CENOZOIC STRATIGRAPHY AND GEOLOGIC HISTORY OF THE TUCSON BASIN, PIMA COUNTY, ARIZONA

By S. R. Anderson

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, the conversion factors for the inch-pound units used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
square mile (mi^2)	2.590	square kilometer (km^2)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

The Tucson basin is a structural depression within the Basin and Range physiographic province. The basin is 1,000 square miles in area and trends north to northwest. Three Cenozoic stratigraphic units—the Pantano Formation of Oligocene age, the Tinaja beds (informal usage) of Miocene and Pliocene age, and the Fort Lowell Formation of Pleistocene age—fill the basin. The Tinaja beds include lower, middle, and upper unconformable units. A thin veneer of stream alluvium of late Quaternary age overlies the Fort Lowell Formation.

The Pantano Formation and lower Tinaja beds accumulated during a time of widespread continental sedimentation, volcanism, plutonism, uplift, and complex faulting and tilting of rock units that began during the Oligocene and continued until the middle Miocene. Overlying sediments of the middle and upper Tinaja beds were deposited in response to two subsequent episodes of post-12-million-year block faulting, the latter of which was accompanied by renewed uplift. The Fort Lowell Formation accumulated during the Quaternary development of modern through-flowing drainage; the overlying stream alluvium was deposited following the maturation of the drainage.

The composite Cenozoic stratigraphic section of the Tucson basin is at least 20,000 feet thick. The steeply tilted to flat-lying section is composed of indurated to unconsolidated clastic sediments, evaporites, and volcanic rocks that are lithologically and structurally complex. The lithology and structure of the section was greatly affected by the uplift and exhumation of adjacent metamorphic core-complex rocks. Similar Cenozoic geologic relations have been identified in other parts of southern Arizona.

INTRODUCTION

The Tucson basin is a 1,000 mi^2 area in Pima County, southeastern Arizona (fig. 1). The sediment-filled structural depression trends north to northwest and lies within the Basin and Range physiographic province (Fenneman, 1931). The basin, which formed as a result of crustal extension during the Cenozoic age, is bounded by rugged mountains that rise abruptly above a broad and gently sloping

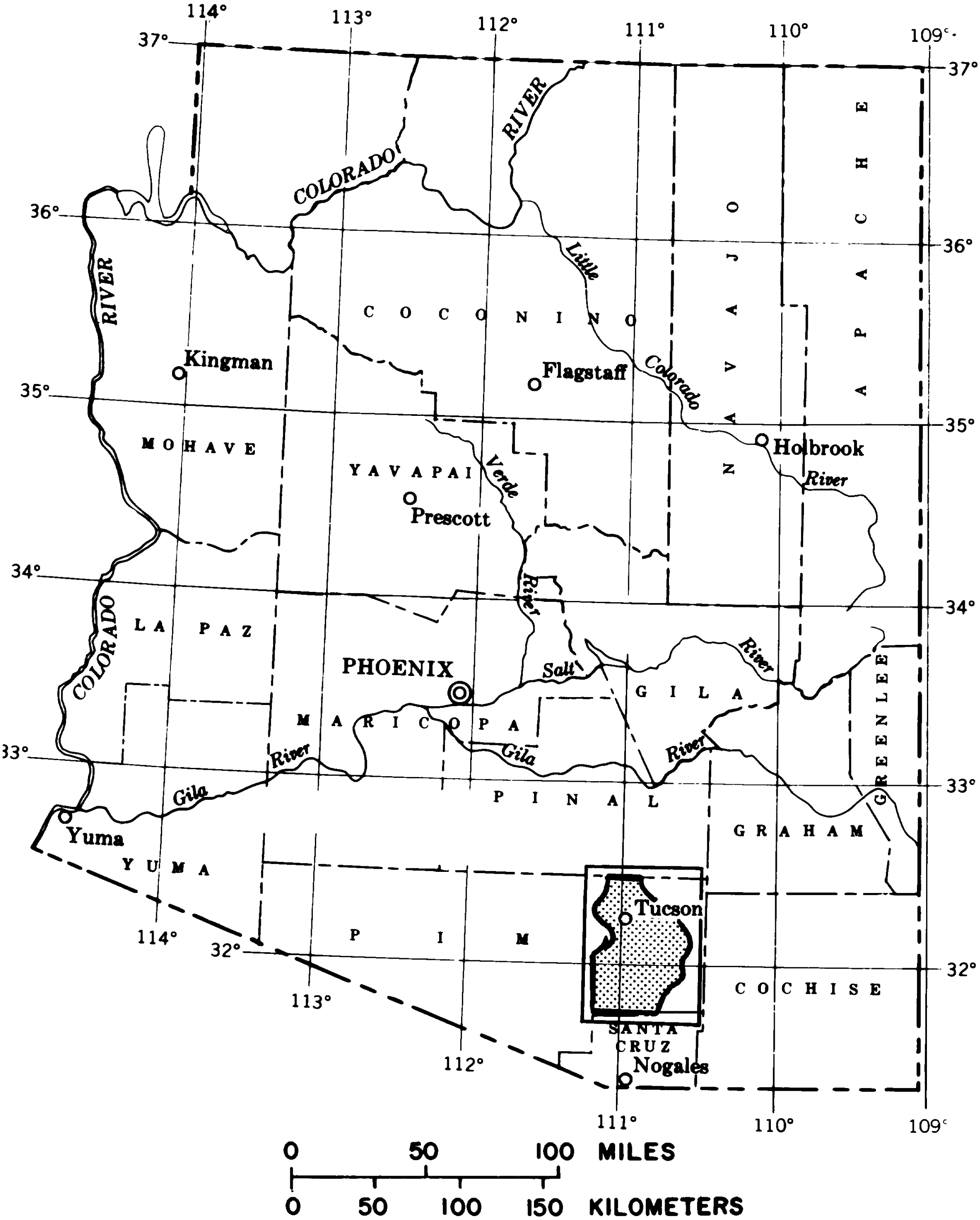

Figure 1.--Area of report (shaded).

valley floor. The mountains consist of igneous, metamorphic, and sedimentary rocks of Precambrian to Tertiary age. Three Cenozoic stratigraphic units—the Pantano Formation of Oligocene age, the Tinaja beds (informal usage) of Miocene and Pliocene age, and the Fort Lowell Formation of Pleistocene age—fill the basin (pl. 1). The composite Cenozoic stratigraphic section is at least 20,000 feet thick.

An interpretation of the Cenozoic stratigraphy and geologic history of the Tucson basin was described by Davidson (1973). This report presents a revised interpretation of the Cenozoic stratigraphy and geologic history of the basin based on currently available information. The reader is referred to Davidson (1973) for detailed lithologic descriptions and other geologic information, such as the differentiation of upper Pleistocene to Holocene alluvial deposits, that are not included with, but are pertinent to, the discussion in this report.

This report was prepared as part of a geohydrologic study of the Tucson basin conducted by the U.S. Geological Survey in cooperation with the city of Tucson. Geologic data from more than 500 water-supply and test wells were analyzed to define characteristics of the basin sediments that may affect the potential for land subsidence induced by ground-water withdrawal (Anderson and others, 1982; Anderson, 1987).

The Tucson basin as defined in this report is the sediment-filled structural depression that lies within the region surrounded by the Tucson, Black, Sierrita, Santa Rita, Empire, Rincon, Tanque Verde, Santa Catalina, and Tortolita Mountains in Pima County (Davidson, 1973). Although affected by a wide variety of geologic processes during the Cenozoic, the basin is treated here as a single complex feature. The oldest deposits that fill the Tucson basin accumulated, in part, during a detachment-related structural regime. Some early depocenters that preceded and accompanied the detachment event probably extended beyond the boundaries of the present-day basin. Subsequent block faulting and sedimentation resulted in the formation and eventual burial of a deep structural trough along the central axis of the modern valley floor. Continued erosion, pedimentation, and deposition of sediment following the cessation of block faulting enlarged the Tucson basin to its present-day extent.

GEOLOGIC HISTORY

The Cenozoic geologic history of the Tucson basin and adjacent areas of southern Arizona was profoundly affected by two major widespread tectonic events—the mid-Tertiary orogeny (Damon, 1964) and the Basin and Range disturbance (Scarborough and Peirce, 1978). The timing of these events and their relation to the Cenozoic stratigraphy of the Tucson basin and adjacent areas are shown on plate 1. Rocks and sediments that pre-date the Basin and Range disturbance in the Tucson basin are highly faulted and tilted, interbedded with volcanic rocks, and composed mainly of detritus unrelated to present-day source areas.

Sediments that accumulated following the onset of block faulting are structurally deformed to flat lying, nearly devoid of interbedded volcanic rocks, and composed mainly of materials derived from the mountains that now lie along the perimeter of the basin.

Deposits of the Pantano Formation and lower Tinaja beds accumulated before the onset of the Basin and Range disturbance, and those of the middle and upper Tinaja beds and Fort Lowell Formation accumulated afterwards (pl. 1). Deposition of the Pantano Formation began during the Oligocene following a long period of Eocene erosion and (or) nondeposition, and continued until gradually interrupted by the effects of the mid-Tertiary orogeny. Accumulation of the lower Tinaja beds began during the late Oligocene to early Miocene height of the mid-Tertiary orogeny and continued until the earliest stages of the Basin and Range disturbance. Middle Miocene to Pliocene time was accompanied by deposition of the middle and upper Tinaja beds, the latter of which overlapped with a latest Miocene to Pliocene transition from Basin and Range tectonic to post-tectonic landscape evolution. Accumulation of the upper Tinaja beds was followed by a late Pliocene erosional event that marked the beginning of interbasin drainage development and the deposition of the Fort Lowell Formation. Finally, deposits of stream alluvium, which overlie the Fort Lowell, were laid down by mature through-flowing drainages similar to those of the present-day basin.

The parallel Cenozoic evolution of the Tortolita, Santa Catalina, Tanque Verde, and Rincon Mountains (pl. 1) is discussed briefly because the evolution greatly affected the Cenozoic stratigraphic framework of the basin. The term metamorphic core complex is used to describe the unique assemblage of rocks that make up these and other similar ranges across the State (Shafiqullah and others, 1980; Rehrig and others, 1980).

Metamorphic Core Complexes

The Tortolita, Santa Catalina, Tanque Verde, and Rincon metamorphic core complexes are broad elevated asymmetrical arches and domes composed mainly of mylonitic gneiss and granite in low-angle fault contact with a wide variety of structurally deformed Precambrian to Tertiary age crystalline rocks and sediments. Although many of their distinctive structural and lithologic features formed during the middle Tertiary, the origin and present-day physiography of these mountain-forming rocks may be related to geologic events that occurred during the Cretaceous through Quaternary (Pashley, 1966; Budden, 1975; Davis, 1975; Drewes and Thorman, 1978; Drewes, 1981).

Two periods of middle to late Tertiary core-complex uplift are indicated by geologic data. Initial uplift during the middle Tertiary occurred in response to Oligocene to middle Miocene detachment faulting and elevated core-complex rocks with respect to overlying Precambrian to Tertiary rocks along the low-angle Catalina fault (Pashley, 1966; Drewes, 1980, 1981). Renewed uplift during the late Tertiary occurred in response to late Miocene to Pliocene block faulting. A late Miocene to Pliocene uplift facilitated by vertical offset along the Pirate fault (Pashley, 1966) may have elevated the Santa Catalina core-complex rocks with respect to the Tortolita range (Budden, 1975).

Uplift and eventual exhumation of the Tortolita, Santa Catalina, Tanque Verde, and Rincon Mountains profoundly affected the Cenozoic stratigraphy of the Tucson basin in several ways. Some Cenozoic rocks that lie next to these ranges were cut by listric faults (Pashley, 1966; Drewes, 1980, 1981), others were folded and tilted, and some were transported by gravity-induced sliding down the flanks of the rising domes (Davis, 1975; Drewes, 1980, 1981). In addition, many Cenozoic sedimentary sequences adjacent to the ranges in the northern part of the basin grade upward from mainly volcanic to predominantly gneissic in composition, a relation that indicates a change in source areas as a result of uplift and erosion of nearby core-complex rocks. Furthermore, other important Cenozoic sediment source areas, such as the rocks of the Tucson Mountains, are conspicuous by their steeply tilted predominantly northeast-dipping strata and proximity to metamorphic core-complex rocks, relations that may owe their origins to middle Tertiary detachment faulting and uplift rather than to thrusting and (or) block faulting as has been proposed by some previous studies.

Pre-Basin and Range Geologic Events

The geologic events of the Laramide orogeny ceased during the early Cenozoic and were followed by general tectonic quiescence and erosion and (or) nondeposition during the Eocene throughout the Basin and Range physiographic province of Arizona (Shafiqullah and others, 1980). Oligocene to middle Miocene time was accompanied by widespread continental sedimentation, volcanism, plutonism, mountain uplift, and complex faulting and tilting of rock units (Eberly and Stanley, 1978; Shafiqullah and others, 1980). Thousands of feet of volcanic and sedimentary rocks accumulated during the Oligocene to middle Miocene time. Subaerial fanglomerates and associated lake beds were deposited in interior drainage basins during the Oligocene. In the Tucson basin, sedimentation was accompanied by andesitic volcanism. Volcanism intensified during the late Oligocene and early Miocene as a result of a profound magmatic event. The event, which is referred to as the mid-Tertiary orogeny (Damon, 1964) (pl. 1), was accompanied by regional heating of the crust, plutonism, and extrusion of great quantities of rhyolitic to andesitic tuffs, breccias, and flows (Eberly and Stanley, 1978).

The mid-Tertiary orogeny contributed, in part, to the deformation and uplift of the metamorphic core-complex rocks that make up the Tortolita, Santa Catalina, Tanque Verde, and Rincon Mountains (pl. 1) (Pashley, 1966; Budden, 1975; Davis, 1975; Drewes and Thorman, 1978; Drewes, 1981). Deformation and uplift of the rocks greatly altered earlier topographic features and sedimentary relations. For example, fine-grained sedimentary rocks and evaporites that were deposited in a shallow lake before the onset of uplift became, in places, part of a mountain block in response to uplift (Drewes, 1981). These and other uplifted rocks were eroded and redeposited in the reconfigured basin or were transported by gravity-induced sliding down the flanks of the rising domes. Volcanic accumulations related to the orogeny buried older rocks in many places. Along the west edge of the basin, lower to middle Oligocene sedimentary rocks were overlain by upper Oligocene to lower Miocene basaltic andesite flows of Black Mountain (pl. 1). Late Oligocene to early Miocene uplift and volcanism were accompanied by complex sedimentation. The sediments that accumulated were highly deformed and richly interbedded with volcanic rocks.

Volcanism gradually decreased during the early to middle Miocene following the late Oligocene to early Miocene magmatic pulse (Eberly and Stanley, 1978; Shafiqullah and others, 1980). Lingering volcanism was accompanied by continued uplift, widespread sedimentation, and complex faulting and tilting of rock units. Tuffaceous gravels and conglomerates were widely deposited, and mudstones and evaporites accumulated in places. These deposits and older rocks were faulted and tilted. Tilting was apparently accomplished by rotation of small crustal blocks along shallow listric normal faults (Shafiqullah and others, 1980). Volcanism, sedimentation, uplift, and complex faulting and tilting of rock units occurred well into the middle Miocene. The resulting landscape, which consisted largely of faulted and tilted volcanic and sedimentary sequences, was subsequently and profoundly altered by intense block faulting during the Basin and Range disturbance. Transformation of the landscape greatly altered pre-Basin and Range sedimentation patterns.

Basin and Range Disturbance

The Basin and Range disturbance (pl. 1) was accompanied by block faulting, the formation of a pervasive horst-and-graben terrain, and the accumulation of sedimentary basin fill. The disturbance, which overprinted earlier formed structural features, transformed the landscape in the Tucson area from one of generally moderate relief into one of extreme relief characterized by a deep structural basin bounded by high-mountain ranges. Vertical offset between the basin and the mountains was accomplished by adjustment of crustal blocks along deep-seated, steep-angled normal faults. Materials eroded from the mountains were transported by flowing water and deposited in the closed basin. Coarse-grained sediments were deposited in alluvial fans that formed near mountains where streams entered the basin. Fine-grained sediments and evaporites were deposited in shallow playas that formed basinward of the fans. Some shallow intermittent lakes may have been surrounded by beach deposits and sand dunes (Davidson, 1973). Fan and playa deposits interfingered near the edges of the basin. These deposits are collectively referred to as basin fill.

The Basin and Range disturbance began in the Tucson area about 12 million years (m.y.) ago (Scarborough and Peirce, 1978) and gradually ceased during latest Miocene and Pliocene time (Menges and McFadden, 1981) (pl. 1). The disturbance was most active during the middle and late Miocene (Eberly and Stanley, 1978). Two distinct episodes of faulting and basin-fill accumulation occurred in the Tucson area during the disturbance. The interpretation is based on the geometry and lithology of the middle Miocene to Pliocene deposits in the subsurface (pl. 1).

The first episode of faulting in the Tucson area resulted in the formation of a deep structural trough bounded, in part, by the Santa Cruz fault and a segmented subparallel fault system on the north and east edges of the basin (pl. 1). Faulting was accompanied by erosion and sedimentary accumulations in an oxidizing environment. Extensive erosion and pedimentation occurred in upthrown structural blocks (Scarborough and Peirce, 1978). Basin fill consisting of thousands of feet of interbedded coarse- to fine-grained sediments and evaporites accumulated in the trough. Sediments were deposited in some upthrown structural blocks during a time when the rate of sedimentation was greater than the rate of trough deepening and horst-block erosion. These sediments, many of which probably were removed by later erosion, may represent a late stage of basin-fill accumulation prior to the second episode of faulting.

The second episode of block faulting probably began during the late Miocene (pl. 1) and was accompanied by renewed uplift of the Santa Catalina, Tanque Verde, and Rincon Mountains. Older deposits were faulted and folded and were overlain by coarser sediments along the flanks of the Santa Catalina Mountains in response to uplift. Fine-grained sediments accumulated in the central parts of the basin, but conditions were unfavorable for the deposition of evaporites. Sediment in the central parts of the basin was initially deposited in shallow structural troughs formed by faulting along trends, in part, oblique to those of earlier fault offsets. Hundreds of feet of sedimentary detritus accumulated in response to trough deepening. Faulting gradually ceased during the early(?) Pliocene and decreased structural activity was accompanied by renewed widespread pedimentation along the edges of the basin (Pashley, 1966; Budden, 1975; Menges and McFadden, 1981). Continued sedimentation eventually buried most pediments and scarps. Some pediments and scarps were buried by several hundred feet of younger basin fill.

The uppermost few hundred feet of sediment in the basin accumulated during and following a transition from closed-basin to interbasin depositional environments brought about by the development and eventual maturation of through-flowing drainage systems. The river system in the Tucson basin is tributary to the Gila River, which began to form in the early Pliocene and may have been through flowing to the Colorado River by the late Pliocene (Eberly and Stanley, 1978). Although the river system in the Tucson basin probably began to form during the late Pliocene, it was not fully through flowing to the Gila River however until after the middle Pleistocene (Davidson, 1973). Mature through-flowing drainage during the late Pleistocene and Holocene was accompanied by several cycles of erosion and deposition. Preserved alluvial-fan, sheetflow, and stream-channel deposits of this age are tens of feet thick (Davidson, 1973).

Although widespread basin faulting ceased during the early(?) Pliocene, observations indicate that isolated structural deformation continued during the late Pliocene to Quaternary in parts of the Tucson basin and adjacent areas of southeastern Arizona (Morrison and others, 1981). Some fault characteristics suggest probable Quaternary reactivation of earlier formed basin-bounding faults, but the relation between earlier Basin and Range faulting and the later deformation is not clear. Although late Pliocene and Quaternary structural deformation affected some basin sediments, Menges and McFadden (1981) demonstrated that nontectonic climatic and geomorphic variables dominated tectonic influences in controlling the Pliocene and Quaternary landscape evolution of southeastern Arizona.

STRATIGRAPHY

The Cenozoic stratigraphic framework of the Tucson basin described in this report (pl. 1) is a revision of the framework described by Davidson (1973). The Pantano Formation, Tinaja beds (informal usage), Fort Lowell Formation, and equivalent units in adjacent areas are subdivided here on the basis of their lithologic and structural characteristics and (or) stratigraphic relation to dated Cenozoic volcanic rocks and tectonic events. Although tenuous in places because of a paucity of dated rocks, the stratigraphic relations indicate that the Pantano Formation may be more deeply buried in the central parts of the Tucson basin than earlier thought. The relations also indicate that the Tinaja beds contain three subunits rather than two. These interpretations are consistent with the regional Cenozoic stratigraphic frameworks described by Eberly and Stanley (1978) and Pool (1984).

Pantano Formation

The Pantano Formation described in this report includes the Pantano Formation described by Davidson (1973). Sediments of the Pantano Formation crop out along the north, east, and southwest edges of the basin and lie deep in the subsurface elsewhere (pl. 1). The Pantano Formation unconformably overlies a wide variety of Precambrian to Tertiary rocks, and is unconformably overlain by the Tinaja beds. Sediments of the formation are as much as thousands of feet thick and consist of conglomerate, sandstone, mudstone, and gypsiferous mudstone. In places, the sediments are interbedded with volcanic flows and tuffs and locally contain landslide debris and lenses of megabreccia (Cooper, 1960; Finnell, 1970; Davidson 1973; Drewes, 1981). Outcrops of the Pantano Formation are highly faulted and tilted.

As mapped in this report, the Pantano Formation includes the San Xavier conglomerate beds of Heindl (1959) near Black Mountain and the Helmet Fanglomerate described by Cooper (1960) along the eastern flanks of the Sierrita Mountains (pl. 1). The Pantano Formation also includes the Rillito I beds of Pashley (1966) that crop out along the southern flanks of the Santa Catalina Mountains and the Pantano type section described by Finnell (1970) south of the Rincon Mountains. The Rillito I beds and unit 5 of the Pantano type section however are tenuously assigned to the formation (Davidson, 1973).

The Pantano Formation is Oligocene in age on the basis of its relation to dated volcanic rocks along the edges of the basin. The Pantano type section south of the Rincon Mountains is interbedded with volcanic ash and flows that range in age from about 37 to 24 m.y. (Finnell, 1970; Davidson, 1973). The Pantano also includes a thin conglomerate (Brown, 1939) that underlies a sequence of andesite flows along the northwestern flanks of the Tucson Mountains (pl. 1). The flows, which include the Rillito andesite, range in age from about 38 to 28 m.y. (Davidson, 1973). On the basis of outcrop relations, the Pantano Formation ranges in age from about 38 to 24 m.y.

The Pantano Formation is correlative, in part, with the regional upper Eocene and Oligocene rocks of lower unit I (Eberly and Stanley, 1978) as shown on plate 1. Outcrops of the Pantano Formation unconformably overlie rocks of Eocene age along the edges of the Tucson basin (Davidson, 1973). In the subsurface, however, rocks of the Pantano Formation, in places, may be conformable with Eocene rocks on the basis of regional correlations (Eberly and Stanley, 1978).

Sediments of the Pantano Formation lie deep in the subsurface in the central part of the Tucson basin (Eberly and Stanely, 1978). Subsurface information concerning the Pantano in other areas is sparse, however, and the extent of the formation between the center and edges of the basin is uncertain. Davidson (1973) tentatively assigned some subsurface rocks to the Pantano based on correlations of well cuttings and cores, but many of these age assignments are doubtful on the basis of subsequent information. A well that penetrates the formation in the central part of the basin (Eberly and Stanley, 1978) (pl. 1, section F-F', well F6) indicates that the Pantano is buried by more than 8,000 ft of younger rocks and sediments along the central axis of the basin. Pantano rocks lie at shallower depths closer to the edges of the basin where the formation crops out, but, in general, the depth of the contact between the Pantano and younger rocks and sediments in the basin is uncertain because few wells penetrate the formation.

Tinaja Beds

The Tinaja beds described in this report include the Tinaja beds described by Davidson (1973); however, as mapped in this report, they are subdivided into three unconformable units and differentiated in the subsurface (pl. 1). The lower and upper Tinaja beds of this report are equivalent to the lower and upper beds described and dated by Davidson along the edges of the basin. The middle Tinaja beds, which are described and dated here, lie mainly in the central subsurface parts of the basin and are late Miocene in age. As mapped here, the middle beds include deposits of gypsiferous and anhydritic clayey silt and mudstone in the central downfaulted part of the basin that were previously assigned by Davidson (1973, p. E21) to the lower Tinaja beds.

The Tinaja beds crop out along the north, east, and southwest edges of the basin and lie in the subsurface elsewhere (pl. 1). The Tinaja beds unconformably overlie the Pantano Formation, and are unconformably overlain by the Fort Lowell Formation. In the central part of the basin, the middle Tinaja beds unconformably overlie the lower Tinaja beds and are unconformably overlain by the upper Tinaja beds. Along the edges of the basin, however, the middle Tinaja beds generally are missing from the sequence, and the upper beds rest unconformably on the lower beds (pl. 1). Deposits of the Tinaja beds are, in places, thousands of feet thick and consist of gravel and conglomerate to gypsiferous and anhydritic clayey silt and mudstone. Where penetrated by wells, the lower Tinaja beds consist mainly of silty gravel and conglomerate and the sediments of the middle beds consist primarily of gypsiferous and anhydritic clayey silt and mudstone. Subsurface deposits of the upper Tinaja beds consist mainly of sand and clayey silt in the central parts of the basin and gravel and sand adjacent to the mountains. In places, the Tinaja beds are faulted, tilted, and folded and some sediments are interbedded with volcanic flows and tuffs.

The Tinaja beds include the Rillito II and III beds of Pashley (1966) that crop out along the southern flanks of the Santa Catalina Mountains, the lowermost deposits of basin fill that overlie the Rillito erosional surface within the subsurface of the Tucson basin (Pashley, 1966), and the formation of Tinaja Peak and the Nogales Formation mapped by Cooper (1973) and Drewes (1980, 1981) along the southeastern flanks of the Sierrita Mountains (pl. 1). The Tinaja beds are correlative with the collective rocks of middle and upper unit I and all but the uppermost part of unit II in southwestern Arizona (Eberly and Stanley, 1978), the Nogales Formation of Simons (1974) that crops out near the city of Nogales, and the lower and upper basin fill of Menges (1981) and Menges and McFadden (1981) in the Sonoita Creek area. Unit 5 of the Pantano type section (Finnell, 1970) and the Rillito I beds of Pashley (1966), which are tenuously included with the Pantano of this report, may be, in part, equivalent to the Tinaja beds based on correlations by Pashley (1966) and Davidson (1973). Unit 5 of the Pantano lies stratigraphically above a 24.4-m.y. andesite porphyry (Finnell, 1970). The Rillito I beds contain erosional detritus of similar porphyry rocks (Pashley, 1966).

The lower Tinaja beds are correlative with the formation of Tinaja Peak (Cooper, 1973; Davidson, 1973) and the rocks of middle and upper unit I (Eberly and Stanley, 1978) (pl. 1). The lower beds are also correlative with the Nogales Formation of Simons (1974) and may be correlative, in part, with unit 5 of the Pantano type section and the Rillito I beds. The middle Tinaja beds are correlative with the sediments and evaporites of the Nogales Formation mapped by Drewes (1980, 1981) in the south-central subsurface parts of the Tucson basin, the sediments and evaporites that make up the lowermost part of unit II (Eberly and Stanely, 1978), and the lower basin fill of Menges (1981) and Menges and McFadden (1981). The middle Tinaja beds may be correlative, in part, with the Rillito I beds mapped by Pashley (1966) in T. 13 S., R. 14 E., but otherwise lack recognizable outcrop counterparts in the basin. The upper Tinaja beds are correlative with the lowermost deposits of basin fill that overlie the Rillito erosional surface within the subsurface of the Tucson basin (Pashley, 1966), the upper basin fill of Menges (1981) and Menges and McFadden (1981) in the Sonoita Creek area, and the uppermost Miocene and Pliocene sediments of unit II in southwestern Arizona (Eberly and Stanely, 1978). The upper beds probably are correlative with the Nogales Formation as mapped by Cooper (1973) and Drewes (1980) along the southeastern flanks of the Sierrita Mountains and the Rillito II and III beds of Pashley (1966), but additional evidence will be needed in order to verify these suggested age relations.

The Tinaja beds generally do not contain interbedded volcanic rocks where penetrated by wells in the central parts of the Tucson basin; however, few wells penetrate deeply into the lower and middle beds and much of their mass is unexplored. Outcrops of rocks and sediments of equivalent age indicate that the lower beds in the subsurface are, in places, richly interbedded with volcanic flows and tuffs. Subsurface sediments of the middle and upper beds, however, probably contain only scarce beds of tuff or volcanic ash. Davidson (1973) indicates that in the Sierrita Mountains the lower Tinaja beds includes basaltic andesite and dacitic volcanic rocks that are of probable late Tertiary age—Miocene(?), or 26 to 12 m.y. old. Deep in the central part of the basin (pl. 1; section F-F', well F6), the Pantano Formation is overlain by a sequence of flows, tuffs, and interbedded sediments that range in age from 23.4 to 11.6 m.y. (Eberly and Stanley, 1978; Scarborough and Peirce, 1978). This volcanic and sedimentary sequence, which is overlain by sediments of the middle Tinaja beds, is correlative, in part, with a sequence of basaltic andesite flows that crop out in the Black Mountain-Sentinel Peak areas. The flows of Black Mountain and Sentinel Peak range in age from 26 to 19 m.y.; those of Black Mountain overlie the Pantano Formation (Davidson, 1973).

The lower Tinaja beds range in age from about 26-23 to 12 m.y. on the basis of their relation to volcanic rocks in and adjacent to the basin; therefore, they are early and middle Miocene and perhaps latest Oligocene in age (pl. 1). Geologic relations in well F6 indicate that the middle Tinaja beds are younger than 12 m.y. and probably range from middle to late Miocene in age. The upper Tinaja beds are Pliocene and perhaps late Miocene in age, but the suggestion of this age is permitted only by regional correlation with sediment of similar structural involvement and stratigraphic position (Davidson, 1973). On the basis of these criteria and correlation of the upper Tinaja beds to a dated sequence of upper basin fill in the adjacent Sonoita Creek area (Menges and McFadden, 1981), the upper beds may range in age from about 5.8 to 2.0 m.y.

Fort Lowell Formation

The Fort Lowell Formation described in this report includes the Fort Lowell Formation described by Davidson (1973). Sediments of the Fort Lowell Formation underlie most of the basin surface but crop out extensively only in the foothills of the Santa Catalina and Rincon Mountains. Throughout most of the basin, the Fort Lowell Formation is unconformably overlain by a thin veneer of younger sediments. The Fort Lowell as mapped on plate 1 includes overlying sediments where present.

The Fort Lowell Formation unconformably overlies the upper Tinaja beds in the middle part of the basin and the upper Tinaja beds and older rocks and sediments along the basin perimeter. Sediments of the Fort Lowell Formation consist of gravel to clayey silt and throughout most of the basin are 300 to 400 ft thick. Overlying surficial deposits, which include the alluvium of the University, Cemetery, and Jaynes terraces (Smith, 1938; Pashley, 1966; Davidson, 1973) are tens of feet thick and consist mainly of gravel and gravelly sand of fluvial origin.

The type section of the Fort Lowell Formation was described from drill cuttings and cores from well (D-13-14)31dba in the Tucson basin (Davidson, 1973). The Fort Lowell Formation probably is correlative with the outcrops of basin fill mapped by Pashley (1966) along the southern flanks of the Santa Catalina Mountains, the basin fill of Davidson (1961) in the Gila River Valley, the upper unit of the basin fill of Brown and others (1966) in the upper San Pedro Valley, the alluvium of the Martinez surface described by Menges (1981) and Menges and McFadden (1981) in the Sonoita Creek area, and, in part, the Pleistocene sediments of unit II in southwestern Arizona (Eberly and Stanley, 1978) (pl. 1).

The Fort Lowell Formation is early and middle Pleistocene in age on the basis of correlations with sediments of similar lithology and stratigraphic position in areas adjacent to the Tucson basin (Davidson, 1973). The age of the base of the Fort Lowell Formation may be about 2.5 to 2.0 m.y. as indicated by magnetostratigraphic-polarity measurements taken beneath the correlative Martinez surface gravels in the Sonoita Creek area. Deposition of the Fort Lowell Formation probably ceased about 1.3 m.y. ago (Davidson, 1973); therefore, the overlying deposits of the University, Cemetery, and Jaynes terraces probably are younger than this age. Deposits of the Jaynes terrace, which are the youngest of the sequence, probably are less than 11,000 years in age (Davidson, 1973).

The youngest deposits in the basin are Holocene in age and include undifferentiated alluvial-fan, sheetflow, and stream-channel deposits.

STRATIGRAPHIC AND STRUCTURAL RELATIONS

Major stratigraphic and structural relations between the Pantano Formation, Tinaja beds, and Fort Lowell Formation are illustrated on plate 1. Some relations or inferred relations however need further explanation. Outcrops of the Pantano Formation that lie along the eastern flanks of the Sierrita Mountains were transported to their present position by thrusting or by gravity-induced sliding (Cooper, 1960; Drewes 1981). If the outcrops were transported by gravity-induced sliding, the mountainous area from which they originated was subsequently down-faulted and buried during the Basin and Range disturbance (Drewes, 1981). Faulting during the disturbance also resulted in the burial, in places, of volcanic rocks similar to those of Black Mountain (Eberly and Stanley, 1978). The volcanic rocks of Black Mountain overlie sedimentary rocks of the Pantano Formation along the edge of the basin (Davidson, 1973). A sequence of flows, tuffs, and sediments that correlate with the lower Tinaja beds and, in part, with the volcanic rocks of Black Mountain, overlie sedimentary rocks of the Pantano Formation deep within the basin (pl. 1, section F-F', well F6). The volcanic and sedimentary sequence in well F6 is overlain by sediments of the middle Tinaja beds and may have been part of a mountainous area before block faulting and deposition of the middle beds.

The middle Tinaja beds were deposited in a complex graben that formed east of the Santa Cruz fault in response to large-scale block faulting during the Basin and Range disturbance (Davidson, 1973; Eberly and Stanley, 1978). Gravity data (Davis, 1967; Oppenheimer and Sumner, 1981) and relations in the subsurface suggest that the north- to northwest-trending graben may extend from Rillito to southeast of Sahuarita and that vertical fault offset may have been small near Rillito in comparison to that which occurred southeast of Sahuarita. Section X-X' (pl. 1) is aligned generally parallel to the longitudinal axis of the graben and illustrates the apparent continuous nature of middle unit deposition in the central regions of the structural trough. The top of the middle beds in well X3 near Rillito lies adjacent to and at a similar altitude—about 1,600 ft above sea level—as a sequence of apparently older volcanic rocks in the subsurface at Rillito in well X2. The volcanic rocks in well X2 are probably equivalent in age to nearby outcrops of Rillito andesite just south of Rillito and may have been a bedrock control of middle unit deposition in the basin. Regional bedrock control of basin depositional systems during the Basin and Range disturbance has been postulated as a possible cause for the seemingly systematic drop in altitude and change in composition of Basin and Range evaporite deposits from Tucson to Phoenix (Scarborough and Peirce, 1978; Peirce, 1984).

The middle Tinaja beds lie in fault contact with pre-Basin and Range volcanic rocks and sediments throughout the central parts of the

Tucson basin and unconformably overlie such rocks and sediments deep in the subsurface. The top of the pre-Basin and Range volcanic and sedimentary sequence in well F6 (pl. 1) lies at an altitude of about 4,400 ft below sea level and may indicate a possible differential offset along the Santa Cruz fault of about 6,000 ft or more between wells F6 and X2. The lower altitudes of the contact between the middle and upper Tinaja beds penetrated by wells X12 and X13 and inferred beneath well X6 are interpreted as being the result of subsequent vertical fault offset along a secondary and oblique, and generally northeast-trending, fault system coincident with deposition of the upper beds and uplift of the Santa Catalina, Tanque Verde, and Rincon Mountains during the late Miocene to Pliocene.

Geologic data presented by Pashley (1966) and Budden (1975) and in this report concerning the structural and lithologic relations between the Tortolita, Santa Catalina, Tanque Verde, and Rincon Mountains and adjacent sediments are interpreted as evidence for a renewed uplift of the mountains during the late Tertiary following the cessation of earlier middle Tertiary detachment faulting. If the data are correctly interpreted, renewed late Tertiary uplift was abrupt, occurred during the late Miocene to Pliocene in response to block faulting, elevated the Santa Catalina, Tanque Verde, and Rincon Mountains with respect to the Tortolita mountains and adjacent sediments, and was facilitated by offset along the Catalina and Pirate faults (Pashley, 1966; Budden, 1975). Timing for the inferred uplift is based on the structural and lithologic characteristics of the middle and upper Tinaja beds in the northern and eastern parts of the basin. The middle and upper Tinaja beds in these areas are faulted, tilted, folded, and lithologically complex—characteristics that are attributed to uplift of the adjacent mountains coincident with block faulting during the late Miocene to Pliocene.

Late Miocene to Pliocene uplift of the Santa Catalina, Tanque Verde, and Rincon Mountains profoundly altered the nature of sedimentary accumulations in the basin. The most abrupt changes occurred in the northern part of the basin adjacent to the Santa Catalina Mountains where the uppermost sedimentary accumulations of Tertiary and Quaternary age consist predominantly of sand and gravel derived mainly from Santa Catalina gneiss (pls. 2 and 3). The gneissic content of these deposits is significant because many older sediments in the area are composed predominantly of volcanic detritus (Pashley, 1966). In the north-central part of the basin between the Tucson and Santa Catalina Mountains near well C5 (pl. 1, section C-C'), the clasts of the upper Tinaja beds grade from mainly volcanic—Tucson Mountain detritus—to gneissic—Santa Catalina Mountains detritus—in composition from the base to the top of the unit. In the southwest corner of T. 13 S., R. 14 E., volcanic and gneissic gravels of the upper Tinaja beds unconformably overlie clayey silts and mudstones of the middle Tinaja beds that appear folded upward against the flanks of the Santa Catalina Mountains (pl. 3).

The structurally deformed Pantano(?) and Tinaja sediments that crop out along the southern flanks of the Santa Catalina Mountains (pl. 1) were beveled by a late Tertiary erosional event (Pashley, 1966).

The surface beveled by this event, the Rillito surface, extends into the basin where it is overlain by several hundred feet of undeformed sedimentary materials of upper Tinaja and Fort Lowell age. The Rillito surface is interpreted as a manifestation of a latest Miocene to Pliocene transition from Basin and Range tectonic to post-tectonic landscape evolution. The interpretation is based on the relation of the surface to deformed and undeformed members of the upper Tinaja beds. Deformed upper Tinaja sediments cut by the surface in the foothills and basin probably are a byproduct of faulting and uplift during the late Miocene to early Pliocene, whereas the surface and overlying undeformed sediments probably are the result of later tectonic quiescence, pedimentation, and backfilling of earlier formed structural remnants.

Deposition of the upper Tinaja beds was followed by a subsequent late Pliocene erosional event. Contours of the erosional surface (pl. 3), which are based on the geologic contact between the upper Tinaja beds and Fort Lowell Formation, suggest a probable early period of development of north- to northwest-trending through-flowing drainage in the basin during the late Pliocene. If the interpretation is correct, a prominent drainage, perhaps the ancestral Santa Cruz River, developed during the late Pliocene parallel to the eastern downthrown side of the Santa Cruz fault (pls. 1 and 3). The present-day Santa Cruz River channel (pl. 1) parallels the western upthrown side of the fault and may have migrated westward during the Quaternary as a result of increased sedimentation along the flanks of the Santa Catalina, Tanque Verde, and Rincon Mountains.

The combined effects of earlier mountain uplift, progressive development of through-flowing drainage, and wetter climate resulted in an increased accumulation of sand and gravel in the basin during the Quaternary compared to the late Tertiary. Grain-size distributions in the Fort Lowell Formation and upper Tinaja beds (pl. 2) indicate a much greater areal extent of sand and gravel accumulation in the Fort Lowell. Grain-size distributions in the Fort Lowell Formation indicate an increase in alluvial-fan development during the Pleistocene in the northern and eastern parts of the Tucson basin, especially along the flanks of the Santa Catalina Mountains. The well-developed alluvial fan in T. 14 S., R. 14 E. is probably the result of discharge from Sabino Creek toward the interior of the basin prior to the capture of Sabino Creek by Rillito Creek. Rillito Creek, which formed during the middle to late Quaternary in response to the maturation of through-flowing drainage, gradually captured the headwaters of streams that previously drained to the interior of the basin (Pashley, 1966). The present-day Rillito Creek and its tributaries, which are in the process of eroding basin deposits, cut across prominant Pleistocene depositional trends.

NEED FOR FORMAL SUBDIVISION OF THE TINAJA BEDS

The results of this investigation indicate a need for formal subdivision of the Tinaja beds. Clarification of the Tinaja terminology is needed because it has been used both formally (Cooper, 1973) and informally (Davidson, 1973) to describe a wide variety of lithologically and structurally dissimilar uppermost Oligocene to Pliocene deposits in the basin. The Tinaja beds could be subdivided into two formations on the basis of their relation to the Basin and Range disturbance. Logic dictates that the lower beds could be assigned to one formation and the middle and upper beds to another. Formal subdivision of the Tinaja beds, however, will require additional data collection and analysis that are beyond the scope of this investigation.

SUMMARY

The Tucson basin is a north to northwest-trending sediment-filled structural depression within the Basin and Range physiographic province. Three Cenozoic stratigraphic units—the Pantano Formation of Oligocene age, the Tinaja beds (informal usage) of Miocene and Pliocene age, and the Fort Lowell Formation of Pleistocene age—fill the basin. The Tinaja beds are made up of three unconformable units—a lower, middle, and upper. The Fort Lowell Formation is unconformably overlain by a thin veneer of stream alluvium of late Quaternary age. These formations and units are the result of contrasting Cenozoic geologic environments that preceded and followed the Basin and Range disturbance.

The Pantano Formation and lower Tinaja beds accumulated before the onset of the Basin and Range disturbance during a time of widespread continental sedimentation, volcanism, plutonism, uplift, and complex faulting and tilting of rock units. Both units are, in places, highly faulted and tilted and are locally overlain by or richly interbedded with volcanic rocks. The Pantano Formation and lower Tinaja beds crop out or are buried at a shallow depth along the edges of the basin; elsewhere, the sediments are deeply buried.

The middle and upper Tinaja beds and Fort Lowell Formation were deposited following the onset of the Basin and Range disturbance. The middle Tinaja beds, which contain evaporites, accumulated in a closed basin during the beginning of large-scale block faulting and locally are faulted and folded. The upper Tinaja beds, which do not contain evaporites, were deposited during a transition from Basin and Range tectonic to post-tectonic landscape evolution and are, in places, also structurally deformed. The Fort Lowell Formation accumulated during the Quaternary development of modern through-flowing drainage; the overlying stream alluvium was deposited following the maturation of the drainage.

The composite Cenozoic stratigraphic section of the Tucson basin is at least 20,000 ft thick. The steeply tilted to flat-lying section is made up of indurated to unconsolidated clastic sediments, evaporites, and volcanic rocks that are lithologically and structurally complex. The lithology and structure of the section was greatly affected by the uplift

and exhumation of adjacent metamorphic core-complex rocks. Similar Cenozoic geologic relations have been identified in other parts of southern Arizona.

REFERENCES CITED

Anderson, S.R., 1987, Potential for aquifer compaction, land subsidence, and earth fissures in the Tucson basin, Pima County, Arizona: U.S. Geological Survey Open-File Report 86-482, 3 sheets.

Anderson, S.R., Schumann, H.H., and Wallace, B.L, 1982, Progress report on measurement of aquifer compaction in the Tucson basin, in Babcock, J.A., and Hix, G.L., 1982, Annual static water level basic data report, Tucson basin and Avra Valley, Pima County, Arizona, 1981, 1982: City of Tucson, Tucson Water Planning Division report, 21 p.

Brown, S.G., Davidson, E.S., Kister, L.R., and Thomsen, B.W., 1966, Water resources of Fort Huachuca Military Reservation, southeastern Arizona: U.S. Geological Survey Water-Supply Paper 1819-D, 57 p.

Brown, W.H., 1939, Tucson Mountains, an Arizona Basin-Range type: Geological Society of America Bulletin, v. 50, no. 5, p. 697-760.

Budden, R.T., 1975, The Tortolita-Santa Catalina Mountain complex: Tucson, University of Arizona, master's thesis, 133 p.

Cooper, J.R., 1960, Some geologic features of the Pima mining district, Pima County, Arizona: U.S. Geological Survey Bulletin 1112-C, p. 63-103.

__________ 1973 (1974), Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-745, scale 1:48,000.

Damon, P.E., compiler, 1964, Correlation and chronolgy of ore deposits and volcanic rocks: Annual progress report COO-689-42, Contract AT(11-1)-689 to U.S. Atomic Energy Commission: Tucson, Geochronology Labs., University of Arizona, 28 p.

Davidson, E.S., 1961, Facies distribution and hydrology of intermontane basin fill, Safford basin, Arizona, in Short papers in the geologic and hydrologic sciences: U.S. Geological Survey Professional Paper 424-C, p. C151-C153.

__________ 1973, Geohydrology and water resources of the Tucson basin, Arizona: U.S. Geological Survey Water-Supply Paper 1939-E, 81 p.

Davis, G.H., 1975, Gravity-induced folding of a gneiss dome complex, Rincon Mountains, Arizona: Geological Society of America Bulletin, v. 86, no. 7, p. 979-990.

Davis, R.W., 1967, A geophysical investigation of hydrologic boundaries in the Tucson basin, Pima County: Arizona University, unpublished Ph.D. thesis, 64 p.

Drewes, Harald, 1972, Structural geology of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 748, 35 p.

__________ 1980, Tectonic map of southeast Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1109, scale 1:125,000.

__________ 1981, Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 96 p.

Drewes, Harald, and Thorman, C.H., 1978, New evidence for multiphase development of the Rincon metamorphic core complex, east of Tucson, Arizona: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 103.

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

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill, 534 p.

Finnell, T.L., 1970, Pantano Formation, in Cohee, G.V., Bates, R.G., and Wright, W.B., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1968: U.S. Geological Survey Bulletin 1294-A, p. A35-A36.

Gass, T.E., 1977, Subsurface geology of the Santa Cruz well field, Pima County Arizona: Tucson, University of Arizona, master's thesis, 63 p.

Scarborough, R.B., and Peirce, H.W., 1978, Late Cenozoic basins of Arizona, in Callender, J.F., Wilt, J.C., and Clemons, R.E., eds., The Land of Cochise: New Mexico Geological Society Guidebook, 29th Field Conference, p. 253-259.

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 southwestern Arizona and adjacent areas, in Jenney, J.P., and Stone, Claudia, eds., Studies in western Arizona: Arizona Geological Society Digest, v. 12, p. 201-260.

Simons, F.S., 1974, Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona: U.S. Geological Survey Miscellaneous Investigations Map I-762.

Smith, G.E.P., 1938, The physiography of Arizona valleys and the occurrence of ground water: Arizona University Agriculture Experiment Station Technical Bulletin 77, 91 p.

U.S. Geological Survey, 1984, Geologic time chart, in Stratigraphic notes, 1983: U.S. Geological Survey Bulletin 1537-A, p. A1-A4.