EVIDENCE FOR A LATEST MIOCENE TO PLIOCENE TRANSITION FROM BASIN-RANGE TECTONIC TO POST-TECTONIC LANDSCAPE EVOLUTION IN SOUTHEASTERN ARIZONA

By
Christopher M. Menges
Bureau of Geology and Mineral Technology
845 N. Park Avenue, Tucson, Arizona 85719
and
Leslie D. McFadden[1]
Department of Geosciences, University of Arizona, Tucson, Arizona 85721

Geomorphic, stratigraphic, paleomagnetic, and pedologic data reveal that: (a) the principal phase of the Basin and Range disturbance, *sensu strictu*, terminated within a latest Miocene to early Pliocene interval (~6 to 3 m.y.B.P.) in two basins near Tucson; and (b) general tectonic quiescence has continued in these basins to the present. Approximately correlative relationships in adjacent basins suggest a similarly timed waning of large-scale Basin-Range tectonism throughout most of southeastern Arizona.

In Sonoita Creek basin, fault-bounded syntectonic lower basin fill grades upward into undeformed upper basin fill that contains an Epoch 5 through Gauss Epoch magnetostratigraphic section (5.8 to 3.3-m.y.B.P. age range). These post-tectonic deposits bury basin-bounding faults and extend mountainward across lower levels of an extensive (2- to 7-km-wide) exhumed and dissected bedrock pediment. The basin fill is truncated below an erosion surface that projects into higher bedrock pediment levels; this composite surface is overlain by relatively thin (5- to >20-m) high-stand alluvial fans and associated geomorphic surfaces upon which have formed thick mature soils probably ≥1 m.y. old. The Canada del Oro valley likewise contains undeformed upper basin fill and (or) high elevation fans that once buried both boundary faults and an exhumed 2- to 4-km-wide crystalline pediment.

The observed scale of pedimentation requires significant decreases in the rates and (or) magnitudes of relative vertical tectonic activity on mountain-bounding faults throughout an estimated 2- to ≥5-m.y. minimum formation interval. The late Miocene and Pliocene basin fill itself records the final stages of basin aggradation during or following the transition from tectonic activity to inactivity along these boundary structures. This inference is supported by both progressive changes in sediment dispersal patterns and an upsection decrease in sedimentation rates, which coincide with increasing occurrences of diastems and paleosols. The subsequent deposition of the nontectonic high-stand pediment fans probably reflects climatic changes conducive to hillslope stripping and stream aggradation, following the transition from glacial to interglacial conditions at or near the inception of the Quaternary.

Some basins in southeastern Arizona contain locally deformed Pliocene and early Quaternary upper basin fill and (or) scattered piedmont fault scarps that displace late Pleistocene or older surficial deposits. However, this restricted and small-scale Pliocene-Quaternary deformation does not alter the interpretation cited above that Basin-Range tectonism ceased to be a dominant influence on landscape evolution in the region after late Miocene.

INTRODUCTION

The characteristic mountain and valley landscape of southern Arizona closely conforms to and is largely controlled by the bedrock faults and structural basins produced during the late Miocene Basin-Range disturbance, *sensu strictu*. This correspondence between physiography and structure forms the primary basis for the restricted Basin-Range definition of Scarborough and Peirce (1978), Eberly and Stanley (1978), and Shafiqullah and others (1978, 1980). These studies present geochronologic data that constrain the inception of Basin-Range tectonism throughout southern Arizona to a general 17-to-11- m.y.B.P. interval. Eberly and Stanley (1978) and Shafiqullah and others (1980) considered the Basin-Range event in southwestern Arizona to have essentially terminated by 10 to 6 m.y.B.P. and 8 m.y.B.P., respectively. However, in southeastern Arizona, the timing—and even the existence—of a similar termination for the Basin-Range disturbance remains more controversial. For example, many workers have extended regional Basin-Range tectonic activity in the area into recent time with little qualification (e.g., Loring, 1976; Drewes and Thorman, 1978; and Shafiqullah and others, 1978, 1980). In contrast, Scarborough and Pierce (1978) proposed a cessation of Basin-Range vertical tectonism some time before mid-Pleistocene.

Much of this confusion arises from a paucity of geologic data relevant to this tectonic-termination problem. Further, many previous interpretations of recent tectonism in southeastern Arizona have been

[1]Present address: Dept. of Geology, Univ. of New Mexico, Albuquerque 87131

TABLE 1. Time boundaries adopted in this study for the relevant Cenozoic epochs

EPOCHS	(m.y.B.P.)
Oligocene	38 — 24
Miocene	
early	24 — 16
mid	16 — 11
late	11 — 5.6
Pliocene	
early	5.6 — 3.2
late	3.2 — 1.8
Pleistocene	
early	1.8 — 0.7
mid	0.7 —0.25
late	0.25 — 0.1
Holocene	0.1 — present

influenced by several indirectly related, and hence easily misinterpreted, geomorphic characteristics of the area. For example, southeastern Arizona contains more prominent, extensive, and rugged mountain ranges, greater mountain and valley relief, and a greater apparent conformity between Basin-Range structure and physiography in comparison to the southwestern part of the state. These gross topographic features impart an impression of recent tectonism in southeastern Arizona, an impression reinforced by the presence of several Quaternary piedmont fault scarps in some basins in the area.

This paper presents data relevant to both the recognition and timing of the cessation of regional large-magnitude Basin-Range tectonism in southeastern Arizona. Primary emphasis is placed on stratigraphic, geomorphic, paleomagnetic, and pedologic data drawn from detailed studies of two representative Basin-Range basins in this region (McFadden, 1978; this volume; Menges, 1981). Four primary geologic and landscape elements have been used in the analysis: basin-fill stratigraphy, bedrock pediments, conspicuous high-elevation alluvial fans, and lower-level terraces. Individually and in combination these data provide constraints upon the timing and relative rates of tectonic activity along the major Basin-Range structures in these basins within a critical late Miocene to Quaternary interval. (Note: Table 1 lists the time boundaries used in this study for relevant Cenozoic epochs.)

STUDY BASINS

The Sonoita Creek and Canada del Oro basins are situated 60 and 25 km to the southeast and northwest of Tucson, respectively (Fig. 1), within the Mexican Highland subprovince of the Basin and Range province (Fenneman, 1931). These two north- to northeast-trending elongate basins resemble one another in many gross aspects. Both are characterized by thermic semiarid climates, although the smaller Sonoita Creek basin occupies a somewhat higher altitude range (1,600 to 1,200 m vs 1,450 to 900 m). Both intermontane valleys are flanked on one side by high rugged mountains (3,320 to 2,880 m) and on the other by more subdued lower ranges (1,980 to 1650 m).

The basins are externally drained at present by the Sonoita Creek and the Canada del Oro Wash, tributaries of the Santa Cruz River (Fig. 1). The drainage of each basin has downcut significantly into underlying basin sediments; this dissection has produced, in both basins, a similar nested sequence of inset geomorphic surfaces and surficial deposits.

Gravity and structural studies indicate that both topographic valleys overlie complex subsurface bedrock grabens with pronounced east-directed depth asymmetry in cross section (Budden, 1975; Menges, 1981; Bittson, 1976). Estimates of the maximum vertical bedrock

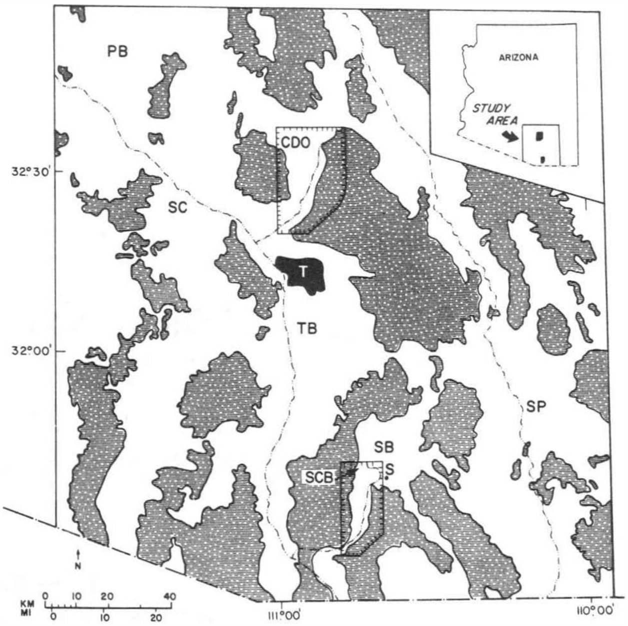


FIGURE 1. Map showing the location of two study basins, Sonoita Creek basin (SCB) and Canada del Oro (CDO), in southeastern Arizona. Shaded areas indicate bedrock mountains; the dashed lines follow the major drainages. Other place names include: Picacho basin (PB); Sonoita (S); Sonoita basin (SB); Santa Cruz River (SC); San Pedro River (SP); Tucson (T); and Tucson basin (TB). Inset map shows the positions of the two basins and the large map relative to the state of Arizona.

separations along master basin-bounding faults vary between 1,200 and 1,500 m. These structural basins enclose a complicated set of basin sediments of probably Oligocene(?) through Pliocene ages.

BASIN-FILL STRATIGRAPHY

The basin-fill stratigraphy of Sonoita Creek basin has been studied in greater detail than that of the Canada del Oro. Sediments exposed in the former basin have been subdivided into six informal stratigraphic units, ranging in age from late Oligocene to late Pliocene, which represent the primary aggradational phase of basin evolution (schematic cross sections and column appear in Fig. 2; see Menges, 1981, for detailed descriptions of all units). The four older deposits (Ts units of Fig. 2) display stratigraphic, sedimentologic, and deformational characteristics that are discordant with the geometry of the present physiographic-structural basin; hence they resemble other pre-Basin-Range stratigraphy of Oligocene to mid-Miocene age recognized throughout southern Arizona (Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Shafiqullah and others, 1978, 1980; Scarborough and Wilt, 1979). Although these sediments have been disrupted and overprinted by subsequent Basin-Range deformation, they provide little direct information about that later disturbance.

In contrast, the sedimentary facies and provenance of the two generally undeformed younger sediment groups (BF units of Fig. 2) clearly reflect deposition contemporaneous with and (or) postdating the structural development of the Basin-Range graben system. Thus these units conform to the definition of "basin fill" proposed by Scarborough and Peirce (1978), and are described in more detail below.

LOWER BASIN FILL (BF_L)

Lower basin fill is characterized by subangular to subrounded cobble-pebble fluvial gravels interbedded with pebbly sands, both

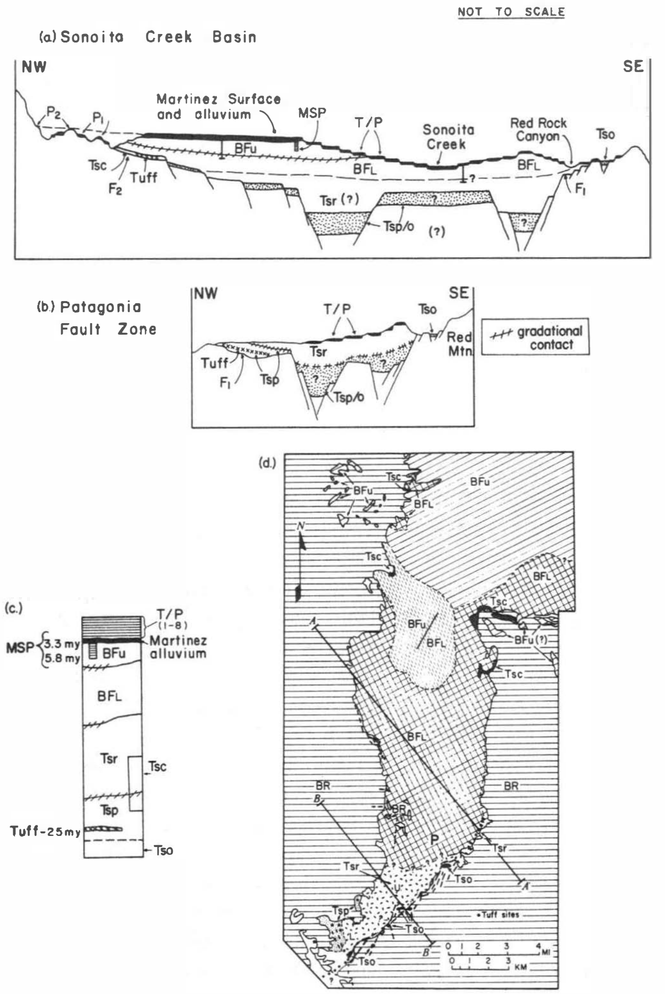


FIGURE 2. Schematic diagram of the stratigraphic relationships among the local basin sediment units of Sonoita Creek basin. The nomenclature used in the diagram is defined as follows: older Tertiary sediments (Ts_o); Patagonia Mountain sediments (Ts_p); Red Mountain sediments (Ts_r); Canelo Hills sediments (Ts_c); lower basin fill (BF_L); upper basin fill (BF_U); BF_U depositionally overlying BF_L (BF_U/BF_L); Ts- and BF_L-related depositional bedrock floors (F_1 and F_2, respectively); lower and upper bedrock pediments (P_1 and P_2, respectively); terrace and piedmont surfaces (T/P); and magnetostratigraphic polarity classification (MSP).

a. Cross section across the main Sonoita Creek basin. Subsurface geometry generalized from gravity modeling (Menges, 1981).

b. Cross section across the Patagonia sub-basin

c. Diagrammatic stratigraphic column, with available local age constraints

d. Generalized distribution map of the basin stratigraphy, showing location of cross sections a and b (above).

enclosed within a pinkish-gray silty matrix. These sediments define a crude textural facies pattern wherein coarser grained piedmont facies gravels grade laterally into finer grained interior-facies siltstones and sandstones. This depositional geometry appears to largely ignore modern drainage; instead, two poorly defined basin interior facies directly overlie the structurally lowest portions of the Sonoita bedrock grabens, as defined by gravity surveys (Menges, 1981; Bittson, 1976). Bedding orientations and limited paleocurrent data are consistent with deposition within these two structural subbasins (Menges, 1981; Cooley, 1968, 1977).

BF_L deposits are in high-angle fault contact with bedrock at the topographically (and stratigraphically) lowest exposures of the basin boundaries. Gravity modeling of the Sonoita Creek basin suggests that a potential maximum thickness of 900 to 1,200 m of BF_L may be structurally confined within the subsurface interior of the bedrock graben (Menges, 1981). However, rising vertically upsection along exposed basin margins, these BF_L-bedrock structural contacts are replaced by depositional boundaries wherein undeformed BF_L deposits overlap the former basin-bounding fault zones and bury gently inclined bedrock surfaces that fringe the main topographic mountains. Similar transitions in the character of boundary contacts have been reported elsewhere along many exposed valley margins in southeastern Arizona (Scarborough and Peirce, 1978) and they are implicit in the upper structural and stratigraphic levels of most subsurface basin cross sections, as interpreted from seismic profiling and gravity surveys (e.g., Eberly and Stanley, 1978; Aiken and Sumner, 1974; Aiken, 1978).

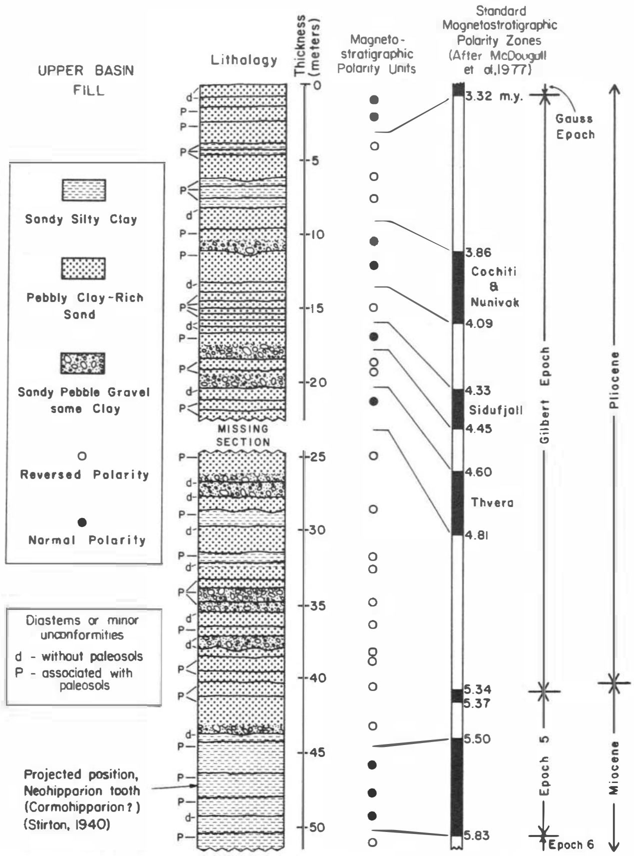
UPPER BASIN FILL (BF_U)

This chiefly alluvial unit occupies the uppermost 80- to 100-m thickness of preserved basin-fill stratigraphy in Sonoita Creek basin. This unit overlies BF_L sediments across primarily gradational contacts within the basin interior, although BF_U deposits commonly appear inset into bedrock or various older basin sediments at the basin margins. The top of the BF_U section is clearly truncated with a slight angular discordance by a basinwide erosional surface underlying the Martinez surface pediment gravels (defined later), which represent the highest altitude geomorphic surfaces and surficial deposits. Thus upper basin-fill deposition represents the final stages of basin-fill aggradation in Sonoita Creek basin.

BF_U sediments may be distinguished from the subjacent BF_L unit on the basis of the following dominant characteristics: (1) increased reddish-brown staining of both the framework gravels and matrix; (2) higher interstitial clay content of the matrix; (3) generally coarser grained and more rounded character of the cobble-boulder-pebble piedmont facies gravels; (4) distinctive fine-grained basin interior facies (described below); and (5) different arrangement of sediment facies within the basin that more closely corresponds to primary modern drainages.

The basin interior facies, centered to the north and northeast of Sonoita, contains a striking vertical succession of thinly bedded (0.5 to 1 m thick) subhorizontal strata, often arranged within textural fining-upward sequences. In order of importance, these strata consist of very poorly sorted sand and silt (often with scattered pebbles), silty clay and clayey silt, and sandy pebble-cobble channel gravels (cf. Fig. 3 for a generalized representative section). Most individual beds are bounded by diastemlike minor unconformities that often overlie or truncate strongly to weakly developed paleosols, thereby suggesting frequent depositional hiatuses of 1,000 to 100,000 years between successive strata.

No intraformational deformation has been recognized to date within BF_U deposits. All sediments retain very shallow and presumably original depositional dips (0 to 3 degrees in the basin interior and 4 to 7 degrees in the piedmont facies). Along many basin margins, BF_U piedmont gravels extend undisturbed across the upward projections of basin-boundary fault zones that have been located either at the surface in outcrop, or in the subsurface by gravity surveys (Menges, 1981; Bittson, 1976). Mountainward of these structural basin boundaries, BF_U sediments in places depositionally overlie the dissected remnants of a formerly extensive bedrock pediment (described under that section).



Location: South side of Gordner Canyon, streambanks and roadcuts to east of state highway 83; T19S, Sec.36, SW/4; T20S, R16E, Sec 1, NE/4.

FIGURE 3. Summary diagram of the magnetostratigraphic polarity classification developed for upper basin fill. Included are generalized stratigraphic column (with paleosols and diastems), sampled polarity units, and the proposed correlation to the standard magnetostratigraphic polarity zones.

MAGNETOSTRATIGRAPHIC POLARITY CLASSIFICATION—UPPER BASIN FILL

A 51-m-thick section near the top of the BF_U unit has yielded a polarity-defined magnetostratigraphy (Figs. 2 and 3). This column, located north of Sonoita (Fig. 1), comprises a typical assemblage of subhorizontal, undeformed, fine-textured basin-interior sediments that contain 45 unconformities and 34 paleosols, both of which increase in frequency upsection (Figure 2, Table 2). A pronounced sequence of magnetic polarity zones has been defined in these sediments by NRM (Natural Remanent Magnetization) determinations from 26 sample horizons with a 1.9-m mean sample interval. Each horizon was sampled and measured in triplicate by a cryogenic magnetometer at the Paleomagnetic Laboratory of the University of Arizona. Rather surprisingly, consistent polarity measurements were obtained not only from the finer grained silty clay samples, but also from the coarser textured pebbly silty sands and sandy silts. Perhaps this unexpected success resulted from the ubiquitous presence of interstitial clay in the matrix of all samples.

The resultant, primarily reversed polarity pattern best matches the Epoch 5 through Gilbert Epoch sequence of the standard magnetic polarity time scale (Fig. 3). If correct, this correlation establishes a 5.8 to 3.3 m.y. age range for this BF_U column, using the time scale of McDougall and others (1977). The section ends an estimated 15 to 25 m below the upper erosional truncation of the BF_U unit beneath the

TABLE 2. Upper basin-fill depositional rates, Sonita Creek basin

BF_U	Thickness (m)	Time Interval (m.y.)	Depositional Rates m/10^6yr	No. of Diastems	No. of Paleosols
Entire column (0 - 51.3 m)	51.3	2.65	19	45	34
Lower section[1]	28.3	1.0	27	21	15
Upper section[1]	23.0	1.5	15	24	19
Maximum rate (in lower section	22.0	0.7	32	18	11
Minimum rate (in upper section	13	0.95	13	13	10

[1]Upper and lower sections refer to the 0 to 23 m and 25 to 51.3 m intervals, respectively, of the magnetostratigraphic column (Fig. 3)

Martinez surface gravels (described later). This would place an approximately 2.5- to 2.0-m.y. minimum age on the preserved BF_U deposits, based on mean depositional rates of 30 to 19 m/m.y. estimated from the magnetostratigraphic column (Table 2).

Although limited, the available independent age control for this column tends to support our age designation. Stirton (1940) and Lance (1960) reported the recovery of a Neohippareon (Cormohippareon?) tooth from the bottom of a well located 1.5 km to the south; this find projects into or slightly below the bottom of the magnetostratigraphic column. The upper part of the Hemphillian-Clarendonian age of this vertebrate agrees with our proposed correlation and mitigates against potential correlations with the younger Matuyama Epoch (E. Lindsay, personal commun., University of Arizona, Tucson, 1978). Further, the characteristic, very strongly developed soil formed on the overlying Martinez surface suggests a 1.0-m.y. minimum of soil formation following Martinez gravel deposition, relationships supporting the older age range proposed above. Correlations with older pre-Gilbert Epoch late Miocene polarity intervals are theoretically possible, although they appear less favorable based not only on more poorly matched zonation patterns but also on local and regional stratigraphic relationships (Menges, 1981).

If the proposed correlation is correct, the magnetostratigraphy establishes a latest Miocene to late Pliocene time for BF_U deposition, which therefore places a latest Miocene (6 m.y.B.P.) minimum age for the subjacent BF_L unit. No specific maximum age criteria exist to date for this latter unit within the Sonoita Creek basin; however, the maximum age for this type of deposit is fairly well constrained elsewhere in southeastern Arizona to a general 15-to-10-m.y.B.P. interval and as post-12 m.y.B.P. in the adjacent Santa Cruz and Sulpher Spring valleys (Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Simons, 1974; Scarborough and Wilt, 1979).

OTHER AREAS

The basin-fill stratigraphy of the Canada del Oro has been studied in reconnaissance by Pashley (1966) and in more detail by Davidson (1973). At present only two fill units—the arkosic sand and gravel deposits of the Tinajas beds and the Fort Lowell Formation—are formally recognized (Davidson, 1973), due in part to less intensive study and in part to less extensive dissection and poorer exposures in the basin, relative to the Sonoita area. The available data do not preclude, and in some cases suggest, a two-stage basin-fill sequence similar to the Sonoita Creek basin scheme outlined above. Also, this bipartite basin-fill classification is not unlike that described in other basins of southeastern Arizona by Cooley (1968, 1977).

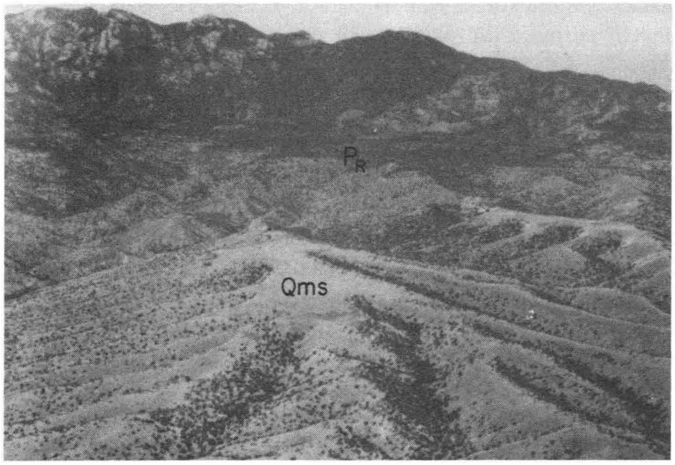
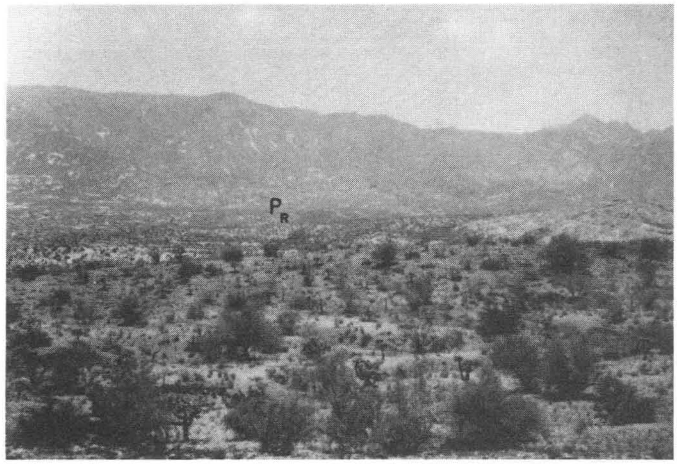


FIGURE 4. High basin stand surfaces and surficial deposits in the two study basins
a. Martinez surface remnant (Qms), overlying basin sediments along the western margin of Sonoita Creek basin. The surface projects and (or) extends into an extensive exhumed, dissected bedrock pediment (P_R), which is eroded into the flank of the Santa Rita Mountains.



b. Exhumed and dissected pediment (P_R) at the base of the Santa Catalina Mountains along the eastern border of the Canada del Oro valley. View from the dissected remnants of the Twin Lakes surface.

BEDROCK PEDIMENTS

Extensive bedrock pediments flank the margins of both the Sonoita Creek and Canada del Oro alluvial basins, extending between 2 and 7 km (averaging ~3-5 km) mountainward from the basin-bounding fault zones (McFadden, 1978, this volume; Menges, 1981, Fig. 4a, b). In both basins these formerly buried pediments have been exhumed and dissected to varying degrees into accordant ridgecrests and uplands by Quaternary basin dissection, factors which hinder pediment recognition. However, upon reconstruction, the scale of pedimentation evident in both valleys is consistent with the large pediments defined elsewhere by geomorphic and gravity studies in other less dissected basins of southern Arizona (e.g., Mammerickx, 1964; Lustig, 1969; Eberly and Stanley, 1978; Aiken and Sumner, 1974).

The extensive bedrock pediments of Sonoita Creek basin have been differentiated into two levels. The lower altitude pediment corresponds with upper-basin-fill deposits, which locally still overlie this surface; this pediment level probably formed during the slow aggradation of this fill unit. The higher and more prominent pediment level (1,600 to 1,500 m altitude) projects into adjacent remnants of the Martinez surface. This pediment represents the bedrock-margin equivalent to the Martinez high basin stand.

Figure 5 depicts the estimated areal extent of the composite bedrock pediment that existed during its maximum development near the end of this high stand, immediately prior to the initiation of basin dissection. This reconstructed predissection landscape is characterized by highly sinuous and embayed topographic mountain-piedmont junctions with numerous inselbergs rising above extensive bedrock pediments that were probably buried beneath a shallow alluvial mantle. Figure 5 suggests that the topographic mountain front had retreated a distance of 2 to 7 km from the structural boundaries of the basin by the end of the high basin stand. (The variation depends in part on the effects of contrasting rocks and structures on pedimentation rates.) In this restoration, the area of exposed bedrock in the ranges shrinks from its present value of 622 km^2 to 278 km^2 prior to basin dissection (a 55 percent reduction). This reduction occurs by the addition of the restored formerly suballuvial pediments, which comprise 260 km^2 or 76 percent of the presently exhumed bedrock surfaces of Figure 5. This must be considered a minimum figure for pediment area, as gravity surveys indicate that large pediments remain buried today in some areas of the Sonoita basin (Bittson, 1976; Menges, 1981).

A broad pediment 2 to 4 km in width has been etched across the plutonic rocks surrounding the northern Canada del Oro valley (Fig. 6). Narrower pediments occur along the southern border of the Catalina Mountains, where more resistant quartz diorite and

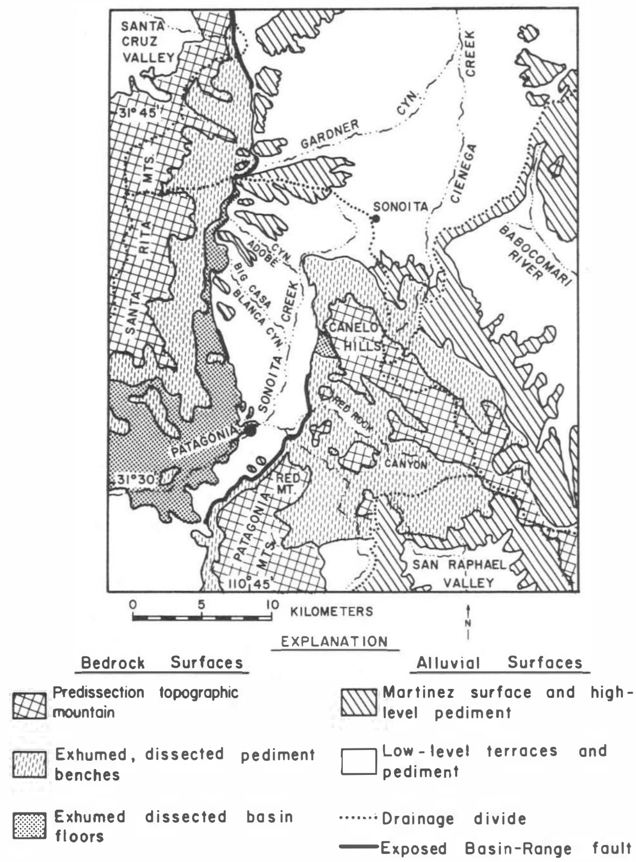


FIGURE 5. Generalized map of the geomorphology of the Sonoita-Patagonia area. Emphasis has been placed on the partial reconstruction of the major predissection landforms associated with the Martinez high basin stand interval.

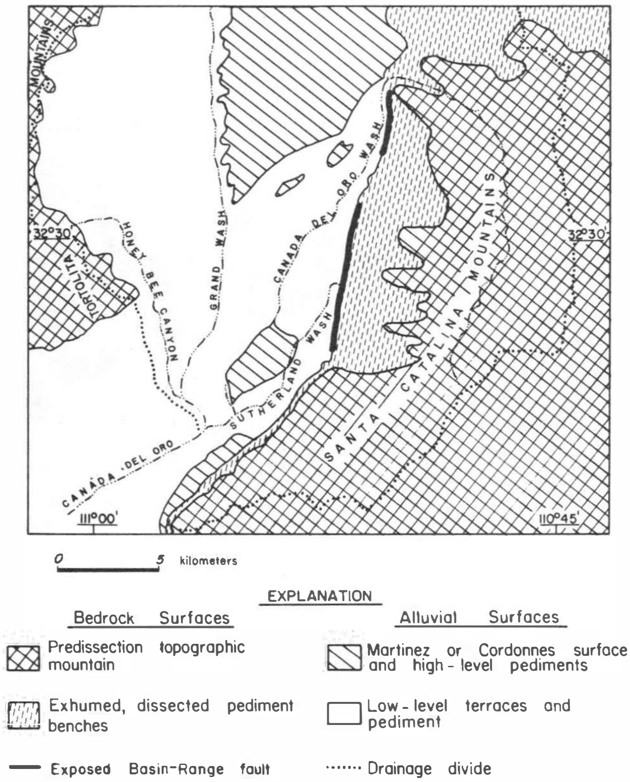


FIGURE 6. Generalized map of the geomorphology of the Canada del Oro basin, depicting the partially reconstructed predissection landforms associated with the Cordonnes high basin stand interval. Map explanation is the same as for Figure 5.

metamorphic rocks appear to have significantly decreased pedimentation rates. Reconstruction of the predissection landscapes suggests that these pediments, although now primarily subaerial, were formerly overlain by uppermost basin fill and (or) Cordonnes surface (see Figs. 4b, 6).

PEDIMENT FANS AND THE HIGH BASIN STANDS

Both the Canada del Oro and Sonoita Creek basins contain the dissected remnants of large alluvial fan complexes that unconformably overlie basin-fill deposits and the higher levels of the bedrock pediments (see above). The Cordonnes surface (which includes much of the Fort Lowell Formation of Davidson, 1973) has been described by McFadden (1978; this volume, Fig. 2) in the Canada del Oro; its approximate correlative in the Sonoita Creek basin is the Martinez surface of Menges (1981). These surficial deposits, the Cordonnes and the Martinez, plus their associated geomorphic surfaces, represent the highest altitude physiographic and stratigraphic units in their respective basins, and hence they have been termed informally *high basin stands*. Numerous similar pediment fans occur at the bases of many of the higher altitude mountains of southeastern Arizona (Melton, 1965), where they occupy similar high stand positions in their respective basins.

Both the Cordonnes and Martinez fans commonly retain an identifiable geomorphic surface despite locally intense dissection; however, in most areas only remnants of this surface are preserved as accordant ridgecrests or mesas (Fig. 4). The fan deposits themselves consist of clay-rich sandy cobble-boulder-pebble gravels that are distinctly coarser grained (often with 1- to 3-m-diameter boulders) than the underlying basin fill. Where well preserved, these deposits occur typically as distinct gravel caps that overlie basin sediments or bedrock above basinwide erosion-pediment surfaces. The thickness of these gravel deposits varies from up to 100 m for the Cordonnes surface to between 20 and 5 m for Martinez alluvium. The internal geometry of both the deposits and geomorphic surfaces clearly indicates original deposition as thin (relative to basin fill) coalescing alluvial fans that emanated from the larger drainage basins prior to integration of the basin to the regional drainage. Like upper basin fill, these fans extend unruptured across the known positions of basin-bounding fault zones and either bury or project onto extensive bedrock pediments (Fig. 4).

The known age relationships imply a latest Pliocene to early Pleistocene depositional interval for these fans of the high basin stand. The magnetostratigraphy of the underlying BF_U unit establishes a maximum age of 3 to 2 m.y.B.P. for the Martinez surface. An approximately similar age constraint seems likely for the Cordonnes surface, based on the correlative geomorphic and stratigraphic relationships between the two units. Very minimum ages of ≥ 1 m.y. may be estimated for both units on the basis of the time constraints implied by their respective soil stratigraphy. Where well preserved, both surfaces contain very well developed relict soils characterized by thick and morphologically complex argillic and (or) petrocalcic horizons (McFadden, 1978, this volume; Richardson, Clemons, and Walker, 1979; Menges, 1981). These soils require long time intervals (probably pre-mid-Pleistocene) for formation regardless of climatic factors.

QUATERNARY TERRACES

Marked Quaternary dissection of both basins is recorded by stair-stepped suites of progressively lower and younger terrace and piedmont surfaces and associated gravel-sand deposits. These units are erosionally inset into basin sediments or bedrock below the elevation of these fans. McFadden (1978; this volume, Fig. 2) has mapped four major terrace levels in the Canada del Oro basin. In the Sonoita Creek basin, more detailed studies combined with deeper dissection and consequent enhanced terrace separation permit the recognition of eight major composite terraces. These units commonly comprise multiple (3 to 5) closely spaced and morphologically similar component surfaces (Figs. 2, 7, and 8; Menges, 1981). Most of the dissected basins of southeastern Arizona contain a generally similar set of four to six easily recognizable nested terraces (e.g., Morrison, 1965; Morrison and Menges, unpub. data).

Detailed field transects of the Sonoita Creek basin terraces have demonstrated that the longitudinal profiles of individual terrace surfaces maintain a remarkable subparallelism with respect both to one another and to the modern floodplain channel (Figs. 7, 8). Further, all terrace profiles extend across the known position of basin-bounding faults without detectable disruption (Menges, 1981). Reconnaissance studies in the Canada del Oro basin indicate that the longitudinal profiles of that terrace sequence either slightly converge or are subparallel to one another in the downstream direction and likewise appear to ignore basin-bounding structures.

Detailed soil-stratigraphic studies of the Canada del Oro terraces have defined a soil chronosequence that suggests a mid-late Holocene to mid-Pleistocene age for the post-Cordonnes surface units (McFadden, 1978, this volume). The enhanced effect of erosion on the soils of the Sonoita Creek basin prohibit the development of a similar chronosequence within the terraces of that area. However, the observed soil and geomorphic relationships in that basin are consistent with a generally similar Holocene through mid-early(?)-Pleistocene age.

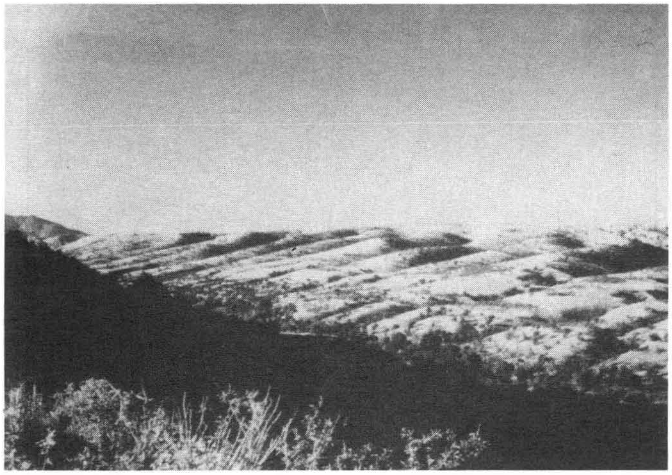
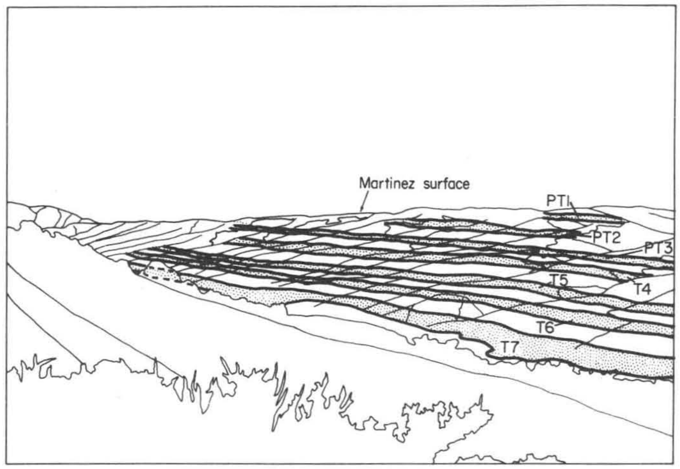


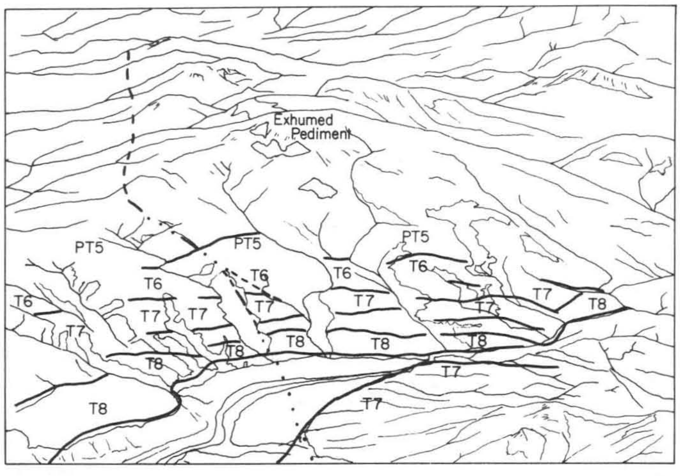
FIGURE 7. Well-preserved flights of Quaternary terraces and associated piedmont surfaces inset into basin sediments of Sonoita Creek basin

a. North side of Adobe Canyon. The Martinez surface remnant of Figure 4a occupies the middle skyline.

b. North side of Red Rock Canyon, near the southeast boundary of the alluvial basin. The terraces extend undisturbed across the trace of a major basin-bounding fault zone (dotted line). Note the high-level, exhumed and stranded bedrock pediment (P_R).



c. Sketch of Adobe Canyon terraces (Fig. 7a), showing major surfaces identified in Fig. 8a.



d. Sketch of Red Rock Canyon terraces (Fig. 7b), showing major surfaces identified in Fig. 8b.

IMPLICATIONS OF DATA FOR BASIN-RANGE TECTONIC ACTIVITY

BASIN-FILL STRATIGRAPHY

Basin-fill stratigraphy in the two study basins clearly records the gradual waning and eventual termination of large-magnitude Basin-Range tectonism, at least along the boundary fault zones of the primary bedrock grabens. Both gravity modeling and outcrop relationships indicate that stratigraphically lower BF_L deposits in Sonoita Creek basin have been downfaulted against the graben boundary faults; presumably at least some of this unit represents the primary syntectonic depositional response to Basin-Range graben subsidence. The encroachment of unfaulted upper BF_L deposits across these former boundary fault zones sometime before latest Miocene to Pliocene, suggests a decline in tectonic activity along these structures. Subsequent basin-fill deposition (uppermost BF_L and BF_U units) continued to bury these faults without displacement and formed a thickening alluvial mantle that progressively overlapped the early developmental stages of the bedrock pediments.

This decrease in tectonism may be reflected in changes in sediment distribution. In Sonoita Creek basin, sediment dispersal patterns appear to have shifted during the basin-fill interval from the multiple, structurally controlled local depocenters of BF_L time to the more restricted area of BF_U deposition centered north and northeast of Sonoita (Fig. 2d). Very likely BF_U drainages may have exited eastward from the Sonoita area, eventually debouching into the adjacent San Pedro Valley (Fig. 1), which at this time was the site of paludal to lacustrine deposition (upper Quiburis and (or) lower St. David formations; cf., Heindl, 1963; Johnson, Opdyke, and Lindsay, 1975; and Scarborough, 1975). These changes suggest a diminishing influence of local structural geometry on patterns of basin-fill dispersal and deposition relative to other factors, such as surrounding physiography and evolving regional drainage patterns.

The effect of decreasing tectonism and basin subsidence is also strikingly illustrated by a comparison between the sedimentation rates of the Sonoita Creek BF_U deposits and the primary basin fill ($\approx BF_L$ unit) of two adjacent basins (Fig. 1). Sedimentation rates for the Tucson and Picacho basins averaged 390 to 210 m/m.y. and 520 to 260 m/m.y., respectively, based upon combined subsurface drillhole and geochronologic data summarized by Scarborough and Peirce (1978). (The large variations in rates arise from both uncertainties in

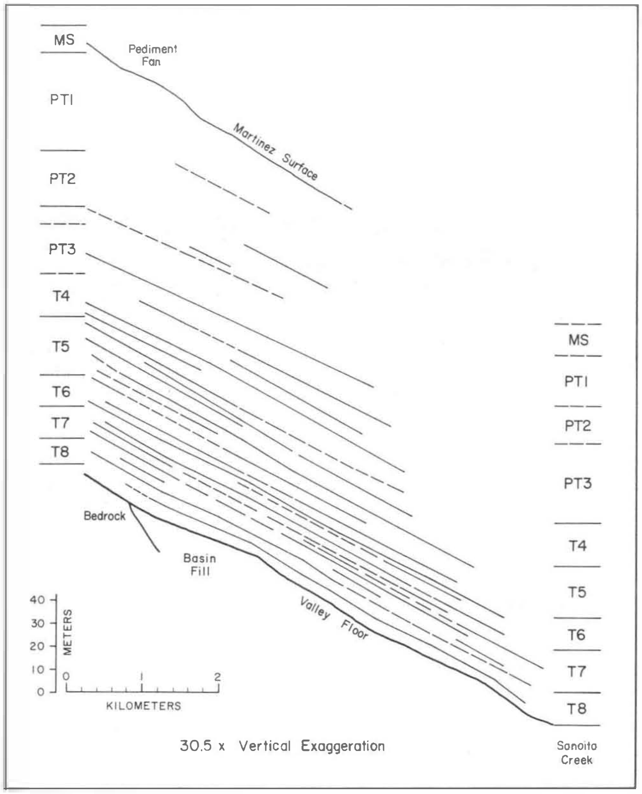
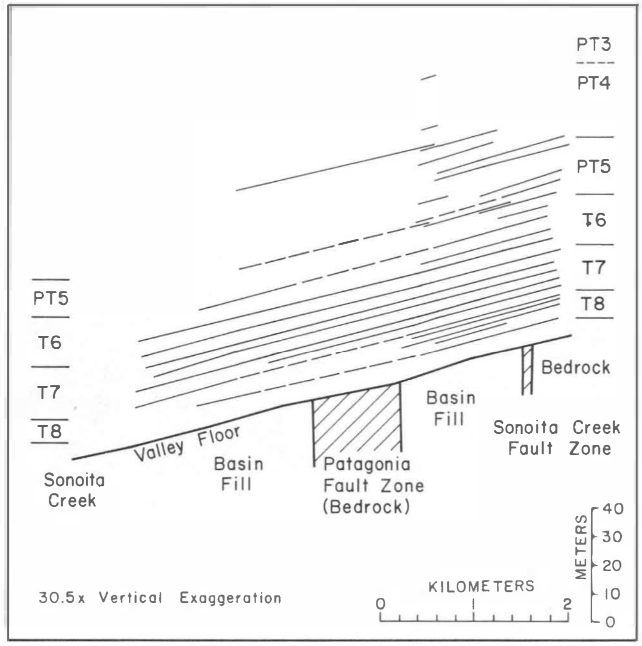


FIGURE 8. The longitudinal profiles of Quaternary terrace (T) and associated tributary piedmont (P) surfaces in Sonoita Creek basin, reconstructed from detailed terrace transects. Similar or clustered individual surfaces have been grouped into major composite units at the profile margins. The fault zone locations are determined from outcrop and (or) gravity data (Menges, 1981).

a. Adobe Canyon terrace sequence (see Fig. 7 a above)



b. Red Rock Canyon terrace sequence (see Fig. 7b above)

age bracketing of the fill and from the inclusion or exclusion of possible BF_U equivalents in the calculations.) Regardless, these rates are an *order of magnitude greater* than the mean sedimentation rate of 19 m/m.y. indicated for the Sonoita Creek upper basin fill by the magnetostratigraphic column (Fig. 3, Table 2). Undoubtedly much of the discrepancy in basin-fill depositional rates may be attributed to differences between basins in such variables as climate, source area rock types, basin size and depth, and drainage basin area and relief. However, high rates and (or) magnitudes of relative vertical tectonic activity on basin-bounding structures profoundly affect the mountain-valley fluvial systems so as to increase the rates and amounts of both downcutting in the mountains and sedimentation in the basins (W. B. Bull, personal commun., 1979). Thus it appears likely that some of the sharp reduction in depositional rates evident in BF_U time (relative to the earlier primary phase of Basin-Range tectonism and sedimentation) reflects in part the contemporaneous decrease in the rate and (or) magnitude of tectonic basin subsidence in Sonoita Creek and adjacent basins in southeastern Arizona during this time.

This inference is reinforced by other characteristics of the Sonoita Creek BF_U unit. The magnetostratigraphic column indicates that the sedimentation rates decreased upsection by about one-half (from 30 to 15 m/m.y.). This decrease coincides nicely with an upsection increase in the frequency of sedimentation breaks, often associated with intervals of landscape stability, that are recorded by the diastem-paleosol sequences of the column (Fig. 3; Table 2). According to Bull (1979), this type of intermittent deposition and landscape stability indicates fluvial systems that fluctuate near their critical power threshold over a long time span (here estimated between 2.5 and 3.8 m.y., minimum), suggesting long-term stability in the major variables, such as tectonism and climatic change, which affect the fluvial system. Thus, the upper basin fill may best be viewed as a "last gasp" basin sedimentation developed primarily as a lag response to mountain-valley relief inherited from the earlier, now largely quiescent, Basin-Range disturbance.

PEDIMENTATION

Extensive bedrock pediments and embayed sinuous mountain fronts can develop only after relative vertical tectonism along the basin-bounding structures has decreased at least to rates or magnitudes incapable of generating or sustaining fault-bounded mountains and valleys (Bull and McFadden, 1977; Bull, 1978). The bedrock pedimentation developed in the two study basins clearly records such a decrease in Basin-Range vertical tectonism along their structural boundaries. Thus the inception of significant pedimentation provides minimum age constraints on the main activity phase of the Basin-Range disturbance. Pediment formation in Sonoita Creek basin began immediately prior to and (or) during the upper basin-fill sedimentation interval (between 6 and 3-2 m.y.B.P.), because this deposit overlies the lowermost and oldest recognized bedrock pediments.

These stratigraphic data are also consistent with estimates of the minimum time required for the development of the scale of pedimentation observed in these basins. Estimates of pediment formation rates vary greatly, based on such factors as lithology and climate. Several workers have proposed rates on the order of 1 km/m.y. for coarse-grained plutonic rocks (Marchand, 1971; Oberlander, 1972; Wallace, 1978), and these estimates probably represent maximum rates associated with the most favorable conditions (W. B. Bull, personal commun., 1981). Application of these estimates to the plutonic rock pediments of the Canada del Oro and southwestern Sonoita Creek basins implies minimum pedimentation intervals of several (≈2 and 5) million years. Pedimentation of the more resistant silicic volcanic rocks underlying much of the Sonoita Creek basin would require even longer time intervals.

HIGH BASIN STAND PEDIMENT FANS

The Martinez and Cordonnes surfaces represent an important period of alluvial fan deposition during probably latest Pliocene to early Pleistocene (~2 to 1 m.y.B.P.), an interval situated between the final stages of basin-fill aggradation and subsequent basin dissection. Several characteristics—including the thinness of the fan deposits (relative to typical basin-fill aggradation), their spatial association with mountain-front pediments, and the lack of detectable deformation, especially when overlying known basin-bounding faults—all preclude a tectonic origin for both fan units and further prohibit significant tectonism during or subsequent to their formation.

Instead, these fans more likely represent depositional responses to one or more climatic perturbations at or near the beginning of the Quaternary. These and other similar fans typically occur at the base of mountain drainage basins characterized by large basin areas, steep hillslopes, large total mountain-valley relief, high altitude divides, and lithologies susceptible to weathering and erosion. These factors all tend to enhance sediment transport and deposition in response to certain types of climatic changes. For example, Melton (1965) suggested that periods of increased freeze-thaw weathering occurred in the higher altitude mountains during Pleistocene full glacial intervals. Subsequent stripping of these thick hillslope mantles near the beginning of interglacial periods would produce larger sediment loads than could be transported by the available critical stream power of the drainages, thereby triggering rapid fan aggradation at the mountain fronts in the manner described by Bull (1979) and Leopold and Bull (1979).

The occurrence of generally similar and probably in part contemporaneous pediment fans in many basins throughout southeastern Arizona requires regionally consistent and approximately synchronous perturbations such as climatic changes. Available data do not suggest a uniform and direct correlation between high stand fan deposition and the inception of basin dissection. In most cases, these fans appear to either coincide with or precede local basin dissection, depending on the specific timing of the often interrelated processes of drainage integration and dissection within a given basin.

QUATERNARY TERRACES AND BASIN DISSECTION

The Cordonnes-Martinez high basin stands were terminated abruptly in both basins by the initiation of locally deep basin dissection, which produced a prominent suite of four to eight inset terraces. These generally subparallel surfaces are traceable throughout their respective basins and extend undeformed across basin-boundary structures into the adjoining ranges. In lieu of identifiable terrace deformation or contemporaneous tectonic perturbations within their basins, the origin of these terraces must be ascribed to other geomorphic or climatic variables. In general, the major terrace units appear to represent intermittent and repetitive interruptions within a longer term basin-degradation event, itself primarily related to nontectonic geomorphic processes (see Menges, 1981). Individual surfaces correspond to strathcutting or minor backfilling events, which in most cases probably reflect climatically induced fluctuations in the fluvial systems similar in style, if not in magnitude, to the mechanism proposed above for the pediment fans.

Some workers have invoked regional Pliocene-Quaternary epeirogenic uplift or warping as a necessary causal mechanism for the Quaternary basin-dissection event in southeastern Arizona (e.g., Cooley, 1968; Scarborough, 1975.) Significantly the geometry, apparent timing, and entire magnitude of the basin dissection present in both Sonoita Creek and Canada del Oro basins may be explained by nontectonic geomorphic processes. We envision integration of formerly closed or partially closed local basin drainages to the externally drained Gila River regional network as the most probable triggering mechanism for basin dissection. This integration process is often accomplished by stream piracy across low-altitude bedrock or alluvial divides between adjoining basins. Such integration can impose a significant external base-level fall upon the fluvial system of the captured basin in the common situation where it is higher in elevation, that is "perched," relative to adjacent externally drained valleys. In the two study basins the potential base-level fall attributable solely to basin integration is of sufficient magnitude to explain all of the present basin dissection (McFadden, 1978; Menges, 1981). This does not preclude the presence of regional Pliocene-Quaternary tectonic uplift in southeast Arizona; very likely it does exist to some degree within or adjacent to the Colorado Plateau. We simply emphasize that additional evidence from sources other than basin dissection are required to document uplift on either local or regional scales within southern Arizona.

SUMMARY AND CONCLUSIONS

The data and interpretations described above persuasively argue against an extension of the primary phase of Basin-Range tectonic activity beyond latest Miocene to Pliocene in the two study basins. More specifically, the basin-fill stratigraphy and bedrock pedimentation suggest a progressive waning and eventual termination of large-scale vertical tectonism within a latest Miocene to early Pliocene interval (i.e., between 6 and 3 m.y.B.P.) with the initial decrease in tectonic activity probably concluded early within this interval. General tectonic quiescence has continued throughout late Pliocene and Quaternary, as evidenced by the presence in both basins of nontectonic pediment fans and younger terraces of that age, which extend undisturbed across known Basin-Range structures. However, it appears that the major regional-scale Basin-Range tectonism ceased somewhat later in southeastern Arizona, relative to the southwestern part of the state, a factor that likely explains much of the obvious physiographic contrast between the mountains and valleys of the two subprovinces.

We further propose that the deposition of the high-level pediment fans likely signals the advent of Quaternary climatic changes in the area. The younger inset terraces reflect fluvial responses to subsequent Quaternary climatic perturbations superimposed upon long-term stream downcutting into basin sediments. Quaternary basin dissection was initially triggered by the imposition of a nontectonic external base-level fall on local basin drainages as they were integrated with the regional drainage network. This basic scenario appears to be applicable in general to basin evolution throughout most of southeastern Arizona, although individual basins may differ with respect to specific details of timing and process.

It should be noted that southeastern Arizona is *not* completely devoid of Pliocene-Quaternary deformation. Upper basin fill of Pliocene to early Quaternary age in some basins displays minor internal faulting, warping, or both (e.g., the upper San Pedro Valley: Scarborough, 1975; Johnson and others, 1975). Recent studies also have identified a relatively few scattered piedmont fault scarps that displace late Pleistocene or older alluvium (Morrison, Menges, and Lepley, 1981; Morrison, Menges, and Lepley, this volume; Bull and Sbar, personal commun., 1981). These piedmont scarps typically occur either within or at the margins of well-developed suballuvial bedrock pediment benches that are similar in scale to those described in the two study basins.

This relationship between faulting and pediments suggest probable Quaternary reactivation of formerly quiescent basin-bounding fault zones, which has partially interrupted a period of pedimentation. A preliminary comparison between known Quaternary deformation and the preceding primary phase of Basin-Range tectonism suggests that, although the former is generally similar in structural style and orientation, it is more restricted in distribution. In addition, Quaternary deformation has occurred less frequently and at reduced rates and magnitudes of tectonic activity, relative to the earlier disturbance. Whatever the exact nature of the relationship between these two episodes of deformation, the data presented in this paper clearly emphasize that, in contrast to the primary late Miocene interval of Basin-Range disturbance, nontectonic climatic and geomorphic variables have dominated over tectonic influences in controlling the Pliocene-Quaternary landscape evolution of southeastern Arizona.

REFERENCES

Aiken, C.L.V., 1978, Gravity and aeromagnetic anomalies of southeastern Arizona, *in* Callender, J. F., Wilt, J. C., and Clemons, R. E., editors, New Mexico Geological Society Guidebook, 29th Field Conference, p. 301–313.

Aiken, C. L. V., and Sumner, J. S., 1974, A geophysical and geological investigation of potentially favorable areas for petroleum exploration in southeastern Arizona: Arizona Oil and Gas Commission, Report 3, 40 p.

Bittson, A. G., 1976, Analysis of gravity data from the Cienaga Creek area, Pima and Santa Cruz Counties, Arizona (M.S. thesis): Tucson, University of Arizona, 76 p.

Budden, T. B., 1975, The Tortolita-Santa Catalina Mountain complex (M.S. thesis): Tucson, University of Arizona, 133 p.

Bull, W. B., 1978, Tectonic geomorphology of the Mojave Desert: Final Report, U.S. Geological Survey, Contract No. 14-08-011-G-394, 188 p.

Bull, W. B., 1979, Threshold of critical power in streams: Geological Society of America Bulletin, Part I, v. 90, p. 453–464.

Bull, W. B., and McFadden, L. D., 1977, Tectonic geomorphology north and south of the Garlock fault, California, *in* Doehring, D. O., editor, Geomorphology in arid regions, Proceedings, Eighth Annual Geomorphology Symposium, State University of New York, Binghamton, p. 115–138.

Cooley, M. E., 1968, Some notes on the late Cenozoic drainage patterns in southeastern Arizona and southwestern New Mexico, *in* Titley, S., editor, Arizona Geological Society Guidebook III, p. 75–78.

Cooley, M. E., 1977, Map of Arizona showing selected alluvial, structural, and geomorphic features: U.S. Geological Survey Open File Report, 77–343, map plus text.

Davidson, E. S., 1973, Geohydrology and water resources of the Tucson basin, Arizona: U.S. Geological Survey Water-Supply Paper 1939-E, 78 p.

Drewes, Harald, and Thorman, C. H., 1978, Major geologic structures between Lordsburg, New Mexico, and Douglas and Tucson, Arizona, *in* Callender, J. F., Wilt, J. C., and Clemons, R. E., editors, New Mexico Geological Society Guidebook, 29th Field Conference, p. 291–295.

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

Fenneman, N. M., 1931, Physiography of Western United States: New York and London, McGraw-Hill Book Co., 534 p.

Heindl, L. A., 1963, Cenozoic geology in the Mammoth area, Pinal County: U.S. Geological Survey Bulletin 1141-E, 41 p.

Johnson, N. M., Opdyke, N. D., and Lindsay, E. H., 1975, Magnetic polarity stratigraphy of Pliocene-Pleistocene terrestrial deposits and vertebrate faunas, San Pedro Valley, Arizona: Geological Society America Bulletin, v. 86, p. 5–12.

Lance, J. F., 1960, Stratigraphic and structural position of Cenozoic fossil localities in Arizona: Arizona Geological Society Digest, v. 3, p. 155–159.

Leopold, L. B., and Bull, W. B., 1979, Base level, aggradation, and grade: Proceedings of American Philosophical Society, v. 123, no. 3, p. 168–202.

Loring, A. K., 1976, The age of Basin-Range faulting in Arizona: Arizona Geological Society Digest, v. 10, p. 229–257.

Lustig, L. K., 1969, Trend-surface analysis of the Basin and Range province, and some geomorphic implications: U.S. Geological Survey Professional Paper 500-D, 70 p.

Mammerickx, Jacqueline, 1964, Quantitative observations on pediments in the Mojave and Sonoran deserts (southwestern United States): American Journal of Science, v. 262, p. 417–435.

Marchand, D. E., 1971, Rates and modes of denudation, White Mountains, eastern California: American Journal of Science, v. 262, p. 417–435.

McDougall, Ian, Saemundsson, K., Johannesson, H., Watkins, N. D., Kristjansson, L., 1977, Extension of the geomagnetic polarity time scale to 6.5 m.y.: K-Ar dating, geological and paleomagnetic study of a 3500-m lava succession in western Iceland: Geological Society America Bulletin, v. 88, p. 1–15.

McFadden, L. D., 1978, Soils of the Canada del Oro valley, southern Arizona (M.S. thesis): Tucson, University of Arizona, 116 p.

Melton, M. A., 1965, The geomorphic and paleoclimatic significance of alluvial desposits in southern Arizona: Journal of Geology, v. 73, no. 1, p. 1–38.

Menges, C. M., 1981, The Sonoita Creek Basin: Implications for late Cenozoic tectonic evolution of basins and ranges in southeastern Arizona (M.S. thesis): Tucson, University of Arizona, 239 p.

Morrison, R. B., 1965, Geologic map of the Duncan and Canador Peak Quadrangles, Arizona and New Mexico: U.S. Geological Survey Miscellaneous Inventory Map I-442; 1:48,000 scale, with text.

Morrison, R. B., Menges, C. M., and Lepley, L. K., 1981, Map of late Pliocene and Quaternary faults in Arizona: 1:500,000 scale, with accompanying tables and report, in press.

Oberlander, T. M., 1972, Morphogenesis of granite boulder slopes in the Mojave Desert, California: Journal of Geology, v. 80, p. 1–20.

Pashley, E. F., 1966, Structure and stratigraphy of central, northern, and eastern parts of the Tucson Basin, Arizona (Ph.D. dissertation): Tucson, University of Arizona, 273 p.

Richardson, M. L., Clemons, S. D., and Walker, J. C., 1979, Soil survey of Santa Cruz and parts of Cochise and Pima Counties, Arizona: Soil Conservation Service and Forest Service, U.S. Department Agriculture, 100 p. (122 map plates; scale 1:20,000).

Scarborough, R. B., 1975, Chemistry and age of late Cenozoic air-fall ashes in southeastern Arizona (M.S. thesis): Tucson, University of Arizona, 107 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., editors, New Mexico Geological Society Guidebook, 29th Field Conference, p. 253–259.

Scarborough, R. B., and Wilt, J. C., 1979, A study of uranium favorability of Cenozoic sedimentary rocks in Basin and Range province, Arizona: Part I, General geology and chronology of pre-late Miocene Cenozoic sedimentary rocks: U.S. Geological Survey Open File Report 79–1429, 101 p.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Kuck, P. H., and Rehrig, W. A., 1978, Mid-Tertiary magmatism in southeastern Arizona, *in* Callender, J. F., Wilt, J. C., and Clemons, R. E., editors, New Mexico Geological Society Guidebook, 29th Field Conference, p. 231–241.

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, C., editors, 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 Quadrangle, Santa Cruz County Arizona: U.S. Geological Survey Miscellaneous Inventory Map I-762 (with text), 1:48,000 scale.

Stirton, R. A., 1940, Phylogeny of North American Equidae: University of California Publications, Department of Geological Science Bulletin, v. 25, p. 165–198.

Wallace, R. E., 1978, Geometry and rates of change of fault-generated range fronts, north-central Nevada: Journal Research, U.S. Geological Survey, v. 6, no. 5, p. 637–650.

ARIZONA GEOLOGICAL SOCIETY DIGEST

VOLUME XIII

1981

Edited by

Claudia Stone and Judith P. Jenney