts of New Mexico, Sonora, and Chihuahua, was deposited in a structurally complex rift trough produced by late Jurassic rifting. This rifting occurred in an area that had previously been subject to Jurassic, subduction-related magmatism. The basal Glance Conglomerate member of the Bisbee Group was deposited in basins flanking uplifted fault blocks within the rift trough, and is characterized by large changes in thickness and clast composition over short distances. The overlying finer grained strata of the

Bisbee Group were deposited as the rift topography was erosionally degraded and buried (Bilodeau et al., 1987; Dickinson et al., 1987, 1989; Dickinson and Lawton, 2001).

The basal unit of the Bisbee Group, the Glance Conglomerate (map unit KJg), varies greatly in thickness and composition across the study area. In the central Empire Mountains, where it overlies Paleozoic units, the Glance Conglomerate consists of coarse-grained, massive conglomeratic rocks that thin rapidly to the south. Finnell (1970) estimated that the formation is over 1500 meters thick in some areas, and that the unit could be divided into units based on the dominant clast type, even though this was not done on his map of the area (Finnell, 1971). We recognized distinctive conglomerate units composed of limestone clasts (KJgl), quartzite clasts (KJgq), granitiod clasts (KJgg), and quartzite and granite clasts (KJgqg). In general, the older conglomerate units consist of clasts derived from the youngest Paleozoic (carbonate) units (Finnell, 1970). These variations are interpreted to represent the sequential unroofing of progressively deeper stratigraphic levels of an uplift directly to the north of the thick wedge of Glance Conglomerate in the Empire Mountains.

In the low hills north of the north end of the Empire Mountains, where Glance Conglomerate directly overlies Proterozoic basement, the Bisbee Group consists of a relatively thin sequence of arkosic sandstone and monolithic granitoid-clast conglomerate. Locally, some of these conglomerates include lenses with abundant carbonate clasts.

In areas where the Bisbee Group is well exposed, such as the southern Empire and Whetstone Mountains, and to some extent the northwestern Santa Rita Mountains, the Bisbee Group typically consists of sandstone, siltstone, and shale with sparse limestone beds (Finnell, 1970; Archibald, 1987; Soreghan, 1999). According to Finnell (1970), strata above or laterally equivalent to the Glance Conglomerate in the northern Empire Mountains consist, from older to younger, of the Willow Canyon (900 meters), Apache Canyon (450 meters), Shellenberger Canyon (1,200 meters), and Turney Ranch Formations (1,000 meters) (thicknesses reported by Finnell, 1970). The formations are defined by dominant lithologies ranging from pebble conglomerate to quartz arenite and dark olive gray silty shale to reddish shale, but in fact, none of these rock types are truly diagnostic. The formation boundaries are defined by distinctive sequences that can be identified in the homoclinal sections exposed in the southern Empire and Whetstone mountains, but in areas of poor, discontinuous exposure and structural complexity it was not feasible to assign formation names to individual outcrops. Based on how these formations were mapped in the Mt. Fagan and Narrows 7 ½' Quadrangles by Finnell (1971), we observed that sandstone in the lower two formations tends to be relatively coarser-grained, more poorly sorted with argillaceous matrix, and more feldspathic than sandstone in the upper two formations which is also typically cleaner, and more quartzose (see also Klute, 1991, p. 167-176; Dickinson and Lawton, 2001). In addition, the shale and siltstone units generally change from dark-olive gray and pyritic to reddish colored (oxidized) upwards. Limestone beds containing molluscan shell fragments are present throughout, and locally serve as useful marker beds.

Freshwater bivalves and gastropods were collected from two locations in the Willow Spring – Apache Canyon lithofacies of the Bisbee Group (sample localities 3-22-01-01smr [Bootlegger Spring; SE¼, SW¼, sec. 31, T. 17 S., R. 18 E.] and 3-8-01-01smr [700 m south-southeast of Fleming Tank; NE¼, NW¼, NE¼, sec. 27, T. 17 S., R. 17 E.]). Both localities contained gastropods of the genera Viviparus and Reesidella, and the Fleming Tank locality yielded unionid bivalves. The Bootlegger Spring locality yielded the bivalve Musculiopsis russelli, which has also been reported in the Apache Canyon Formation in the Whetstone Mountains (Scott, 1987; see also Yen, 1951). These fossils were identified by Spencer G. Lucas, Curator of Paleontology and Geology, New Mexico Museum of Natural History, Albuquerque, and are “no older than Barremian” and “no younger than Aptian” (Spencer Lucas, written communication, 2001). Both localities are within the undivided Willow Spring – Apache Canyon lithofacies of the Bisbee Group.

Kq **Turney Ranch Formation, Bisbee Group (Lower Cretaceous)** — Medium- to thick-bedded quartz sandstone interbedded with thin- to medium-bedded, typically reddish colored, silty mudstone and shale. The mudrocks are typically reddish colored. The quartz sandstone is typically cross-stratified in bed-scale bedforms that range from tabular-planar to wedge-planar in shape. The quartz sandstone is generally strongly fractured and locally shattered.

Ka **Siltstone of the Apache Canyon lithofacies, Bisbee Group (Lower Cretaceous)** — Gray to locally pale reddish tan calcareous siltstone, siltstone, and fine-grained sandstone, with local medium-grained sandstone.

Kw **Sandstone and conglomeratic sandstone of the Willow Canyon lithofacies, Bisbee Group (Lower Cretaceous)** — Unit typically consists of thin- to thick-bedded, fine- to coarse-grained sandstone and silty sandstone. Commonly includes sparse pebbly sandstone beds and olive gray, commonly pyrite-bearing siltstone and mudstone. Examination with hand lens suggests that arkosic and quartzofeldspathic compositions are most common. Pebbly sandstone beds contain abundant black and white, well-rounded to rounded chert clasts. Magnetite laminations locally form low-angle cross beds with truncations that reveal stratigraphic top direction. Sandstone is dominant at lower stratigraphic levels, with increasingly abundant siltstone at higher stratigraphic levels. Interbedded tuff (map unit Kt) is near the top of the sandstone about ~100 m below siltstone of the overlying Apache Canyon lithofacies.

Kt **Tuff bed (Lower Cretaceous)** — Weakly to moderately foliated and lineated crystal-poor tuff with aphyric volcanic lithic fragments up to 30 cm across and sparse biotite flakes up to 6 mm diameter and <2%, 0.5-2mm plagioclase. Foliation wraps around lithic fragments. Pale orangish tan to buff. Approximately 3 m thick. Some fragments of what appear to be pumice are stretched so that long axis, parallel to lineation, is 3 to 5 times length of short axis. Lineation and foliation are especially apparent on top surface, which is beautifully exposed where tuff crosses Fresno Canyon (this is, tentatively, the type area for this tuff).

Kwa **Sandstone and siltstone of the undivided Willow Spring – Apache Canyon lithofacies of the Bisbee Group (Lower Cretaceous)** — Unit typically consists of thin- to thick-bedded, fine to coarse grained, sandstone and silty sandstone with interbedded mudstone that locally contains iron oxides after pyrite. Examination with hand lens suggests that arkosic and quartzofeldspathic compositions are most common. Pebbly sandstone beds contain abundant black and white, well-rounded to rounded chert clasts. Thin- to medium-bedded limestone beds occur in some areas. Gypsum beds several to, rarely, several tens of cm thick are locally associated with shaley sediments that also contain silty carbonate thin beds. Thin limestone beds tend to be laminated, and the medium-bedded limestone (rarely thick-bedded) are commonly mollusk shell, skeletal wackstone with dark micritic, fetid matrix. Mudcracks are present locally, as are redbeds. Color is typically greenish gray with less common brownish or orangish gray and medium brown. Cleavage is locally developed, in some areas strongly so, in fine-grained rocks.

At one location (W½, SE¼, sec. 36, T. 17 S., R. 17 E.), an angular unconformity within this map unit is characterized by sandstone and sparse siltstone overlain by siltstone. Reddish colors that characterize rock for 5 to 10 m stratigraphically below unconformity suggest that subaerial erosion was responsible for the unconformity.

Ksr **Reddish mudstone and sandstone (Lower Cretaceous) —** Thin interval of distinct, reddish mudstone with interbedded thin, lithic-feldspathic sandstone beds. Mapped at base of Bisbee Group in southwestern part of map area, between Hilton Mine and Total Wreck Mine, and one isolated outcrop in the east-center part of the map area, near Smitty Spring. The outcrop in the southwestern part of the map area is separated from typical Willow Canyon lithofacies sandstones by a 1-2 m thick interval of apparently tectonized sandstone that suggests the contact is a fault.

Kba **Basaltic andesite lava, Bisbee Group (Lower Cretaceous) —** Sparse, crystal-poor, fine-grained, thin lava flows interbedded with basal strata of the Bisbee Group near the northwest corner of The Narrows 7 ½' Quadrangle. Locally, clast-supported autobreccia zones are present at the base of some flows.

Kb **Bisbee Group, feldspathic sandstone, mudstone and associated rocks —** A unit encompassing all Bisbee Group strata above the Glance Conglomerate and below the Turney Ranch Formation. This unit is correlative with the Willow Spring, Apache Canyon, and Shellenberger Canyon formations. It is dominated by thin- to thick-bedded, argillaceous, feldspathic sandstone or arkose and pebbly sandstone interbedded with olive gray, typically pyrite-bearing, shale and mudstone. Pebbly sandstone beds contain abundant black and white, well-rounded to rounded chert clasts. Some intervals include thin- to medium-bedded limestone beds. The thin limestone beds tend to be laminated, and the medium-bedded limestone commonly consists of mollusc shell, skeletal wackstone with dark-colored, micritic, fetid matrix. Bed-scale cross-stratified bedforms dominate the sandstone units, but locally contain Bouma (1962) sequence turbidite sedimentary sequences.

Kbu **Bisbee Group, undivided (Lower Cretaceous) —** Small, folded and faulted exposures of Bisbee Group rocks near the Catalina detachment fault in the far northwestern corner of the map area.

Glance conglomerate of the Bisbee Group (lower Cretaceous to upper Jurassic)

Conglomerate, coarse-grained arkose, and rare limestone are present locally at the base of the Bisbee Group. North of the Empire Mountains, conglomerate is less abundant and consists of clast-supported, rounded to sub-rounded cobble-boulder units typically containing mostly granodiorite clasts. Includes the following varieties distinguished by clast composition:

KJg **Conglomerate, undivided**.

KJgl **Monolithic limestone-clast conglomerate**

KJgq **Monolithic quartzite-clast conglomerate**.

KJgg **Monolithic granitoid-clast conglomerate —** Generally consists of subangular to subrounded cobbles and pebbles up to 1 m diameter (most 2 to 20 cm) of granodiorite that resemble local exposures of granodiorite (map unit Xgd). Locally contains sparse clasts of Pinal Schist.

KJgqg **Mixed quartzite-granitoid clast conglomerate —** Includes conglomerate with clasts up to 2 m diameter (NW¼, sec. 22, T. 17 S., R. 17 E., northwest of Fleming Tank).

Gardner Canyon Formation (Jurassic and/or Triassic)

J²g **Gardner Canyon Formation (Jurassic and/or Triassic) —** A heterolithic assemblage of dark red mudstone or slate, volcaniclastic sandstone, and conglomerate, with sparse volcanic flows. Estimated at up to 350 meters thick by Finnell (1971). Lithologically similar to Recreation Redbeds of the Tucson Mountains.

J²gu **Upper sandstone and conglomerate, Gardner Canyon Formation —** Thick-bedded to massive volcanic-lithic sandstone and conglomerate, generally medium-gray color.

J²gl **Lower sandstone and mudstone, Gardner Canyon Formation —** Dark reddish brown mudstone, fine-grained sandstone, and sparse tuff. Generally thick bedded.

Paleozoic map units

¼c **Carbonate rock (Devonian through Permian)** — Undivided carbonate rocks of Paleozoic origin, but of uncertain correlation. May be large blocks in Glance Conglomerate.

¼d **Dolomitic carbonate rocks (Upper(?) Paleozoic)** — Massive gray dolostone and calcareous dolostone. Lithology is most consistent with Rainvalley Formation, or parts of the Scherrer or Epitaph Formations, but may be any of the Paleozoic carbonate units.

¼l **Limestone (Paleozoic)** — Massive gray limestone. Lithology is consistent with Escabrosa, Horquilla or Concha formations.

Prv **Rainvalley Formation (Permian)** — Medium- to thick-bedded, light- to medium-gray dolostone, calcareous dolostone, and sparse limestone and quartz arenite. Chert is nearly always present in small amounts, forming bed-parallel stringers, irregular globs and some nodules. Grape-like 2-10 mm diameter silica spheroids are common in some beds. Two prominent 2-5 m thick fine-grained quartz arenite beds are present in the lower 50 m of the formation, separated by 15-20 m of section. The base of the Rainvalley is difficult to define in detail. Massive limestone beds of the upper Concha Limestone become thinner and have more clearly defined bedding parting up section. The bedding style of the basal Rainvalley is not distinguishable from that in the upper Concha. The contact is placed at the first recognizable dolostone bed; this is recognizable by a change in the weathering character of the carbonate, and a transition from the monotonous medium gray of the Concha Limestone to more varied shades of gray in the Rainvalley. In the relatively thick sections preserved at the top of the Paleozoic section in the southwestern part of the map area, there is an interval of thick bedded to massive limestone or dolomitic limestone 20-30 m up section from the upper quartzite marker bed. These strata are lithologically identical to the upper Concha Limestone.

Pc **Concha Limestone (Permian)** — Medium gray, cherty limestone. Massive to thick bedded except at the base. Chert forms irregular stringers and globs 5-20 cm in diameter, typically these are more irregular than the ellipsoidal, 'bread-loaf' chert in the chert-rich part of the Escabrosa. The basal contact is a sharp transition from quartzite of the upper Scherrer to medium-bedded light gray dolostone (identical in character to dolostone intervals within the Scherrer) that grades rapidly up section into massive limestone. Bedding is commonly indistinct to invisible in the limestone. Limestone is grainstone and wackestone, with scattered identifiable crinoid columnals, echnoid spines, and productid brachiopods.

Ps **Scherrer Formation (Permian)** — Quartzite with minor interbedded dolostone.

Psu **Upper Scherrer Formation** — Quartzite, lithologically indistinguishable from lower quartzite member.

Psm **Middle Scherrer Formation** — Dolostone, medium to light gray packstone to grainstone and very fine grained crystalline carbonate with 5 to 25 cm long chert nodules and stringers. Forms marker horizon 5-25 m thick.

Psl **Lower Scherrer Formation** — Medium to fine grained quartzite, massive to weakly laminated, pale gray to whitish gray on fresh surfaces, weathers pale orangish brown. Typically highly fractured, weathers to form rubbly slopes with generally poor outcrop. Several discontinuous (?) 1-3 m thick dolostone beds are present.

Pe **Epitaph Formation (Permian)**

Peu **Upper Epitaph Formation** — Medium to thick-bedded medium gray limestone in lower part, grades into dolostone in upper part. Boundary appears to be a diagenetic boundary;

there are globs of relict(?) limestone in dolostone in the transition. Limestone is mostly wackestone with common crinoid columnals. This unit probably correlates with strata mapped as Colina Limestone in the Waterman Mountains (Richard et al, 2000), based on comparison of the lithostratigraphy.

Pem **Middle Epitaph Formation** — Mudstone, marl, gypsum, with interbedded sandstone, limestone, and dolostone. Very poorly exposed, forms valley between lower and upper carbonate units of Epitaph.

Pel **Lower Epitaph Formation** — Light to dark gray, medium- to thick bedded carbonate with sparse interbedded sandstone and scattered siliceous stringers and globs. The contact with the Earp Formation is an abrupt transition from marly and sandy carbonate with interbedded sandstone into medium- to thick-bedded dolomite. The basal beds are dark gray along parts of the contact with the Earp Formation, and this apparently prompted Finnell (1971) to correlate these strata with Colina Limestone. The dark colored beds are dolomitic, medium- to thick-bedded, and are locally absent in the section west of the Total Wreck Mine. A second zone of dark gray dolomite appears towards the middle of the lower Epitaph, and is lithologically identical to dark gray strata at the base. These basal dark-colored carbonate strata were not mapped as a separate unit in this area. Based on comparison of lithostratigraphy, we consider it likely that strata mapped as lower and middle Epitaph Formation in the Empire Mountains correlate with strata mapped as middle and upper Earp Formation in the Waterman Mountains (Richard et al., 2000). Strata mapped as lower Epitaph Formation in the Empire Mountains are very similar to dark-colored, medium- to thick-bedded dolomite mapped as lower Epitaph Formation in the Colossal Cave area. The stratigraphy of the Earp-Colina-Epitaph interval needs further detailed study to resolve correlation issues.

P^{3}e **Earp Formation (Pennsylvanian to Permian)** — Very fine grained, calcareous and non-calcareous sandstone and siltstone; variable colors include pale greenish and tannish buff, grayish tan, and pale to medium reddish brown. Also includes thin to medium bedded limestone with partings along thin beds of silty carbonate and very fine grained sandstone. Some limestone contains sparse chert stringers 1-3 m thick. Several zones of terra rosa siltstone suggest multiple episodes of subaerial weathering (NE¼, SW¼, sec. 9, T. 16 S., R. 17 E.). A chert- or limestone-clast conglomerate marker horizon can commonly be located in the lower 1/3 of the formation. This marker consists of one or two conglomerate beds 1 to >3 m thick. Clasts are up to about 10 cm in diameter, and include angular to sub-angular chert fragments, or sub-angular to sub-rounded carbonate clasts. This marker bed is shown as a line on the map where it could be traced.

Along the contact of the Empire Mountains stock, the Earp Formation is converted into calc-silicate hornfels. The rock is very fine-grained, and tan to greenish gray colored. Veins of quartz, epidote, and calcite are common. Irregular 1-5 cm clots of fine-grained calcite marble are scattered in some beds. The calcite clots commonly have a oblate shape, with the flattening surfaces aligned in all clots to define a shape fabric. Bedding is locally preserved in laminated structure in the rock.

P^{3}eh **Earp Formation and Horquilla Limestone, undivided (Pennsylvanian to Permian)**

^{3}Ml **Escabrosa Limestone and Horquilla Limestone, undivided (Pennsylvanian and Mississippian)**

^{3}h **Horquilla Limestone (Pennsylvanian)** — Massive to thick-bedded generally medium gray limestone, with sparse cherty beds and sparse silty beds. Limestone color ranges from light and dark gray. Scattered chert nodules are ubiquitous, but rarely form more than about 25% of the rock. Nodular-weathering micritic carbonate beds are characteristic of the Horquilla in the map area. Map unit contains zones of brecciation with hematitic matrix, and sparse beds of reddish brown siltstone and very fine grained quartzose sandstone. Weathered surfaces commonly appear as packstone. Testing with acid indicates that at least some of this unit consists of limestone.

The base of Horquilla Limestone is placed at the top of the karst deposit horizon where it can be identified. In some areas the karst horizon is present, but too thin an discontinuous to map as a separate unit. Where the karst deposits are absent, the base of the Horquilla is mapped at the first argillaceous or silty carbonate bed in the gradation from massive to thick-bedded upper Escabrosa Limestone to marly, medium- to thick-bedded carbonates that are clearly Horquilla. The siliclastic component typically appears first in thin beds that form partings between the thick to massive limestone beds.

Along the contact of the Empire Mountains stock, the Horquilla is recrystallized to form a light to medium gray calcite marble. Silica in the rock has apparently been redistributed to form ribs that weather in relief on the outcrop surfaces. The ribs consist of aligned trains of flattened siliceous clots that are 1-2 cm thick and 2-5 cm long. The clots are oblate, and the flattening surfaces are aligned to define a shape fabric strongly oblique to the apparent bedding defined by the trains of clots.

Mek **Karst deposits (Mississippian?)** — These deposits consist of a 0.5 to 2 m thick zone of red-brown mudstone, siliceous mudstone, and fine-grained sandstone that form the matrix to irregular clasts of Escabrosa Limestone. Such deposits, produced by weathering of limestone, are known as “terra rosa”. Structure ranges from isolated limestone chunks in mudstone to a limestone framework with interstitial mudstone. Sparse beds of sandstone or pebble conglomerate are also present. This unit is discontinuous, and serves to separate the Escabrosa Limestone and Horquilla Formation where it can be identified.

Me **Escabrosa Limestone (Mississippian)** — Pale gray to medium gray, very finely crystalline limestone with chert nodules and sparse, solitary horn corals. Chert typically occurs as rounded ellipsoidal ‘bread-loaf’ nodules, locally up to 30 cm long aligned parallel to bedding. In contrast to moderate lithologic diversity of the Horquilla Limestone, the Escabrosa Limestone is fairly homogeneous. Bedding is occasionally visible defined by sedimentary laminations in calcarenite beds. Bedding partings are rare.

Dm **Martin Formation (Devonian)** — Pale gray to medium gray, massive micritic dolostone and limestone, locally with sparse chert nodules and stringers. Typically dolomitic, with rare clean quartzite beds up to several tens of cm thick.

°a **Abrigo Formation (Cambrian) —** Carbonate, siltstone, and sandstone of the Abrigo Shale. Upper part consists of tan to brown, sandy and silty, recrystallized limestone, and light to dark brown weathering, laminated carbonate with very fine grained quartz sand (sandy carbonate). Lower part of unit consists of calcareous and non-calcareous siltstone and fine-grained sandstone with sparse trace fossils. Locally includes medium and coarse quartz sand grains in sandy carbonate.

On the nose of a cliff (SE¼, NW¼, sec. 9, T. 16 S., R. 17 E.) the well exposed contact at the top of the Abrigo Shale is placed above a sandy carbonate unit consisting of numerous 3 to 30 cm thick, protruding quartzite and calcareous quartzite layers and gray, recess forming limestone. Overlying Martin Formation consists of 6-8 meter cliff of massive, orangish brown dolostone. Contact is sharp.

°b **Bolsa Quartzite (Cambrian)** — Fine- to coarse-grained, thin- to thick-bedded, resistant quartzite (>95% quartz) and feldspathic quartzite. Includes coarse, granule sandstone with local pebbles, and local thin beds (up to 1 cm thick) containing abundant quartz granules and 2-7 mm pebbles. Dark laminations rich in magnetite reveal cross bedding and are characteristic regionally of Cambrian Bolsa Quartzite in areas where Proterozoic diabase was exposed during initial Cambrian sedimentation. Commonly blocky weathering.

Hill top and east side of hill about 1.2 km southwest of Colossal Cave (Vail 7 ½' Quadrangle) consists of such pure quartzite, with very little mafics and generally too massive to see bedding, that it is possible that this is Proterozoic Dripping Spring Quartzite instead of Cambrian Bolsa Quartzite. This interpretation is not made on the map, however, because Dripping Spring Quartzite commonly contains significant K-feldspar which was not seen.

Proterozoic map units

Yd **Sierra Ancha diabase (Middle Proterozoic)** — Dark greenish gray diabase with acicular plagioclase laths up to 4 mm long and dark clinopyroxene(?).

Yp **Pioneer Formation, Apache Group (Middle Proterozoic) —** Variably silty quartzose sandstone and very fine grained silty sandstone and sandy siltstone. Unlike poorly to moderately well sorted sandstone in the Cambrian Bolsa Quartzite, Pioneer Formation sandstone is typically well sorted. Typically light to dark brown, medium gray, or reddish brown. Reduction spots, common in Pioneer Formation elsewhere in Arizona, were not seen. Quartzite near base consists of medium to fine grained, light gray orthoquartzite with 1-2% magnetite. Local magnetite rich laminations are present in the basal few meters. Diabase intrusions locally produced spotted hornfels in contact-metamorphosed silty rocks. Formal unit defined by Ransome (1919).

Basal conglomerate in the Pioneer Formation, known as the Scanlon Conglomerate, is represented by a 10 to 100 cm thick rubble zone rich in subangular fragments of vein quartz up to 10 cm diameter and deposited on weathered and discolored granitoids of map unit Xgd. Basal rubble zone is 2 meters thick in a channel cut into underlying granitoids (SW¼, NW¼, sec. 9, T. 16 S., R. 17 E.). Basal conglomerate here is reddish brown with 1-5 cm, angular, unsorted, white quartz fragments (vein quartz?) that are mostly matrix supported. Fifteen meters above base at this location, Pioneer Formation consists of dark gray, quartz-rich sandstone with 20 to 25% chloritized mafic grains (hornblende?).

South of Pistol Hill the basal 1-5 meters of the Pioneer Formation contains sparse to abundant 1-10 cm subangular fragments of vein quartz. Overlying sandstone is medium to fine grained quartzite and silty quartzite with no reduction spots (e.g., Wrucke, 1989). Near base sandstone is medium to coarse grained.

Early to Middle Proterozoic granitic rock units

Rincon Valley Granodiorite (Drewes, 1977; formally named after earlier designation as granodiorite of Rincon Valley by Drewes [1974]) is the name applied to an extensive granitoid unit exposed in and around the Rincon Mountains. Eight radiometric age determinations listed by Reynolds et al. (1986) for the Rincon Valley Granodiorite range from 1340 to 1570 Ma, with 5 of 8 dates ranging from 1390 to 1460 Ma (dates from Marvin et al. [1973] and Marvin and Cole [1978]). The eight dates were from four samples: Two from northwestern Saguaro East National Park (Marvin and Cole, 1978; locations plotted by Drewes, 1977), one from Rincon Valley about 2 km northeast of Colossal Cave (Marvin et al., 1973), and one from the Happy Valley area on the east side of the Rincon Mountains (Marvin et al., 1973). The two dates that are older than 1460 Ma have large uncertainties (1550 ± 60 Ma, K-Ar biotite; 1570 ± 100 Ma, K-Ar hornblende). Furthermore, these uncertainties are at the 1σ level, which means that the 95% confidence interval (2σ) is twice as large (Robert Fleck, USGS, written communication, 2001). Given the large uncertainty in the two older dates, and the clustering of the other ages around 1400 Ma, it seems likely that the Rincon Valley Granodiorite cooled through the argon closure temperature for biotite and muscovite at about 1400 Ma.

Mapping done as part of this report identified two granitoids in the area mapped as Rincon Valley Granodiorite by Drewes (1977): One is a porphyritic biotite granite, and the other is a medium grained, non-porphyritic granodiorite(?). The granodiorite resembles other 1.7 Ga rocks in southeastern Arizona, and we consider it likely that the granodiorite is early rather than middle Proterozoic. The porphyritic biotite granite is lithologically similar to 1.4 granites in southeastern Arizona, and we consider it likely that this granite is middle Proterozoic. Furthermore, intrusion of the middle(?) Proterozoic granite may be at least partly responsible for the middle Proterozoic radiometric ages derived from the granodiorite.

Yg **Porphyritic granite (Middle Proterozoic) —** Coarse-grained, equigranular to K-feldspar-porphyritic granite containing up to 10% biotite.

Xgd **Granodiorite (Early to Middle Proterozoic) —** Equigranular, medium to fine grained granite or granodiorite with biotite, hornblende(?), and secondary chlorite. Probably equivalent to Rincon Valley Granodiorite of Drewes (1977) but suspected to be early Proterozoic based on lithologic dissimilarity to 1.4 Ga granites in southeastern Arizona (see above).

Xp **Pinal Schist (Middle Proterozoic) —** Pale-gray to medium-gray schist and psammitic schist that is sufficiently metamorphosed that pelitic rocks have significant phyllosilicate development and cleavage parallel to preferred orientation of phyllosilicates. Phyllosilicates, locally visible in hand sample without the aid of a hand lens, impart a silvery sheen to the rock. Also, quartz veins and stringers are locally abundant, especially in pelitic rocks.

Rocks below the Catalina detachment fault of uncertain protolith age

f **Fault rocks (Proterozoic to Tertiary protolith with probable Mesozoic to Tertiary deformation) —** Altered and bleached granitoids along a fault zone. Fault zone locally hosts small copper deposits that are now represented by green copper minerals and prospect pits.

cs **Calc-silicate tectonite (probable Paleozoic protolith age with probable Mesozoic to Tertiary deformation)**

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