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

Tucson North and Sabino Canyon Quadrangles

by

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Introduction

This report and accompanying maps describe the surficial geology, geomorphology, and geologic hazards of the northern Tucson metropolitan area. The mapping covers the Tucson North and Sabino Canyon 7 1/2' quadrangles and includes portions of the City of Tucson and unincorporated Pima County (Figure 1). The map area encompasses the northern part of the basin floor, the southern flank of the Santa Catalina Mountains, and the dissected piedmont between them known as the Catalina foothills. Basin floor areas have been thoroughly altered by urban development, and the Catalina foothills have undergone substantial development during the past 30 years or so. The mountains generally are within the Coronado National Forest and are not developed, but some homes have been built on the lower flanks of the mountains up to the forest boundary. This report is intended to enhance our understanding of the recent geologic development of the northern Tucson metropolitan area and to aid in assessing and understanding geologic hazards in this area.

This surficial geologic mapping is part of continuing efforts by the AZGS to map the geology of the Phoenix – Tucson urban corridor, and it complements previous mapping efforts in the Tucson area (McKittrick, 1988; Jackson, 1989; Demsey and others, 1993; Field and Pearthree, 1993). We have incorporated recent mapping and description of the geologic framework of the Catalina foothills (Dickinson, 1999) into this map. 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.

Acknowledgments. Several people contributed to the development of this map and report. Klawon mapped and described the Quaternary surficial geology, with a few minor revisions by Pearthree. She is the primary author for most of the text of this report. Dickinson mapped, described and interpreted the Tertiary geology of the Catalina foothills. He collected all of the structural information depicted on the map. Pearthree compiled the mapping and wrote the section on geologic hazards, with contributions of information and text by Ray Harris. Ed McCollough has pointed out many of the geologic hazards summarized in this report during field trips over the past few decades. 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 #1434-HQ-97-AG-0182.

Climate. The climate of the map area is hot and dry, with extreme seasonal temperature variations and two distinct seasons of rainfall. The average July high temperature at the Tucson International Airport (elevation 2580 feet above sea level) is 100° F, and the average January low temperature is 39° F. Average annual precipitation at the airport is 12 in., and is probably somewhat greater in the foothills due to the orographic effect of the adjacent mountains. Freezing temperatures are common during most winters, but snow is uncommon and not persistent. Slightly more than ½ of the annual precipitation falls during the summer monsoon season (Western Regional Climate Center, 1999). 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 may occur in this region as a result of

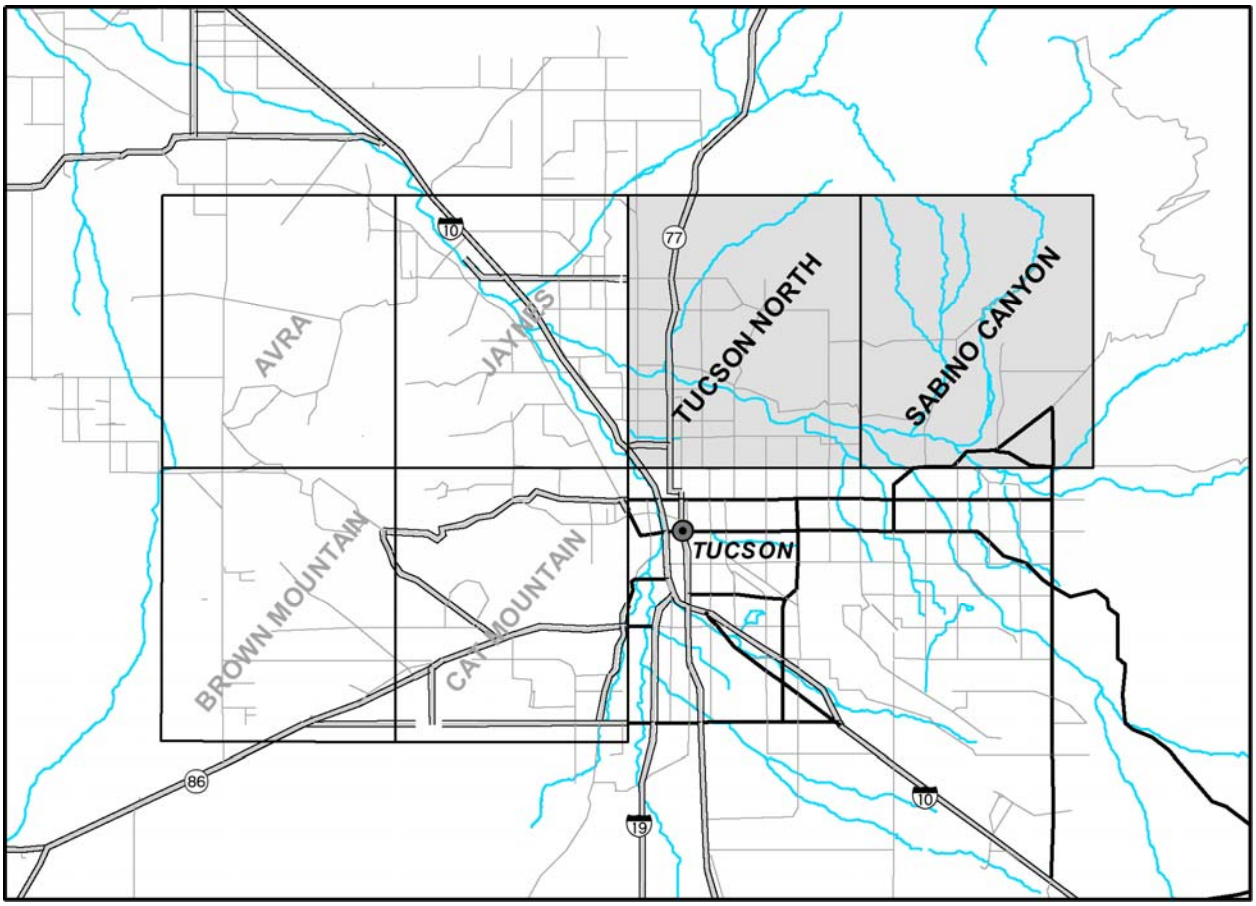


Figure 1. Location of the area covered by this map and report, on the north side of the Tucson basin. The surficial geology of the adjacent four quadrangles to the west and southwest is summarized in Arizona Geological Survey Open-File Report 99-22 (Pearthree and Biggs, 1999).

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 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 field mapping and observations of soils and stratigraphy. The Catalina foothills area was mapped primarily using 1:24,000 color aerial photos from the U.S. Forest Service, which were flown in 1977. The aerial photos predate much of the development in the foothills, which facilitated reconnaissance mapping of areas that have subsequently been obscured by intense development in the past 20 years. Jeanne Klawon mapped and field-checked the surficial geology in the foothills utilizing the extensive network of roads that lace the area, with assistance from Phil Pearthree and Tom Biggs. Bill Dickinson mapped the middle Tertiary to early Quaternary deposits of the Catalina foothills, and he is responsible for all of the strikes and dips and most of the fault locations depicted on the map. Pearthree compiled the surficial geologic mapping and integrated it with Dickinson’s (1999) mapping of Quaternary-Tertiary and older units. Mapping of the urbanized river terraces was modified by Pearthree 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. Terraces and alluvial fans that are less than a few thousand years old still retain clear evidence of the original depositional topography, such as 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, have little soil development, and 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).

On this map, Quaternary surficial deposits are subdivided based on their source (through-going rivers 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. These descriptions can be found in Appendix A at the end of the report. 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), Demsey and others (1993) and Pearthree and Biggs (1999). These correlations were also used to estimate the ages of surficial deposits in the map area.

Tertiary and Quaternary to Tertiary deposits of the Catalina foothills were mapped by Dickinson (1999). He utilized aerial photos and extensive field investigations to map and characterize these older units. Natural outcrops of these units are rather limited through the foothills, as older units are commonly mantled by Quaternary surficial deposits or hillslope colluvium derived from erosion of the older deposits. Nonetheless, Dickinson (1999) characterized the relative deformation of progressively older units by careful observation of natural exposures and roadcuts.

Map Unit Descriptions

Piedmont Alluvium

Quaternary and latest Tertiary deposits cover most of the Catalina foothills piedmont between the Santa Catalina Mountains and Rillito Creek (also known as the Rillito River). 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 foothills piedmont is defined by its intersection with the planar, very gently northwest-sloping Holocene floodplain of the Rillito Creek. 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, sediment load is generally sand and cobbles with some boulders; terraces may be mantled with finer sediment. On lower piedmont areas, young deposits consist predominantly of sand, silt, and cobbles. Channels generally are incised less than 1 m below adjacent Qy2 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. Local relief varies from fairly smooth channel bottoms to the undulating bar-and-swale topography that is characteristic of coarser deposits. Soil development associated with Qy2 deposits is minimal, and terrace and fan surfaces are brown. Channels appear light-colored on aerial photos, whereas Qy2 terraces generally appear darker than surrounding areas. Vegetation density is variable. Channels typically have sparse, small vegetation, but 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, cottonwood, willow, and sycamore; smaller bushes and grass may also be quite dense. Smaller washes typically have palo verde and mesquite trees, large creosote, and other bushes along them.

Qy1 - Holocene alluvium (0 to 10 ka). Unit Qy1 consists of low terraces and alluvial fans found near the mountain front and at scattered locations along drainages throughout the foothills. Qy1 surfaces are slightly higher than adjacent Qy2 surfaces and are generally subject to inundation only in extreme floods. Surfaces are planer to broadly rounded and typically are 1 to 2 m above adjacent active channels. Surfaces typically are sandy and brown in color, but locally Qy1 surfaces have fine, unvarnished open gravel lags. Qy1 surfaces generally appear fairly dark on aerial photos mainly because of their vegetation cover, but where a gravel lag is present, vegetation is sparse and surfaces are light colored. Channel patterns consist of tributary or distributary networks. Qy1 surfaces support mesquite and palo verde trees, and typically smaller bushes are quite dense. Qy1 soils typically are weakly developed, with some soil structure but no obvious clay accumulation and stage I calcium carbonate development.

Ql - Late Pleistocene alluvium (10 to 130 ka). Unit Ql consists of moderately dissected terraces and relict alluvial fans found on the upper, middle and lower piedmont. Active channels are typically incised up to about 3 m below these surfaces, with incision generally increasing toward the mountain front. Ql fans and terraces commonly are inset below adjacent Qm and older surfaces, but the lower margins of Ql deposits lap out onto more dissected Qm surfaces in many places on the middle and upper piedmont. Weakly to moderately incised tributary drainage networks are typical on Ql surfaces. 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 vegetation types 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 typically several meters above adjacent active channels. Qm surfaces are drained by well-integrated, moderately incised tributary channel networks. Planar Qm surfaces are smooth with pebble and cobble lags; rock varnish on surface clasts is typically orange. More eroded Qm surfaces are characterized by loose cobble lags with moderate to strong varnish, ridge-like topography and carbonate litter on the surface. Qm surfaces have a distinctive dark orange 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 cemented petrocalcic horizons are uncommon. Qm surfaces generally support bursage, ocotillo, creosote, cholla, and saguaro.

Qml – Middle and late Pleistocene alluvium (10 to 500 ka). Unit Qml consists of middle or late Pleistocene alluvium that we could not differentiate.

Qmo - Middle to early Pleistocene alluvium (500 ka to 2 Ma). Unit Qmo consists of moderately to deeply dissected relict alluvial fans and terraces with variable soil development found mainly in the western foothills. Qmo surfaces are typically 5 to 10 meters above adjacent active channels. Qmo surfaces are drained by well-integrated, deeply incised tributary channel networks. Well-preserved planar Qmo surfaces are uncommon. 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 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 reddish brown, 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.

QT - Early Pleistocene to Pliocene alluvium (1 to 5 Ma). Two subunits are used to designate very old, deeply dissected and highly eroded alluvial fan deposits across the map area, modifying the usage of Dickinson (1999). The QT unit is used for the high-level, undeformed deposits in the central part of the map area (the Campbell Avenue fan complex of Dickinson [1999]) and similar, less extensive deposits in the western part of the map area. QT ridgecrests are typically at least 10 meters above adjacent active channels. QT surfaces are alternating eroded ridges and deep valleys. They are drained by well-integrated, 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, with minor lenses of brown or reddish sand and silt. Clast lithology is predominantly gneiss. Deposits are weakly to moderately indurated, but are quite resistant to erosion because of the large clast size. Soils typically are dominated by pedogenic carbonate development, which is typically stage V (cemented petrocalcic horizons with laminar cap) on ridgecrests. Carbonate litter is common on ridgecrests and sideslopes. On aerial photos, QT surfaces are gray to white. QT surfaces generally support mesquite, palo verde, ocotillo, creosote, cholla, and saguaro. QT deposits record the highest levels of sediment accumulation in the foothills, and they predate the downcutting and erosion that have dominated the Quaternary evolution of the foothills. Beds dip from 2° to 3° basinward and are not tilted. Locally, QT deposits overlie older, tectonically tilted Tsc and Tpa deposits in an angular unconformity. At the mountain front west of Finger Rock Canyon, QT deposits clearly onlap the Catalina detachment fault and are not displaced. QT deposits are cover much of the foothills piedmont in the area of Campbell Avenue (Tucson North quadrangle). Isolated remnants of QT deposits in the middle and upper piedmont indicate that these deposits mantled the entire piedmont in the area of Campbell Avenue, and have subsequently been eroded from much of the upper piedmont.

QTvb – Ventana Benchlands fan complex. This second Quaternary – late Tertiary map unit consists of bouldery gravel deposits that form the high Ventana benchlands on the piedmont downslope from the Sabino and Ventana canyons (east-central part of the map area, Sabino Canyon quadrangle). Beds dip from 0° to 3° basinward, and there is no evidence of tilting of these deposits. These coarse sediments were probably deposited by ancestral Sabino Creek and Ventana Wash; they apparently filled a broad paleovalley on the downthrown (southwest) side of the Finisterra fault. QTvb deposits may have thinned to the northwest onto an erosion surface cut on the deformed Swan-Craycroft gravels (unit Tsc). No QTvb deposits are preserved on the upthrown side of the fault. There are no exposures of the stratigraphic relationship between QTvb deposits and the fault, but QTvb deposits are undeformed and were probably deposited after the fault was active (Dickinson, 1999). QTvb deposits on the upthrown northeast side of the Finisterra fault may have been restricted to the bottoms of valleys cut into the underlying Pantano Formation. If so, they have been completed removed by erosion.

River Deposits

Sediment deposited by Rillito and Tanque Verde creeks and the Santa Cruz River cover most of the southern part of the map area. Surfaces consist of active channels, young stream terraces that compose the geologic floodplain, and several broad, older relict terraces that date to the Pleistocene. Deposits are composed of a mix of gravel and sand and finer material; they exhibit mixed clast lithologies reflecting the large drainage areas of the Rillito and Santa Cruz watersheds. Most of the area covered by river deposits has been altered by intense urban development, 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 composed primarily of sand and gravel. Modern channels are typically entrenched several meters below adjacent young terraces. The current entrenched channel configuration began to form with the development of arroyos in the late 1800's, and continued to evolve through this century (Pearthree and Baker, 1987). Historically, channels had variable widths and 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. The banks of the small length of the Santa Cruz River channel in the map area and most of the banks of Tanque Verde Creek are unprotected and are subject to 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. Most Qyr areas 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, with gravel lenses in former channels. 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). 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 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.

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, silt, 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 labeled the Jaynes terrace by Smith (1938) and Pashley (1966), and Qt3 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 and are inset below Qor terraces. Deposits consist of sand, silt, clay and gravel. Soils are reddened and have variable development, but moderate to strong, clay-rich argillic horizons are typical. Calcic horizon development is also quite variable, but typically is stage III or stage IV (cemented). Terraces are quite broad and terrace surfaces are quite flat away from drainage and terrace margins. Qmr terraces were labeled the Cemetery terrace by Smith (1938) and Pashley (1966), and Qt4 by McKittrick (1988). Based on the strong soil development associated with Qmr terraces, they are likely of middle Pleistocene age.

Qor - Middle to early Pleistocene river deposits (~500 ka to 2 Ma). Relict very old basin-floor deposits in the central portion of the Tucson basin. Qor surfaces form elongate ridges. They are found at the topographically highest locations in the central basin, and thus record the highest level of basin filling. Deposits consist primarily of sand and gravel, and are generally coarser than younger terrace deposits. These surfaces are distinguished by strongly cemented calcic horizons with laminar caps suggestive of great antiquity. Qor surfaces were labeled the University terrace by Smith (1938) and Qt5 by McKittrick (1988).

<u>Older Foothills Deposits</u> (from Dickinson [1999])

Tsc – Miocene alluvium (5 to 20 Ma). This map unit consists of dissected, tectonically deformed alluvial fan deposits of probable Miocene age. Deposits consist of moderately indurated, cobbly to bouldery gravel with finer sand deposits; clasts are predominantly gneiss and schist. Beds commonly dip 10° to 15°to the southwest, and are cut by minor faults. Tsc deposits are widely exposed in the middle part of the map area, where Quaternary deposits are relatively sparse. Because they are dominated by clasts of rock currently exposed in the Santa Catalina Mountains and are deformed, Tsc deposits probably record the late phase of displacement on the Catalina detachment fault and the Finisterra fault splay. Accordant ridges formed in Tsc deposits suggest that two distinct erosional surfaces were cut across Tsc deposits during the late Pliocene to early Quaternary in the area of Swan and Craycroft roads (Dickinson, 1999). These erosion surfaces were likely mantled by thin early Pleistocene to late Pliocene deposits (unit QT or QTvb) at one time, but no clear evidence of these deposits exists at present. Qm and younger surfaces are inset below the level of the erosion surfaces cut on Tsc deposits.

Tpa – Late Oligocene to early Miocene deposits (20 to 30 Ma). This map unit consists of tectonically deformed, moderately indurated beds of the Pantano Formation. Deposits are pebble and cobble clast-supported conglomerate, bouldery matrix supported conglomerate, and clay-rich beds that may represent ancient playas. The fine-grained matrix of these deposits is a distinct maroon color. Volcanic and granitic clasts are dominant in the conglomerates, and gneissic clasts are rare. These deposits thus record early displacement on the Catalina detachment fault and pre-date exposure of the gneissic rocks that are the predominant rock type in the southern Catalina Mountains today. Strata are tilted by various amounts, but are typically in the range of 12° to 30°; minor faults are common (from Dickinson, 1999).

Bedrock

R – Bedrock was not mapped in detail for this project. Exposed bedrock in the southern Santa Catalina Mountains is primarily granitic gneiss, in the footwall of the Catalina – Rincon metamorphic core complex.

Rp – Bedrock pediment. Fairly planar erosional surfaces cut onto bedrock on upper margin of foothills piedmont. Pedimented surfaces are found are narrow and dissected. They are perched several meters or more above active channels. Based on their topographic position, these pediments probably formed in the Pliocene to early Pleistocene, concurrent with deposition of the highest levels of QT deposits (Morrison, 1991).

Table 1. Correlation of map units with other Quaternary/Tertiary map reports in the northern Tucson basin.

Unit (this report)	McKittrick (1988)	Dickinson (1999)	Pashley (1966)	Anderson (1987)
Qy2	ch	Qal		
Qy1	Y	Qal		
Qycr	cha			
Qyr	T1, T2			
Ql	M2	Qpc/Qfr/Qss		
Qlr	T3		Jaynes	
Qm	M1	Qpc/Qfr/Qss		
Qmr	T4		Cemetery	
Qmo	O, QTbf	Qpc/Qfr?		
Qor	T5		University	
QT	O, QTbf	QTca, Qpc	Basin fill	Ft. Lowell
QTvb	QTbf	QTvb	Basin fill	Ft. Lowell(?)
Tsc	QTbf	Tsc	Rillito III	Tinaja
Tpa	Ts	Tpa	Rillito I and II	Pantano

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 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 Tertiary deposits of the Catalina foothills record major normal faulting on the Catalina detachment fault and at least one major splay, the Finisterra fault (Pashley, 1966; Dickinson, 1999). The Tertiary history of the map area is discussed in more detail by Dickinson (1999). Beds of the late Oligocene to early Miocene Pantano Formation are moderately to strongly faulted and tilted, and they do not contain significant amounts of gneissic clasts. These sediments were deposited in a fault-controlled basin prior to exposure of the gneissic rocks in the footwall of the detachment fault. The next younger sedimentary package, the Miocene Swan-Craycroft gravels, lie unconformably on the Pantano Formation (Dickinson, 1999). The Swan-Craycroft gravels are variably tilted, but are less deformed than the Pantano beds and are dominated by clasts of gneiss and schist. They record a later phase of displacement on the Catalina detachment fault and the Finisterra fault, a southeast-trending splay off of the detachment fault in the eastern part of the map area (Figure 2). After faulting ceased, the Swan-Craycroft gravels were subsequently eroded and at least one broad erosion surface was formed prior to deposition of the highest levels of sediment in the basin, the QT units. These younger deposits are also dominated by clasts of gneiss. QT deposits are not deformed and they are approximately graded to narrow bedrock pediments that exist in a few places along the mountain front (Figure 3), so they post-date activity on the normal faults in the map area. The QT units of the Catalina foothills are probably broadly correlative with other high-standing, coarse-grained gravel deposits found throughout southeastern Arizona (Menges and McFadden, 1981).

The highest levels of basin-fill deposits (unit QT) in the Catalina foothills were probably graded approximately to the highest levels of basin-fill deposits in the central Tucson basin. It is

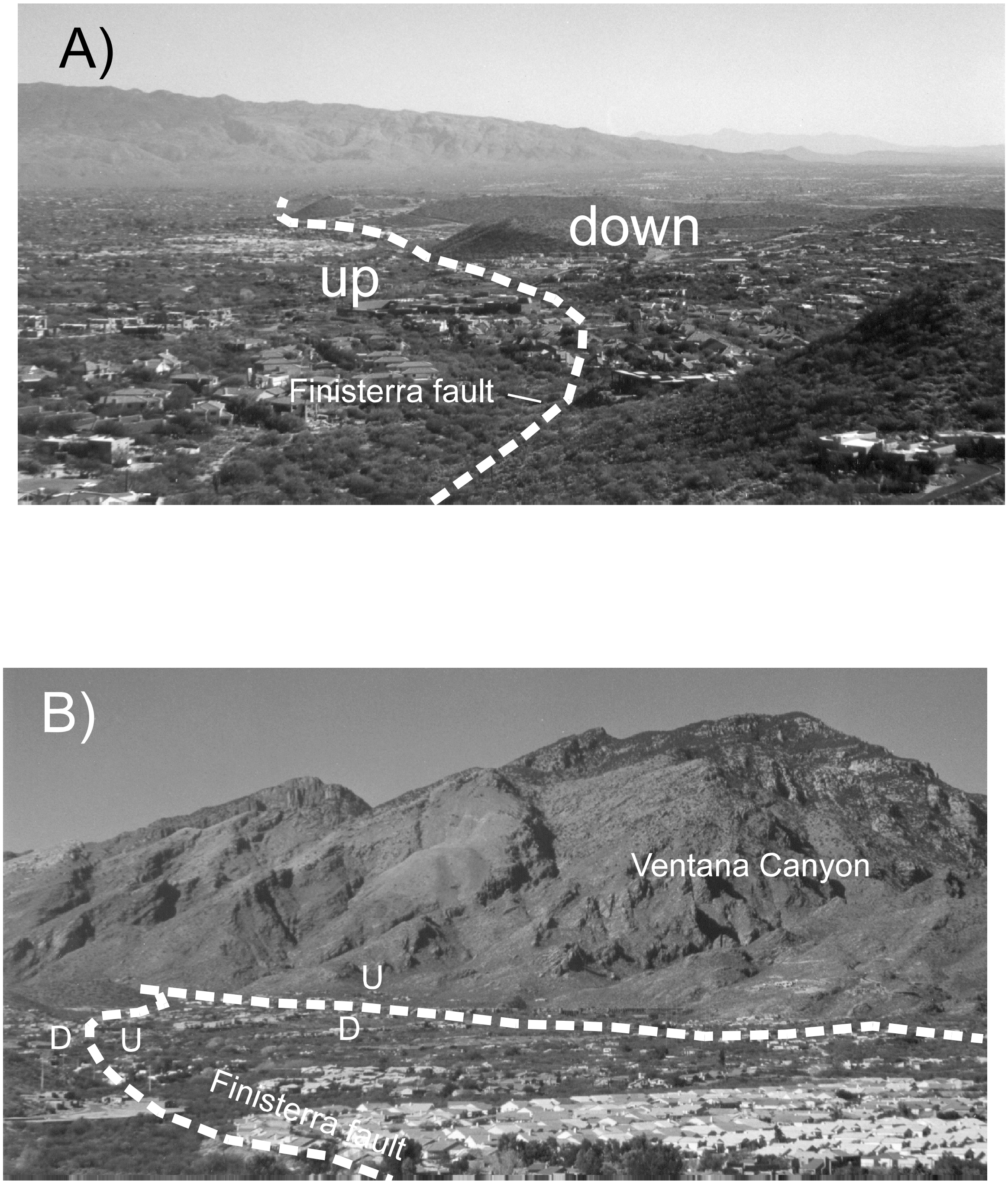
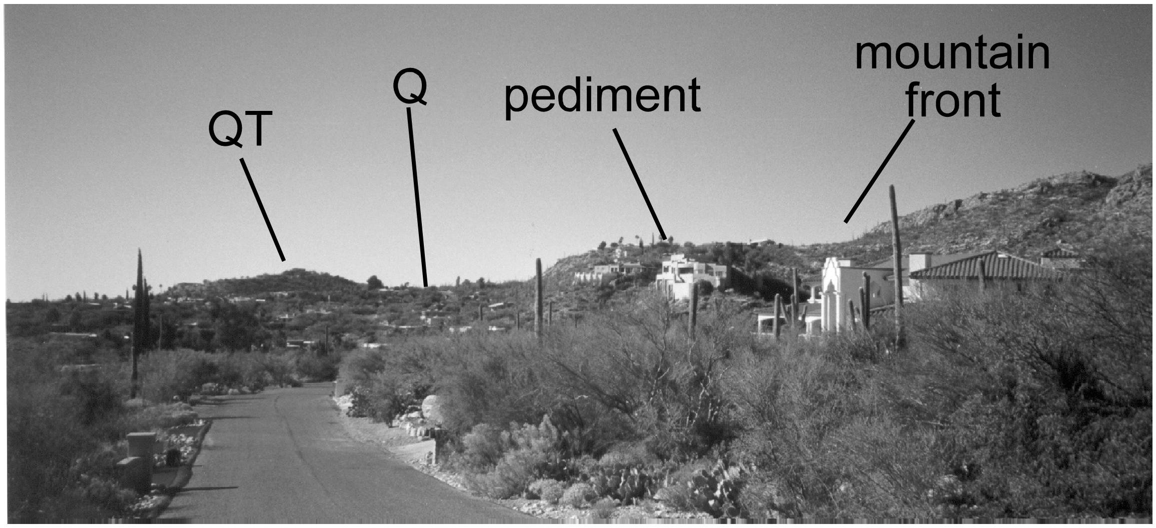


Figure 2. Photos looking southeast (A) and northwest (B) along the Finisterra normal fault splay off of the Catalina detachment fault. The Finisterra fault trends southeast, with the southwest side down. Coarse, resistant Tsc and QTvb sediment was deposited on the downthrown side of the fault during and after it was active. Erosion in the past few million years has preferentially removed more of the less resistant Tpa deposits on the upthrown side of the fault, resulting topographic relief that is opposite to the sense of fault movement.



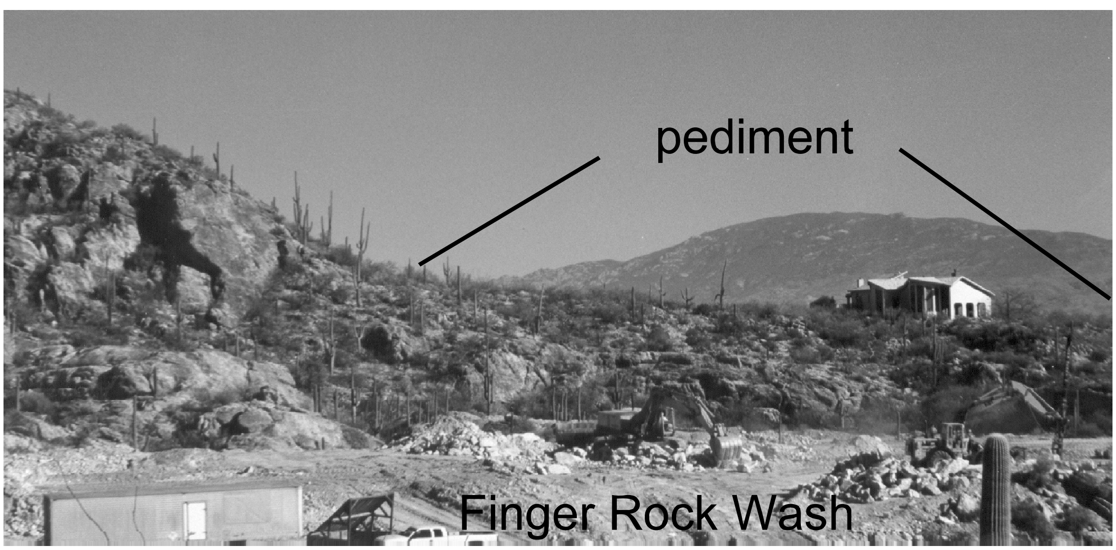


Figure 3. Photos of highest QT deposits and bedrock pediment near Finger Rock Canyon. The highest QT deposits are graded approximately to the narrow bedrock pediment along this part of the mountain front. Younger Quaternary deposits occupy the lower areas in the photos.

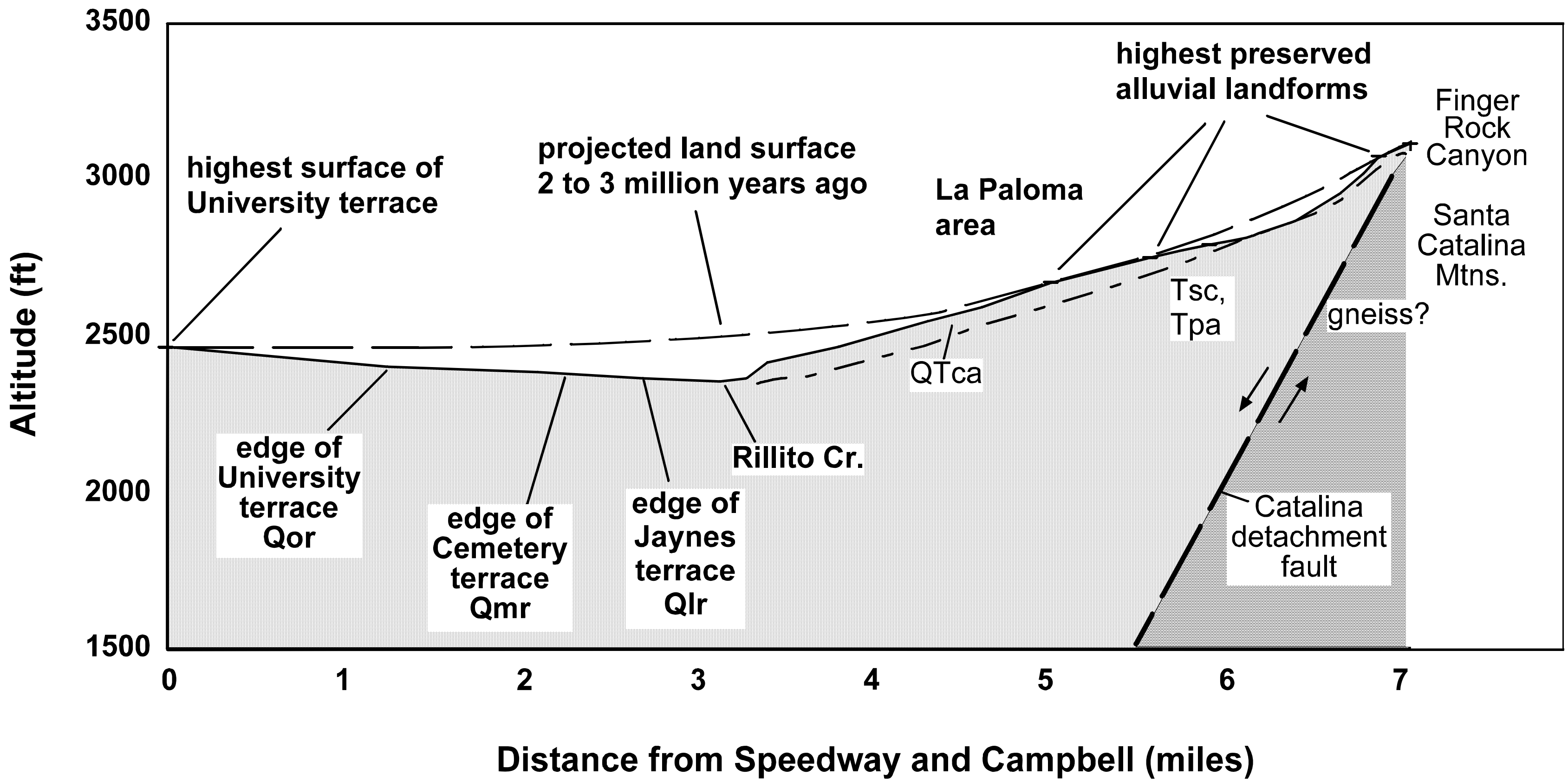


Figure 4. Cross section from the intersection of Speedway and Campbell north to the mouth of Finger Rock Canyon in the Santa Catalina Mountains. The top of the stippled area is the land surface today. The highest preserved levels of alluvial fill in the Catalina foothills and the central Tucson basin can be fit with a reasonable concave-upward profile that may represent the approximate land surface in late Pliocene to early Quaternary time (~1.5 to 3 Ma). Vertical exaggeration is about 10 times.

possible to reconstruct a reasonable longitudinal profile from the mountain front to the central part of the basin using the highest remnant surfaces formed on QT deposits in the Finger Rock – La Paloma area and the University terrace in the area of the University of Arizona (Figure 4). It is likely that in the late Pliocene to early Quaternary, the most of the surface of the Catalina foothills was fairly planar with minimal dissection. There were areas of reasonably thick young deposits (unit QT and QTvb) and areas with minimal or no young deposits between them (erosion surfaces cut onto unit Tsc).

During the Quaternary, Rillito Creek and its tributaries have downcut substantially into the Tertiary deposits of the Catalina foothills. The high ridges and deep valleys characteristic of much of the foothills area 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 Rillito Creek also reflect long-term downcutting. These episodes of downcutting and northward migration of Rillito Creek caused erosion of the toes of alluvial fans in the Catalina foothills, and resulted in much of the tributary stream downcutting in the foothills. This happens because erosion along Rillito Creek steepens the slopes of tributary streams. The tributary streams then downcut to adjust to the new base level in Rillito Creek. The ultimate cause of the Rillito Creek downcutting is not certain. It is probably a delayed result of integration of the Tucson basin streams into the larger regional drainage system and long-term climatic changes that altered the balance between sediment supply and the ability of streams to transport sediment out of the basin.

Broad middle Pleistocene and younger alluvial fans and terraces that exist in portions of the foothills are evidence for periods of aggradation (net sediment accumulation) that were superimposed on the long-term downcutting trend. These deposits overlie all of the older units in erosional unconformity, and in most areas, exposures indicate that the younger deposits are quite thin (Figure 5). We are not certain what caused the aggradation events that are represented by these deposits, 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 (Van Devender and others, 1987), so that the vegetation was different and water was probably present for more of the year in the larger 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).

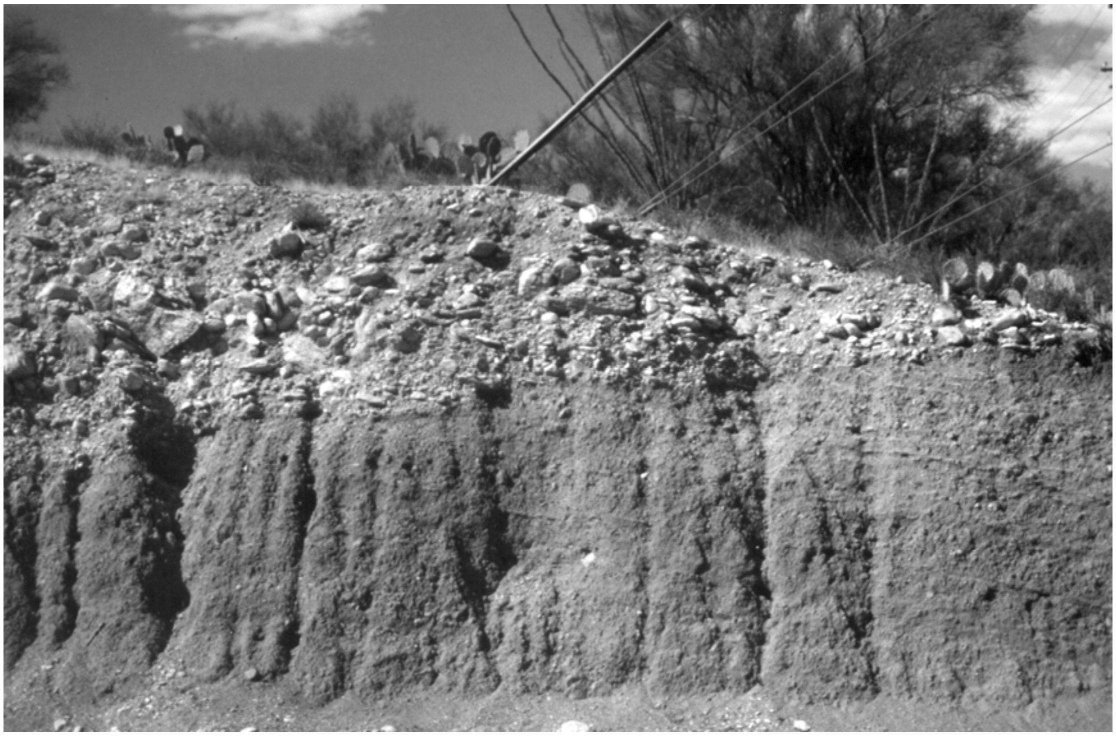


Figure 5. Angular unconformity between Quaternary and Tertiary sediments in the Catalina foothills just east of the intersection of Campbell Avenue and Skyline Road. The overlying unit is coarse gravel of unit Qmo. The darker, finer-grained underlying deposits of the Pantano Fm were tilted by faulting and eroded prior to deposition of the Qmo gravel. Photo by T.M. McGarvin.

Geologic Hazards

(with the contribution of information and text by Ray Harris)

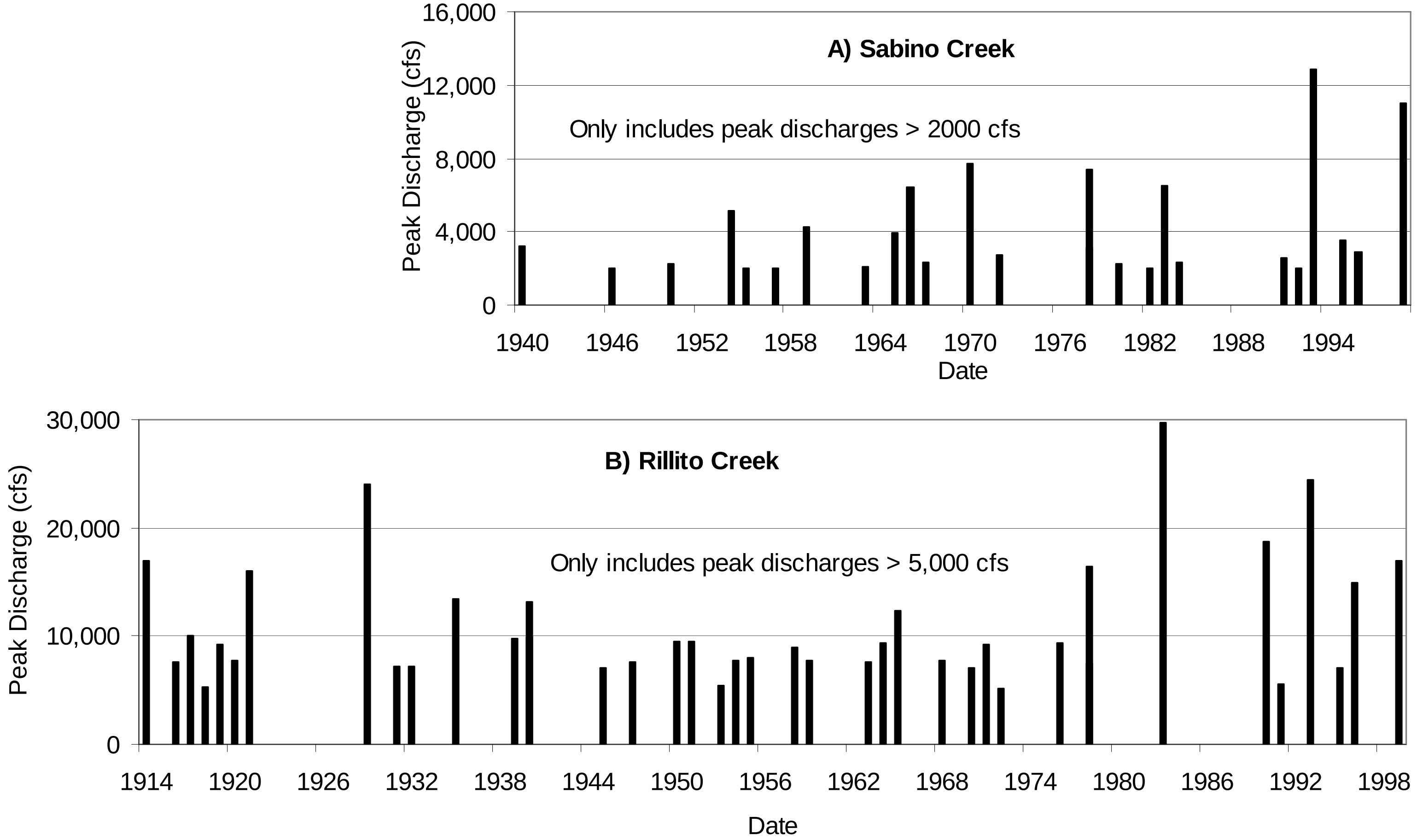
This section summarizes the character and distribution of the principal geologic hazards that exist in the northern Tucson basin. This information is fairly general in nature. Detailed site-specific geologic, engineering, hydrologic, or soils investigations may be required to thoroughly assess potential hazards at particular locations. More specific information on soil properties may be obtained from the U.S. 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.

***Flooding hazards*.** Flooding hazards in the Tucson area may be subdivided into those associated with major regional drainage systems and those associated with smaller tributary drainages. Major drainages in the Tucson area are the Santa Cruz River and its tributaries, Rillito Creek, Tanque Verde Creek, and Pantano Wash. The largest floods on these drainages have resulted from regional storms in the winter and late summer - early fall, but summer storms have generated fairly large floods as well. In the middle and late 1900's, the primary flood hazard associated with these large drainages has been lateral bank erosion, although widespread overbank inundation has occurred along Tanque Verde Creek. Smaller tributaries that drain the mountain ranges, the piedmonts, and the basin floor are subject to flash floods. Floods on these drainages typically result from intense, localized thunderstorms that usually occur during the summer or early autumn, and water levels rise and fall rapidly during floods.

Rillito Creek and its principal tributaries flow from southeast to northwest across the map area, and they have posed the greatest flood hazard to basin-floor areas historically. Large, damaging floods in the historical record occurred in 1914, 1921, 1924, 1929, 1965, 1978,1983, and 1993, with 29,000 cubic feet per second (cfs) in 1983 being the peak of record (Garrett and Gellenbeck, 1991; Pope and others, 1998; see Figure 6). In the latter half of the 20^{th} century, overbank inundation during floods has been a minor issue along Rillito Creek because its channel is entrenched several meters below the historical floodplain. Lateral bank erosion has been a far greater hazard along Rillito Creek, with hundreds of feet of erosion occurring during several floods (Pearthree and Baker, 1987). Soil cement bank erosion was put in place sporadically through the 1980's, which probably exacerbated erosion in unprotected areas (Pearthree and Baker, 1987). Bank protection for the entire length of Rillito Creek was completed in the mid-1990's. Pantano Wash is similarly entrenched, but bank erosion remains a significant hazard because only part of the banks of Pantano Wash within the map area have been stabilized with soil cement. There is very little structural bank protection along Tanque Verde Creek, and the channel is less entrenched than along Rillito Creek. Therefore, widespread inundation occurs along the creek during large floods and bank erosion is common. Areas mapped as Qyr along Tanque Verde Creek may be subject to flooding, and banks formed in young, weakly to unconsolidated Qyr deposits along both Tanque Verde Creek and Pantano Wash are especially susceptible to lateral erosion.

Floods on the smaller streams that cross piedmont areas are generated by intense, localized thunderstorms that usually occur in the late summer and early fall. A classic example of this type of flood occurred on Sabino Creek during the morning of July 15, 1999. Parts of the upper Sabino Creek drainage basin received nearly 6 in. of rainfall between 2:30 am and 6:30 am, with 4.6 in falling between 4:30 and 6:30 am (Pima County Flood Control District, written communication, 1999). In response to this intense precipitation stream discharge near the mouth of Sabino Canyon rose from a few hundred cubic feet per second (cfs) to about 11,000 cfs in 1.5 hours (Sabino Creek stream gage; U.S. Geological Survey, preliminary data, July, 1999). The flood began to recede almost immediately, and within a few hours flow was less than 1,000 cfs. There was some overbank flooding along lower Sabino Creek, and a U.S. Forest Service picnic area and a few structures in the floodplain farther downstream were damaged. 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

Figure 6. Large historical flow events on Sabino Creek and Rillito Creek. Data are from U.S. Geological Survey stream gages (Pope and others, 1998. Discharge estimates for the flood of July 1999 are preliminary.



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. Flood hazards are relatively easy to manage where topographic relief confines floodwater to channels and adjacent low terraces. It is much more difficult to assess and manage flood hazards associated with unconfined flow (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.

The extent of young deposits is limited through most of the Catalina foothills, as modern drainages are entrenched into older deposits. In these situations, the areas that may be impacted by flooding are of limited extent and should be easy to avoid. Flood hazards may be minimized by avoiding development in channels and on low terraces adjacent to channels (unit Qy2). Along small drainages that head in the foothills, the widths of these potentially flood-prone areas are quite narrow. Along larger drainages that head in the mountains, Qy2 channel and terrace deposits are more extensive, but the margins of potentially flood-prone areas are obviously limited by topography associated with older deposits. Alluvial fan flooding may occur at a few places along the front of the Santa Catalina Mountains where young deposits (units Qy2 and Qy1) are extensive (the mouths of Pima and Finger Rock canyons, and several much smaller drainages east of Bear Canyon). Portions of these areas may be subject to widespread, relatively shallow inundation during large floods, with deeper, higher-velocity flow in channels. Unconfined flow during floods also occurs along the margin of Rillito Creek, where tributaries debouch from the topographically confined foothills onto the Qyr terrace (see the terminus of Finger Rock Wash, for example). Widespread inundation also occurs near the mouth of Agua Caliente Wash in the eastern part of the map area.

Soil problems. Soils in the northern Tucson basin present a number of problems for structures. Cracking of foundations, walls, driveways and swimming pools are nuisance problems in many cases, but more severe problems that exist in some areas cost in 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 leaching of atmospheric dust into soil profiles.

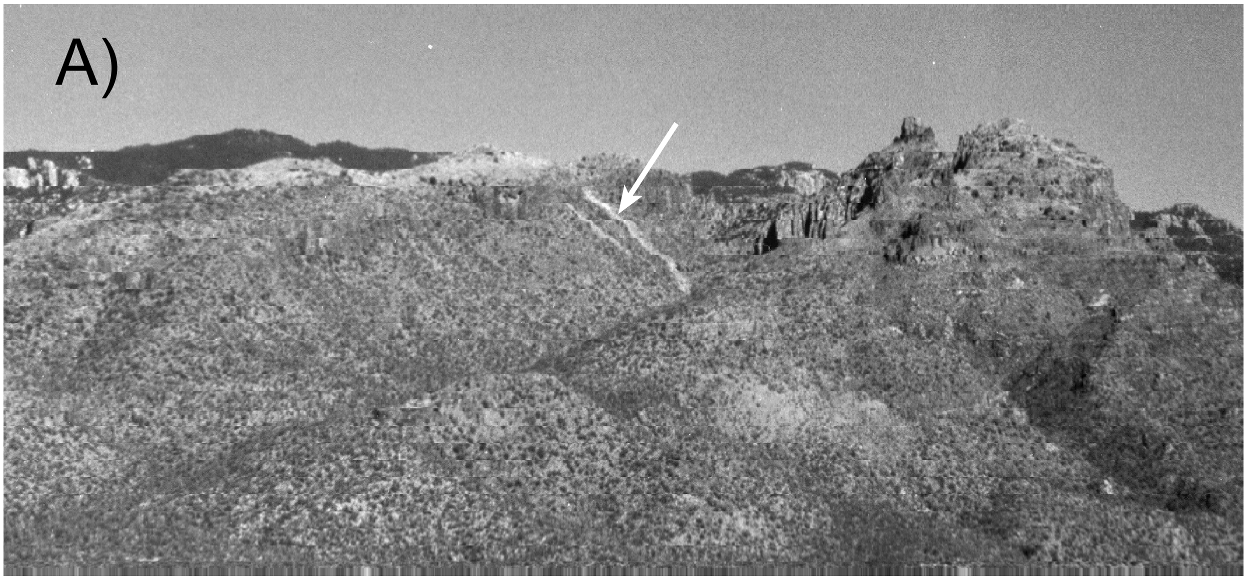
In the Tucson area, soils that expand typically have a high content of clay minerals of the smectite family, which includes montmorillonite and bentonite (Brooks, 1989). This clay acts like a sponge and can absorb several times its volume in water. Expansive clays can be identified by their characteristic “popcorn” texture in surface exposures. This texture is the result of the shrinkage that occurs upon drying. Expansive soils are found in numerous places around Tucson. Many of these areas are associated with exposures of clays in the Pantano Formation, mostly around the north and east margins of the valley, against the Santa Catalina and Rincon Mountains. Sediments of the Pantano formation (map unit Tpa) are exposed in the northern and eastern Catalina foothills, along Sunrise Boulevard from Campbell Avenue to Sabino Canyon

Road and Snyder Road from Sabino Canyon Road to the east end of Snyder Road (Dickinson, 1999). Mitigation of problems associated with expanding clay soil can be accomplished in some cases by removing the topsoil down to the depth where expansive clays have formed, usually a few feet, and replacing it with non-expansive fill. Drainage around a structure can be controlled to ensure a minimum of infiltration of water near the building.

Soils with the potential to collapse or compact are found in the floodplains and young terraces of the Rillito and Tanque Verde creeks and Agua Caliente Wash (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.

Debris flows and rockfalls. Debris flows and rockfalls are potential hazards in and immediately adjacent to the Santa Catalina Mountains. Debris flows are concentrated mixtures of poorly sorted sediment and water. The coarse sediment load transported by debris flows tends to be concentrated along their margins, while high pore pressures are maintained in the interior mass of the flow such that they are essentially liquified (Major and Iverson, 1999). In southern Arizona, debris flows typically are triggered by intense precipitation events on steep mountain hillslopes.

Many fresh debris-flow scars exist on steep slopes of the Santa Catalina Mountains, and a number of debris flows occurred during the storms of October, 1983, and January, 1993. These mass movements most likely occurred during intense precipitation events embedded within the larger storms. A debris flow that occurred in a tributary of Bear Creek in 1983 was visited shortly after the event. This debris flow began as two slope failures on a very steep mountain hillside that was covered by a shallow mantle of weathered material (colluvium) (Figure 7). When these mass movements encountered channels at the bases of the hillslopes, they developed boulder levees characteristic of debris flows. The debris flow stopped and deposited a pile of boulders a short distance downstream as the gradient of the stream channel decreased. This debris flow and all of the other recent debris flows remained in the mountains, and none came close to the piedmont. Very coarse bouldery Holocene deposits associated with unit Qy1 at the mouths of Finger Rock and Pima Canyon suggest that debris flows have gotten as far as the canyon mouths, but these debris flows are not fresh and may date to the early Holocene. There is no evidence of debris-flow activity in the young deposits mapped farther out on the piedmont.



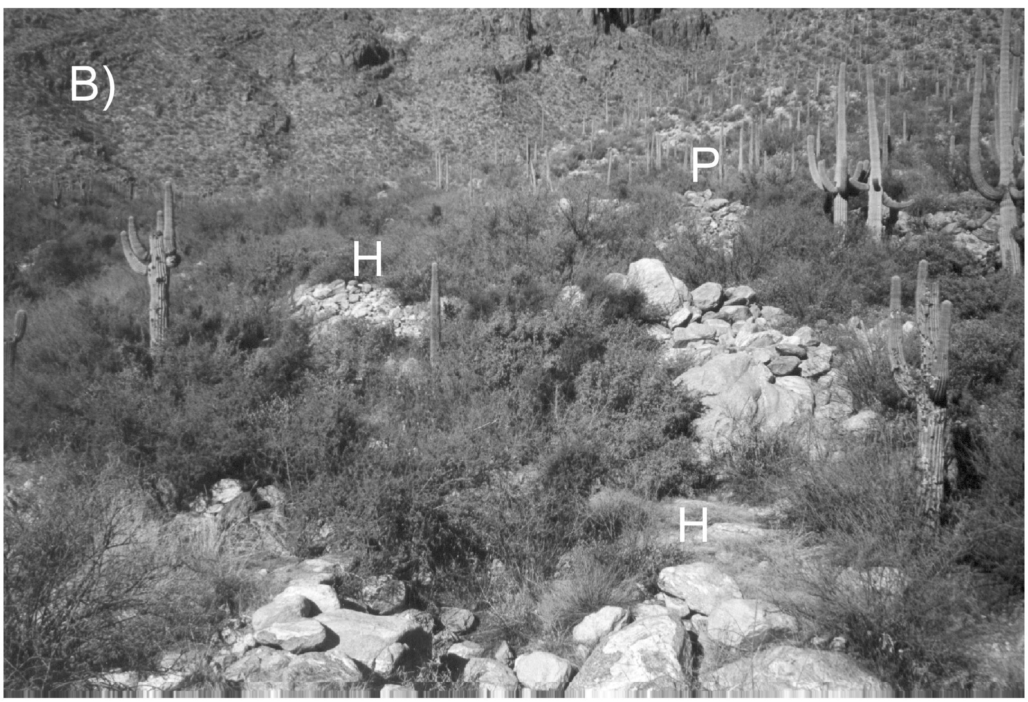


Figure 7. Evidence of debris flow activity in the Santa Catalina Mountains. Scars on the hillside in the upper photo record debris flows that occurred in October, 1983. These mass movements began as shallow landslides that became debris flows as they entered the drainage at the bottom of the slope. Large boulders in Holocene (H) and Pleistocene (P) deposits at mouth of Finger Rock Canyon strongly suggest that debris flows have reached the canyon mouth in the past, although there is no evidence of recent flows in this area.

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. Review of aerial photographs and topographic maps suggests that rockfall hazards along the mountain front are higher from the area of Esperero Canyon to the western end of the mountains. The hillslopes along this part of the mountain front are quite steep, and many ridges are capped by resistant, cliff-forming bedrock that could be the source of rockfalls. Obviously, the existence of large boulders near the base of a steep slope should be considered more definitive evidence of potential rockfall hazard (Figure 6).

Land subsidence and earth fissures. In the Tucson area, development and population increases have resulted in the heavy use of ground-water resources. 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. 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 Tucson, 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). Measurements in these two studies 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 interferomtery. 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. Tucson 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 somewhere along the margins of the Tucson basin as they have elsewhere.

References

Abdullahtif, A.A., 1969, Physical testing of engineering properties of collapsing soils in the city of Tucson: University of Arizona unpublished Masters Thesis, Department of Mining and Geological Engineering, 135 p

Anderson, F.J., 1968, Collapsing soils and their basic parameters in an area in the Tucson, Arizona vicinity: University of Arizona unpublished Masters Thesis, Department of Mining and Geological Engineering, 104 p.

Anderson, S.R., 1987, Cenozoic stratigraphy and geologic history of the Tucson basin, Pima County, Arizona: U.S. Geological Survey Water-Resources Investigations Report 87-4190, 20 p.

Anderson, S.R., 1988, Potential for aquifer compaction, land subsidence, and earth fissures in the Tucson basin, Pima County, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA-713, 3 sheets, scale 1:250,000.

Brooks, M.W., 1989, Distribution and assessment of expansive clay soils in the Tucson Basin, Arizona: University of Arizona unpublished Masters thesis, Department of Civil Engineering and Engineering Mechanics.

Bull, W.B., 1991, Geomorphic Response to Climatic Change, New York: Oxford University Press, 326 p.

Crossley, R.W., 1969, A geologic investigation of foundation failures in small buildings in Tucson, Arizona: University of Arizona unpublished Masters Thesis, Department Geology.

Demsey, K.A., House, P.K., and Pearthree, P.A., 1993, Detailed surficial geologic map of the southern piedmont of the Tortolita Mountains, Pima County, southern Arizona: Arizona Geological Survey Open-File Report 93-14, 8 p. scale 1:24,000.

Dickinson, W.R., 1999, Geologic framework of the Catalina foothills, outskirts of Tucson (Pima County, Arizona): Arizona Geological Survey Contributed Map CM-99-B, 31 p., 1 sheet, scale 1:24000

Field, J.J., and Pearthree, P.A., 1993, Surficial geologic maps of the northern Avra Valley – Desert Peak area, Pinal and Pima counties, southern Arizona: Arizona Geological Survey Open-File Report 93-13, 11 p., 9 sheets, scale 1:24,000.

Garrett, J.M., and Gellenbeck, D.J., 1991, Basin characteristics and streamflow statistics in Arizona as of 1989: U.S. Geological Survey Water-Resources Investigations Report 91-4041, 612 p.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the basin and range area of southern New Mexico -- guidebook ot the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222 p.

Hatch, M.A., 1991, Global positioning system measurement of subsidence in the Tucson Basin, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 87 p.

Haynes, C.V., Jr., and Huckell, B.B., 1986, Sedimentary successions of the prehistoric Santa Cruz River, Tucson, Arizona: Arizona Geological Survey Open-File Report 86-15, 44 p.

Jackson, G.W., 1989, Surficial geologic maps of the northeastern, southeastern, and southwestern portions of the tucson metropolitan area: Arizona Geological Survey Open-File Report 89-2, 6 p., 7 sheets, scale 1:24,000.

Major, J.J., and Iverson, R.M., 1999, Debris-flow deposition: Effects of pore-fluid pressure and friction concentrated at flow margins: Geological Society of America Bulletin, v. 111, p. 1424-1434.

McKittrick, M.A., 1988, Surficial geologic maps of the Tucson metropolitan area: Arizona Geological Survey Open-File Report 88-18, 7 p., 12 sheets, scale 1:24,000.

Menges, C.M., and McFadden, L.D., 1981, Evidence for a latest Miocene to Pliocene transition from Basin-Range tectonic to post-tectonic landscape evolution in southeastern Arizona: Arizona Geological Society Digest 13, p. 151-160.

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

Morrison, R.B., 1991, Quaternary geology of the southern Basin and Range province, in Morrison, R.B., ed., Quaternary nonglacial geology: Coterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-2, p. 353-371.

Pashley, E.F., 1966, Structure and stratigraphy of the central, northern, and eastern parts of the Tucson basin, Pima County, Arizona: Ph.D. dissertation, University of Arizona, unpublished.

Pearthree, M.S., and Baker, V.R., 1987, Channel change along the Rillito Creek system of southeastern Arizona, 1941 through 1983; Implications for flood-plain management: Arizona Geological Survey Special Paper 6, 58 p., scale 1:24,000.

Pearthree, P.A., and Biggs, T.H., 1999, Surficial geology and geologic hazards of the Tucson Mountains: Arizona Geological Survey Open-File Report 99-22, 12 p., 2 sheets, scale 1:24,000.

Platt, W.S., 1963, land-surface subsidence in the Tucson area: University of Arizona unpublished Masters Thesis, Department of Geology, 38 p.

Schumann, H.H., 1992, Land subsidence and earth-fissure hazards near Luke Air Force Base, Arizona, *in* U.S. Geological Survey Subsidence Interest Group conference, Edwards Air Force Base, Antelope Valley, California, November 18-19, 1992 - Abstracts and Summary: US Geological Survey Open-File Report 94-532, p. 18-21.

Sellers, W.D., and Hill, R.H., 1974, Arizona Climate, 1931-1972: Tucson, University of Arizona Press, 616 p.

Shafiquallah, M., Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 201-260.

Slaff, Steven, 1993, Land Subsidence and Earth Fissures in Arizona: Arizona Geological Survey Down-to Earth Series 3, 24 p.

Smith, G.E.P., 1938, The physiography of Arizona valleys and the occurrence of ground water, University of Arizona Agricultural Experiment Station Technical Bulletin No. 77, 91 p.

Van Devender, T.R., Thompson, R.S., and Betancourt, J.L., 1987, Vegetation history of the deserts of southwestern North America; the nature and timing of the late Wisconsin-Holocene transition, in Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last glaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 323-352.

Western Regional Climate Center, 1999, Arizona climate summaries, in Western U.S. historical climate summaries, WRCC Web Page, Desert Research Institute, University of Nevada.

Appendix A - Soil Descriptions

Date: 5/20/99
Described by: JEK, PAP
Geomorphic Surface: Qm
Location: 1st Ave. and Agave, west cut bank
Vegetation: small trees, desert shrubs including bursage

Depth (cm)	Horizon	Description
0-3	A	Yellowish red (moist) weak medium platy sandy loam, slightly sticky, slightly plastic, soft consistence, clear abrupt boundary, slightly effervescent
3-53	Bt1	Red (moist), moderate, fine to medium angular blocky to subangular blocky gravelly sandy clay loam, sticky and plastic, hard to very hard consistence, common distinct to prominent clay films, clear irregular boundary, effervescent with carbonate filaments and thin discontinuous carbonate coatings on clasts.
53-91	Bt2	Red, moderate fine to medium subangularblocky sandy loam, slightly sticky, nonplastic, very hard, few to common distinct clay films, clear irregular boundary, slightly effervescent with carbonate filaments and thin discontinuous coatings on clasts.
91-105+	Bkm	Reddish yellow, massive, very hard to extremely hard, very effervescent, carbonate pervasive in matrix, continuous carbonate coatings on clasts.

Date: 5/20/99
Geomorphic Surface: Qmo
Described by: JEK, PAP
Location: Campbell and Sunrise Ave., NE corner, below parking lot of Anthony's in the Foothills
Vegetation: none present (asphalt covered)

Depth (cm)	Horizon	Description
0-22	None	Gravelly fill, abrupt wavy boundary
22-36	Bt1	Yellowish red (moist), moderate fine to medium angular to subangular blocky gravelly sandy clay loam, slightly sticky, slightly plastic, slightly hard, moderate distinct clay films, effervescent with very thin carbonate filaments on gravels, gradual smooth boundary.
36-52	Bt2	Yellowish red (moist), medium fine to medium subangular blocky gravelly sandy clay, sticky, plastic, soft consistence, moderate distinct clay films, slightly effervescent with thin discontinuous carbonate coatings on clasts, abrupt irregular boundary.
52-98	Btk1	Mottled pink and pinkish white (moist) massive and platy at top, gravelly sandy loam?, very hard to extremely hard, weak faint clay films, violently effervescent with a semi-laminated top, clear wavy boundary.
98-143	Btk2	Mottled yellowish red and white (moist) massive breaking to medium to coarse subangular blocky, sandy loam, slightly sticky, slightly plastic, very hard, weak to moderate faint to distinct clay films, violently effervescent, clear wavy boundary.
143+	Bk	Yellowish red (moist) single grain gravelly loamy sand, non plastic, non sticky, loose, violently effervescent with 1to 3 mm carbonate coatings on clasts.

Date: 5/20/99
Geomorphic Surface: QTvb
Describe by: JEK, PAP
Location: top ridge, new construction site east of Sabino Canyon Rd.
Vegetation: small paloverde and mesquite, low shrubs, grass
Parent Materials: cobbly, bouldery gneissic gravel

Depth (cm)	Horizon	Description
0-10	A	Dark brown (moist) weak medium subangular blocky sandy loam, non sticky, slightly plastic, soft to slightly hard, moderate faint clay films, noneffervescent, clear smooth boundary.
10-40	Bt1	Dark reddish brown (moist) moderate medium angular to subangular blocky, gravelly sandy clay to sandy clay loam, sticky, plastic, hard, moderate distinct clay films, noneffervescent, gradual wavy boundary.
40-105	Bt2	Yellowish red (moist) moderate fine to medium subangular blocky gravelly sandy clay loam, sticky, plastic, hard, moderate distinct clay films, noneffervescent.
105+	Btk	Light reddish brown (moist) fine to medium angular blocky gravelly sandy clay loam, sticky, plastic, hard to very hard, moderate distinct clay films, noneffervescent in matrix with some cementation locally and discontinuous moderately thick carbonate coatings on clasts.

Date: 5/20/99
Geomorphic Surface: QT
Described by: JEK/PAP (brief description)

0-10 cm	platy laminar carbonate cap found locally
10-130 cm	Indurated carbonate horizon, clast supported
130+ cm	Less indurated horizon, light orange in color