Surficial Geology and Geologic Hazards of the Tucson Mountains, Pima County, Arizona

Avra, Brown Mountain, Cat Mountain, and Jaynes Quadrangles

by

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Arizona Geological Survey
Open-File Report 99-22

December, 1999

Arizona Geological Survey
416 W. Congress, Tucson, AZ 85701

Includes 19 pages of text and two 1:24,000 scale geologic maps

Funded by the Arizona Geological Survey
and the U.S. Geological Survey STATEMAP Program
Contract #98HQAG2064

Introduction

This report and accompanying maps describe the surficial geology, geomorphology, and geologic hazards around the Tucson Mountains, on the western margin of the Tucson metropolitan area. The mapping covers the Avra, Brown Mountain, Cat Mountain, and Jaynes 7 1/2' quadrangles and includes part of the City of Tucson and unincorporated Pima County (Figure 1). The map area encompasses the western edge of the Tucson basin floor, the eastern half of Avra Valley, and the Tucson Mountain foothills on the eastern and northern flanks of the Tucson Mountains. The Tucson basin floor area has been thoroughly altered by urban development, and the Tucson Mountain foothills have undergone substantial development during the past 30 years or so. The steeper mountain slopes generally are within Tucson Mountain Park (Pima County) or the western unit of Saguaro National Park, but development is occurring immediately adjacent to these parks. This report is intended to enhance our understanding of the surficial geology around the Tucson Mountains and to aid in assessing and understanding geologic hazards in this area. This new mapping complements previously published bedrock mapping (Lipman, 1993).

This surficial geologic mapping in the western portion of the Tucson area is part of continuing efforts by the AZGS to map the geology of the Phoenix – Tucson urban corridor. It builds on and complements previous surficial geologic mapping efforts in the Tucson area (McKittrick, 1988; Jackson, 1989; Demsey and others, 1993; Field and Pearthree, 1993). The report is organized into a brief introduction and explanation of mapping methods, unit descriptions, a summary of the geologic and geomorphic framework of the area, and a discussion of geologic hazards. Tim Orr digitized the map information, generated the final linework and map layout, and provided quality control for the map compilation. Pete Corrao assisted with map and report layout. Mapping was conducted as part of the STATEMAP Program of the U.S. Geological Survey, contract #98HQAG2064.

Climate. Several weather stations close to the Tucson Mountains, including a number in nearby Tucson, Arizona, have operated during intervals over the past century. The station at the University of Arizona in the central Tucson basin has records from 1894 to the present, whereas stations to the northwest of the mountains at Silver Bell (1906-1974) and Red Rock (1893-1973) provide data for the Avra Valley area. Using the records of seven stations, the average recorded daily maximum temperature was 83.9° F, and the average daily minimum was 54.0° F (Western Regional Climate Center, 1999). Average annual precipitation for the area is about 12", with slightly more than 50% falling during the July through September monsoon thunderstorm season and about 35% occurring as winter precipitation. Freezing temperatures are common during most winters, but snow is uncommon and not persistent. 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. Winter precipitation generally is caused by cyclonic storms originating in the Pacific. It is

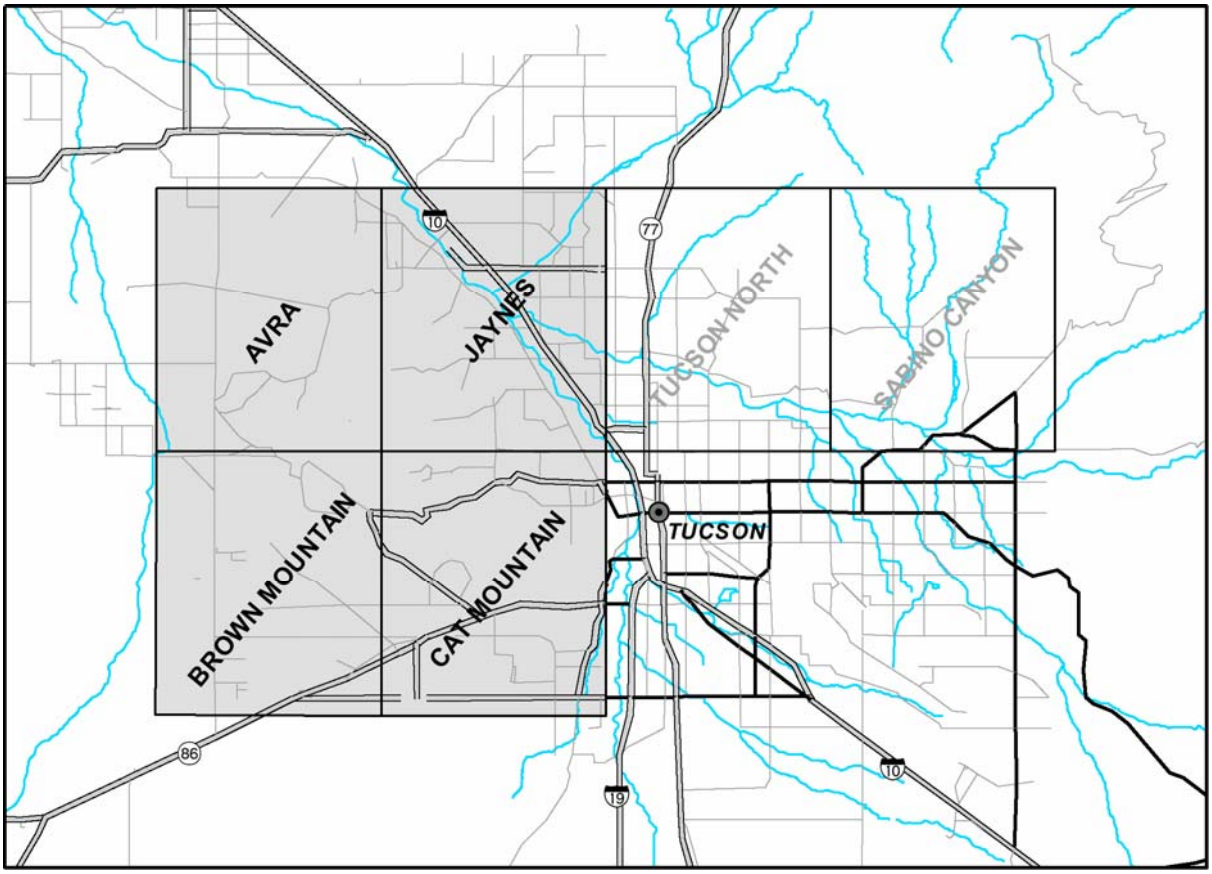

Figure 1. Location of the four quadrangles covered by this report, on the west side of the Tucson basin. The surficial geology of the adjacent two quadrangles to the northeast is summarized in Arizona Geological Survey Open-File Report 99-21 (Klawon and others, 1999).

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).

Methodology

The surficial geology of the project area was mapped using several sets of aerial photographs and soil survey maps, with extensive field mapping and observations of soils and stratigraphy. The Avra Valley and Tucson Mountains foothills areas were mapped primarily using 1:12,000 black-and-white aerial photos provided by the Pima County Flood Control District, which were flown in the late 1970's. The aerial photos predate much of the development in the foothills, which facilitated reconnaissance mapping of areas that have been obscured by intense development in the past 20 years. Surficial geologic relationships in the foothills were extensively field checked utilizing the extensive network of roads that lace the area. Mapping of the western fringe of the Tucson basin floor was modified from Smith (1938) and McKittrick (1988), with limited field checking.

The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, stream terraces) 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 coarse 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 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 1 to 10 m 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 on piedmonts) 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 Katzer and Schuster (1984), Jackson (1989), Demsey and others (1993) and Klawon and others (1999). These correlations were also used to estimate the ages of surficial deposits in the map area.

Map Unit Descriptions

Piedmont Alluvium

Quaternary and late Tertiary deposits cover the virtually all of the piedmont areas around the Tucson Mountains. This sediment was deposited primarily by larger streams that head in the mountains; smaller streams that head on the piedmont have eroded and reworked some of these deposits. Deposits range in age from modern to early Pleistocene or Pliocene. The lower margin of the piedmonts are defined by their intersection with stream terraces of the Santa Cruz River on the eastern and northern sides of the map area and the basin-floor deposits of Brawley Wash and Black Wash on the western and southern sides of 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.

Qy2 - Late Holocene alluvium (<2 ka). Unit Qy2 consists of channels, low terraces, and small alluvial fans composed of cobbles, sand, silt and boulders that have been recently deposited by modern drainages. In areas proximal to the mountain front, channel sediment is generally sand, pebbles and cobbles, with some boulders; terraces typically are mantled with sand and finer sediment. On lower piedmont areas, young deposits consist predominantly of sand and silt, and some cobbles in channels. Channels generally are incised less than 1 m below adjacent terraces and fans, but locally incision may be as much as 2 m. Channel morphologies generally consist of a single-thread high flow channel or multi-threaded low flow channels with gravel bars adjacent to low flow channels. Downstream-branching distributary channel patterns are associated with the few young 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. 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. See Table 1 for correlations between units defined in this report and those of Katzer and Schuster (1984) and McKittrick (1988).

Qy1 - Holocene alluvium (0 to 10 ka). Unit Qy1 consists of low terraces found at scattered locations along drainages throughout the Tucson Mountain foothills and broad, minimally dissected alluvial fans on the west side of the Tucson Mountains. Qy1 surfaces are slightly higher and less subject to inundation than adjacent Qy2

surfaces. Surfaces are generally planar; local relief may be up to 1 m where gravel bars are present, but typically is much less. Qy1 surfaces are less than 2 m above adjacent active channels. Surfaces typically are sandy but locally have fine, unvarnished open gravel lags. Qy1 surfaces generally appear fairly dark on aerial photos, but where a gravel lag is present, surfaces are light colored. Channel patterns on alluvial fans are weakly integrated distributary (branching downstream) systems. Qy1 terrace surfaces support mesquite and palo verde trees, and smaller bushes may be quite dense. Qy1 fans support scattered trees along channels, but creosote and other small bushes are dominant. Qy1 soils typically are weakly developed, with some soil structure but little clay and stage I to II calcium carbonate accumulation (see Machette, 1985, for description of stages of calcium carbonate accumulation in soils).

Qy – undifferentiated Holocene alluvium (0 to 10 ka)

Qc – Holocene and Pleistocene hillslope colluvium. Unit Qc consists of locally-derived deposits on moderately steep hillslopes in the Tucson Mountains. Colluvium is very extensive in the mountains, but is mapped only where sufficiently thick and extensive as to obscure underlying bedrock (derived from Lippman, 1993). 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.

Ql - Late Pleistocene alluvium (10 to 130 ka). Unit Ql consists of moderately dissected relict alluvial fans and terraces found on the upper, middle and lower piedmont. Well-developed, moderately incised tributary drainage networks are typical on Ql surfaces. Active channels are incised up to about 2 m below Ql surfaces, with incision typically increasing toward the mountain front. Ql fans and terraces are commonly lower in elevation than adjacent Qm and older surfaces, but the lower margins of Ql deposits lap out onto more dissected Qm surfaces in some places. Ql deposits consist of pebbles, cobbles, and finer-grained sediment. Ql surfaces commonly have loose, open lags of pebbles and cobbles; surface clasts exhibit weak rock varnish. Ql surfaces appear light orange on aerial photos, reflecting slight reddening of surface clasts and the surface soil horizon. Ql soils are moderately developed, with orange to reddish brown clay loam argillic horizons and stage II calcium carbonate accumulation. Dominant forms of vegetation include creosote, bursage, and ocotillo.

Qm - Middle Pleistocene alluvium (130 to 500 ka). Unit Qm consists of moderately dissected relict alluvial fans and terraces with strong soil development found throughout the foothills. Qm surfaces are drained by well-developed, moderately incised tributary channel networks; channels are typically several meters below adjacent Qm surfaces. Well-preserved, planar Qm surfaces are smooth with pebble

and cobble lags; rock varnish on surface clasts is typically orange or dark brown. More eroded, rounded Qm surfaces are characterized by loose cobble lags with moderate to strong varnish, broad ridge-like topography and carbonate litter on the surface. Qm surfaces have a distinctive dark color on aerial photos, reflecting reddening of the surface soil and surface clasts. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular blocky structure. Soil carbonate development is typically stage III to IV, but strongly indurated petrocalcic are uncommon. Qm surfaces generally support bursage, ocotillo, creosote, cholla, and saguaro.

Qml – undifferentiated middle and late Pleistocene alluvium (10 to 500 ka)

Qmo - Middle to early Pleistocene alluvium (500 ka to 2 Ma). Unit Qmo consists of moderately to deeply dissected relict alluvial fans with variable soil development. Qmo surfaces are typically 5 to 10 meters above adjacent active channels. Qmo surfaces are drained by well-developed, deeply incised tributary channel networks. Well-preserved planar Qmo 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 or black. Well-preserved soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular blocky structure. Soil carbonate development is typically stage IV (cemented petrocalcic horizons, little or no laminar cap). More eroded Qmo surfaces are characterized by loose cobble lags with moderate to strong varnish, ridge-like topography and carbonate litter on the surface. On aerial photos, ridge crests on Qmo surfaces are dark, reflecting reddening of the surface soil and surface clasts, and eroded slopes are gray to white. Qmo surfaces generally support bursage, ocotillo, creosote, cholla, and saguaro.

Qo – Early Pleistocene alluvium (1 to 2 Ma). Unit Qo consists of very old, high, dissected alluvial fan remnants with moderately well preserved fan surfaces and strong soil development. Qo deposits and fan surfaces are found in a few locations near mountain fronts on both sides of the range. Qo surfaces typically are fairly smooth to broadly rounded and light-colored as a result of abundant litter from underlying petrocalcic horizons. Qo deposits consist of cobbles, boulders, and sand and finer clasts. Stage V petrocalcic horizons are typical, but clay-rich argillic horizons are poorly preserved or have been stripped away completely by erosion. Qo surfaces are dominated by creosote. Qo surfaces record the highest levels of aggradation in the Tucson basin and Avra Valley, and may be correlative with other high, remnant surfaces found at various locations throughout southern Arizona (Menges and McFadden, 1981).

QT - Early Pleistocene to Pliocene alluvium (1 to 5 Ma). Unit QT consists of very old, deeply dissected and highly eroded alluvial fan deposits mainly found in the Tucson Mountain foothills. QT surfaces are alternating eroded ridges and deep valleys, with ridgecrests typically 10 to 30 meters above adjacent active channels. The thickness of QT deposits is not known. They are drained by deeply incised tributary channel networks. Even the highest surfaces atop QT ridges are rounded, and original highest

capping fan surfaces are not preserved. QT deposits are dominated by gravel ranging from boulders to pebbles. Deposits are moderately indurated quite resistant to erosion because of the large clast size and carbonate cementation. Soils typically are dominated by carbonate accumulation, which is typically stage V (cemented petrocalcic horizons with laminar cap) on ridgecrests. Carbonate litter is common on ridgecrests and hillslopes. On aerial photos, QT surfaces are gray to white. QT surfaces generally support creosote, with lesser amounts of mesquite, palo verde, ocotillo, cholla, and saguaro.

Axial Stream Deposits

Sediment deposited by the Santa Cruz River and Rillito Creek cover the eastern part of the map area, and deposits of Brawley Wash and Black Wash cover the southwestern part of the map area. Surfaces consist of channels, young stream terraces that compose the geologic floodplain, and several older relict terraces that date to the Pleistocene. Deposits are a mix of gravel and sand and finer material; they exhibit mixed lithologies reflecting the large drainage areas of these streams. Most of the area covered by river deposits in the Tucson basin has been altered by intense urban develop, so there is greater uncertainty regarding the locations of unit contacts than in piedmont areas.

Qycr - Modern river channel deposits (< 100 years). This unit consists of river channel deposits of the Santa Cruz River, Rillito Creek, and Brawley Wash. They are composed primarily of sand and gravel. Along the Santa Cruz River and Rillito 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 (Betancourt, 1990; Wood and others, 1999). Historically, channels had variable widths and or were braided, but modern channels in much of the map area are relatively uniform within artificially stabilized banks. Channels are extremely flood prone and are subject to deep, high velocity in moderate to large flow events. Channel banks along Rillito Creek have been stabilized by soil cement, and the channel will convey the calculated 100-year flood without overtopping. Banks along some portions of the Santa Cruz River have been protected with soil cement, but other reaches are unprotected and are subject to several lateral erosion during floods.

Qyr - Holocene floodplain and terrace deposits (<10 ka). The Qyr unit consists of floodplains and low terraces flanking the main channel system along the Santa Cruz River and Rillito Creek. It also includes areas in the Brawley Wash floodplain where surfaces have been obscured by agricultural activity. Most Qyr areas along the Santa Cruz River and Rillito Creek were part of the active floodplain prior to arroyo development in the past century or so. Terrace surfaces are flat and uneroded, except immediately adjacent to channels. Qyr deposits consist of weakly to unconsolidated sand, silt, and clay. Stratigraphic investigations of Qyr deposits indicate that several

sequences of arroyo development and filling have occurred in the past 5,000 years (Haynes and Huckell, 1986; Freeman, 1997). Qyr deposits contain archaeological features ranging in age from Middle Archaic to historical (summarized in Freeman, 1997). Soils are weakly developed, with some carbonate filaments and fine masses and weak soil structure in near surface horizons. Locally, Qyr surfaces may experience sheetflooding during large floods in areas where the main channel is not deeply entrenched, and as a result of flooding on local tributaries that debouch onto Qyr surfaces. Unprotected channel banks formed in Qyr deposits are very susceptible to lateral erosion.

Qy2r – Late Holocene channel and proximal floodplain deposits of Brawley Wash and Black Wash. Deposits in stream channels and on primary floodplains of these major washes. Deposits generally consist of sand, silt, and clay, with local gravel concentrations. Shallow, small, discontinuous channels are common; many of them are linear, suggesting that channels developed along roads or wagon tracks. Vegetation typically is large creosote and low grass and shrubs, with local concentrations of mesquite, acacia, and palo verde trees. Variegated surface color depends mainly on vegetation density, dark brown color along channels and where vegetated, brown where more sparsely vegetated. Eolian features around bushes commonly have been streamlined by flow.

Qy1r – Holocene distal floodplain deposits of Brawley Wash and Black Wash. Deposits associated with upper or secondary floodplains of these major washes. Typically, they are flat surfaces that are on the fringes of and less than 1 m above the primary floodplain, but small, poorly defined channels exist in some places within this unit. Deposits are generally fine-grained, but surfaces have weak, discontinuous gravel lags composed of mixed lithologies. Surface color typically is light brown, and surface clasts have no varnish. Very limited low (0.5 m high) coppice dunes associated with creosote bushes and bioturbated sand and finer sediment. Portions of these surfaces are inundated in the largest floods. They gradually merge upslope into young lowermost piedmont deposits (units Qy2 and Qy1).

Qlr - Late Pleistocene river terrace deposits (10 to 130 ka). Unit Qlr consists of late Pleistocene river terraces that are 1 to 3 m higher than the historical floodplain. Deposits consist of gravel, sand, and clay. Soils are somewhat reddened, have weak argillic horizons, and have moderate calcic horizon development. These terraces are generally narrow and have fairly irregular surfaces, implying that they have undergone substantial erosional modification. Qlr terraces were named the Jaynes terrace by Smith (1938) and Pashley (1966), and T3 by McKittrick (1988). Qlr deposits are probably inset into and banked against older Qmr deposits. Haynes and Huckell (1986) reported a radiocarbon date of 18 ka from carbonate in a Qlr soil, which is likely a minimum age for the Jaynes terrace.

Qmr - Middle Pleistocene river terrace deposits (~130 to 500 ka). Unit Qmr consists of middle Pleistocene river terraces that cover much of the floor of the northern Tucson basin. Qmr terraces are typically ~2 m higher than adjacent Qlr terraces.

Deposits consist of gravel, sand, silt and clay. Soils and reddened and have moderate to strong, clay-rich argillic horizons. Calcic horizon development is quite variable, but locally is as strong as stage IV (cemented). Terraces are quite broad and terraces surfaces are quite flat away from drainage and terrace margins. Qmr terraces were labeled the Cemetery terrace by Smith (1938) and Pashley (1966), and T4 by McKittrick (1988). Based on the strong soil development associated with Qmr terraces, they are likely of middle Pleistocene age.

Miscellaneous units and symbols

R – undifferentiated bedrock

d – Disturbed. Areas that have been so profoundly disturbed by human activity as to completely obscure the preexisting natural surface. Much of the area within these quadrangles had been substantially disturbed by development. This unit label is used only in areas where there was no chance of evaluating the nature of the surface on the aerial photographs used in this study, which date to 1977.

Table 1. Approximate correlation of map units used in this report with the Quaternary/Tertiary map units used by Katzer and Schuster (1984) and McKittrick (1988).

Unit (this report)	McKittrick (1988)	Katzer and Schuster (1984)
Qy2	ch	Q4, Q2b
Qy1	Y	Q2a, Q2b
Qycr	cha	Q4
Qyr	T1, T2	Q3
Ql	M2	Q1c
Qlr	T3	Q1d
Qm	M1	Q1b
Qmr	T4	
Qmo	O	Q1a
Qo	O, QTbf	Q1a
QT	QTbf	Q1a

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 of the Basin and Range. 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. The axial portions of valleys are typically occupied by unentrenched drainages with very broad floodplains. In stark contrast, the eastern and northern 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. Intervals of aggradation have punctuated the long-term trend toward downcutting along the major streams and their tributaries.

The highest levels of basin-fill deposits (unit QT or Qo) in the Tucson Mountain foothills may have been graded approximately to the highest levels of basin-fill deposits in the central Tucson basin. 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). It is likely that in the late Pliocene to early Quaternary, the surfaces of the Catalina and Tucson Mountain foothills were fairly planar, undissected piedmonts that graded downslope to the floodplains of the through-flowing ancestral Santa Cruz river system.

During the past two million years, the Santa Cruz River and its tributaries have downcut substantially into the Tertiary deposits of the Tucson Mountain foothills. The high ridges and deep valleys characteristic of parts of the foothills attest to the amount of stream erosion that has occurred since the highest levels of alluvium were deposited. Several broad terraces in the Tucson basin that record progressively lower positions of the Santa Cruz River and Rillito Creek also record long-term downcutting. These episodes of downcutting caused erosion of the toes of alluvial fans in the Tucson Mountain foothills, and resulted in much of the stream downcutting in the foothills. Streams that head in the Tucson Mountains flow through the foothills and eventually join the Santa Cruz River. The lower ends of these streams are linked with Santa Cruz River, so if the Santa Cruz downcuts, the slopes of its tributary stream channels steepen and they tend to downcut as well. The ultimate cause of the Santa Cruz River downcutting is not certain, but it is probably a delayed response of the integration of the Tucson basin streams into the larger regional drainage system.

The geomorphology and surficial geology on the west side of the Tucson Mountains is quite different from the Tucson Mountain foothills. Streams that drain the west side of the range are linked to Brawley Wash, a major tributary of the Santa Cruz River that flows north through Avra Valley. Brawley Wash is similar to many streams in

southwestern and south-central Arizona in that it flows through a broad, undissected Holocene floodplain in the middle of the valley. Evidently, Brawley Wash has generally been aggrading through the Quaternary, so there has been slow base-level rise over that period. Because of this factor, dissection on the western piedmonts of the Tucson Mountains is far less than on the eastern side of the range. The topographic front of the mountain range is deeply eroded and embayed, and small to medium bedrock hills extend far out onto the piedmont. A shallow bedrock pediment underlies all of the upper piedmont and much of the middle piedmont as well. Some older alluvial fan deposits near the western mountain front have been entrenched quite deeply, but the entrenchment on the middle and lower piedmont slopes is minimal and young alluvial fans cover much of this area.

Broad alluvial fans and terraces are evidence for periods of aggradation (net sediment accumulation) that were superimposed on the long-term downcutting trend. We are not certain what caused these aggradation events, but changes in climate that increased the amount of sediment supplied to streams are likely culprits. The global climate has changed between glacial and interglacial conditions many times during the past two million years. Glaciers did not directly affect the Tucson basin, but the glacial climate here was wetter and cooler than present, the vegetation was different, and there was more water in streams. Streams draining the Catalina Mountains and the Tucson basin transported more and larger bed material than modern streams. The most recent change from glacial to interglacial climate, which occurred about 8,000 to 15,000 years ago, may be an example of many such changes that occurred in the past 2 million years or so. Decreases in vegetation on hillslopes due to increased aridity, coupled with an increase in intense thunderstorms associated with our hot summer monsoon season, resulted in removal of much sediment from hillslopes. This increase in erosion in turn triggered widespread stream aggradation during this time in southern and western Arizona (Bull, 1991).

Geologic Hazards

This section summarizes the character and distribution of the principal geologic hazards that exist in and around the Tucson Mountains. 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 (unincorporated areas) and the City of Tucson Floodplain Management Section.

***Flood hazards*.** Hazards related to flooding in the Tucson area may be subdivided into three categories. Along the large streams with well defined channels (the Santa Cruz River and Rillito Creek), flood hazards consist mainly of lateral erosion of unprotected channel banks. Along the smaller regional drainages with multiple, discontinuous channels (Brawley and Black washes in Avra Valley), inundation during large floods may be very widespread. The most widespread flood hazards are those associated with

smaller tributary drainages, where the extent of flood-prone area varies with the size of the stream and local topographic confinement of floodwater.

The largest floods on the Santa Cruz and Rillito drainages have resulted from regional storms in the winter and late summer - early fall, but summer storms have generated fairly large floods as well. Large floods in the historical record on the Santa Cruz occurred in 1914, 1916, 1977, 1978, 1983, and 1993. At the Congress Street crossing near downtown Tucson, the 53,000 cubic feet per second (cfs) discharge in October 1983 is the peak of record (Webb and Betancourt, 1992). The channels of these drainages are entrenched several meters below the historical floodplain in most places. In the middle and late 1900's, almost all floodwater has been contained within the channel banks and the primary flood hazard along these drainages has been lateral bank erosion. Lateral bank erosion has been a far greater hazard, with hundreds of feet of erosion occurring during several floods (Pearthree and Baker, 1987; Parker, 1995). The banks of Rillito Creek have been stabilized with soil cement, and the channel is designed to contain the 100-year flood. Portions of the Santa Cruz channel banks have been similarly stabilized, but the potential for serious bank erosion exists along extensive, unprotected banks formed in weakly consolidated Qyr deposits.

Brawley Wash is a regional drainage with a broad, intermittently entrenched floodplain. It experienced its largest historical flood in September, 1962, when much of the axial part of Avra Valley was inundated as a result of precipitation derived from dissipating tropical storm Claudia. In central Avra Valley, just west of the map area, the peak discharge estimated for this flood was 38,800 cfs (Lewis, 1963; 1968). This is about twice as large as any other flood recorded since 1940 (Pope and others, 1998), and was probably the largest flood that has occurred on Brawley Wash since at least 1885 (Roeske and others, 1989). Brawley Wash also experienced large floods in 1970, 1983, and 1993, each of which occurred in the late summer or early autumn. There have been substantial alterations of channel patterns for agricultural purposes in the Brawley Wash floodplain, and arroyos have developed locally in the western part of the Brown Mountain and Avra quadrangles. Nonetheless, all of the areas mapped as Qy2r are probably flood prone, and areas mapped as Qy1r or Qyr may be inundated in extreme floods (see Roeske, 1978). Black Wash, a major tributary of Brawley Wash that crosses the southern part of the map area, has multiple small channels and a broad, unentrenched floodplain that is inundated in large floods. Although development in this floodplain is now discouraged or prohibited, many homes along Black Wash are located in flood-prone areas.

Smaller tributaries that drain the mountain ranges, the piedmonts, and the basin floor are subject to flash floods. Floods on these drainages result from intense, localized thunderstorms that usually 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 restricted 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 Qy2 and Qy1). Active alluvial fans may exist in areas with 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 Tucson Mountain foothills are topographically confined, tributary networks. Along these drainages, flood hazards are restricted to active channels and adjacent low, young terraces (unit Qy2). Portions of the slightly older and higher terraces that are mapped as unit Qy1 may be subject to rare inundation in extreme floods. There are a few distributary drainage systems in the Tucson Mountain foothills, but channels are generally entrenched into much older deposits and thus these systems are not active alluvial fans. Unconfined flow during floods also occurs along the margin of the Santa Cruz floodplain, where tributaries debouch from the topographically confined foothills onto the Qyr terrace. On the southern and western sides of the Tucson Mountains, drainages in the upper piedmonts are topographically confined and flood hazards are of limited extent. Farther downslope, however, most drainages have unconfined reaches that are subject to broad sheetflooding and possibly alluvial-fan flooding. Flood hazards are greatest at the upslope end of these areas, at the transition from confined to unconfined flow, because of fairly deep flow, high flow velocities, and the potential for significant changes in channel position during floods.

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 expansive soils and collapsing soils. 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.

Soils with the potential to collapse or compact are found in the floodplains and young terraces of the Santa Cruz River, Rillito Creek, and Brawley and Black washes (map unit Qyr) (Anderson, 1968). Compaction problems are also associated with soils of the Cemetery Terrace (map unit Qmr) (Platt, 1963; Abdullatif, 1969; Crossley, 1969). These soils are characterized by low moisture content (less than 15%), porosity >40%, and low bulk density. In these soils, the particles are loosely-packed and have never been subjected to loading. The clay in these soils supports the framework of randomly-oriented larger soil grains. Upon wetting, the clay loses its cohesive strength, resulting in the displacement of the soil particles to a more densely-packed configuration. Soils with compaction potential may be treated by application of large amounts of water, followed by several weeks or months to allow settling to occur before construction on the site. A

large weight, called a pre-load, can also be applied to fully compact the soil before building.

Potential soil problems in middle and upper piedmont areas consist of shrink-swell potential, low infiltration rates, and hard substrate. Shrink-swell problems may exist on clay-rich soils of unit Qm and Qmo, although the gravel that is common in these deposits may minimize these problems. Excavation may be difficult and near-surface infiltration rates low on the oldest piedmont units (Qmo, Qo, and QT) due to the existence of carbonate- and silica-cemented hardpans (petrocalcic and duric horizons). Any some upper piedmont areas, cemented horizons related to old surficial units exist in the shallow subsurface but are mantled by young deposits. In these situations, less resistant upper horizons of old soils was removed by erosion, and subsequently much younger sediment was deposited over the cemented horizons. Similar 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.

Debris flows and rockfalls. Debris flows and rockfalls are potential hazards in and immediately adjacent to the steepest slopes of the Tucson Mountains. Many fresh debris-flow scars exist on steep slopes of the Tucson Mountains. Based on observations of the first author during the past 20 years, most of the recent debris flows have occurred as a result of intense summer precipitation events. They began as landslides on very steep mountain hillsides that continued a short distance downslope as debris flows following stream channels. They stopped in areas where topographic confinement or channel slope decreased. All of the recent debris flows remained in the mountains, and none came close to the piedmont. There is no evidence of debris-flow activity in the young deposits mapped farther out on the piedmont.

Rockfalls are a potential hazard below bedrock cliffs and where bedrock outcrops exist at or near the top of steep mountain hillslopes. In these situations, large rocks that are loosened by weathering may cascade violently downhill. Homes built on the lower slopes of the mountains and immediately adjacent to the mountains may be at some risk from rockfalls, and the existence of large boulders near the base of a steep slope should be considered evidence of potential rockfall hazard in most cases. In the Tucson Mountains, rockfall hazards are highest on and near steep colluvial slopes below bedrock cliffs on the southwest flank of the range. An example of this is the south side of Cat Mountain, where a resistant rhyolite unit forms a cliff that looms over a steep colluvial slope (Figure 2). Numerous boulders on and near the base of the slope are evidence of past rockfalls.

Land subsidence and earth fissures. In the Tucson area, agricultural development and population increases have resulted in the heavy use of groundwater resources. Because groundwater recharge in the area is limited, groundwater levels have been lowered by up several hundred feet in parts of the Tucson area. Earth fissures have developed in Avra Valley, and recent measurements have indicated that the surface of the central part of the Tucson basin (south of the map area) has begun to subside.

Withdrawal of groundwater at rates faster than natural recharge leads to declines in water tables. Water levels in parts of Tucson’s central well field had declined by more than 150 feet by 1981 (Anderson, 1988) and are continuing to decline. Water levels have

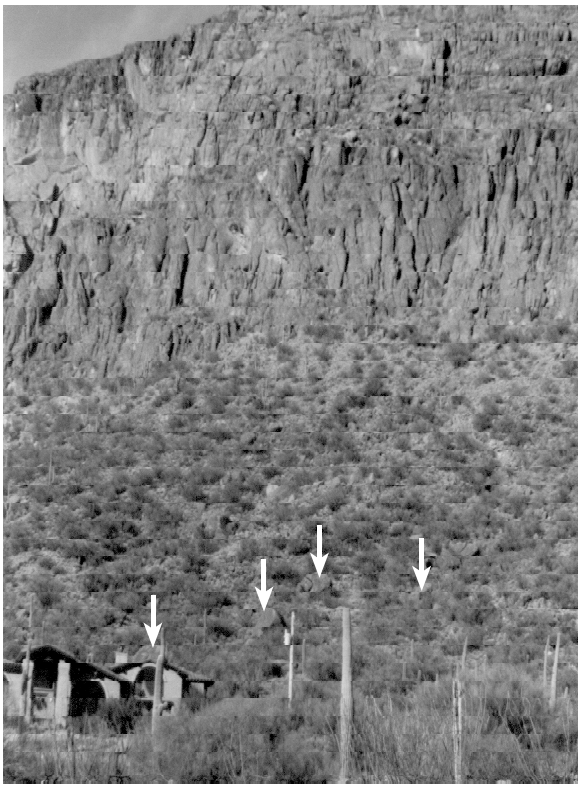

Figure 2. Rockfalls on southwest side of Cat Mountain in the southern Tucson Mountains. White arrows point to boulders on the lower part of the colluvial slope on Cat Mountain. The boulders have fallen from the upper face of Cat Mountain and rolled down the slope. Most of the hillslope is in Tucson Mountain Park and will not be developed, but some development has occurred along the lowermost fringe of the rockfall area. Upper photograph is by John Vuich or Wes Peirce, circa 1975.

declined by 50 to 150 ft in most of Avra Valley, but levels may not be declining in that area at present (Anderson, 1989). Dewatering of sediments causes compaction, which in turn results in lowering of the land surface. In every Arizona groundwater basin where groundwater overdraft has occurred, subsidence has followed. Land subsidence is as much as 15.4 feet near Eloy (Slaff, 1993) and 18 feet west of Phoenix (Schumann, 1992). In the Tucson basin, subsidence was detected in re-leveling surveys in 1952 (Platt, 1963), but maximum total subsidence was only about 0.5 feet by 1980 (Anderson, 1988).

Recent surveys have indicated continuing subsidence as water levels decline under Tucson. Hatch (1991) measured an average subsidence rate of 1 cm per year over the Tucson basin from 1987 to 1991. Based on the amount and rate of past subsidence, parts of the Tucson basin can expect subsidence of more than 10 feet by the year 2030 (Anderson, 1988). In Avra Valley, 10 ft or more of subsidence is possible in the northern part of the basin if water levels continue to decline (Anderson, 1989). Measurements in in the Tucson basin suggested that the rate of subsidence had increased markedly since 1980. Confirmation of the increased rate of subsidence is provided by a preliminary survey of subsidence using satellite-based synthetic aperture radar interferometry. Using SAR interferometry, a British company measured 9 cm of subsidence over a 3 year, 9 month period, ending in March, 1997, yielding a rate of 2.4 cm/yr (Ren Capes, NPA Group, personal communication).

In Arizona basins where subsidence is more than a few feet, earth fissures have developed. A fissure developed in northern Avra Valley east of Marana High School adjacent to the Central Arizona Project aqueduct (Arizona Geological Survey, 1988). It was quickly filled and surface water was diverted from it, and it has not reopened. The Tucson basin is the only one of Arizona's deep groundwater basins where groundwater level declines and land subsidence have not yet been followed by earth fissures, probably because the amount of total subsidence has thus far been relatively small compared to other basins. With the expected lowering of water tables and subsequent predicted land subsidence, earth fissures will most certainly develop in Tucson as they have elsewhere.

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