Surficial Geology and Geologic Hazards of the Amado-Tubac area, Santa Cruz and Pima Counties, Arizona

Amado and Tubac 7.5' Quadrangles

by

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INTRODUCTION

This report and accompanying maps describe the surficial geology, geomorphology, and geologic hazards of the rapidly developing Amado-Tubac area, south of the Green Valley area. The mapping covers the Amado and Tubac 7 1/2' quadrangles (Figure 1). The map area is in unincorporated Santa Cruz and southern Pima Counties. It includes much of the southern part of the upper Santa Cruz Valley, between the Santa Rita Mountains on the east and the Tumacacori Mountains on the west.

There are several potentially conflicting land use issues in the area covered by these maps. The Santa Rita and Tumacacori mountain ranges are public lands owned by the U.S. Forest Service. Several large ranches are located within the mapping area and are interspersed with state trust lands. Urbanization has occurred, and continues to occur, along the Santa Cruz River and around the communities of Arivaca Junction, Tubac, and Rio Rico, just south of the map area. Many areas of the Santa Rita piedmont have been subdivided and prepared for development, although development remains sparse. This report is intended to enhance our understanding of the surficial geology of the Amado-Tubac area and to aid in assessing and understanding geologic hazards in this area.

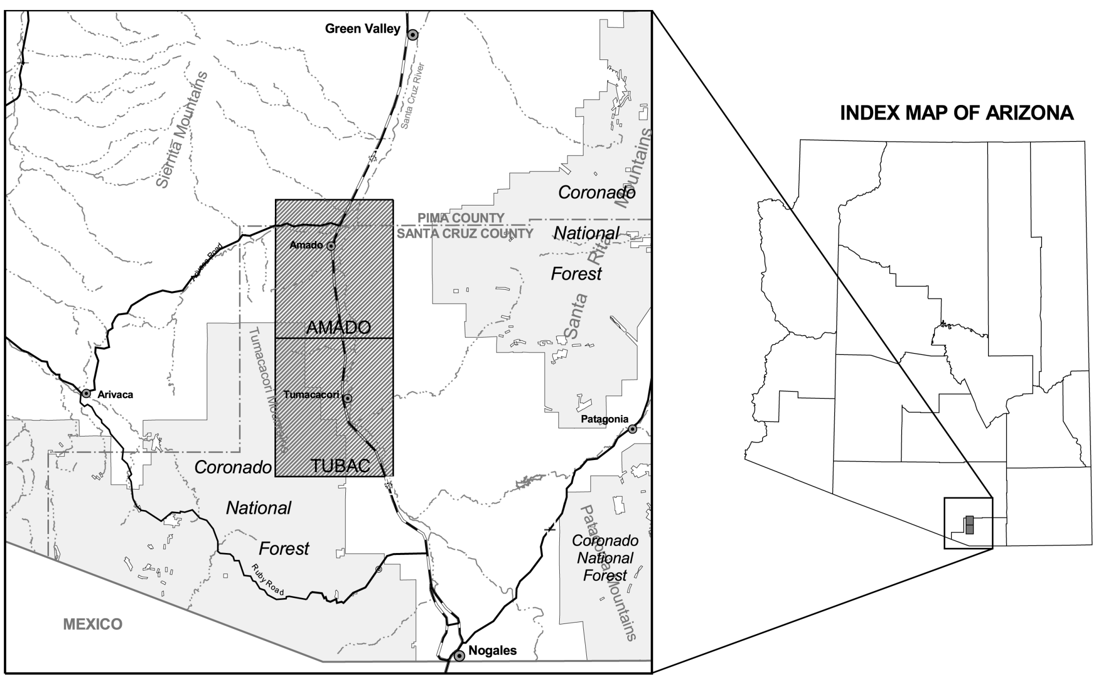

Figure 1. Location of the two quadrangles covered by this report.

This surficial geologic mapping in the Amado-Tubac 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 (Helmick, 1986, McKittrick, 1988; Jackson, 1989; Jackson, 1990; Field and Pearthree, 1993; Klawon and others, 1999; Pearthree and Biggs, 1999, Pearthree and Youberg, 2000), and previously published mapping that focused on the bedrock (Drewes, 1980; and Gettings and Houser, 1997). 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. Mapping was conducted as part of the STATEMAP Program of the U.S. Geological Survey, contract

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Climate. Three weather stations along the Santa Cruz River, and one at the base of the Santa Rita Mountains, have operated during intervals over the past century and provide climatological data for the study area. The weather station maintained at Tumacacori National Monument (northern Tubac quadrangle) has records from 1948 to present. Nogales 6 N (near Rio Rico about 5 miles south of the map area) has records from 1952 to present. The station at Sahuarita (north of the map area about 15 miles) has records from 1956 to 1972. The Santa Rita Experimental Range Headquarters (ERH, north of the map area about 10 miles) has records from 1950 to present.

Throughout this region, most of the annual precipitation (50-60%) falls during the summer monsoon from June to September. 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 usually less intense and may be more prolonged, and therefore infiltrates into the soil more deeply than summer rainfall (summarized from Sellers and Hill, 1974). Freezing temperatures are common during most winters, but snow is uncommon and not persistent.

Climate records from these stations illustrate the precipitation and temperature gradients along the Santa Cruz River, and from the river valley to the upper piedmont areas. Sahuarita approximates the relatively warm and dry climate in the lower elevations and northern portion of the map area. The southern end of the upper Santa Cruz River valley and the upper piedmonts are wetter and cooler. Sahuarita, at about 2700 ft asl, has an average annual precipitation of 10.6 in. while Tumacacori, at about 3200 ft asl, and Nogales 6 N, at about 3500 ft asl, report average annual precipitations of 16.0 in. and 17.9 in., respectively (Western Regional Climate Center, 2001). The ERH, at 4000 ft asl, reports an average annual precipitation of 22.3 in., more than double that of Sahuarita. The average annual precipitation for ERH is probably a maximum for the map area because of its proximity to the base of the Santa Rita Mountains. The average maximum temperature for Sahuarita is 84.7° F, with an average high temperature of 101.3° F in July and 67.0 ° F in January. The average maximum temperature at Tumacacori is 82.0° F, with an average high temperature of 96.8° F in July and 65.9° F in January. Nogales 6 N is a few degrees cooler. The average maximum temperature at the ERH is 76.4° F, with average high temperatures of 91.5° F in July and 60.2° F in January.

Methodology. The surficial geology of the project area was mapped using 1996 false color NAPP aerial photographs (1:40,000), 1936 black and white (1:28,000, limited coverage) and 1956 black and white (1:60,000) aerial photos, 1987 color (1:24,000) aerial photos (limited coverage), provided by the U.S. Forest Service, and USDA 1979 soil survey maps. Unit boundaries were checked in the field, and mapping was supplemented by observations and descriptions of soils and stratigraphy. The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, stream terraces) evident on aerial photographs and in the field were used to differentiate their associated deposits by age. Surficial deposits of this quadrangle were then correlated with similar deposits in this region in order to roughly estimate their ages. Mapping was done on aerial photos and compiled on 7 ½' quadrangle maps. Original mapping on the Santa Rita piedmont between Montosa and Josephine canyons by Helmick (1987) was modified by Youberg. The map compilations were then digitized and the final maps were generated from the digital data.

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 bars of gravel deposits, swales (troughlike depressions) where low flows passed between bars, and distributary channel networks, which are characteristic of active alluvial fans. Young alluvial surfaces have little rock varnish on surface clasts, 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).

In these maps, Quaternary surficial deposits are subdivided based on their source (axial valley streams 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), Jackson (1990), Klawon and others (1999), Pearthree and Biggs (1999) and Pearthree and Youberg (2000). 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 most of the piedmont areas east of the Tumacacori Mountains and west of the Santa Rita Mountains. This alluvium 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 floodplains and stream terraces of the Santa Cruz River and Sopori Wash. 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. See Table 1 for general surface and soil characteristics of most of the piedmont units.

Qy_2 **Late Holocene alluvium (<~2 ka)**--Unit Qy_2 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 upper piedmont areas, channel sediment is generally sand and gravel, but may include cobbles and boulders; terraces typically are mantled with sand and finer sediment. On lower piedmont areas, young deposits consist predominantly of sand and silt, with some gravels and 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. Terraces typically have planar surfaces, but small channels are also common on terraces. Soil development associated with Qy_2 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 Qy_2 terraces along channels. Along the larger washes, tree species include mesquite, acacia, ash and willow; shrubs and grass may also be quite dense. Smaller washes typically have mesquite, acacia and shrubs along them. This map unit includes units AC (active channel) and Q5 of Helmick (1986).

Qy_1 **Holocene alluvium (~2 to 10 ka)--**Unit Qy_1 consists of low terraces found at scattered locations along incised drainages on the piedmonts. Qy_1 surfaces are slightly higher and less subject to inundation than adjacent Qy_2 surfaces. Surfaces are generally planar; local relief may be up to 1 m where gravel bars are present, but typically is much less. Qy_1 surfaces are less than 2 m above adjacent active channels. Surfaces typically are sandy but locally have unvarnished, open, fine gravel lags. Qy_1 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. Qy_1 terrace surfaces support mesquite, acacia, shrubs and grasses. Qy_1 fans support scattered trees along channels, but shrubs and grasses are dominant. Qy_1 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). This map unit includes units Q4 of Helmick (1986).

Qy **undifferentiated Holocene alluvium (<~10 ka)**--Unit Qy includes both Qy_2 and Qy_1 deposits. It is used where it was not possible, at a scale of 1:24000, to separately map Qy_1 and Qy_2 surfaces. Unit Qy consists of smaller incised drainages on the piedmonts and more extensive young alluvial fans at the base of the piedmonts, adjacent to the Santa Cruz floodplain. Soil development consists of cambic horizons over weak to moderate (stage I to II) calcic horizons. This map unit includes units Q5 and Q4 of Helmick (1986), and units 3B and 4 of Pearthree and Calvo (1987).

Qly **Holocene to Late Pleistocene alluvium (<~130 ka)**--Broadly rounded alluvial fan surfaces approximately 1 m above active channels composed of mixed alluvium of late Pleistocene and Holocene age. Drainage networks consist of a mix of distributary channel networks associated with larger drainages and tributary channels associated with smaller drainages that head on Qly surfaces. Qly areas are primarily covered by a thin veneer of Holocene fine-grained alluvium (unit Qy), but reddened Pleistocene alluvium (unit Ql and rarely, Qm) is exposed in patches on low ridges and in roads and cut banks of washes. The Holocene surfaces usually are light brown in color and soils have weak subangular blocky structure and minor carbonate accumulation. Qly fans support palo verde and mesquite trees along washes and low shrubs and grass in interfluve areas. This unit is generally correlative with units 2d and 3a of Pearthree and Calvo (1987). Unit Qly is found only at the northern end of the Amado quadrangle.

Ql **Late Pleistocene alluvium (~10 to 130 ka).**
Ql_2 **latest Pleistocene member (~10 to 20 ka)**
Ql_1 **late Pleistocene member (~75 to 130 ka)**

Unit Ql consists of slightly to moderately dissected relict alluvial fans and terraces found on the upper, middle and lower piedmont. Moderately to well-developed, slightly to 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, and towards the southern end of the Santa Cruz Valley. 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 to dark orange on color aerial photos, reflecting reddening of surface clasts and the surface soil horizon. Ql soils are moderately developed, with orange to reddish brown clay loam to light clay argillic horizons and stage II calcium carbonate accumulation. Ql_1 soils have more clay, redder surface horizons, and generally more extensive drainage networks on them, reflecting their greater antiquity. Unit Ql is correlative with unit Q3 of Helmick (1986). Unit Ql_2 is correlative with unit 2d of Pearthree and Calvo (1987). Dominant forms of vegetation include grasses, small shrubs, cholla, prickly pear, barrel cacti, and mesquite. Ocotillo occurs where carbonate parent material exists.

Qm **Middle Pleistocene alluvium (~130 to 750 ka)**--Unit Qm consists of moderately to highly dissected relict alluvial fans and terraces with strong soil development found throughout the map area. Qm surfaces are drained by well-developed, moderately to deeply incised tributary channel networks. Channels are typically several meters below adjacent Qm surfaces with channel dissection increasing towards the mountains and the southern end of the map area. Well-preserved, planar Qm surfaces are smooth with scattered pebble and cobble lags; surface color is reddish brown; rock varnish on surface clasts is typically orange or dark brown. More eroded, rounded Qm surfaces are characterized by scattered cobble lags with moderate to strong varnish and broad ridge-like topography. Well-preserved Qm surfaces have a distinctive dark red color on color aerial photos, reflecting reddening of the surface soil and surface clasts. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Underlying soil carbonate development is typically stage II-III, with abundant carbonate through at least 1 m of the soil profile; indurated petrocalcic horizons are rare. Carbonate development is stronger towards the north end of the map area, and in areas where carbonate parent material exists. Qm surfaces generally support grasses, cholla, prickly pear, barrel cacti, mesquite and ocotillo. This unit is generally correlative to unit Q2 of Helmick (1986) and unit Q2b of Pearthree and Calvo (1987).

Qo **Early Pleistocene alluvium (~750 ka to 2 Ma)**--Unit Qo consists of very old alluvial fan remnants on top of highly dissected basin fill deposits (unit QTs). Remnant fan surfaces are moderately to well preserved with strong soil development. Qo deposits and fan surface remnants are best preserved on the upper piedmonts near the mountain fronts. Qo deposits consist of cobbles, boulders, and sand and finer clasts. Where surfaces are planar and well-preserved, soils typically have a distinct dark red, heavy clay argillic horizon, and stage III to IV calcic horizons. Qo surfaces are dominated by mesquite, ocotillo, scattered cacti, and grasses. This map unit is generally correlative to unit Q1 and Q1E of Helmick (1986), and unit Q2a of Pearthree and Calvo (1987). Qo surfaces record the highest levels of aggradation in the Santa Cruz valley, and are probably correlative with other high, remnant surfaces found at various locations throughout southern Arizona (Menges and McFadden, 1981; Pearthree and Calvo, 1987).

QTs **Early Pleistocene to Pliocene alluvium (~1 to 5 Ma)**--Unit QTs is a basin fill deposit consisting of very old, deeply dissected and highly eroded alluvial fan deposits derived from nearby mountains. QTs surfaces are alternating eroded ridges and deep valleys, with ridgecrests typically 10 to 30 meters above adjacent active channels. QTs ridges are more deeply incised towards the mountains and the southern end of the map area. The thickness of QTs deposits varies from a few meters near the mountains to 260 m near Amado (Gettings and Houser, 1997). They are drained by deeply incised tributary channel networks. Generally QTs ridges are rounded except where topped by planar remnants of Qo alluvium near the mountain fronts. Pockets of red, well developed soil mantle some of the hillslopes. QTs deposits are dominated by subangular to subrounded boulders, cobbles, and gravels with layers and lenses of sand, silt and clay. Deposits are moderately indurated and are quite resistant to erosion because of the large clast size and carbonate accumulation, which can vary locally from stage III-V (cemented petrocalcic horizons with laminar cap). Vegetation on QTs surfaces typically are grasses with scattered cacti, mesquite, acacia, and ocotillo.

Surficial unit / age	Maximum Redness	Maximum % clay	Maximum % iron	Depth to carbonate (cm)	Maximum stage calcic horizon
Qy_2 <2 ka	7.5 YR 4/3 brown	7	0.6	35	I or none
Qy_1 2-10 ka	7.5 YR 3 /4 dark brown	4	0.5	25 - 60	II
Ql_2 10-20 ka	5 YR 4/6 yellowish red	6	0.4	80 - 150	I
Ql_1 75-130 ka	5 YR 4/6 yellowish red	22	0.6	140 – 200	I-III
Qm 200-500 ka	2.5 YR 3/6 dark red	31 - 44	1.0 – 1.3	65 - 140	II-IV
Qo 1-2 Ma	10 R 3/6 dark red	67	1.3	--	--

Table 1. Soil characteristics for selected surficial units in the Amado-Tubac area. This particular soils chronosequence was described on the Santa Rita piedmont in the Madera Canyon area (northwest of the map area). The original source for this data is Pearthree and Calvo (1987).

<u>Axial Stream Deposits</u>

Axial stream deposits include floodplains and river terraces deposited by the Santa Cruz River and Sopori Wash. Deposits are a mix of gravel, cobbles, sand and finer material; older deposits are coarser than younger deposits; they exhibit mixed lithologies and a higher degree of rounding reflecting the large drainage areas of these streams. Virtually all of the area covered by younger (< 10 ka) river deposits has been altered by intense agricultural and urban develop, so there is greater uncertainty regarding the locations of unit contacts than in piedmont areas. Unit boundaries in these areas are based on 1936 and 1956 aerial photographs, and the soil survey report (USDA, 1979).

Qyc_r **Modern river channel deposits (< 150 years)**--This unit consists of river channel deposits of the Santa Cruz River and Sopori Wash. They are composed primarily of sand and gravel. Along the Santa Cruz River, 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). Channels are extremely flood prone and are subject to deep, high velocity in moderate to large flow events. Channel banks have been protected with soil cement in a few areas, but in general reaches in the map area are unprotected and are subject to several lateral erosion during floods.

Qy_r **Holocene floodplain and terrace deposits (<10 ka)**--The Qy_r unit consists of floodplains and terraces flanking the main channel system along the Santa Cruz River and Sopori Wash. Terrace surfaces are flat and uneroded, except immediately adjacent to channels. These surfaces typically have been altered to agricultural fields or urban development. Qy_r deposits consist of weakly to unconsolidated sand, silt, and clay. Soils are weakly developed, with some carbonate filaments and fine masses and weak soil structure in near surface horizons. Some Qy_r surfaces are part of the active floodplain and may be inundated in large floods. However, most Qy_r terraces were abandoned during the arroyo cutting of the late 1800s and are no longer part of the active floodplain. Locally, Qy_r 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 Qy_r surfaces. Unprotected channel banks formed in Qy_r deposits are very susceptible to lateral erosion.

Qly_r **Holocene to Late Pleistocene river terraces (<~130 ka)**--Qly_r terraces are 2 to 3 m above Qy_r floodplains. These deposits are late Pleistocene river terraces (unit Ql_r) overlain by thin veneers of Holocene fine-grained alluvium (units Qy, Qy_2 and Qy_1). Reddened Pleistocene alluvium is exposed in patches on low ridges, in roads, and cut banks of washes. The Holocene surfaces usually are light brown in color, and soils have weak subangular blocky structure and minor carbonate accumulation. The Pleistocene soils are moderately developed, with reddish brown clay loam to light clay argillic horizons and stage I-II calcium carbonate accumulation.

Ql_r **Late Pleistocene river terraces (~10 to 130 ka)**--Ql_r terraces are typically 3 to 5 m above Qly_r terraces. Unit Ql_r consists of late Pleistocene river terrace deposits composed of gravels, cobbles, and finer-grained sediment. These deposits are often intermixed with late Pleistocene distal piedmont alluvial fan deposits (unit Ql) along drainages where they exit from the lower piedmonts. Ql_r surfaces commonly have loose, open lags of pebbles and cobbles; surface clasts exhibit weak to moderate rock varnish. Ql_r surfaces appear light orange to dark orange on color aerial photos, reflecting reddening of surface clasts and the surface soil horizon. Ql_r soils are moderately developed, with orange to reddish brown clay loam to light clay argillic horizons and stage II calcium carbonate accumulation. Vegetation on Ql_r surfaces is sparse with mesquite and grasses the most common.

Qm_r **Middle Pleistocene river terrace deposits (~130 to 750 ka)**--Unit Qm_r consists of high, scattered river terrace remnants on basin fill deposits (unit QTs) along the west side of the Santa Cruz River. These terraces are typically 45 to 50 m above the modern Santa Cruz River. Qm_r deposits are thin (< 2m) and coarse, consisting of boulders, cobbles, and gravels with finer-grained sediment. Qm_r surfaces appear orange in color aerial photos, reflecting reddening of surface clasts and the surface soil horizon. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Underlying soil carbonate development is typically stage III. Dominant vegetation includes few mesquite and scattered grasses.

Qo_r **Early Pleistocene river terrace deposits (~750 ka to 2 Ma)**--Unit Qo_r consists of very high, scattered river terrace remnants on basin fill deposits (unit QTs) along the west side of the Santa Cruz River. These terraces are typically 50 to 60 m above the modern Santa Cruz River. Qo_r deposits are thin (< 2m) and very coarse, consisting of boulders and cobbles with some finer-grained sediment. Qo_r surfaces appear dark orange in color aerial photos, reflecting reddening of surface clasts and the surface soil horizon. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Vegetation is very sparse, consisting of a few, scattered mesquite and some grass.

Hillslope Deposits

Qc **Holocene and Pleistocene hillslope colluvium**--Unit Qc consists of locally-derived deposits on moderately steep hillslopes in the mountains. Colluvium is very extensive in the mountains, but is mapped only where sufficiently thick and extensive to identify in aerial photographs. 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.

GEOLOGIC/GEOMORPHIC FRAMEWORK

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

The highest levels of basin-fill deposits (unit QT or Qo) in the Amado-Tubac area may have been graded approximately to the ancestral Santa Cruz River before it was significantly entrenched. They are probably approximately correlative with QT deposits mapped in the Catalina foothills on the north side of the Tucson basin (Klawon and others, 1999), Qo and QT deposits mapped in the Tucson Mountain foothills on the west side of the Tucson basin (Pearthree and Biggs, 1999) and in the Green Valley-Sahuarita area (Pearthree and Youberg, 2000), and other high remnant deposits throughout southeastern Arizona (Menges and McFadden, 1981). It is likely that in the late Pliocene to early Quaternary, the surfaces of the Santa Rita and Tumacacori piedmonts were fairly planar, undissected piedmonts that graded downslope to the floodplain 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 Quaternary and Tertiary deposits of the upper Santa Cruz Valley. The high ridges, deep valleys and high remnant fan surfaces characteristic of the Santa Rita and Tumacacori piedmonts, especially towards the southern portion of the map area, attest to the amount of stream erosion that has occurred since the highest levels of alluvium were deposited. Episodes of downcutting of the Santa Cruz caused erosion of the toes of alluvial fans on both sides of the valley, and resulted in much of the stream downcutting in the piedmonts. Streams that head in the Santa Rita and Tumacacori mountains flow across the piedmonts and eventually join the Santa Cruz River. The lower ends of these streams are linked with the 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 downcutting by the larger streams in southeastern Arizona is not certain. Although the upper Santa Cruz River valley was never an enclosed basin (Gettings and Houser, 1997), downcutting along the Santa Cruz River may have occurred as a delayed response of the integration of the Tucson basin streams into the larger regional drainage system. The oscillating climatic conditions of the Quaternary may have resulted in higher long-term erosion rates than during the Miocene and Pliocene (Peizhen and others, 2000). Alternatively, the downcutting may have been driven by some broad regional upwarping of southeastern Arizona, the cause of which is not known (Menges and Pearthree, 1989). Gettings and Houser (1997) attribute the increased incision of the lower piedmonts along the Santa Cruz River in the southern portion of the map area to differential movement of subbasins within the upper Santa Cruz valley through the Holocene.

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

Geologic Hazards

This section summarizes the character and distribution of the principal geologic hazards that exist in and around the upper Santa Cruz River valley. 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 Santa Cruz Public Works Department or Pima County Flood Control District.

Flood hazards. Hazards related to flooding in the Amado-Tubac area may be subdivided into two broad categories. Along the Santa Cruz River and Sopori Wash, flood hazards consist mainly of channel and floodplain inundation and lateral erosion of unprotected channel banks. 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 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 River occurred in 1968, 1974, 1977, 1978, 1983, and 1993. At the Santa Cruz River gage near Nogales, the 31,000 cubic feet per second (cfs) discharge in October, 1977 is the peak of record (Pope and others, 1998). Other large floods recorded at this station occurred in January, 1974 (17,100 cfs) and October, 1983 (16,200 cfs) (Figure 2). At the Santa Cruz River gage near the village of Continental, the 45,000 cubic feet per second (cfs) discharge in October, 1983 is the peak of record (Pope and others, 1998). Other large floods recorded at this station occurred in January, 1993 (32,400 cfs) and October, 1977 (26,500 cfs) (Figure 2). The channel of the Santa Cruz River is entrenched one to several meters below the historical floodplain in most places. The channel capacity in not large enough to convey large flood discharges through this area, however, and floodplain inundation has occurred in the larger historical floods. Lateral bank erosion has been a significant hazard during, with hundreds of feet of erosion occurring during several floods (Parker, 1995; Wood and others, 1999). The banks of some short reaches of the Santa Cruz River have been stabilized with soil cement, but the potential for serious bank erosion exists along extensive, unprotected banks formed in weakly consolidated Qy_r deposits.

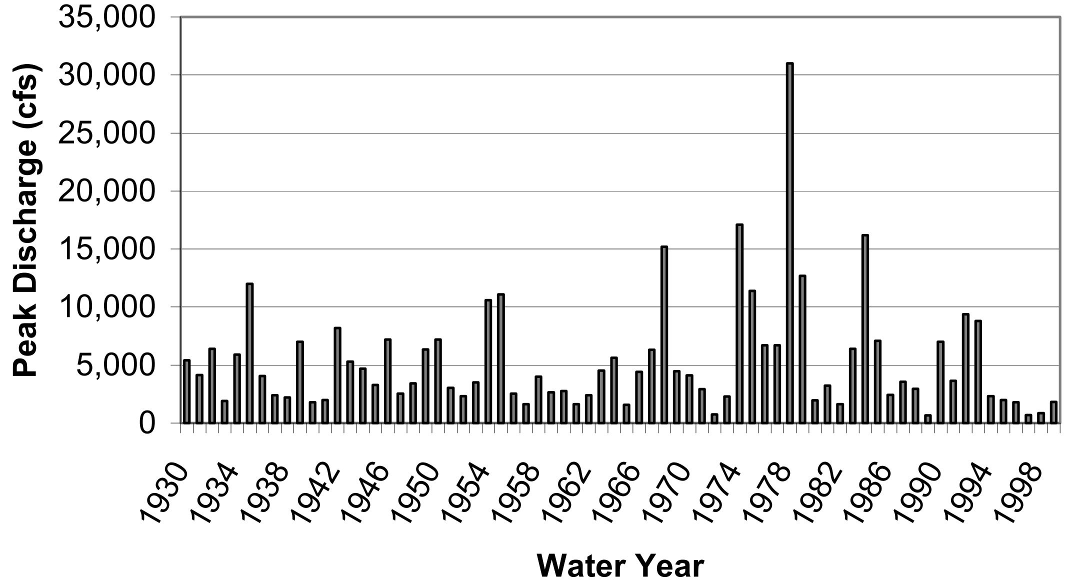
At the gage on Sopori Wash at Amado, which was maintained from 1948 to 1978, a discharge of 16,000 cfs in August, 1948, is the peak of record. Other floods recorded at this station occurred in 1954 (6,500 cfs), 1958 (8,000 cfs) and July, 1972 (7,300 cfs). Lower Sopori Wash is entrenched near its confluence with the Santa Cruz River and has been stabilized with soil cement, but the potential for serious lateral bank erosion exists along extensive, unprotected banks formed in weakly consolidated Qy_r deposits.

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, their positions may shift during floods, and inundation is likely to be widespread.

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 Qy, Qy_2 and Qy_1). 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 on the piedmonts have tributary networks that are topographically confined by ridges of older alluvium. Along these drainages, flood hazards are restricted to active channels and adjacent low, young terraces (unit Qy_2). Portions of the slightly older and higher terraces that are mapped as unit Qy_1 may be subject to rare inundation in extreme floods. There are a few distributary drainage systems on the piedmonts, but channels are generally entrenched into much older deposits and thus these systems are not active alluvial fans. Unconfined flow during floods occurs along the margins of the Santa Cruz and Sopori Wash floodplains, where tributaries debouch from the topographically confined foothills onto the Qy_r

Santa Cruz River Gage near Nogales



Santa Cruz River Gage at Continental

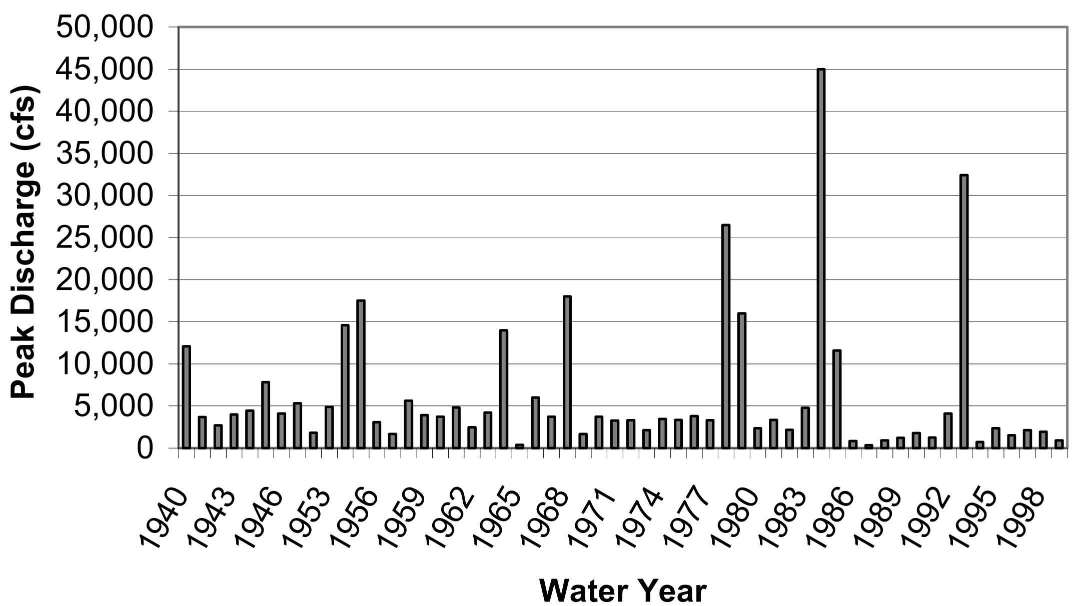


Figure 2. annual peak discharge estimates for the Santa Cruz River at Nogales, south of the map area, and at Continental, north of the map area (U.S. Geological Survey, 2001).

terrace. Drainages in the upper piedmonts and in the southern part of the map area are topographically confined and flood hazards are of limited extent. In the northern most part of the map area, some drainages have unconfined middle piedmont 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 map 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.

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 Qo, 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 (Qo, and QTs) due to the existence of carbonate- and silica-cemented hardpans (petrocalcic and duric horizons). Excavation and infiltration problems may be encountered on all surficial units in the uppermost piedmont areas because of the existence of bedrock at shallow depths.

Land subsidence and earth fissures. In the Tucson metropolitan 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 several hundred feet in parts of the Tucson area. Earth fissures have developed in Avra Valley (northeast of the map area), and recent measurements have indicated that the surface of the central part of the Tucson basin (north of the map area) has begun to subside.

Gettings and Houser (1997) conducted a geological and geophysical investigation of the upper Santa Cruz River valley to determine size and shape of groundwater subbasins, and to evaluate basin-fill sediments as potential aquifers. They found three subbasins within the map area. Depth to bedrock within the subbasins ranged from one kilometer to 500 meters (Figure 3). Upper basin-fill sediments are less consolidated than the lower basin-fill, and are the better aquifer. The thickness of the upper basin-fill ranged from 200 to 300 meters (Figure 4). These results indicates relatively small and limited groundwater aquifers.

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 within the map area have not been monitored, but can be expected to decline as growth in the area continues. 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.

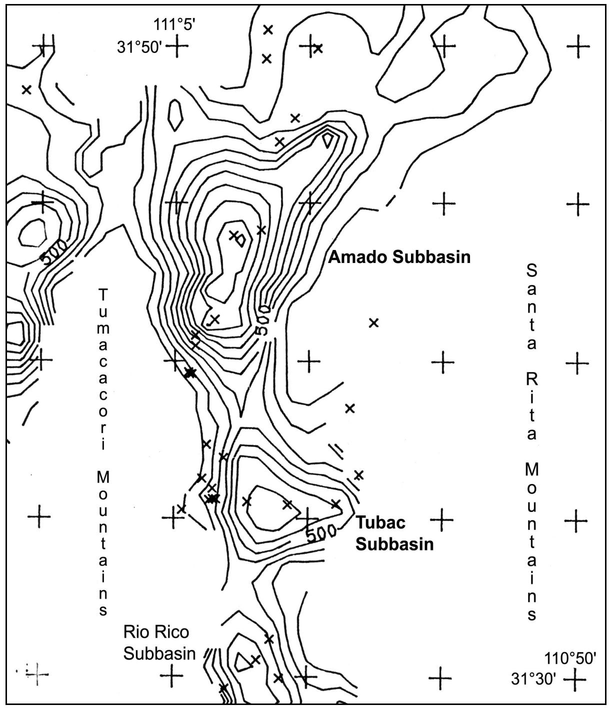


Figure 3. Location of upper Santa Cruz River valley subbasins and depth to bedrock based on geological and geophysical evidence. Contour intervals are 100m, with the shallowest contour equal to 100 m. From Gettings and Houser (1997).

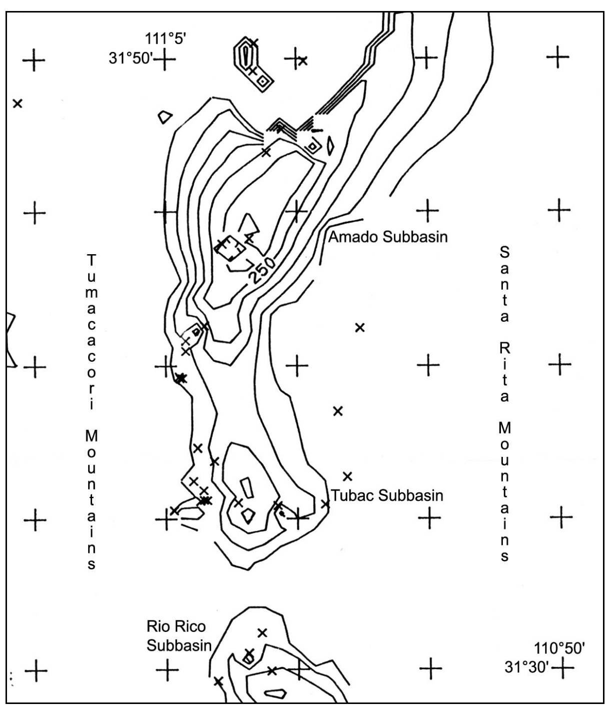


Figure 4. Depth of upper basin fill, upper Santa Cruz River valley subbasins. Contour intervals are 50m, with the shallowest contour equal to 50 m. From Gettings and Houser (1997).

Measurements 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 (Galloway and others, 1999).

In Arizona basins where subsidence is more than a few feet, earth fissures have developed. 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. 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). With the expected lowering of water tables and subsequent predicted land subsidence, earth fissures will most certainly develop in Tucson as they have elsewhere. Within the map area, there is potential for land subsidence with increasing groundwater withdrawal, and for the development of earth fissures along the margins of the subbasins.

Earthquake hazards. The surficial geology of the Santa Rita piedmont provides data with which to evaluate the behavior of the Santa Rita fault zone, which extends from Tubac to just northeast of Corona de Tucson. A discontinuous zone of fault scarps offset Pleistocene alluvium along about 60 km (35 miles) of the western piedmont of the Santa Rita Mountains. Scarps trend northeast to north-south and are 1 to 6 km west of the base of the Santa Rita Mountains. Scarps range up to about 5 m in height and have maximum slope angles up to 9° (Pearthree and Calvo, 1987). Surficial units as young as late Pleistocene (unit Ql_1) are displaced, but latest Pleistocene (unit Ql_2) and Holocene (unit Qy) deposits are not faulted, which brackets the age of youngest faulting between 10-20 ka and 75-130 ka. Quantitative analysis of fault scarp morphologies indicates that the youngest surface rupture occurred between about 60-130 ka (Helmick, 1986; Pearthree and Calvo, 1987). In the central part of the fault zone, displacement of late Pleistocene surfaces averages about 2 m, in contrast to 4 to 5 m of displacement of middle and early Pleistocene surfaces. Using surface displacement estimates and various estimates of surface rupture length, Pearthree and Calvo (1987) concluded that two paleoearthquakes of magnitude 6 ¾ to 7 ¼ occurred along the Santa Rita fault zone in the past 200 to 300 ka. Helmick (1986) also concluded two periods of surface rupture based on profile analysis using a diffusion-equation model derived from the continuity equation for hillslope degredation.

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

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