Surficial Geology and Geomorphology of the Tinajas Altas Area, Barry M. Goldwater Air Force Range, Yuma County, Southwestern Arizona

by Thomas H. Biggs, Karen A. Demsey and Philip A. Pearthree

Arizona Geological Survey
Open-File Report 02-02

January, 2002

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

Includes 21 pages of text and one 1:24,000-scale geologic map

Research supported by the U.S. Dept. of Defense, Luke Air Force Base and the Arizona Geological Survey

Research done in cooperation with SWCA, Inc. and Arcadis Geraghty and Miller

INTRODUCTION

This report summarizes the surficial geology and geomorphology of the Tinajas Altas area on the Barry M. Goldwater Air Force Range in southwestern Arizona (Figure 1). The purpose of these investigations is to provide a geologic and geomorphic framework for an archaeological survey of this area. The geologic map included with this report covers parts of several 1:24,000-scale topographic quadrangles that cover the study area (Plate 1). Interpretation of aerial photographs was done primarily by Karen Demsey, with review and field checking by Thomas Biggs, with field assistance from Philip Pearthree of the Arizona Geological Survey. Map compilation and report preparation was done by Biggs. Final editing and formatting of this report was done by Pearthree.

Acknowledgments. Numerous individuals contributed to these geomorphologic investigations. We would like to thank all of the members of the archaeological field crew. In particular, we thank Mark Slaughter, who oversaw the field efforts, coordinated our field investigations with those of the archaeological survey, provided lots of information about the archaeology of the region, and generally kept us from getting into too much trouble.Sean Kneale and Tim Orr assisted with production of surficial geologic maps, and Tim Orr is responsible for the final map layout.

Previous Work. Previous geologic investigations conducted in the Tinajas Altas area mapped units ranging in age from Early Tertiary to modern (Table 1). However, detailed mapping of the bedrock and surficial deposits has not previously been done. Bryan (1925) explored the region as part of a project to locate, survey, and describe potential water sources; he described the general geology and geomorphology of the area. Wilson described the rocks of the Tinajas Altas Mountains as “coarse-grained, grayish-white sodic granite with pegmatite dikes” and “Mesozoic granite and related crystalline intrusive rocks” in an overview of the bedrock geology of southern Yuma County (Wilson 1933: p. 178), later published as part of a 1:375,000-scale geologic map of the Yuma area (Wilson 1960). Olmsted et al (1973) mapped the mountains as “Upper Cretaceous and older crystalline rocks” bordered by undissected piedmont slopes covered with alluvium divided into two units. Later investigations indicated the granites are about 53 million years old (Eocene) and gave the name “Gunnery Range Batholith” to the leucocratic (“light-colored”) two-mica granite that is the principle bedrock unit (Shafiqullah et al 1980). Arnold (1986) described the detailed geochemistry of the Gunnery Range granite, including two samples with age determinations from the Tinajas Altas Mountains, and discussed the tectonic implications of batholith emplacement. Bull (1973a, 1973b, 1991) developed a conceptual framework for understanding the impacts of climatic changes on arid region fluvial systems of the lower Colorado River region. The tectonic geomorphology of the Luke Air Force Base was described by Tucker (1980) and included interpretations of landform characteristics that incorporated some generalized surficial geology of the study area.

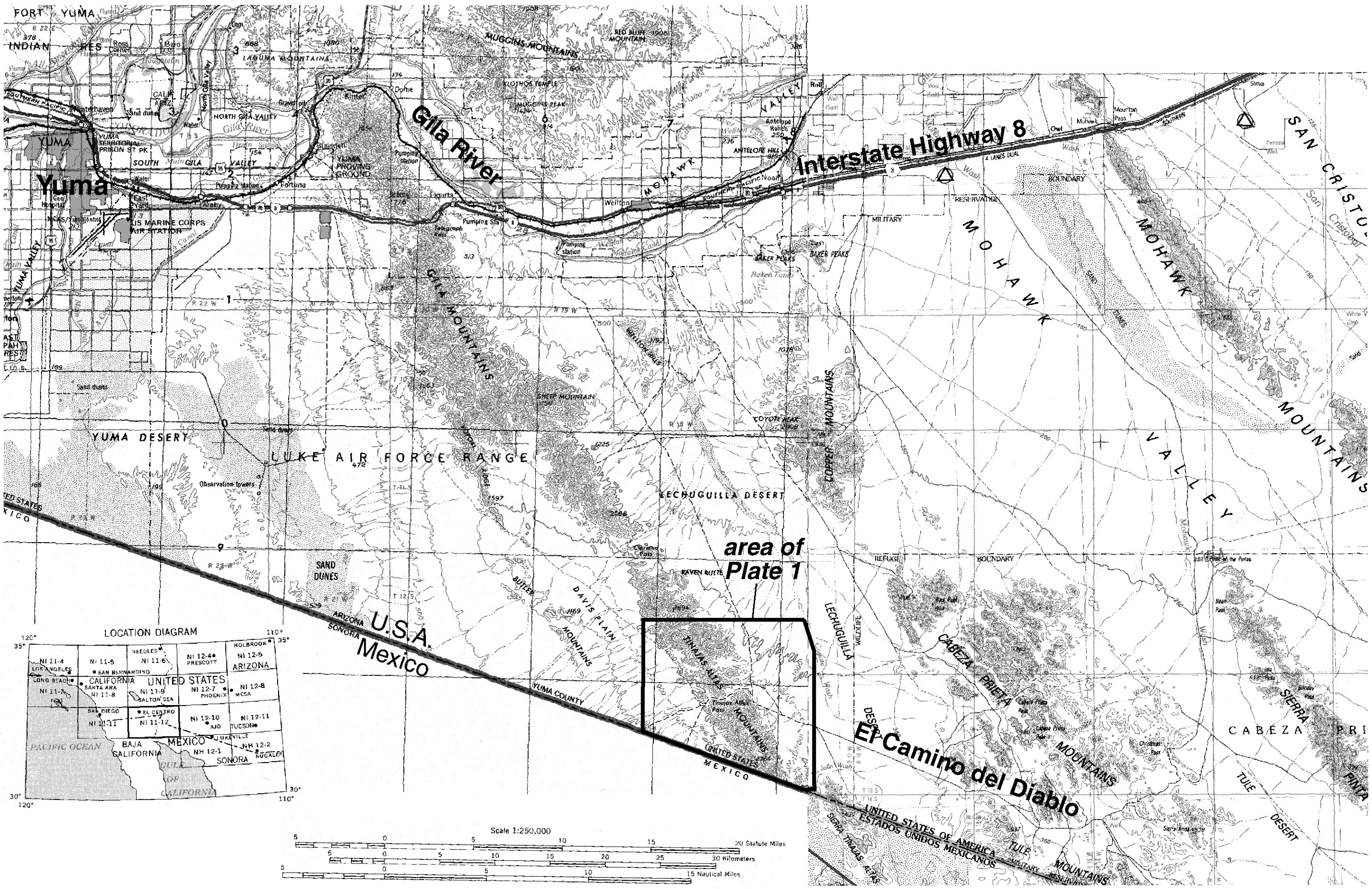


Figure 1. Location of the study area on the Barry M. Goldwater Air Force Range, southwestern Arizona.

Quaternary (0 to 1.8 Ma)	Holocene (0 to 10 ka)	late Holocene (0 to 4 ka)
		early to middle Holocene (4 to 10 ka)
	Pleistocene (10 ka to 1.8 Ma)	late Pleistocene (10 to 150 ka)
		middle Pleistocene (150 to 750 ka)
		early Pleistocene (750 ka to 1.8 Ma)
Tertiary (1.8 to 65 Ma)	Pliocene (1.8 to 5.5 Ma)	
	Miocene (5.5 to 22 Ma)	
Proterozoic (570 Ma to 2.5 Ga)		

Table 1. Time intervals as used in this report. "Thousands of years before present" is abbreviated as **ka**; "millions of years before present" is abbreviated as **Ma**; "billions of years before present" is abbreviated as **Ga.**

Climate. The climate of the study area is currently hot and dry, with marked seasonal temperature variations. The nearest weather station to the Tinajas Altas is at Yuma (elevation 194 feet asl), where the average July high temperature is 106 ^{o} F and the average December-January low temperature is 44^{o} F (Western Regional Climate Center, NOAA). Freezing temperatures are rare. The average annual precipitation at Yuma is 3.17" and is spread fairly evenly from August to March, although August (0.6") averages slightly more than twice the typical precipitation of the other months. The months of April thru June are usually dry. Late summer monsoon thunderstorms, generated by moist air from the eastern Pacific Ocean or dissipating tropical depressions, and winter precipitation originating from Pacific cyclonic storms provide the minimal rainfall that reaches the Tinajas Altas region.

The climate of the Sonoran desert has not remained constant over the time period represented by the alluvial deposits and surfaces flanking the Tinajas Altas Mountains (Van Devender 1990). The transition from the relatively warm and stable Pliocene climate to the dramatic glacial-interglacial cycles of the Pleistocene resulted in major aggradation and erosion events recorded as alluvial fans and fan remnants in the study area (Bull, 1991). Late Pleistocene midden samples from the western Sonoran Desert contain fragments of juniper, pinyon pine, and Joshua tree, indicating cooler summers and a greater proportion of winter rain than today (Van Devender et al 1987). Precipitation probably reached a maximum during the late Pleistocene (30 to 10 ka), which, combined with reduced seasonal temperature extremes, apparently caused the late Pleistocene climate to be more conducive to weathering of bedrock and soil minerals than the dry interglacial moisture regime of the present. Late Pleistocene to early Holocene (~12 to 9 ka) was a period of two distinct pluvial episodes, the first characterized by lowered temperatures and enhanced winter rainfall, the second by temperatures similar to the modern with enhanced monsoons (Spaulding and Graumlich 1986). Stronger monsoons would result in greater runoff and possibly greater biodiversity, although desert-scrub communities probably persisted along the Colorado River at elevations below about 400 m (approximately the elevation of the base of the Tinajas Altas Mountains) between 11 and 8 ka (Van Devender et al 1987). During the middle Holocene, dramatically increased summer temperatures produced maximum summer monsoonal rainfall in the Tinajas Altas Mountains; winter freezes and drought were more frequent (Van Devender et al 1987). Analyses of packrat middens indicate that the climate similar to today has existed since about 4 ka (Van Devender 1990).

GENERAL GEOLOGY AND GEOMORPHOLOGY

The Tinajas Altas Mountains are located in the western portion of the Sonoran Desert subprovince of the Basin and Range physiographic province (Menges and Pearthree 1989). The Basin and Range province includes southern, central, and western Arizona, all of Nevada, parts of California, New Mexico, Oregon, Texas, and Utah, as well as much of northwestern Mexico. The physiography of the Basin and Range province is characterized by alluvial basins and intervening mountain ranges that formed as a result of widespread tectonism beginning about 25 million years ago (Ma), followed by regional block faulting related to extension of the crust between 15 and 8 Ma (Eberly and Stanley 1978; Shafiqullah et al 1980). As a result, relatively narrow and not very high, north- to northwest-trending ranges and broad, minimally dissected basins are typical of the Sonoran Desert. These basins, bounded by high-angle normal faults, were depositional sites, initially as closed drainages, for locally derived material shed from adjacent highlands. Beginning about 3 Ma, upwarping and eustatic changes of sea level have increased the gradient along the Colorado and Gila Rivers, which allowed these river systems to remove great quantities of alluvial material from tributary valleys, thus exposing older valley-fill material on the alluvial surfaces in portions of southern and central Arizona (Eberly and Stanley 1978). Tectonic activity also changed to strike-slip faulting associated with the San Andreas system to the west, although the study area apparently has had minimal fault movements during the past 1 My. (Tucker 1980).

Strike-slip faulting that has only a small vertical component will not display the typical landforms of a tectonically active mountain front. Instead of a change to the base level of fluvial systems producing fault scarps and incised channels, strike-slip movements result in features such as offset ridges and disrupted drainage patterns. The faulting created a zone of weakness for subsequent erosion, producing lower topographic relief along the trace of the fault: where such movements cut a mountain range, a gap or pass may develop through the range. Cipriano Pass, to the north of the study area, formed where two left-lateral late Cenozoic strike-slip faults cut the Tinajas Altas Mountains with about 200 m of offset (Tucker 1980). Tinajas Altas Pass, one of the principle routes of the *El Camino del Diablo*, is roughly parallel to Cipriano Pass and probably has a similar origin. The strike-slip faults have apparently been inactive during the late Quaternary.

Although the overall trend of the Tinajas Altas Mountains is straight, most of the mountain fronts on both east and west flanks are highly embayed. Embayed topography and the high sinuousity of the mountain fronts indicates that differential weathering of the tectonically active fronts has had a long time to operate in the absence of renewed tectonic activity (Bull 1973). The southern part of the mountains have less sinuous mountain fronts, particularly on the western side, and there are numerous narrow straight valleys within the mountains that parallel the overall mountain trend that suggest the possibility of intermittent Quaternary uplift (Plate 1), although these valleys more likely reflected bedrock joint patterns. Olmsted et al (1973) mapped a fault along the western flank of the range from Tinajas Altas Pass to the southeast along an unnamed valley. Most of the alluvium near the mountains appears to be of late Pleistocene and Holocene age, and the absence of old dissected alluvial deposits adjacent to the mountain fronts and the lack of recognizable fault scarps cutting the Pleistocene deposits support the conclusion that the area has been tectonically quiescent through the late Quaternary.

Bryan (1925) described the tanks at Tinajas Altas (described in detail below) as being the result of renewed uplift along the range-bounding normal faults in which downcutting of the stream has not kept pace with the change in stream grade across the fault scarp. However, valleys to the northwest and southeast of the tanks do not show similar evidence of “renewed uplift”. It appears preservation of the upland valley above the tanks, perhaps due to bedrock variables, is unique in the mountain range. The apparent lack of extensive old alluvial surfaces away from the mountains also suggests tectonic stability, in that base-level fall has not caused incisement of trunk and tributary streams in the flanking basins and the older alluvium remains buried.

The landscape of this part of Arizona may be divided into three main elements:

Rugged, but not very lofty mountain ranges. Although the overall trend of the Tinajas Altas Mountains is straight, the topographic fronts of the mountains are generally very embayed and sinuous (Figure 2). Outlying bedrock hills (inselbergs) are common on both

Figure 2. Rugged topography and embayed mountain front on the west side of the Tinajas Altas Mountains. Qm fan forms the surface in the foreground.

Figure 3: View east from upper tanks across Lechuguilla Desert and Coyote Wash axial drainage. The dissected Ql surface is prominent in the lower left part of the photo. Younger surfaces dominate farther down the piedmont. A remnant of a Qm fan is preserved near the right edge of the photo (arrow).

sides of the range. Mountain slopes meet the flat desert floor at a sharp angle, except where major channels exit from the mountains. Very steep, embayed topography with minimal colluvial cover indicates that erosion of the mountain fronts has had a long time to operate in the absence of renewed tectonic activity (Bryan 1925; Bull 1973a). Erosion is facilitated by uncommon but intense rainfall and runoff, steep slopes, and sparse vegetative cover.

Broad valley floors covered by deposits of larger axial washes. The larger washes in this region generally flow down the axes of the valleys about midway between the adjacent ranges. Floodplains associated with these washes are composed mainly of sand, silt, and clay, with local gravelly channel deposits. Lechuguilla Valley forms the eastern part of the present study area, and Coyote Wash is an anastomosing channel in the broad, nearly horizontal center of the valley (Figure 3). The channel can be up to 30 m wide with banks about 1 m high; the channel bottom is filled with coarse sand, which locally forms large wave bedforms. The tributary streams feeding Coyote Wash are all ephemeral, active only during or immediately after rains. During storm events, these streams may have multiple channels or spread out into broad sheets. The sand waves observed in the main channel in 1998 attest to the large volumes of water that can move through this arid landscape.

Piedmonts with minimal topographic relief. Piedmonts are the broad plains that slope gently from the mountains to the axial washes. They are covered by a more or less continuous veneer of alluvial deposits, which range in age from modern to early Pleistocene. Geophysical studies indicate the alluvial cover adjacent to the Tinajas Altas Mountains may be greater than 500 m thick (Sumner 1972; Scarborough 1985), although the presence of inselbergs more than a kilometer from the main range suggest a thinner blanket is present on the Davis Plain to the west (Figure 4). Upper piedmont areas typically have tributary (converging downstream) drainage systems that flow in entrenched, well-defined channels. Entrenchment can be 2 to 5 m below adjacent relict fan surfaces on upper piedmonts, but the relief usually decreases to less than 1 m less than a kilometer downstream of the mountain front.

The archaeological survey was centered on the Tinajas Altas Pass and the natural tanks just south of the eastern end of the pass. Although the area covered by the survey and this map is fairly small, each of the three landscape elements are represented. Granite bedrock is the source for virtually all the alluvial material in the study area. The deposits associated with the central valley tributary washes and the piedmont washes are identical and, therefore, were not differentiated on the map. Deposits associated with the axial Coyote Wash were mapped as separate units.

GEOLOGIC IMPACTS ON HUMAN ACTIVITIES

In a harsh arid environment like that of the Tinajas Altas area, the availability and accessibility of water is the key factor in the survival of plants and animals. Human efforts to inhabit the region, or merely pass through it, have also been tied to finding an

Figure 4: View west across Davis Plain on west side of Tinajas Altas Mountains. Most of alluvial surface is Qy3 and Qy2 material, with remnants of white Qm fans in middle distance. Note inselburgs in near-distance, suggesting the total alluvial cover is not thick.

adequate source of portable water. Reports of numerous graves along the *El Camino del Diablo* and below the rock tanks of Tinajas Altas attest to the thin line between a successful journey and untimely demise. The geology of the Tinajas Altas played a critical role in the availability of water supplies to travelers in the form of rock tanks. Rock tanks ("tinajas" after the Spanish word for bowl or jar) refer to depressions or cavities in rock formed by unequal erosion of the streambed by current eddies. In ephemeral streams, water may fill these tanks after rainfall or flow events and remain there for some time.

The granite bedrock that makes up the Tinajas Altas Mountains has several characteristics that facilitate the development of rock tanks. Most rocks are divided into blocks by sets of intersecting fractures (or joints), which provide zones of weakness for water and sediment to erode the otherwise resistant rock. Three prominent joint sets are conspicuous in the rugged, blocky topography of the Tinajas Altas Mountains. Topographic relief is the second key aspect to the development of cavities in the granite bedrock, for it is at the base of waterfalls that the most significant erosion may occur. Plunge pools are formed by the impact of water, gravel, and sand and resulting turbulence below waterfalls. Even in areas of infrequent flow, the erosive effects can be quite significant. A third aspect for the development of large tanks is a watershed of considerable size to funnel sporadic runoff to the stream channel. In the rugged Tinajas

Altas Mountains, a sizeable upland valley may be the most important element for the development of significant rock tanks.

The most important of the tanks in the study area are the series of nine plunge pools that make up the principal tinajas in the map area. The map (Plate 1) shows that the falls occur in a cove of the mountain front about one kilometer south of the Tinajas Altas Pass. An upland valley forms the headwaters of the stream that cascades more than 100 vertical meters to reach the alluvial fan below the lowest waterfall. The development of the falls and the plunge pools are a direct result of the intersection of three major joint sets. The main set has a strike of N 2^{o} E and dips 65^{o} NE, and divides the granite into slabs 0.5 to 3 m thick (Figure 5); a second set has a strike approximately parallel to the mountain front and is nearly vertical (Figure 6). A third joint set, with a strike of N 80^{o} E and a near-vertical dip, probably provided the zone of weakness and controlled the pathway for the stream to cut its channel through the granite. Bryan (1925) noted that the falls are generally parallel to the dip of the joints and that the plunge pools occur in places where the joints are closely spaced; the steepest grades are parallel to the two minor joint systems. Smaller tanks in Surveyors Wash and near Raven Butte, as well as numerous unmarked ones, are controlled by similar joint patterns, but lack the upland valley present at Tinajas Altas.

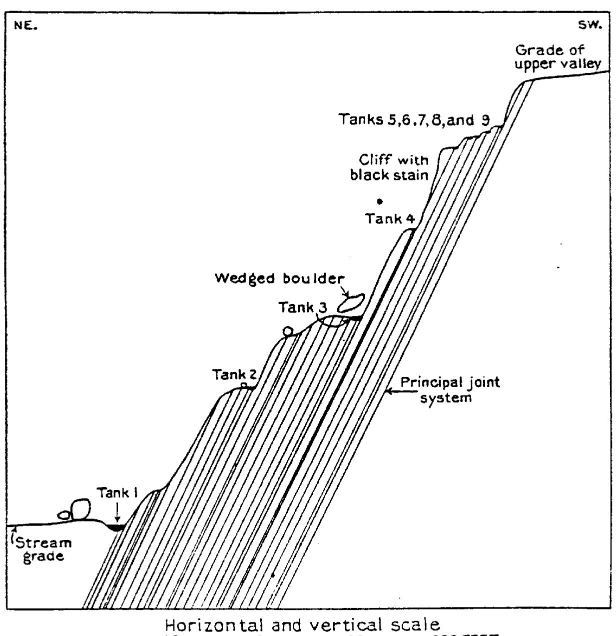


Figure 5: Diagrammatic profile of the falls of Tinajas Altas (from Bryan 1925), showing the main joint set and distribution of tanks.

Figure 6. The uppermost tank of Tinajas Altas; the rounded gravels help form the potholes in the granite bedrock. The prominent layers in the bedrock are the main joint set, which dips 65^{o} NE; the near-vertical joint set is also evident.

Coyote Water is another type of natural water storage found in the study area. Unlike the bedrock tanks, Coyote Water is located in the main stream channel of the Lechuguilla Valley. Coyote Wash is a channel filled with coarse sand, but at Coyote Waters the scouring action of sand and water on the outside of a channel meander during periods of flow has scoured a depression in the hardpan that underlies the sand of the channel (Bryan 1925). As a result, water is trapped in the void spaces between the sand grains that fill the cavity approximately four feet below the surface. The amount and duration of the water supply are limited due to the size and depth of the scour depression, and plant roots give it a bad taste (Bryan 1925).

Beginning with Padre Kino in 1699, the *El Camino del Diablo* served as a principle overland route for immigrants heading for California. Some of these travelers no doubt examined the few scattered exposures of hematite-stained bedrock in the Tinajas Altas Mountains for deposits of gold, silver, copper, or other metals, especially after the discovery of the Fortuna gold mine 25 miles to the north. No workings or mineral production have been reported from the study area (Keith 1978). One prospect adit approximately 20 m deep was dug on the north side of Borrego Canyon about 2 km south of Tinajas Altas, apparently to explore a thin hematite-stained quartz veinlet with minor pyrite and copper oxides that cut the granite.

Another feature of the geology and geomorphology of the Tinajas Altas Mountains is the development of numerous cavities in the granitic bedrock. These cavities, also known as “niches” (Bryan 1925) or “tafoni” (Fairbridge 1968), range in size from a few cubic centimeters to caves more than a meter high and several meters deep (Figure 7). The larger examples provided shelter for prehistoric inhabitants as well as later travelers, as evidenced by soot and rock art on walls and artifacts found inside. The tafoni interiors have a rough friable surface and lack desert varnish; retreat of interior walls is locally quite rapid, but painted graffiti was legible after 50 years (Bryan 1925) and the prehistoric rock art is considerably older.

Tafoni have been described in numerous environments and locales around the globe (Fairbridge 1968), although coarse-grained granitic rocks similar to the Gunnery Range Granite are typically the host rock. The origins of the features are not clearly understood. Tafoni in the Atacama Desert of Chile were described as forming due to differential wetting and drying, hydration of feldspar crystals to clay minerals, and removal of waste by wind erosion (Segerstrom and Henriquez 1964). Bryan (1925) noted the “niches” work inward from the rock face, loosening successive flakes and chips, and appeared to be the work of variable solar insolation and solution. Because of the wide range of environmental settings in which tafoni form, Fairbridge (1968) favored a combination of physical and chemical weathering factors with water acting as a catalyst; tafoni development was thought to favor more persistently moist places. In South Australia, Bradley et al (1977) argued that tafoni configuration, distribution, and mineralogy ruled out thermal changes or wetting-and-drying as major contributors to development of the features. They suggest salt crystal growth is the principal cause of tafoni growth, with the salts originating from fluid inclusions within the fresh granite, not from external sources. Several lines of evidence favor this hypothesis for the Tinajas Altas area: (1) the development of tafoni does not favor any particular exposure or orientation; (2) the granite has been affected by metamorphism, as indicated by the gneissic texture and mineralogy; (3) the granite has been affected by tectonic stresses, which produced multiple joint sets, in addition to residual strain produced by magmatic cooling and erosional unloading; (4) whole-rock geochemistry indicates higher than typical granite Na_2O values for the Gunnery Range Granite; (5) the abundance of large feldspar crystals and quartz crystals which could contain fluid inclusions; and (6) the lack of clay minerals on tafoni walls, which should be there if hydrolysis of feldspar or biotite crystals were a factor.

Figure 7. Tafoni development in granite cliff face, east-facing exposure on the north side of Tinajas Altas Pass. Features range in size from small cavities to sizeable caves.

MAPPING TECHNIQUES AND GROUND CONTROL

We employed standard surficial geologic mapping techniques to produce geologic maps of the project area. We produced a 1:24,000-scale geologic map of the overall project area, which included portions of the Tinajas Altas, Butler Mountains, and Coyote Waters 7.5' quadrangles (Plate 1). The reconnaissance mapping was based primarily on interpretation of approximately 1:24,000-scale color photographs flown in November 1985 that were supplied by the Air Force. More extensive field surveys were conducted in selected areas and natural exposures were examined; field checking in the rest of the mapped area was limited.

Surficial geologic units in the project area were differentiated by the source and process of emplacement of the deposits and their relative age. The physical characteristics of sedimentary units and surfaces -- such as alluvial fans, river channels, or stream terraces -- are shaped by large-scale depositional processes. If the initial surfaces of such deposits are not buried by subsequent deposits or destroyed by erosion, they are gradually modified over thousands of years by other processes, which operate very slowly and on a smaller scale in arid and semiarid environments. These modifying processes include (1) small-scale erosion and deposition (for example, wind or rain effects) and bioturbation that smooth the original surface topography; (2) the development of soils, primarily through the chemical breakdown of original rock constituents and the accumulation of silt, clay, and calcium carbonate; (3) the development of surficial gravel pavements ("desert pavements") above zones of accumulated silt and clay; (4) accumulation of rock varnish on exposed bedrock and rock fragment surfaces; (5) development of dendritic tributary stream networks on alluvial surfaces; and (6) entrenchment of these secondary streams below the original depositional surfaces and subsequent dissection of those surfaces.

Alluvial surfaces of similar age have a characteristic appearance because they have undergone similar post-depositional modifications. There are distinct differences between younger and older surfaces and the ages of alluvial surfaces in the southwestern United States may be roughly estimated based on these surface characteristics, especially the extent of soil development (Bull, 1991). Old surfaces that have been isolated from deposition or reworking for hundreds of thousands of years are characterized by strongly developed soils with thick clay- and calcium carbonate-rich horizons; such surfaces may also have smooth, closely packed desert pavements of strongly varnished surface rocks above entrenched drainages. Young fan surfaces often retain characteristics of the original depositional topography, show minimal development of soil, desert pavement, or rock varnish, and are basically undissected.

Surficial deposits were grouped into two broad genetic categories. Piedmont alluvium deposited by tributary streams consists of small channels and adjacent floodplains, terraces, and alluvial fans. Alluvium on the central valley floor deposited by Coyote

Wash consists of channels and low terraces. Alluvial deposits were further subdivided based on their ages, using criteria described below.

DESCRIPTION OF MAP UNITS

Surficial deposits on the accompanying map (Plate 1) are classified by inferred age. Deposits are divided by age into late Holocene (Qy3; less than about 2 ka), late to middle Holocene (Qy2; about 2 to 6 ka), middle to early Holocene (Qyl; about 6 to 10 ka), latest Pleistocene to very early Holocene (Qly; about 8 to 15 ka), late Pleistocene (Ql; about 10 to 130 ka), late middle-Pleistocene (Qml; about 50 to 250 ka), middle Pleistocene (Qm; about 130 to 750 ka), and early Pleistocene (Qo; 750 ka to 2 Ma). Ages of all these deposits are roughly estimated by correlation with other similar areas, because no useful constraints have been developed for most of the surficial deposits in these valleys. Age estimates given here are based on correlations with surface chronosequences developed in the lower Colorado River Valley by Bull (1991) and previous studies conducted farther east on the Goldwater Range (e.g. Pearthree et al, 2001; Demsey et al, 2002).

Surficial Geologic Units

Qdf - recent debris flows and rock falls

Historic and young prehistoric landslides and rock falls of spalled bedrock and unconsolidated rocks from steep slopes, with lack of uniform desert varnish on exposed surfaces.

Qy3, Qy3r - latest Holocene alluvium (< 2 ka)

Active channels, undissected floodplains, low terraces, and active or recently active alluvial fans. On middle and lower piedmonts, deposits consist of sand, silt, and clay, with local channel gravel deposits. Channels are typically small, shallow, discontinuous, and usually braided, except along the active Coyote Wash riparian area (**Qy3r**), which has a channel >20 m wide and 1-2 m deep with thick accumulations of coarse sand. On the upper piedmonts, deposits typically consist of sand to large boulders in well-defined braided channels, with sand and finer clastic deposits on adjacent slightly higher areas subject to overbank flooding.

Qy2, Qy2r - late to middle Holocene alluvium (2 to 5 ka)

Undissected terraces and alluvial fans somewhat isolated from active channels. Alluvial surfaces are typically < 1 m above the adjacent washes and are partially covered by weak pavements or residual gravel deposits composed of coarse sand and pebbles with minimal rock varnish. Locally, there is some eolian overprint consisting of linear to semicircular coppice dunes associated with small shrubs and cacti. Vegetation is usually sparse, although grasses may be abundant in wet seasons. Surface color is light brown, typically somewhat lighter than **Qy3** surfaces.

Qy1 - middle to early Holocene alluvium (5 to 10 ka)

Weakly to moderately dissected terraces and alluvial fans that are higher and lighter brown than surrounding **Qy2** surfaces. In upper piedmont areas, surfaces have weak to moderate pavements composed of subangular to subrounded cobbles and pebbles and may be up to 2 m above active channels. In lower and middle piedmont areas, **Qy1** surfaces typically have tributary drainage networks that are incised less than 1 m with pavements composed of subrounded pebbles and coarse sand. Soils associated with this unit are weakly developed, with minimal clay and thin discontinuous carbonate coatings on the tops of clasts (Table 5.2). **Qy1** deposits are probably correlative with units Q3a and Q3b of Bull (1991).

Table 2. Description of soil profile - Unit Qy1

Location: Tinajas Altas 7.5' quadrangle, ~ 32°19'52", 114°04'11", northern Tinajas Altas Pass

Altitude: 1170 ft Landform: stream terrace Slope Steepness: < 5%

Parent material: Granite alluvium Land use: Unused Vegetation: Sparse

HORIZON	DEPTH (cm)	DESCRIPTION
surface	--	Lag deposit of subangular granite cobbles and small pebbles with interstial sand and silt about 1.5 to 2 m above the active stream channel.
A	0-3	Loamy sand; light brown (7.5YR, 6/4); fine grained, weakly vesicular, platy; soft to loose, very slightly sticky, very slightly plastic; abrupt, wavy boundary.
Bt	3-17	Loamy sand; light brown (7.5YR, 6/4); weak, massive to weak subangular blocky; soft, non-sticky, non-plastic; sharp, wavy boundary.
Btk	> 17	Gravelly sandy loam; light brown (7.5YR, 6/4); loose; soft, non-sticky, non-plastic; very thin discontinuous carbonate coatings on tops of pebbles, cobbles.

Qly - early Holocene to latest Pleistocene alluvium (8 to 15 ka)

Moderately dissected alluvial fans and terraces adjacent to mountain fronts with well-developed tributary drainage networks. Modern channels are typically incised about 2 m below **Qly** surfaces. Surfaces are light brown to light grayish brown and have weak pavements of cobbles and pebbles.

Ql - late Pleistocene alluvium (10 to 130 ka)

Older relict fans with moderate soil development and well-developed, entrenched tributary drainage networks. Surfaces are very light brown to creme colored and sparsely vegetated (Figure 8). Modern channels are incised up to 3 m below **Ql** surfaces adjacent to mountain fronts, but only about 1 m in more distal lower piedmont areas. Between modern channels, surfaces are planar with subdued bar and swale topography, weakly developed pebble and small cobble pavements (average clast size diminishes with distance from bedrock source), and incipient rock varnish. Soils are weakly to moderately developed with weakly indurated carbonate zones and discontinuous carbonate coatings on pebbles and cobbles (Table 3). **Ql** deposits are probably correlative with Q2c of Bull (1991).

Qml - middle to late Pleistocene alluvium (50 to 250 ka)

Relict alluvial fans and terraces with well-developed tributary drainage networks. Most of these surfaces are preserved adjacent to mountain fronts. Modern channels are typically incised about 2 m below **Qml** surfaces. Surfaces are light brown to cream colored, planar to slightly rounded, and are moderately dissected with weak pavements of cobbles and pebbles. **Qml** is probably correlative with unit Q2b of Bull (1991).

Qm - middle Pleistocene alluvium (130 to 750 ka)

Relict alluvial fans with cream to white planar to slightly rounded surfaces typically preserved away from mountain fronts (Figures 2 and 4). Surfaces are well dissected, have moderate to well-developed bar-and-swale pavements of granitic cobbles and pebbles, and are very sparsely vegetated. Soil development is moderate (Table 4); carbonate development is also moderate, with soft nodules giving subsurface horizons a mottled look. Carbonate coatings on pebbles are thin and discontinuous. **Qm** is probably correlative with units Q2a and Q2b of Bull (1991).

Figure 8. Ql surface in Tinajas Altas Pass just east of drainage divide. Cutbank exposure reveals weakly developed soils. Surface is incised by Qy3 drainages.

Table 3. Description of soil profile - Unit Ql

Location: Tinajas Altas 7.5' quadrangle, ~ 32°19'48", 114°04'10", northern Tinajas Altas Pass

Altitude: 1180 ft　　Landform: stream cutbank　　Slope Steepness: vertical

Parent material: Granite alluvium　　Land use: Unused　　Vegetation: Sparse

HORIZON	DEPTH (cm)	DESCRIPTION
surface	--	Weakly developed pavement of broken quartz and feldspar crystals and granitic pebbles, cobbles, and boulders;
A	0-2	Gravelly sandy loam; pink (7.5YR, 7/4); slightly vesicular, medium to coarse platy; soft, slightly sticky, slightly plastic; abrupt, smooth boundary.
Btk1	2-8	Loamy sand; pink (7.5YR, 7/4); massive breaking to weak, medium subangular blocky; soft, very slightly sticky, non-plastic; minor carbonate as loose nodules (up to 1 cm) and thin discontinuous coatings on pebbles; sharp, smooth boundary.
Btk2	8-30	Gravelly loamy sand; light brown (7.5YR, 6/4); weak, medium to coarse subangular blocky; soft, very slightly sticky, non-plastic; carbonate as variable discontinuous coatings, thicker than above; zones of weakly indurated carbonate which are vertically, but not laterally, continuous; clear, wavy boundary.
Btk3	30-150	Loamy fine sand; light brown (7.5YR, 6/4); massive, weakly indurated and somewhat oxidized; hard, non-sticky, slightly plastic; carbonate as filaments and discontinuous coatings on pebbles; widely dispersed pebbles and cobbles and lack of sedimentary structures suggest debris flow origin.

Table 4. Description of soil profile - Unit Qm

Location: Tinajas Altas 7.5’ quadrangle, ~ 32°18’13”, 114°01’05”, about 3.2 km southeast of *Tinajas Altas*

Altitude: 1120 ft   Landform: Alluvial slope   Slope Steepness: < 5%

Parent material: Granite alluvium   Land use: Unused   Vegetation: Sparse

HORIZON	DEPTH (cm)	DESCRIPTION
surface	--	Pavement of broken quartz and feldspar crystals and granitic rock fragments; surface nearly white in color, sparsely vegetated.
A	0-3	Gravelly silt loam/clay loam; pinkish light brown (7.5YR, 7/3); vesicular, coarse platy; soft, slightly sticky, plastic; abrupt, smooth boundary.
Btk1	3-13	Gravelly clay loam; yellowish red (5YR, 5/6); weak, fine to medium subangular blocky; soft, sticky, plastic; carbonate as soft nodules and discontinuous thin coatings on pebbles, giving the soil a mottled appearance; gradual, smooth boundary.
Btk2	13-30	Sandy clay loam; yellowish red (5YR, 5/6); massive; soft, sticky, slightly plastic; carbonate as soft nodules and discontinuous coatings, more abundant than above; soil has mottled appearance; coarse sand more abundant, clay component decreased.

Qo - early Pleistocene alluvium (750 ka to 2 Ma)

Oldest, deeply eroded relict fans that are probably correlative with unit Q1 of Bull (1991). Surfaces are light gray to creme gray with well-developed pavement of weakly varnished granitic material and scattered well-varnished basalt boulders. Tributary drainage networks are well-developed and moderately entrenched; areas between channels are rounded by erosion.

Qc - basalt colluvium

Dark gray to black vesicular boulders of mafic lava forming a colluvial armor on scattered hillslopes in the southeastern portion of the study area. Outcrops of the lava were not seen and the origin of the colluvium is unknown, although bedrock exposures of similar material are present on the Mesa de Malpais just south of the U.S.- Mexico border (dated as 8.5 - 10.5 Ma), in the Cabeza Prieta Mountains (e.g. Tordillo Mountain, 16.4 Ma) about 8-10 km to the northeast, and at Raven Butte (11.1 Ma) about 15 km to the northwest (Shafiqullah et al, 1980; Damon et al, 1996).

Age Range	Lower Colorado River	Growler	Tinajas Altas
	(Bull, 1991)	(Pearthree et al, 2000)	(This report)
historical (<100 yr)	Q4	Qy2	Qy3, Qy3r
late Holocene (0-4 ka)	Q3c	**Qy2, Qy2r, Qy1r**	Qy3, Qy3r, Qy2, Qy2r
middle Holocene (4-7 ka)	Q3b	Qy1	Qy2, Q2yr,
early Holocene to latest Pleistocene (7-15 ka)	Q3a	Qy1, Ql	Qy1, Qly, Ql
late Pleistocene (15-150 ka)	Q2c	Ql	Ql, Qml
middle Pleistocene (150-750 ka)	Q2b, Q2a	Qm, Qmo	Qml, Qm
early Pleistocene (750 ka to 2 Ma)	Q1	Qmo, Qo	Qo

Table 5. Tentative correlation table for deposits of the lower Colorado River Valley and southwestern Arizona.

Bedrock Geologic Units

Tgr - Gunnery Range Batholith

The Gunnery Range batholith outcrops within an oval-shaped area of nearly 15,000 km^2 and forms part of five northwest-trending parallel mountain ranges in southwestern Arizona, including the Tinajas Altas Mountains. The batholith is composed primarily of light-colored, medium to coarse crystalline monzogranite to granodiorite (Arnold 1986), or “granite” in a generic sense. The main minerals in the granite are quartz, potassium feldspar, and plagioclase, with minor amounts of biotite, muscovite, and magnetite, and accessory garnet. Potassium feldspar crystals up to 2 cm long are common. The texture of the granite is usually massive, although some fresher exposures exhibit gneissic (or banded) texture. Dikes of fine crystalline ("aplites") and coarse crystalline ("pegmatites") granite are common. Outcrops are typically weathered and friable, with a pavement of quartz and feldspar crystals common on surfaces adjacent to outcrops. Surfaces of granite outcrops are mottled brown by desert varnish, indicating long exposure to weathering processes. The cooling age of the batholith is 53 m.y. (Shafiqullah et al 1980; Arnold 1986).

REFERENCES

Arnold, A.H., 1986, Geologic implications of a geochemical study of three two-mica granites in southern Arizona: Unpublished thesis, University of Arizona, Tucson, 155 p.

Bradley, W.C., Hutton J.T., and Twidale, C.R., 1978, Role of salts in development of granitic tafoni, South Australia: Journal of Geology, v. 86, p. 647-654.

Bryan, K., 1925, The Papago Country, Arizona: A geographic, geologic, and hydrologic reconnaissance with a guide to desert watering places: U.S.G.S. Water Supply Paper 499, 436 p.

Bull, W.B., 1973a, Summary of the geomorphic reconnaissance of the region of the Yuma Dual Purpose Nuclear Plant (YDPNP), *in* Woodward-McNeill & Associates, Geotechnical investigation Yuma Dual-Purpose Nuclear Plant, Yuma, Arizona, v. II, Appendix F.

________, 1973b, Local base-level processes in arid fluvial systems: Geol. Soc. America Abstracts with Programs, v. 5, p. 562.

________ , 1991, Geomorphic responses to climatic change: New York, Oxford University Press, 326 p.

Damon, P.E., Shafiqullah, M., Harris, R.C., and Spencer, J.E., 1996, Compilation of unpublished Arizona K-Ar dates from the University of Arizona Laboratory of Isotope Geochemistry, 1971-1991: Arizona Geological Survey, Open File Report 96-18, 56 p.

Demsey, K.A., Meglioli, Andres, Biggs, T.H., And Pearthree, P.A., 2002, Surficial geology and geomorphology of central Sauceda Valley, Barry M. Goldwater Air Force Range, Maricopa County, Arizona: Arizona Geological Survey Open-File Report 02-01, 12 p., 1 sheet, scale 1:24,000.

Eberly, L.D., and Stanley, T.B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geol. Soc. America Bull., v. 89, p. 921-940.

Fairbridge, R.W., ed., 1968, Tafoni: Encyclopedia of Geomorphology, p. 1103-4.

Keith, S.B., 1978, Index of mining properties in Yuma County, Arizona: Arizona Bureau of Geology and Mineral Technology, Bull. 192, 185 p.

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

Olmsted, F.H., Loeltz, O.J., and Irelan, B., 1973, Geohydrology of the Yuma area, Arizona and California: U.S. Geological Survey, Professional Paper 486-H, 227 p., 17 plates.

Pearthree, P.A., Freeman, A.K.L., and Demsey, K.A., 2001, Surficial geology and geoarchaeology of San Cristobal and Growler Valleys, Barry M. Goldwater Air Force Range, Southwestern Arizona: Arizona Geological Survey Open-File Report 01-01, 40 p., 3 plates, scales 1:24,000 and 1:100,000.

Scarborough, R.B., 1985, Geologic cross sections of western Arizona Basin and Range, with accompanying geologic maps and other information: Arizona Bureau of Geology and Mineral Technology Open-file Report 85-02, 10 p., 34 sheets, scales 1:250,000 and 1:500,000.

Segerstrom, K., and Henriquez, H., 1964, Cavities, or "tafoni", in rock faces of the Atacama Desert, Chile: U.S. Prof. Paper 501-C, C121-C125.

Shafiqullah, 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 southeastern Arizona and adjacent areas, *in* Jenney, J.P. and Stone, C., eds., Studies in western Arizona: Tucson, Arizona Geological Society Digest v. 12, p. 201-260.

Spaulding, W.G., and Graumlich, L.J., 1986, The last pluvial climatic episodes in the deserts of southwestern North America: Nature, v. 320, no. 3, p. 441-444.

Sumner, J.R., 1972, Tectonic significance of gravity and aeromagnetic investigations at the head of the Gulf of California: Geol. Soc. America Bull., v.83, p. 3103-3120.

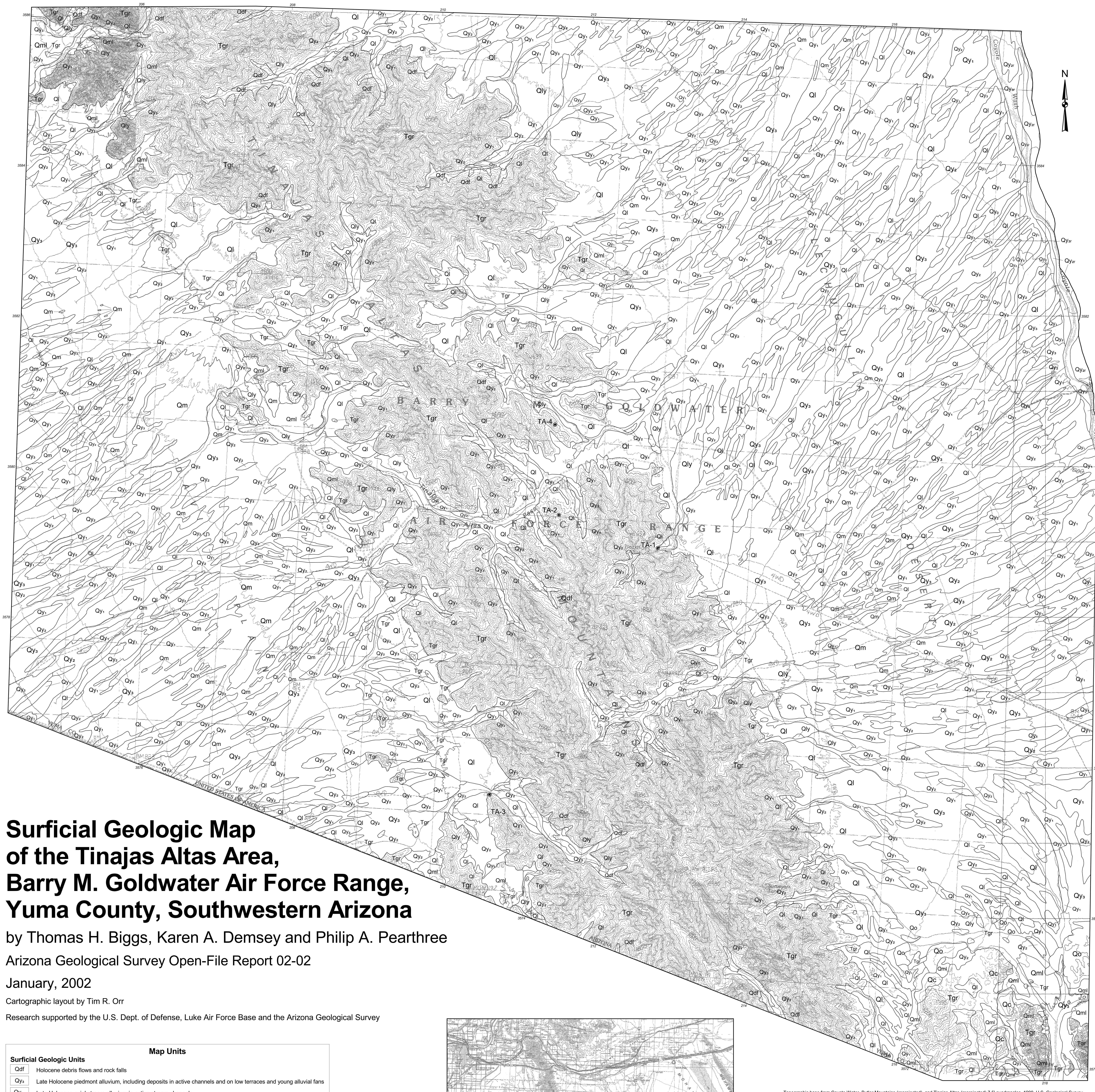
Tucker, W.C., Jr., 1980, Tectonic geomorphology of the Luke Air Force Range, Arizona, *in* Jenney, J.P. and Stone, C., eds., Studies in western Arizona: Tucson, Arizona Geological Society Digest v. 12, p. 63-87.

Van Devender, T.R., 1990, Late Quaternary vegetation and climate of the Sonoran Desert, United States and Mexico, *in* Betancourt, J.L., Van Devender, T.R., and Martin, P.S., eds., Packrat Middens: The Last 40,000 Years of Biotic Change: University of Arizona Press, Tucson, p. 134-164.

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.

Wilson, E.D., 1933, Geology and mineral deposits of southern Yuma County, Arizona: Arizona Bur. Mines Bull. 134, 236 p.

Wilson, E.D., 1960, Geologic map of Yuma County, Arizona: Arizona Bureau of Mines, 1 sheet, scale 1:375,000, now available as Arizona Geological Survey Map M-3-11.



Surficial Geologic Map of the Tinajas Altas Area, Barry M. Goldwater Air Force Range, Yuma County, Southwestern Arizona

by Thomas H. Biggs, Karen A. Demsey and Philip A. Pearthree

Arizona Geological Survey Open-File Report 02-02

January, 2002

Cartographic layout by Tim R. Orr

Research supported by the U.S. Dept. of Defense, Luke Air Force Base and the Arizona Geological Survey

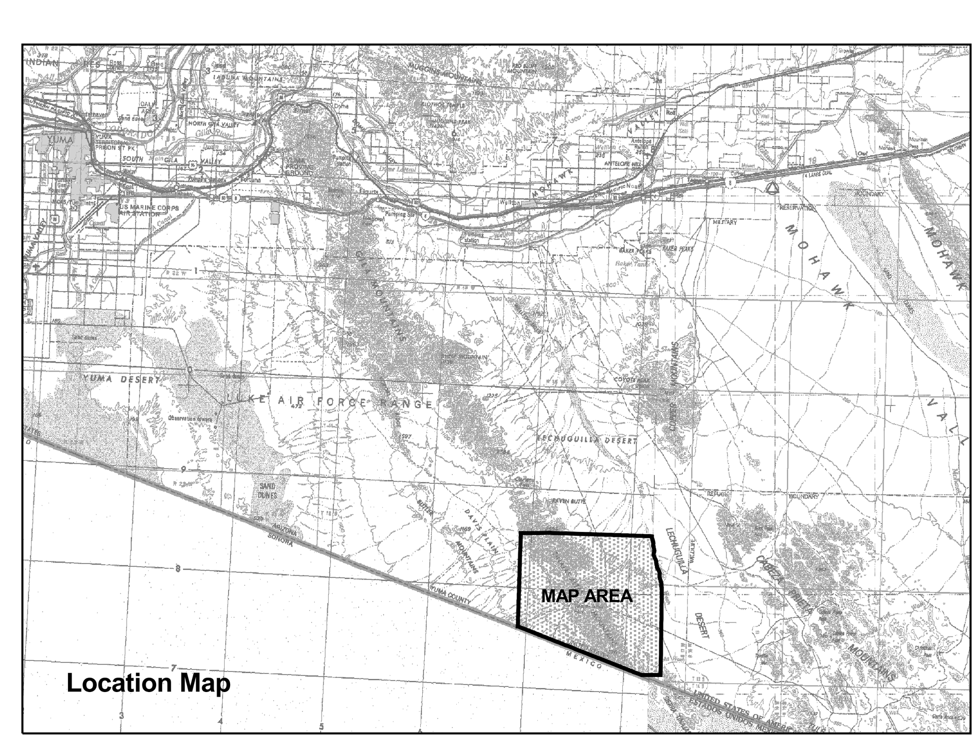
Map Units

Surficial Geologic Units

Qdf	Holocene debris flows and rock falls
Qy_3	Late Holocene piedmont alluvium, including deposits in active channels and on low terraces and young alluvial fans
Qy_{3r}	Late Holocene axial stream alluvium in active stream channels
Qy_2	Late to middle Holocene piedmont alluvium on low terraces and young alluvial fans
Qy_{2r}	Late to middle Holocene axial stream alluvium on low terraces
Qy_1	Middle to early Holocene piedmont alluvium on young alluvial fans and terraces
Qly	Holocene and late Pleistocene piedmont alluvium, undifferientated
Ql	Late Pleistocene piedmont alluvium on relict alluvial fans
Qlm	Middle to late Pleistocene piedmont alluvium on relict alluvial fans
Qm	Middle Pleistocene piedmont alluvium on relict alluvial fans
Qo	Early Pleistocene alluvium on deeply eroded relict alluvial fans
Qc	Relict basalt colluvium, found in areas where no basalt is currently preserved

Bedrock Geologic Units

Tgr	Light-colored, medium to coarse crystalline monzogranite to granodiorite of the Eocene Gunnery Range Batholith



Location Map

Topographic base from Coyote Water, Butler Mountains (reprojected), and Tinajas Altas (reprojected) 7.5' quadrangles, 1990, U.S. Geological Survey
Transverse Mercator projection; Universal Transverse Mercator zone 12 grid; 1927 North American Datum

Map Scale 1:24,000

1 — 0 — 1 Miles

5000 — 0 — 5000 Feet

1 — 0 — 1 Kilometers