Cenozoic Erosion and Sedimentation in Arizona

by

Robert B. Scarborough

Open-File Report (OFR) 85-03

GMT 3.3:0 63/85-2
GOVT.
DOCS.

CENOZOIC EROSION

AND

SEDIMENTATION IN ARIZONA

by

Robert B. Scarborough

Arizona Bureau of Geology and Mineral Technology

Tucson, Arizona

November 16, 1984

This report is preliminary and has not been edited or reviewed for conformity with Arizona Bureau of Geology and Mineral Technology standards.

STATE OF ARIZONA
BUREAU OF GEOLOGY
AND MINERAL TECHNOLOGY
OPEN-FILE REPORT

85-3

UNIVERSITY OF ARIZONA LIBRARY

TABLE OF CONTENTS

INTRODUCTION 1

COLORADO PLATEAU

Eocene Erosion Surface 1
Eocene Deposits 2
Miocene-Pliocene History 5
Bidahochi Formation and Hopi Buttes Volcanism 5
Post-Hopi Lake History 7
Summary 7

SOUTHERN ARIZONA

Introduction 8
Basin and Range Disturbance 9
Colorado Plateau - Basin and Range Differentiation 10
Stratotectonic Assemblages of Southern Arizona 10
Whitetail Assemblage 10
Pre-Volcanic Hiatus 12
Volcanic Assemblage 13
Big Dome Assemblage 14
Big Dome Basin Trends 17
Gila Group Assemblage 17
Gila Group Contact Characteristics 18
Basin and Range Grabens 18
Regional Sedimentology 19
Relationship to Pediments 21
Deposits Along the Colorado River 21
Muddy Creek Formation and Hualapai Limestone 21
Bouse Formation 22
Youngest Gila Group Deposits 22
Pediment Gravels 23
Alluvial Fans 23
Terrace Deposits 24
Late Pleistocene Record at Willcox Playa 25
Pleistocene Glaciation 26
Integration of Southern Arizona River System 26
Basin Dissection 29

FIGURES 31-44

REFERENCES 45-61

CENOZOIC EROSION AND SEDIMENTATION IN ARIZONA

by

Robert Scarborough
Tucson, Arizona

INTRODUCTION

This report summarizes important parts of the history of Cenozoic sedimentation and sedimentary rocks throughout Arizona. It is an expanded version of the report that appears in AGS Digest 15. In particular, the section on the Gila Group is expanded, and sections on Pleistocene glaciation, river integration, and basin dissection are included. A more detailed reference list documents more fully previous work.

In this summary, the physiographic provinces of the State shown in Figure 1 will be used. The Colorado Plateau province is bounded on the southwest by the Mogollon Rim, as shown, and on the west by the Grand Wash cliffs. The remainder of Arizona shall be called the Basin and Range province, or "southern Arizona." The transition zone is a region separating the Colorado Plateau and the well-defined Basin and Range country, with intermediate structural and physiographic characteristics. It will be included with the Basin and Range in the main discussion of stratotectonic assemblages. Its main attributes relative to Cenozoic sedimenta- tion may be that it in general does not exhibit extensive tracts of tilted mid-Tertiary strata as does the Basin and Range, and so probably contains a different history of Cenozoic tectonism, erosion, and sedimentation. Even today, stream gradients within the transition zone are two to five times as great as those in the Basin and Range to the south. The details of these differences will not be focused on in this paper, but indeed are important enough for a separate discussion.

COLORADO PLATEAU

Cretaceous sediments in central Arizona as young as Turonian (90 m.y.) contain marine fauna (Miller, 1962) and indicate the presence of a low relief coastal area in the Mogollon Rim region that today is a geologic, geographic and climatic divide, reaching to elevations of 2380 meters (7800 ft.) asl. The post-Turonian uplift to these elevations of the ill-bounded region bounding the southern Colorado Plateau and encompassing the Plateau edge resulted ultimately in the physiographic and structural differen- tiation of the state into two physiographic provinces, the southern Colorado Plateau and the Basin and Range, each with its own characteristic style of subsequent Cenozoic tectonics and sedimentation.

Eocene Erosion Surface

Truncation surfaces beneath Triassic Moenkopi Formation, Cretaceous Dakota

Sandstone, and Eocene rim gravel on the Plateau near its southern edge all trim progressively older rocks to the southwest, yet dip gently northeast, indicating progressive, episodic Mogollon Highland uplift, regional beveling of the broad piedmont, and sedimentation to the northeast of the present Colorado Plateau southern margin. The hingeline of that uplift lay very close to the Mogollon Rim of today.

The regional Eocene erosion surface hypothesized to exist through much of the Cordillera (Castil and others, 1981; Gresens, 1981; Epis and Chapin, 1975) represents a period of tectonic quiescence that produced a regionally extensive low relief surface upon which was developed mature, leached soils (in part, laterites) in adjacent New Mexico and south-central Colorado. Floral remains in the Eocene of the San Diego area indicate a sub-humid, warm climate conducive to rapid regional weathering and planation. Regional land surfaces probably wholly below perhaps 1,000 meters are hypothesized by Epis and Chapin, (1975). In southern Arizona, this period of intense weathering and erosion is considered responsible for the production of the mineralized supergene caps over many of the region's porphyry copper deposits (Livingston, et al., 1968).

Some constraints on the age of the surface exist. Regionally, the late Eocene surface is overlain by 34-37 m.y. old volcanics in Colorado, New Mexico and Washington. The fossiliferous Baca Formation overlies the surface and is thought to occupy the last half of the Eocene (Lucas and others, 1981). Looser constraints on the age of the surface and rim gravels in Arizona are that the gravels contain clasts of 54 m.y. old Laramide volcanics, and are unconformably overlain by a 28 m.y. old remnant cap of rhyolite (Peirce and others, 1979). The regionality of the late Eocene planation event and the resultant surface allows one to further hypothesize that the rim gravels are close time equivalents of the Baca Formation of western New Mexico and may therefore also rest on the mid-late Eocene surface that in New Mexico and Colorado is capped by the 34-37 m.y. old volcanics.

Eocene Deposits

The oldest Cenozoic sedimentary deposits on the Colorado Plateau portion of the state are a series of fluvial and lacustrine sediments of Paleocene-Oligocene(?) age, deposited along the margin and interior of what appears to have been one or more large basins. One large basin lying astride the Arizona-New Mexico border is termed the Baca-Eager basin by Chapin and Cather (1981), and is hypothesized by them to resemble in general appearance the other Green River-type Paleocene-Eocene basins of the western Interior, and to resemble them in origin by tectonic damming by uplift of marginal blocks and downwarping of the basin interiors in such a way as to produce "quasi concentric facies zonation." The ponding of the Baca-Eager basin is hypothesized by Chapin and Cather to have resulted from the formation of the Sierra Uplift east of the basin in New Mexico. This damming may be related to the overall tectonic impetus for the deposition of sediments on the Arizona Colorado Plateau, once they were shed off a Mesozoic-early Tertiary positive element, the Mogollon Highland of Harshbarger and others (1957), whose northeastern border closely coincides with the southwestern Colorado Plateau

margin. The elevation of the Baca-Eager basin at the time of formation is thought to be low (Epis and Chapin, 1975; Chapin and Cather, 1981). The Paleocene Nacimiento Formation of the central San Juan Basin to the north contains crocodilian fossils, suggestive of essentially frost-free, low elevation conditions at that time (R. McCord, pers. comm., 1984).

Colorado Plateau sediments in Arizona of this age are thought to include the rim gravels of Peirce and others (1979), the Eager Formation of Sirrine (1950) (equivalent to the sedimentary member of the Datil formation of Wrucke, 1961), sediments around Rose Well and Long Point in western Coconino county (Koons, 1964; Young, 1982), and possibly the Chuska Sandstone of Gregory (1917) along with the underlying Deza Formation of Wright (1954). These outcrops are generalized on Figure 1. Overwhelming evidence based upon clast lithology and regional northeast flow pebble imbrication demands that the rim gravels (sensu strictu of Peirce and others) were derived from the Mogollon Highland source terrain (Cooley and Davidson, 1963) that was represented by a northwest-trending uplift that extended throughout Central Arizona.

The rim gravels are part of the proximal braided alluvial plain facies of the Baca basin of Chapin and Cather (1981) with identified outcrops shown in their figure 4. The gravels consist of fluvially sorted light colored coarse conglomerates and some interbeds of channel and overbank grits and sands, and now lie at elevations between 2140 m (7000 ft.) and 2440 m (8000 ft.). The rim gravels are preserved in patches atop ridge crests; maximum thickness report by Finnell (1966) is 70 m (200 ft.). He reports bouldery gravel mixed with coarse sandstone and mudstones, with clasts composed of quartzite, chert, and limestone of Precambrian and Paleozoic age, and a few diabase and granite clasts in fresh exposure. The probable more distal counterpart, the Eager Formation, where viewed by this author, contains clasts of resistant volcanic, metasedimentary, and crystalline rock types half the size or less of those in the rim gravels. These beds are found at elevations between 2600 m (8500 ft.) and 2980 m (9800 ft.). The minimum age of the pre-volcanic Eager can be inferred from age dates on overlying Datil volcanics in nearby areas that are as old as 38 m.y. (Elston and Northrop, 1976).

To the north lies the Chuska Sandstone (Figure 1), a predominantly aeolian sand body with a basal sand-shale-clay-conglomerate unit (Deza formation of Wright, 1954) that caps the Chuska Mountains at elevations above 2280 m (7500 ft.). The Deza formation, where exposed in the southern Chuskas is 76 m (250 ft.) thick, while the overlying Chuska Sandstone thickens from south to north in the mountains from 150 m (500 ft.) to 540 m (1750 ft.) thick. Deza beds were deposited by streams flowing to the east and contain a few gypsiferous sand layers, indicative of local ponded condi- tions. At Washington Pass, New Mexico, the aeolian Chuska is unconformably overlain by a 26 m.y. old andesite flow, one of a number in the Chuska Mountains (Damon and Shafiqullah, 1981). Wright (1954) was the first to point out a probable mid-Tertiary age for the Chuska Sandstone. A similar-appearing cross-stratified sand body underlies all of Escudilla Mountain 150 km south of the Chuska Mountains, and was called the "upper sedimentary formation" by Wrucke (1961). He reported thickness ranging from 65 m (200 ft.) to 370 m (1200 ft.) and relief on its upper surface of 430 m (1400 ft.) due probably to erosion before deposition of younger rocks. It is

unconformably overlain by a 25 m.y. old moonstone tuff (Damon and Shafiqullah, 1981), is underlain by a 25 m.y. old northern ash flow of the Blue Range Primitive area (Berry, 1976), and has feldspar grain chemistry greatly resembling the Chuska, although northerly cross-strata dips on the Chuska contrast with southerly dips on the Escudilla sediments (Trevena, 1979). Wrucke's curious reporting of heulandite cement in both these sand bodies was unconfirmed by Trevena's detailed investigation. Trevena's possible correlation of the two units, at least in so far as they were derived from very similar source terrains, is important because the Escudilla sand is bracketed at about 25 m.y. in age, which may also apply to the Chuska Sandstone. Trevena also suggests derivation of feldspars for these sand bodies both from the Mogollon Highlands and the San Juan Mountains to the north. However, it appears unlikely that these aeolian sands are fully as old as the rim gravels and Baca Formation, but they may well have been derived from them by aeolian action. The greater volcanic feldspar component of the Escudilla sand compared to the Chuska (Trevena, 1979) probably comes from older nearby Datil volcanics upon which it rests.

Farther west a few scattered outcrops of sediments occur at high elevations on the Hualapai Indian Reservation. Koons (1964) notes the presence of patches up to 75 m (250 ft.) thick of Frazier Well gravels at elevations of 1920 m (6300 ft.) to 2160 m (7100 ft.) near Frazier Well, Rose Well, and a high point, the Pinnacle. They contain clasts of quartzites, granites, gneisses, and chert that Koons suggests were derived, like the rim gravels, from south of the Plateau Paleozoic outcrops, north of Prescott. Their high elevation and southerly source certainly suggest they belong to the rim gravel episode. Farther east by 25 km, Young (1982) discusses the presence of lacustrine limestones and interbedded gravels and sands as thick as 50 m (165 ft.) at elevations around 1830 m (6000 ft.) exposed beneath the northern portion of the Mt. Floyd basalt field, around Long Point. The limestones contain freshwater gastropods very similar to those found in the late Paleocene Flagstaff limestone in southern Utah. Young suggests in his Figure 1 a possible 4000 km^2 size for the unnamed lake, ponded perhaps on the northeast by the northwest-trending Supai monocline with presumed Laramide offset and on the south by the Mogollon Highland country. The sediments overlie a terrain consisting of Kaibab Limestone with only local patches of Moenkopi Formation preserved in local lows, hence recording a pre-late Paleocene, post-Moenkopi erosional stripping of the region. Just east of Young's proposed lake, at Red Butte (T28N, R3E), the lake beds are not reported present between Moenkopi beds and an overlying 8.6-8.9 m.y. old basalt flow remnant (Damon and others, 1974) that caps the butte (elev. above 2200 m, 7200 ft.) and preserves the Moenkopi patch. A basalt flow that concordantly overlies the lakebeds at Long Point has a K/Ar age of 14 m.y. (McKee and McKee, 1972). Hence a hiatus of considerable duration exists that represents quiescent times for the interval between the lakebeds and the mid-Miocene lavas.

The lower elevation (1730-1780 m) gravels described by Koons (1964) under 17 m.y. old volcanics at Blue Mountain, and correlated to the Frazier Well gravels by Koons, probably belong to a younger, post-drainage reversal episode, as deduced for similiar lower elevation gravels farther east by Peirce and others (1979).

No other rocks of this age are known to the northwest in Arizona. In southwestern Utah, the Claron Formation consists of 300-400 m of lower red colored conglomerates, sandstones and limestones, an often-present middle white limestone, and a 100-350 m thick upper section of tuffaceous sandstones, limestones and conglomerates. The unit is conformably overlain by volcanics as old as a 31 m.y. old ash-flow tuff. The Claron drapes over the landscape in such a way as to be assumed to have been deposited before the structural differentiation of the Colorado Plateau and Basin and Range (Anderson and others, 1975; Rowley and others, 1978, 1979). The Claron and equivalents "were deposited in marginal basins east of the highlands formed during (thrusting of the Sevier orogeny and warping of the Laramide orogeny)" (Rowley and others, 1979, p. 3). Paleocene-Eocene units in southwestern Utah are seen to unconformably overlie beveled Laramide folds (Bowers, 1972), a relationship not observed anywhere in Arizona.

Miocene-Pliocene History

Following the deposition of the Chuska sandstone, no other significant sedimentary events are recorded on the Colorado Plateau until the deposition of the Bidahochi Formation in the Hopi Buttes country. Much has been written on the details of this and younger sediments, as well as the Hopi Buttes volcanics, and the subsequent downcutting history along the valley of the Little Colorado (Reagan, 1924; Williams, 1936; Kiersch and Keller, 1955; Repenning and others, 1958; Cooley, 1958 and 1962; Childs, 1948; Repenning and Irwin, 1954; Sabels, 1962; Shoemaker and others, 1962; Cooley and others, 1969; Sutton, 1974; Scarborough,1981; Wenrich-Verbeek and others, 1982). Much of the work has employed the formulation of regional surfaces to help visualize the sedimentary and erosional history of the region.

Bidahochi Formation and Hopi Buttes Volcanism

The Bidahochi Formation consists of three members. The lowest consists of a series of four or more lacustrine clays and silts of various white to reddish colors, attaining a uniform thickness throughout most of its extent of 60 m (200 ft.). Its depositional base is termed the Valencia Surface by Cooley and Akers (1961), and the body of water responsible for the deposition of the lacustrine rocks was called Hopi Lake by Williams (1936). The middle member is composed of thin basaltic tuff layers and an associated series of over 300 vents and diatremes (Wenrich-Verbeek and others, 1982) that erupted through the still active lake. The presence of aquatic fossils in the tuffs confirms that the volcanics indeed erupted through the lake before it dried up (Sutton, 1974). The upper member is a fluviatile sandstone sequence that varies in thickness from 90 to 180 m (270-600 ft.), and was deposited by some south-to-southwest streams flowing generally parallel to the modern Rio Puerco drainage direction that only recently has been captured by the Chinle Wash system. The sands contain trough cross-bedding, and are petrographically very similar to the Chuska Sandstone, which may have served as a partial source terrain. Repenning and others (1958, Figure 3) and Akers (1964) show the known distribution of the Bidahochi Formation in Arizona and adjacent New Mexico.

Some radiometric and fossil ages exist for Bidahochi units. The only

fossil age known for lower Bidahochi beds is from a isolated exposure near Sanders that contains Clarendonian or Barstovian (15-10 m.y. old) fauna (Lance, 1954; Sabels, 1962). Sabels (1962) suggests a derivation of some tuffs in the lower member from the Thirteen Mile volcano at the south end of Verde Valley. Dacitic volcanism was active there apparently between 13 and about 7 m.y. ago (Elston and others, 1974), probably overlapping the time of Hopi Lake sedimentation. The basalt tuff middle member around the White Cone area is associated with a 6.7 m.y. old basalt flow on the south flank of Roberts Mesa (Scarborough and others, 1974). The age range for a number of Hopi Buttes mesa-type flows diatreme spatter flows, and late stage dikes is 8.5-4.1 m.y. (Damon and Shafiqullah, 1984; Evernden and others, 1964, p. 190; Naesar, 1971; Wenrich-Verbeek and others, 1982). Scarborough (1975) tentatively correlated air-fall tuffs in southern Arizona with K/Ar ages of 5.5 m.y. to at least one rhyolitic ash vent at White Cone Maar, on the basis of glass chemistry. The lower part of the upper member at White Cone Peak contains a middle-late Hemphillian fauna containing beaver, mole, shrew, rabbit, and camel remains along with lacustrine mollusks and an ancestral Colorado River squawfish, and pollen indicative of xeric conditions, like today, with a distinctively seasonal climate (Baskin, 1975, and references therein). The fauna were in transitional lacustrine-fluvial strata, about 20 m above the Bidahochi middle member, indicating the continuation of lacustrine conditions for a short time post-6.7 m.y. (Baskin, 1975; Scarborough and others, 1974). This relationship and age may be a very critical one because the shift in sedimentary conditions around Hopi Lake and the squawfish remains probably relate directly to the establishment of a through-flowing Colorado River system being fed from this region by the developing Little Colorado River.

The base of the Chuska Sandstone in the Chuska Mountains (the Tsaile surface of Cooley, 1958) lies almost entirely above 2436 m (8000 ft.) elevation. The base of the Bidahochi Formation lies at elevations of 1796 m (5900 ft.) and higher. The 640 m of relief between the two depositional bases should be accounted for. It may represent any combination of two factors: post-Chuska, pre-Bidahochi erosional carving of the Little Colorado Valley, and tectonic upwarping of the Chuska-Defiance and/or the Mogollon slope areas relative to the Hopi Buttes area. The lack of critical Tertiary datums in the region compound the problem. Schafer and others (1974, p. 735) indicate the presence of some "rounded siliceous gravel or lag gravel" at elevations between 2300-2000 m (7600-6500 ft.) north of, and on top of, Black Mesa; deposits that are not obviously correlatable to either the Chuska or Bidahochi Formations. If correlated with either sequence, these deposits could further elucidate the region's history. The erosional carving of the valley probably predominated the relief-making, but in conjunction with what drainage outlet? Was this a north-flowing Little Colorado river that emptied into a northeast-flowing Colorado River during the 'barbed drainage' event of the Marble Platform? Alternately, Cooley (unpub. information) notes that a topographic saddle at the south end of the Kaibab upwarp, now at an elevation of 1980 m (6500 ft), could have served as a western outlet for Valencia cycle erosion. Cooley (1962) notes the presence of 15 m of calichified sands and silts under the basalts and above Chinle beds at East and West Sunset Buttes (30 km southwest of Winslow) at elevations between 1830-1950 m (6000-6400 ft.). He likened them to upper Bidahochi sands that lie at similar elevations east of Hopi Buttes. This may

indicate that lacustrine Bidahochi beds were not deposited this far southwest. Based upon some newly described outcrops of probable lacustrine Bidahochi Formation near Shumway (Secs. 22, 23, 26; T12N, R21E; Peterson, 1983) that lie at an elevation of 1750-1820 m (5770-5950 ft.) the southern extent of Hopi Lake should probably be extended southward 80 km from existing positions (Sutton, 1974), as shown in Figure 1. The Shumway exposures render inadequate Sutton's (1974, p. 661) hypothesis that north-dipping resistant sandstones in the Chinle Formation acted as a southern barrier to Hopi Lake, since Shumway is well south of the Chinle outcrops. They also make the possible size of Hopi Lake much larger. The present elevation of the lowest outcrop of the erosional top of the Kaibab Limestone at the mouth of the Little Colorado River is about 1875 m (6140 ft.), and when compared to elevations at which Bidahochi Formation beds are found (1770-1960 m, 5800-6450 ft.), only 85 m (280 ft.) of post-Bidahochi denudation in the downstream part of the Little Colorado River valley plus the incision of the Little Colorado gorge is necessary in post-Bidahochi time in order for a very large Hopi Lake (>7500 sq. miles) to have been totally confined in The Little Colorado River Valley. As pointed out by Damon and others (1974), there has been at least 215 m of denudation and river incision in the last 2.4 m.y. (age of a basalt flow sitting on the first major post-Hopi Lake surface, see Childs, 1948, plate 4), seemingly an amount large enough to require no post-Bidahochi tectonic warping in order to have Hopi Lake confined to an extent shown in Figure 1.

Post-Hopi Lake History

The younger history of the valley includes the downcutting of the Little Colorado River and the formation of four major pediment terrace systems (Early and Late Black Point and approximately equivalent Dilkon, Early and Late Wupatki; Childs, 1948; Cooley, 1962; Sutton, 1974), and continued basaltic volcanism around the San Francisco field and the Springerville area. No equivalent post-4 m.y. volcanism is yet identified in the Hopi Buttes area.

Summary

The majority of evidence at present tends to suggest the following for the Tertiary history of the Arizona Colorado Plateau: The oldest preserved Tertiary surface on the Plateau is under the unnamed lakebeds around Long Point and indicates a post-Moenkopi, pre-late Paleocene regional erosional stripping of the Plateau margin. This time encompasses the deposition of Chinle through Glen Canyon Group rocks, and the Sevier and Laramide orogenies. The ponding of the Paleocene-Eocene lake in southern Coconino County ensued, with roughly contemporaneous sedimentation of the rim gravels and fluviatile sediments into the Baca-Eager basin, possibly including the Chuska Sandstone. The Tsaile pediment, by definition the surface under the Chuska Sandstone, can generally be thought of as underlying the lake sediments at Long Point, the rim gravels, and the Datil volcanics around Alpine as well, although slightly different ages and elevations are involved. Regional drainage was to the north and east, and prevailing wind direction was from the southwest.

The Valencia cycle of pedimentation carved the Little Colorado River valley starting in the mid-Miocene in response to a new external drainage exit

somewhere to the north (McKee and others, 1967). The Valencia pedimentation cycle beveled moderate-sized monoclines and small upwarps throughout northeastern Arizona. The Valencia pediment is preserved beneath the lavas at Red Butte on the Coconino Plateau, somewhere above the basalts atop the Chuska Mountains, perhaps under the Tertiary gravels atop Black Mesa, and under Bidahochi Lakebeds.

Generalized regional topographic arguments (such as in Cooley and others, 1969,m p. 34) then suggest a renewed base level lowering, 300-460 m (1000-1500 ft.) of river incision, and a new cycle of Hopi Buttes-Zuni pedimentation. Hopi Lake started ponding around 10 + 3 m.y. ago and lacustrine conditions prevailed until slightly after the majority of Hopi Buttes and coeval San Francisco early Pliocene (6-5 m.y.) volcanism, burying some of the surface. The lake finally drained at about 6.5-6.0 m.y. as the downstream Colorado River became through-flowing. The Colorado River then responded to a major base level fall during the period 5.9-3.8 m.y. ago and incised at least 900 m through the Grand Canyon. Upper fluvial Bidahochi sands flooded over the lake beds, fed from sources around the Defiance and Zuni upwarps by a series of streams flowing generally southwestward. As a new stable river gradient was achieved in the Grand Canyon circa 3.5-3.0 m.y. ago, the Little Colorado and its many tributaries began cutting the Black Point pediment, a stable local base level that was covered by, and mostly predated, a 2.4 m.y. basalt flow at Black Point. Upper Bidahochi fluviatile sediments and local sediments atop the Black Point pediment accumulated until a renewed incision and subsequent stabilization took place, cutting the Wupatki cycle pediment dated at before 0.5 m.y. ago (age of the post-Wupatki Tappen basalt, Damon and others, 1974). Since that time, there has been 50-55 m (164-180 ft.) of Little Colorado River incision and five cycles of backfilling in northeastern Arizona, as detailed by Cooley (1962). The Jeddito Formation of Hack correlates with late Pleistocene (±60,000 years BP?) glaciofluvial outwash terraces from the San Francisco Peaks. The younger terrace deposits, called locally the Tsegi and Naja Formations by Hack (1942), contain human cultural remains and date from the last 2,000 years.

SOUTHERN ARIZONA

Introduction

The Cenozoic sedimentary history of southern Arizona is much more complex than that of the Colorado Plateau portion of the State, indicating something of the relative intensity of Cenozoic tectonics in the two regions. There are grand examples in southern Arizona of the marriage between tectonism, volcanism, and sedimentation, a few of which shall be mentioned.

Through a series of astute observations accompanied by very little detailed field work, a number of early workers (King, Dutton, Powell, Davis, Gilbert, and Louderback) prior to 1930 had collectively amassed enough data to surmise that the Great Basin mountain ranges contained strata folded during the "Jura" or Cretaceous and subsequently reduced to a peneplain condition prior to "rejuvenation" by block faulting that affected rocks as young as Miocene lavas

(see Davis, 1930; Eaton, 1932). Examples of step-faulting of Louderbacks as an indication of block faulting (Davis, Figure 1), or curviplanar faults that back-rotate strata relative to transport direction (Davis, Figure 3) were known at that time.

As well, the concept of a two-fold Cenozoic depositional history that is manifested by deformed "Miocene(?)" sediments and volcanics found capping mountain blocks and younger undeformed Gila conglomerate filling the valleys is at least as old as Ross's 1925 (p. 29-31) description in the Aravaipa and Stanley mining districts. The biggest contribution since that time has perhaps been to fine tune many of the old concepts with the aid of more detailed mapping and drilling studies and various refined age dating techniques.

Basin and Range Disturbance

Heindl (1925, 1954, 1958, 1962) was first to call attention to the unfortunate sustained informal use of the term "Gila Conglomerate" by many workers as applied to both deformed Tertiary strata and undeformed basin fill, and noted that Gilbert's 1875 original definition unfortunately suffered from the same malady. Heindl suggested (1962) that the name "Gila Group", still honoring Gilbert's work, be employed instead to refer to only those basinal strata that, in essence, were laid down within the confines of the present physiography and must therefore be products of the last relief-making tectonic event, Gilbert's block faulting. These strata, it turns out, are uniquely different from the older Tertiary clastic deposits in that the definition demands that the Gila Group deposits only contain detritus from current or recent upslope areas, and must not contain exotic, nor be missing necessary, materials. This author is of the conviction that Heindl's concept is valid, and the term "Gila Group" is useful within the boundaries of this definition. One of its uses is to call attention to the singular last tectonic event, an event this author calls the Basin and Range disturbance, and to focus on the differences between it and older deformations.

Damon and Mauger's (1966) paper was the first to clearly demonstrate a bimodal distribution of the Laramide volcanics and the volcanic rocks of the "mid-Tertiary Basin and Range orogeny". This paper set the stage for all subsequent geochronological statements of southern Arizona Cenozoic history since it is volcanic strata more so than fossiliferous strata that serve as tie points in regional correlations. Initial attempts have been made to date the onset of the Basin and Range disturbance (sensu strictu) in Arizona by inferences gained from new observations and a few key radiometric age dates. Shafiqullah and others (1976), Scarborough and Peirce (1978), Eberly and Stanley (1978), and recently, Zoback and others (1981) all suggest that the period 13-12 m.y. appears to approximate the initiation of the distur- bance. Available evidence confines the crucial period to post 14-13 m.y. (age of youngest rocks involved in block faulting) and pre 6-10 m.y. (age of oldest strata that by direct observation or inference are unfaulted and fill the faulted depressions). That the northern Basin and Range in Nevada experienced a similar (although now suspected to be a somewhat later) deformation by block faulting was first indicated by Gilbert and Reynolds (1973).

Colorado Plateau-Basin and Range Differentiation

It is not the goal here to elaborate on the Cenozoic history of the Colorado Plateau - Basin and Range boundary -- details of this complex mid-Tertiary phenomenon are given in Peirce and others (1979) and Young (1982). However, certain aspects of this history relate directly to sedimentation. The rim gravel aspect of the story on the Colorado Plateau has already been noted. South of the zone containing preserved rim gravels, new Oligocene drainages started to erode into Precambrian terrain whose Paleozoic cover by this time was removed, at least in central Arizona. The present northwest average trend of the Mogollon Rim and the relief across it may be a function of erosion controlled by two main factors: (1) the northwest regional strike of Paleozoic strata that was imposed early in the Mesozoic (Harshbarger and others, 1957), and along which trend strike valleys are assumed to have roughly localized in post-rim gravel time; and (2) the north-south and northwest orientation of faults south of the Mogollon Rim, movement on which may have caused or aided both the creation of new low base levels for the central Arizona region somewhere out in the Basin and Range, and the orientation of new stream directions. In the San Pedro Valley farther south, it is noted that a common regional flow direction for stream systems of mid-Oligocene strata (Mineta Fm., etc.) is consistently toward the northwest (Scarborough and Wilt, 1979, Fig. 33). One wonders if this trend is indicating that other northwest-flowing drainages were operative at the edge of the Plateau during Oligocene erosion. However, northeast-sloping surfaces down which ash flows traveled around Kingman at 18 m.y. (Young and Brennan, 1974) and along the Salt River at 20 m.y. (Peterson, 1968; Faulds, 1984), seem to indicate a northeast drainage trend inherited from rim gravel time, even though at 20 m.y. ago considerable drainage evolution must have taken place and the Mogollon Rim by that time was probably a barrier to northeast drainage.

Stratotectonic Assemblages of Southern Arizona

A conceptual model of the stratigraphic and tectonic framework of the Cenozoic of southern Arizona is given in Figure 2. Sediments in the region will be discussed within this context. Variously evolved forms of this classification scheme are given in Heindl (1960, Figure 1.3), McKee and others (1967), Sell (1968, Figure 2), Eberly and Stanley (1978, Figure 2), Scarborough and Wilt (1979, Figure 30), and Wilt and Scarborough (1981, Figure 1). The diagramatically accurate scheme of Heindl shows four major and one minor regional erosion surfaces (depicted also in Figure 2) that underlie four unconformity-bound "stratotectonic assemblages," implying four periods of erosion and deposition. For the purpose of this discussion, the packages will be called from oldest to youngest, the Whitetail assemblage, the volcanic assemblage, the Big Dome assemblage, and the Gila Group assemblage. The Gila Group assemblage corresponds to Eberly and Stanley's Unit II, and the older three assemblages to their Unit I.

Whitetail Assemblage

The Whitetail assemblage is defined here as those strata that were deposited before the main pulse of mid-Tertiary volcanism in any given area.

Tertiary volcanism is now thought to be time transgressive, younging to the northwest through the State (Coney and Reynolds, 1977). Defined this way, Whitetail assemblage deposits are constrained in age only as post-Cretaceous with a variable upper age limit (Figure 2). The type Whitetail Conglomerate in the Globe area was recognized as containing no mid-Tertiary volcanics by Ransome (1903); not until later did it become known that the type section underlies volcanics dated at about 20 m.y. old, and so may represent only a local prevolcanic condition.

A small patch of fluvial and lacustrine sediments near Artillery Peak in northern La Paz County, judged to be Eocene(?) aged based on the presence of Chara fruit by Lasky and Webber (1949), has some new confirmatory paleontology (Otton, J.K., pers. comm., 1982). Similar floral remains are known from the Paleocene-Eocene Green River Formation of central Utah (Lasky and Webber, 1949, p. 21-22).

In many exposures, the Whitetail is a fluvial assemblage of conglomerates to pebbly sands, light in color, and derivable from local prevolcanic sources. Where these exposures are relatively abundant in Gila and Pinal Counties, they consist of gently tilted and beveled fault blocks under the volcanic cover, usually less than 80 m thick. One exception is a north-south trending graben north of Ray filled with 1070 m (3500 ft.) of Whitetail, steeply folded into a syncline, beveled, and unconformably overlain by the 20 m.y. old Apache Leap Tuff (Peterson, 1968; Keith, 1981). Cornwall and others (1971) report a 180-m thick Whitetail Conglomerate section near Ray that contains a tuff near its top dated at 32 m.y. Krieger and others (1979) report a 33.5 m.y. age date on a 8-m thick tuff bed contained in a 66-m thick Whitetail Conglomerate section at the west end of Aravaipa Creek.

The general style of sedimentation in pre- to early-volcanic time in the San Pedro Valley region can be surmised from outcrops of the Mineta Formation (Clay, 1970), Pantano Formation (Finnell, 1970; Balcer, 1984), Teran Basin beds (Scarborough and Wilt, 1979; called Mineta Formation by Grover, 1982; see Figure 4), and Hackberry Formation (Schmidt, 1971; equivalent to San Manuel Fm. of Krieger and others, 1974), and the Threelinks Conglomerate (Cooper and Silver, 1964). Space does not permit detailed descriptions; the essence is that local depocenters evolved and filled rapidly with fluvial and lacustrine strata as relief was created by tectonic conditions. A good example of a sedimentary cycle is the progression in the 600-m thick Mineta Formation of lower conglomerates overlain by variegated shales and thin-bedded fetid limestones, and finally a gypsiferous siltstone, implying alluvial fan, lacustrine, and finally playa conditions. Similar progressions are found in the Pantano and Teran Basin sediments. Sedimentation in these areas progressed from 38 to 27 m.y. ago, based upon ages of enclosing volcanics. Often, intercalated limestones contain algal stromatolitic laminae and oncolitic horizons (Grimm, 1978). Elsewhere, sediments of the Whitetail Assemblage consist of red-brown fanglomerates with both fluvially sorted and thick tabular-bedded debris flow horizons, as the Helmet Fanglomerate in the Sierrita Mountains (Cooper, 1960) and the Locomotive Fanglomerate at Ajo (Gilluly, 1947; see Figure 5).

An unusual 150-m (500 ft.) thick red-colored cross-bedded aeolian

sandstone lies at the base of the Sil Murk Formation near Gila Bend (Heindl and Armstrong, 1963; see Figure 6). An ash flow in an unconformable capping volcanic-sedimentary sequence dates at 27 m.y. (Eberly and Stanley, 1978). The basal contact of the sand dips 30°SW (Scarborough and Wilt, 1979, Fig. 10), implying a tectonic tilting of the sediments. A thin basal conglomerate reflects underlying lithologies of a possible source rock to the sand, the Precambrian granites of the Maricopa batholith.

Since the sediments of the Whitetail Assemblage are usually only preserved as highly deformed masses faulted against edges of mountain blocks, and since there are no known throughgoing regional stratigraphic markers, the real shapes and sizes of the original depocenters cannot be surmised now. As noted later, this problem also exists for sediments as young as the Big Dome Assemblage.

Local relief during Whitetail deposition must have been comparable to that in the region today for at least the San Pedro Valley region, based on the inclusion into the Hackberry Formation of tabular "megabreccia" landslide masses composed of crystalline rocks and Paleozoic sediment blocks of considerable size (Schmidt, 1971; Krieger, 1977). A precise more recent analog for the inclusion of these masses into sedimentary basins exists in the Dripping Spring Valley where a 3.8-km long x 1.5-km wide x 5-35-m thick mass of Devonian-Mississippian carbonates became detached from near the crest of the Mescal Mountains and slid southward, internally brecciating and thinning by a factor of ten as it moved, coming to rest on the then-flat Dripping Spring Valley floor that was at that time (during the Pliocene) sedimenting with silts and sands in a flood plain environment (Krieger, 1977). This mass descended about 3,000 m along maximum slope angles of about 6-8° and traveled laterally about 4-5 km. The very thick, poorly sorted fanglomerates at Ajo and the Sierrita Mts. (Locomotive and Helmet units already mentioned) also imply impressive local relief conditions, possibly in excess of what is seen today in the region.

Bases of Whitetail Assemblage rocks are hidden by fault contacts with only a few exceptions. The Whitetail Conglomerate at Ray laps out against a hill of Pinal Schist; a local base of deposition of the Pantano Formation is a fetid pisolitic limestone unconformable on Cretaceous shales; and locally the Mineta Formation basal conglomerate rests depositionally on Precambrian granite near the north end of its extent.

Whitetail-aged sediments may be considered locally as old as 35-40 m.y. and as young as the time of local initiation of main phase volcanism, usually 28± m.y. (Shafiqullah and others, 1978; Wilt and Scarborough, 1981).

Statewide, only two Oligocene fossil finds are reported from Whitetail Assemblage rocks, a rhinoceros (Diceratherium sp.) from the Mineta Formation (Lance and Wood, 1958) and an oreodont from unnamed tuffaceous sediments near New River (Lindsay and Lundin, 1972). Grover (1982) notes footprints in the Teran Basin beds of a large mammal, perhaps Brontotherium sp.

Pre-Volcanic Hiatus

The oldest documented Whitetail Assemblage sediment in southern Arizona is a thin conglomerate in the northern Tucson Mountains that rests disconformably on Laramide volcanics (Imswiler, 1959) and that is overlain by the 39 m.y. old Rillito andesite. Overlying this section unconformably is a mid-Tertiary volcanic sequence with a thin blanket of basal conglomerate and a 25 m.y. old lowermost volcanic, the Safford tuff (Damon and Bickerman, 1964). This 10 m.y. hiatus is found elsewhere in the southeastern part of the State, and implies the presence of a period of non-deposition in the region.

At the north end of the Huachuca Mountains near the Babocomari River (Drewes, 1972; Vice, 1974), a deformed sequence may represent a southwest-dipping 38 m.y. old ash flow tuff overlain by a 1000-m thick sedimentary section containing three 24-27 m.y. age dates on intercalated ash flows and basaltic andesites. The sediments contain conglomerates, sandstones, mudstones, and freshwater limestones (to 10-m thick) with algal laminae horizons. In the Higley basin east of Phoenix, a well drilled in sec. 1, T2S, R6E encountered at the base of the Tertiary section an andesite dated at 39.4 m.y. (Shafiqullah and others, 1980, No. 58) overlain by 885 m (2,900 ft.) of ash flows (probably all post-25 m.y.) and then by 2,020 m (6,600 ft.) of sediments (Arizona Bureau of Geology file data). The thin, partial blanket-like nature of most pre-volcanic sedimentary strata and the apparent 10 m.y. hiatus beneath the volcanics suggest a period of erosion and/or nondeposition in many areas that ended with the volcanic cycle.

Volcanic Assemblage

Statewide, the initiation of mid-Tertiary volcanism is a time-transgressive event, noted roughly in Figure 2. Associated sedimentary rocks are typically composed solely of local volcanic materials. Depocenters for the Volcanic Assemblage strata were probably created by local faulting, warping, and damming effects related to volcano tectonics, as well as other regional detachment faulting events, covered by other papers in this volume. Volcanic assemblage sedimentary rocks tend, as a first approximation, to be more red-colored, unlike some older and some younger sequences. It is assumed, but not shown, that Oligocene deposits of southern Arizona were formed in a hot, semi-arid climate, shown by Walker (1967) and Walker and Honea (1969) to produce red bed colors.

Examples of Volcanic Assemblage sediments in southern Arizona include the dark-colored ± 32 m.y. old volcanoclastic Nipper Formation in the eastern Chiricahua Mountains (Sabins, 1957; Shafiqullah and others, 1978), the red-colored coarse and fine-grained Bonita Park formation of Chiricahua National Monument (Yetman, 1974), the thick deformed fanglomeratic redbed section containing 27-25 m.y. old andesite flows at Babocomari Ranch (Brown, 1966; Vice, 1974), similar-appearing fanglomerate redbeds of the upper part of the Helmet Fanglomerate (Cooper, 1960) and the 28-22 m.y. old Cloudburst Formation (Creasey, 1967; Weibel, 1981), the Rillito 1 Beds of Pashley (1966), the 4,500 m (!) thick fanglomerate package above the Eagle Pass detachment fault of Aravaipa Valley (Blacet and Miller, 1978; Davis and Hardy, 1981), the pre-21 m.y. old redbeds and intercalated volcanics north of the Tortolita Mountains (Banks and others, 1977), and the 21 m.y. old Apsey Conglomerate

volcaniclastic blanket atop the Galiuro Mountains (Krieger, 1979, Figure 2). Weibel notes the redbed fanglomerates of the upper Cloudburst Formation near Mammoth lie between volcanic flows dated at 28.3 and 22.5 m.y., and so coincide well with the time of Galiuro volcanism to the east. However, in more detail, Krieger (1979) discusses a profound unconformity in the middle of the Galiuro volcanics that may be reflected by sedimentation of the Cloudburst Formation.

In central and western Arizona by contrast, sediments associated with mid-Tertiary volcanics contain more tuffaceous deposits are thinner and tend to be light-colored, although conglomeratic redbeds are recognized. Interesting examples include the pre-15 m.y. old Daniels Conglomerate near Ajo (Gilluly, 1974), fanglomerates and floodplain sands and muds of the pre-17.6 m.y. old Papago Park sediments near Phoenix (Scarborough and Wilt, 1979, Fig. 11; Peters, 1979; see Figures 7 and 8 of this report), yellow-stained mudstones and thin-bedded limestones of the Gila Bend Mountains containing a 23 m.y. old ash flow, mudstones and ledge-forming limestones of the Clanton Hills, and a poorly sorted conglomerate interbedded into a volcanic section that was involved in rotational faulting in the southeastern Harcuvar Mountains (all mentioned in Scarborough and Wilt, 1979).

Big Dome Assemblage

A heterogeneous series of generally light-colored fine-to- coarse grained sediments are found capping the mid-Tertiary volcanics Statewide. They typically contain a significant component of tuffs and reworked tuffaceous sediments, occasional ash flows, and many are strictly volcanic-derived. They are distinguished from the younger Gila Group sediments in that they are usually moderately deformed and highly internally faulted, and are visibly in high-angle fault contact with mountain horst blocks, and often contain "exotic" clasts (i.e., not derived within present drainage system). The conglomeratic and fluvial Big Dome Formation of Krieger and others (1974), exposed between Ray and Hayden, exemplifies this age group. It contains an ash flow dated at about 17 m.y. and has facies relationships indicative of deposition in a drainage system somewhat modified from the modern one, although clearly related to the modern Gila River system.

Other formations in southern Arizona considered as part of this assemblage are the Nogales Formation (Drewes, 1972, 1981), the Rillito 2 and 3 Beds near Tucson (Pashley, 1966), possibly the Tinaja beds of the eastern Sierrita Mountains (Davidson, 1973), the San Manuel Formation near Mammoth (Heindl, 1963) and equivalents along the west side of the San Pedro Valley including the upper part of Schmidt's (1971) Ripsey Wash sequence, the Hell Hole Conglomerate of Aravaipa Valley (Simons, 1964), and the "breccia" of Mesquite Flat (Sheridan, 1978) in the Superstition Mountains. This post-volcanic fanglomeratic unit filled a WNW-trending structural low that was fault-bounded on the southwest (Scarborough, 1981b).

The Tinaja beds are a series of cemented fanglomerates poorly exposed beneath a thin verneer of upper Gila Group rocks along the eastern flank of the Sierrita Mts., as mapped by Cooper (1960). Davidson (1973) correlated these outcrops to units in the subsurface of various parts of the Tucson basin that

he suggested were overlain by the Ft. Lowell Formation, a Gila Group unit exposed at the surface on the southern and western flanks of the Santa Catalina Mts. Absolute age dates on both these units are lacking at this writing. This author would not make such bold correlations as Davidson did, mostly because of the probability that Davidson's Tinaja-Ft. Lowell break in the subsurface corresponds to a minor hiatus high in the 5000+ft. thick Gila Group section within the Tucson basin fill, and in no way is easily correlatable to the area of the type Tinaja beds. If the Tinaja beds are a Big Dome Assemblage unit, they should be found buried under the 5000 ft. of Gila Group rocks in the center of the basin, not nearly as high as the break in the subsurface identified by Davidson.

The conglomeratic San Manuel Formation near Mammoth contains at its very base a basalt dated at 22.1 m.y. (Weibel, 1981) and near the San Manuel interchange is intruded by a thin NNW-trending rhyolite dike similar to one farther north dated at 22 m.y. It is not clear if the dike has been rotated along with the San Manuel beds to their present 15-30°E dips. Part of the San Manuel Formation along the west side of the lower San Pedro Valley contains clasts of Galiuro volcanics and pebble imbrication directions suggestive of southwest- and west-flowing drainages across the present valley. This clearly predates the imposition of the eastward dips on the beds by later valley-making tectonics; the San Manuel Formation probably predates the modern Santa Catalina Mountains and the modern San Pedro River drainage. However, certain facies relation- ships in the somewhat younger Big Dome Formation near Hayden suggest the present Gila River drainage was already cutting into the upstream Williamson Canyon volcanics in Big Dome time (Krieger and others, 1974).

Pashley's study of clast composition in the Rillito beds along the south flank of the Catalina Mountains suggests a tripart makeup, with an up-section decrease in red-brown color and increase of mylonitic gneiss clasts shed from the adjacent Catalinas-Rincons as they unroofed during Rillito bed time. West to northwest-dipping crossbeds and clasts of Cretaceous sedimentary rocks now exposed to the southeast suggests derivation of the Rillito beds from easterly and southeasterly sources, perhaps from the northern flanks of the Whetstone and Empire Mountains. Clasts in Rillito beds that resemble Galiuro volcanic ash flows suggest a post-21 m.y. age for these sediments. Lindgrey (1982) suggests the Paige gravels east of the Rincon Mountains are a Big Dome equivalent, and were deposited as a result of rotational and high-angle normal faulting with easterly source areas, at a time before the Rincon Mountains were topographically high. These criteria of deposition and easterly direction of source terrain match with the Rillito Beds around Tucson, and the two assemblages thus may be contemporaneous, both pre-existing the Rincons as a topographic high. The rotational faulting may have accompanied basement distension and movement on the Catalina fault that preceded or accommodated Rincon Mountains uplift. Similarly, coarse-grained redbed sediments north of the Tortolita Mountains contain rare mylonitic gneiss clasts in conglomerates beneath a 21 m.y. old intercalated basalt flow (Banks and others, 1977), indicating unroofing of nearby outcrops of gneiss, possibly from the Suizo hills, at that same time. Hence, sedimentation of Big Dome Assemblage rocks in the Tucson-Hayden region was contemporaneous with the first exposure of metamorphic core complex mountains in the area, but probably predated the fully

modern drainage condition.

The Tertiary volcanic and sedimentary section around Mt. McDowell at the confluence of the Salt and Verde Rivers undergoes rapid lateral variations, but near the Salt River, just upstream from the CAP canal crossing, is capped by at least 220 m (700 ft.) of aeolian sandstone. Several hundred feet beneath the sand body lies an unwelded ash flow K/Ar dated at 17.7 m.y. (Scarborough, 1981b). Beneath the sand, red-brown conglomerates and volcano- clastic sediments interfinger with volcanics that appear to have been deposited at the western edge of the Superstition volcanic field, in a manner remenescent of the older Cloudburst Formation deposited adjacent to the Galiuro Volcanics farther south.

In central and western Arizona, a series of fluvial and lacustrine sediments fit roughly into the Big Dome assemblage. They include the deformed arkosic sediments and limestones on the east side of the Big Sandy Valley (pre-12 m.y. old), and a sequence of tuffaceous calcareous mudstones around Lake Pleasant, New River, and Chalk Mountain (Horseshoe Dam area) (Scarborough and Wilt, 1979), the post 14. 7 m.y. old Milk Creek beds (Plafker, 1956; Reed, 1950, Mckee and Anderson, 1971); the lacustrine Artillery Formation and alluvial Chapin Wash Formation around Artillery Peak (Lasky and Webber, 1949), and the uraniferous Anderson mine beds and equivalents in the Date Creek Basin (Sherborne and others, 1979; Otton, 1978). A welded ash flow sheet near the base of the 600-m thick Artillery Formation around Artillery Peak has a K/Ar age date of 19.9 m.y. (Scarborough and Wilt, 1979, Fig. 18). Fine-grained fluvial and lacustrine mudstones and interbedded aphanitic dolomites (often radioactive) are found overlying a 17.7 m.y. basalt and intruded by a 13.6 m.y. basaltic dike, in a downfaulted block near New River. Similar lithologies are found underlying a 15.9 m.y. old basalt in a north-dipping section north of Phoenix at the 'rifle range' (Scarborough and Wilt, 1979, Figs. 16 and 17, respectively). Possible correlative rocks, including bedded dolomites, are seen along the south flank of the Mazatzal Mountains where they are involved in a west-dipping flexure within the Cherry Creek fault complex, and are bracketed between 14.7 and 16.2 m.y. old dated basalts (Faulds, 1984). Other similar-appearing sections of light-colored marlstones, limestones, and tuffaceous mudstones are seen northeast of Lake Pleasant, and at Chalk Mountain north of Horseshoe Dam (Scarborough and Wilt, 1971, Figs. 23 and 22). The lacustrine character and other unusual identifying features of this group of mid-Miocene sedimentary rocks signifies an important time of ponding and interior drainage in central and western Arizona that represents sedimentation in a series of poorly integrated basins near the time of detachment faulting, and heralding the development of the integrated Gila River System.

In the eastern Big Sandy Valley of Mohave County (Figure 3), an east-tilted sedimentary section consists of lower arkosic sands and upper mudstones, tuffs, basalt flows, and uraniferous limestones. A basalt flow nearly at the top of the section has been K/Ar age dated at 12.2. m.y. The section is estimated to be nearly 2,000 m (6,500 ft.) thick, and unconformably overlain by piedmont facies of the Pliocene Big Sandy Formation (Scarborough and Wilt, 1979, Figs. 24 and 25). Worley (1979) has sub-divided the older sediments into a lower arkosic Burro Wash formation and an upper lacustrine and

volcanic Tule Wash Formation. The basin displays a striking overall sense of asymmetry, as indicated in Figure 3.

Big Dome assemblage sedimentary rocks in western Arizona are represented by another distinctive rock type, dark red-brown colored alluvial fan and floodplain sediments. Examples of these include the Chapin Wash Formation (Lasky and Webber, 1949), the fossiliferous Lincoln Ranch red beds (Gassaway, 1977), Copper Basin Formation (Teel and Frost, 1982), the upper redbeds of the northern Plomosa Mountains (Scarborough and Meader, 1983), and possibly the redbeds of Baker Peaks (Pridmore and Craig, 1982), redbeds of Osborne Wash and the Adair Park redbeds (Scarborough and Wilt, 1979, Figs. 13 and 4, respectively).

The present distribution of proximal and distal facies of the Big Dome assemblage in central and western Arizona bears a poor correlation with present physiography since rocks of both facies rest atop or directly astride mountain blocks. This observation suggests that some fraction, perhaps a majority, of the landscape in the region was finalized only after the deposition of these sediments, and as a result of the subsequent mid-Miocene detachment and high-angle block faulting tectonic events. An interesting model of syn-orogenic sedimentation of the redbed alluvial fans is given for the Copper Basin Formation by Teel and Frost (1982 and the Baker Peak redbeds by Pridmore and Craig (1982). The model involves listric rotation and sedimentation during the uplift of northeast-trending basement arches.

Big Dome Basin Trends

The trend of the valley segment that contains the Big Dome Formation around Kearney is WNW. In the Comobabi Mountains west of Sells, a similar-trending structure confines some tuffaceous sedimentary rocks, mapped in reconnaissance by Haxel and others (1978) that may be time equivalent. An interesting, possibly analogous, basinal assemblage in the Mojave Desert in California is the Barstow Formation, dated as between 13.5 and 16.5 m.y. old, deposited apparently in a WNW-trending trough, and containing lacustrine muds, limestones, and dolomite pods in a valley-center facies (Link, 1980). Menges and McFadden (1981) suggest, based upon a regional strike rotation of graben long axes, using the Arizona examples, a clockwise rotation of least principle stress between Big Dome and Gila Group time from north-northeast to roughly east-west.

Gila Group Assemblage

The youngest major assemblage of sedimentary rocks in southern Arizona is called here the Gila Group, based on the pioneering work of G.K. Gilbert (1875). The best studied areas containing Gila Group rocks are the San Pedro Valley (Heindl, 1963; Gray, 1965; Agenbroad, 1967; Smith, 1967; Jacobs, 1973; Montgomery, 1963; Ladd, 1975; Lammers, 1970; Johnson and others, 1975; Scarborough, 1975; Lindgrey, 1982), the Tucson basin (Pashley, 1966; Davidson, 1973), the Gila River Valley above Coolidge Dam (Marlowe, 1961; Van Horn, 1957; Harbour, 1966; Davidson, 1961; Wood, 1962; Clay, 1960; Seff, 1962; Morrison, 1965; Tomida, in press), the Verde Valley (Twenter and Metzger, 1963; Nations

and others, 1981; McKee and Anderson, 1971; Wadell, 1972; Bressler, 19__), the Big Sandy Valley (Sheppard and Gude, 1972 and 1973; McFadden and others, 1979), the Tonto and Payson basins (Royce and Barsch, 1971, Pederson, 1969; Lance and others, 1962) the Grand Wash trough (Lucchitta, 1972, 1979; Blair and Armstrong, 1979), and the Lower Colorado River Valleys, discussed below.

These valley fill units always have facies relationships relative to valley geometry and mountainward lapout characteristics indicative of deposition totally within the confines of the present valleys. In addition, the Pliocene axial fluvial facies in several valleys contain well-defined bedding and magnetozones that dip downvalley parallel to the present gradient of the valley's trunk stream (Gray, 1965; Johnson and others, 1975), implying that throughgoing, but sluggish, external drainage was established before the deposition of these sediments.

Gila Group Contact Characteristics

Upper basin fill is only rarely faulted or mildly deformed in southern Arizona (Menges and others, 1983), but lower levels, where exposed, usually are faulted against pediment edges. This implies that beveling of the adjacent bedrock pediments (commonly 2-5 km wide) that were covered with only uppermost basin fill proceeded approximately synchronously with basin fill sedimentation, and only following the majority of Basin and Range faulting. Cooley (1977) indicates the positions of pediments, once buried but now partially exhumed, in southern Arizona. The quasi conformable contact between undeformed basin fill and underlying progressively more deformed strata in southeastern valleys is exposed in a variety of places, notably in the Aravaipa Valley (Simons, 1964), at the north end of Allen Flat between the Galiuro and Winchester Mountains, about 16 km south of Redington on the west side of the San Pedro River, and near Patagonia (Menges and McFadden, 1983). Figure 9 shows Gila Group sediments lapping out against deformed older redbeds at the north end of the Sonoita Basin. Lack of absolute ages for the deformed rocks in these areas precludes knowledge of the timing of this shutoff of deformation; it is assumed to be post 11-12 m.y. and the deformed rocks are assumed to represent Big Dome assemblage or oldest Gila Group rocks.

Basin and Range Grabens

Gila Group sediments are assumed to have been deposited in structural grabens that now lie approximately centered beneath most southern Arizona valley segments that trend N-S, NNE, and NNW. This hypothesis is difficult to defend because the structures are invariably buried; however, two lines of evidence support the contention. A few high-angle normal, valleyward-dipping faults are observed that cut the edge of and trend parallel to the mountain fronts. As well, numerous negative residual Bouger gravity anomalies (10-40 mgal range) are centered along valley axes and are presumed to represent the gravity signature of a boat-shaped wedge of non-dense basin fill that was deposited in the grabens (Oppenheimer and Sumner, 1981). The negative gravity anomalies represent areas of greatest local mass deficiency beneath the valleys, probably due to a combination of thicknesses of poorly consolidated basin fill, non-dense early or mid-Tertiary volcanic and pyroclastic rocks, and

basin fill halite and gypsum accumulations. A statewide map by Scarborough and others (1983) outlines the most probable positions of Basin and Range grabens based upon Oppenheimer and Sumner's data and inferred positions of pediments.

Regional Sedimentology

In a regional sense, there is a history of stream integration between basins throughout much of later basin fill time. Initial basin filling is expected to be dominated by interior, closed basin deposits in those basins with rapid rates of graben subsidence. Once the rate of sedimentation effectively surpassed the rate of graben subsidence, spill-over points between adjacent basins were established and basin integration proceeded. It is likely that modern regional drainage patterns were established sometime before Pliocene basin filling because Gila Group strata of that age appear sedimentologically linked to grades of major stream systems, at least in southeastern Arizona (noted later). Doubtlessly, numerous local tectonic perturbations temporarily but repeatedly ponded otherwise throughgoing drainages, since ponded deposits that represent lacustrine, playa, and paludal conditions are locally common in upper Gila Group sections.

Elevations of the top of basin fill deposits in valleys separated by a mountain range sometimes are appreciably different, as across the Santa Rita, Growler, and Puerto Blanco Mountains. This author assumes that in these cases, basin filling proceeded in each of the two valleys while each was linked to a different base level. For example, in the case of the Santa Ritas, the last filling of Sonoita Valley was graded to the Santa Cruz and/or Babocomari Rivers at an elevation just under 5000 ft asl, while to the west of the Santa Ritas around Sahuarita, secondary streams in the valley were graded to the Santa Cruz at a level of about 3000 ft asl, thus accounting for differences in elevation of highest piedmont levels across the range of nearly 2000 ft.

Several older basin fill deposits contain massive evaporite bodies. The post-15 m.y. old Picacho anhydrite body (1,590 m or 5,200 ft. thick) and the pre-10.5 m.y. old Luke halite body (possibly more than 50 km^3 volume) were deposited in closed basin conditions (Peirce, 1976; Eaton et al., 1972) potentially shortly after the startup of Basin and Range grabening subsequent to about 12-13 m.y. Peirce (1976) developed the idea of the "Gila Low" region enclosing a series of basins containing the above-mentioned evaporite masses. The "Gila Low", shown in Figure 1, potentially represents terminal basin conditions relative to upslope basins that surround the region to the north, east, and south that do not contain known massive chloride-bearing evaporites. Curiously, the Gila Low has continued to act as a sump through the Quaternary for sediments derived from the Verde, Salt, Agua Fria, and Gila River systems. Today, the gradient of the Gila River downstream from the Phoenix area is about 4 ft./mile, less than a third the gradient (8-20 ft./mile) of many of the major streams above Phoenix. Downstream-convergence terraces along the Salt River above Phoenix illustrate, whatever their cause, modern sedimentation in the Phoenix area and upstream river incision and denudation (see Pewe, 1978).

The bulk of basin fill consists of piedmont alluvial fan complexes and axial fluvial deposits. The alluvial fan complexes consist of debris flow

lobes mixed with fluvially washed prograded gravelly sands deposited as sheetwash and in small or moderate-sized channels. The axial fluvial complexes were deposited by the main axial (trunk) stream of the valley. These contain distal overbank sands and silts deposited on floodplains, dispersed with proximal gravelly to bouldery sands deposited as backfills of the meandering axial stream. Davidson (1960) mapped the Gila Group facies in the Safford area of the Gila River valley, and showed the relationship between alluvial fans with north and easterly sources, and fluvial overbank and channel deposits of the Gila and San Simon Rivers near their confluence. Cooley (1977) shows the general distribution of fine-grained valley center facies in southern Arizona valleys. Average thickness of Gila Group deposits in centers of valleys is about 1500 m (5000+ ft) where drilling has penetrated older rocks (Scarborough and Peirce, 1978).

Ponded deposits are known in upper basin fill deposits as well. Notable examples are shown in Figure 1. Most of these are known from exposures in exhumed valleys; undoubtedly, undissected basins contain similar deposits. Moderate-sized lakes (relatively permanent bodies of water, larger than several km^2 surface area) are evidenced by the clay-dominated facies of the St. David Formation in the upper San Pedro Valley (Gray, 1965), the "blue clay" deposit in the San Simon Valley between Thatcher and San Simon (Knechtel, 1938; Harbour, 1966; Stone and Witcher, 1983) and the limestones, marls and clays southeast of San Carlos just north of the Gila River (Marlowe, 1961), the clays of the Big Sandy Formation (Sheppard and Gude, 1972), clay facies in the Tonto Basin northeast of Lake Roosevelt very near the Sierra Ancha Mountain front (Pederson, 1969; Lance and others, 1962), the limestones and marls of the upper Verde Formation in the Verde Valley (Twenter and Metzger, 1963); Nations and others, 1981), the Perkinsville beds (Lehner, 1958, McKee and Anderson, 1971), and the 300-m thick Hualapai Limestone in the Grand Wash trough (Lucchitta, 1972; Blair and Armstrong, 1979). These lakebeds are shown in Figure 1. The Bouse Formation along the Lower Colorado River is discussed below. Many other local ponded deposits are known; they are not treated as lakes because of limited extent or thickness.

The presence of halite in basin fill is assumed to signify total closed basin conditions with water leaving only by evaporation and infiltration. If one assumes that all surface waters contain some sodium chloride, then the presence of mixed muds and gypsum layers, perhaps with accompanying marlstones (a common occurrence), but without accompanying halite, may signify deposition in a paludal-like situation with local near-total evaporation, but with coevel sluggish surface drainage carrying the sodium chloride from the basin (Gray, 1965). Ponded deposits are found locally in most basins and represent temporary lacustrine, playa, or paludal conditions. These not infrequently contain thin air-fall ash beds that can serve as marker beds (Harbour, 1966; Scarborough, 1975).

Axial fluvial and ponded deposits are occasionally found directly adjacent to mountain fronts with essentially no intervening alluvial fan material (Harbour, 1966, Lance and others, 1962; Seff, 1962); the lack of local hillslope debris in these cases suggests a temporary dominance of overbank and paludal sedimentation from an actively meandering axial or main tributary

stream directly adjacent to a mountainfront.

Relationship to Pediments

Bedrock pediments are found throughout southern Arizona. These beveled areas at the foot of mountain ranges signify times of tectonic quiescence when erosional processes bevel mountain fronts down to, but not beyond, grade of streams exiting the mountain. Granites and tuffaceous volcanics are particularly susceptible to pedimentation, as seen in the Tortolita-Santa Catalina Mountains (Budden, 1975) and the southern Santa Rita Mountains (Menges and McFadden, 1981). Cooley (1977) indicates positions of some, but not all, pedimented areas in southern Arizona that have been partially exhumed because of Pleistocene stream entrenchment. In these areas the relationship may be observed that in general the only Gila Group deposits that overlap the pediments are those of Pliocene (Hemphillian) or younger in age (see Menges, 1981). Hence, Gila Group deposits may really consist of two sets, an older, still mostly buried set (13-9 m.y. old?, synchronous with initial Basin and Range faulting), followed by a stable period characterized by pedimentation (9-5 m.y?), and synchronous and later deposition of the upper set of deposits that onlapped the upper parts of the pediments, at 6-1 m.y. The tectonically quiescent time corresponds to the initiation of the through-flowing Gila-Salt-Colorado Rivers. The deposition of the upper set may correspond to renewed faulting or warping that caused ponding within the valleys.

To what extent older Gila Group deposits are synchronous with pedimentation can only be surmised by knowing their relationships near basin bottoms, observations that are now beginning to accumulate (Eberly and Stanley, 1978, Figs. 9, 11; Anderson, Zoback, and Thompson, 1983).

An older set of pediments that were related to pre-Basin and Range faulting regional stream systems were termed the Tortolita Surface by Melton (1960, 1965) and discussed in the Tortolita and Santa Catalina Mountains by Budden (1975). One can imagine that they may have coincided with some period of stable base level, perhaps in Big Dome time. However, to track them is very conjectural because of their highly disrupted nature.

Deposits Along the Colorado River

Muddy Creek Formation and Hualapai Limestone

The Muddy Creek Formation and the Hualapai Limestone Member are Gila Group deposits of the Grand Wash trough and Lake Mead area (Longwell, 1936; Lucchitta, 1979, see his Figure 6; Blair and Armstrong, 1979). The age of a basalt intercalated into the lower part of the Muddy Creek Formation near a local base of the Hualapai Limestone is 11 m.y. (Blair, 1978). Blair cites faunal, isotopic, and chert petrology evidence that suggests that the Hualapai Limestone, an upper valley-center facies of the Muddy Creek Formation, was deposited "in a marine to brackish environment, probably an estuary of what was then the north end of the Gulf of California." Similar results are suggested by study of diatoms and ostracods by Bradbury and Blair (1979). Lucchitta (1979) suggests instead that the limestone and the rest of the Muddy Creek

Formation are of interior basin origin. As well, Lucchitta suggests the lake in which the Hualapai Limestone was deposited was shallow and near or below sea level, with abundant gypsum and minor dolomite formed along the lake edge. Lucchitta suggests that the Hualapai Limestone and the Bouse Formation are roughly age equivalent, but probably no standing water connected them. He assumes that the Hualapai Limestone gets as young as the Fortification Basalt Member (K/Ar age of 5.9 m.y.) that caps fine-grained Muddy Creek beds. An 8.7 m.y. age on a basaltic tuff within the Hualapai Limestone (Blair, 1978) has a 2.2 m.y. analytical uncertainty, so may not accurately represent its age. Lucchitta cites clear evidence based upon source area studies that Grand Wash trough sedimentation proceeded with very minimal, if any, influx of materials from the mouth of the Colorado River. The valley was filled predominantly by a series of large alluvial fans with westerly and northerly sources, and the Hualapai Limestone was deposited in the lowest part of the basin (Figure 1) under conditions that most likely could not have existed if a Colorado River with modern flow magnitudes had existed.

Bouse Formation

The Bouse Formation of Metzger (1968) represents a marine estuary along the lower Colorado River region from Yuma northward to near Lake Havasu (Wilson, 1931; Smith, 1970; Lucchitta, 1972, 1979; Blair, 1978). Possible extent of the embayment is shown in Figure 1, as well as in Miller (1981) in an alternate fashion. Fossils such as marine foraminifera, marine to freshwater clams and snails, and brackish- to fresh-water ostracods occur in a thick section of limestones, siltstones, and claystones in the south. These represent depositional conditions of open marine circulation with "shelf benthonic fauna", with progressively more estuarine, brackish, and fresh water conditions to the north. A representative section is reported by Metzger in a well in sec. 31, T7N, R21W (La Paz County) as 7 m (24 ft.) of basal gray, green, and yellowish marls, overlain by 62 m (203 ft.) of olive-gray clays, and then 165 m (540 ft.) of green and gray sandstones interbedded with clays (0.5-3 m average thickness of beds), for a total thickness of 234 m (767 ft.). In outcrop the basal marlstones and the abruptly overlying claystones and sandstones are almost invariably separated from bedrock outcrops by a thin algal tufa deposit that coats the bedrock.

Age constraints on the Bouse Formation include (1) a transitional Miocene-Pliocene globigerinid, Sphaeroidinella dehiscens, from sediments underlying the Bouse Formation at 550 m (1,800 ft.) depth (Bouse Formation limits 319-427 m) in well LCRP-29, east of Yuma (Smith, 1970; Olmstead, and others, 1973, p. 40); (2) a K/Ar age of 5.5 m.y. on a vitric air-fall ash at a local depositional base of the basal Bouse marlstones near Milpitas Wash in California (Damon and others, 1978); and (3) upper Miocene benthonic foraminifera with clams and echinoids from a 488 m (1,600 ft.) thick marine sedimentary section underlying a 663 m (2,170 ft.) thick Bouse section in Exxon's Yuma Federal No. 1 well south of Yuma (Eberly and Stanley, 1978). These constrain the Bouse Formation around Yuma to totally within the Pliocene.

Youngest Gila Group Deposits

The youngest rocks of the Gila Group Assemblage in southeastern Arizona are pediment gravels, local alluvial fans, inset terrace deposits, some sand dunes, all mostly of Pleistocene age, and Holocene channel back-fill alluvium. In undissected valleys, concentrated in the western part of the State, interior basin deposits consist of marginal fanglomerates and distal fine-grained sheet-flood silts and sands, channel fills and overbank deposits, covered with sporadically distributed aeolian sands.

Pediment Gravels

Pediment gravels lie above the youngest basin fill along mountain-front piedmont areas, usually with a slight angular discordance. They are coarse-grained, reddish colored, poorly sorted deposits. They sometimes thicken mountainward, and occasionally contain narrow entrenched channel gravel deposits that trend perpendicular to mountain fronts and at times become calichified and stand up as topographically inverted ridges (examples in the San Pedro Valley northwest of Benson). In the dissected valleys of southeastern Arizona, the pediment gravels near the mountain fronts usually are capped by thick relict paliargid soils, estimated to be one plus m.y. old (McFadden, 1981). The highest level pediment gravels and their alluvial fan counterparts are the youngest preserved deposits formed during the constructional or aggradational phase of basin filling (the 'high basin stands' of Menges and McFadden, 1981).

Alluvial Fans

Alluvial fans are found as local remnants throughout southeastern Arizona. The term is used here to mean a cone of alluviated gravelly and bouldery material disgorged from a large canyon at its mouth, sometimes on top of deposits derived from other sources such as the axial stream of the valley. No obvious analogous features are noted in the more arid western part of the State, where piedmonts consist of pediments mantled with thin pediment gravels (Tuan, 1954, 1959; Cooley, 1977). Southeastern Arizona examples of alluvial fans include the Frye Mesa fan and others nearby along the northern Pinaleno Mountains, the Cordonnes fan remnant near Vista Catalina (McFadden, 1981), and an unnamed fan complex along the eastern Rincon Mountains. As might be expected because of erodibility characteristics, predominant rock types in alluvial fan source areas are granites and some other crystalline metamorphic rocks. The Frye Mesa fan remnant (Figure 10) is capped by a relict soil very similar to those that cap the basin edge pediment gravels; hence both deposits can be considered synchronous depositional responses to the same early Pleistocene hillslope erosion event, the differences in the style of deposition being probably related to stream power and erodibility of bedrock (see Melton, 1965; Lustig, 1966; Menges and McFadden, 1981). The Frye Mesa fan graded laterally into fine-grained basin fill deposits whose deposition brought the basin to a high stand. The distal end of the fan coincides nearly with the scarp at the base of the fan remnant visible in Figure 10. Since that time the center of the basin has been denuded by perhaps 50-120 m, and younger terrace levels may have been formed in the valley. Menges and McFadden suggest that the alluvial fans are all approximately synchronous, that they generally overlie or project above nearby stripped pediments, and "most likely represent

depositional responses to one or more climatic perturbations at or near the beginning of the Quaternary."

Terrace Deposits

Inset terrace deposits consist of reddish-colored gravelly sands that cap strath terraces cut into basin fill along main axial streams and tributaries. In the dissected valleys of the Gila-Salt River systems, usually three to four main inset terrace levels may be recognized (Pewe, 1978; Royce and Barsch, 1971; Kokalis, 1971; Drewes, 1972, Fig. 26; Harbour, 1966; Smith, 1963). In the deeply dissected Sonoita Creek basin, Menges (1981) has recognized eight major composite terrace levels whose longitudinal profiles are "remarkably" subparallel to both one another and to the modern floodplain. Possible causes of this basin dissection are noted in the section on Basin dissection. Terrace gravels consist of fluvially deposited channel gravels and interbedded riverine sands and gravelly sands deposited within the confines of a floodplain of an axial stream or tributary. Extensive sheets of laminar-bedded sands were deposited within a wide floodplain of the lower Colorado River, probably in early Pleistocene time, sometimes reaching miles from the River. in many spots along the River, these sands have been deflated and overlain by a thin veneer of derived aeolian sand. New deflation hollows through the overlying aeolian sheet on the Cactus Plain have uncovered fragmentary tortoise shell fossils (Gopherus sp.) undiagnostic as to age but related more to a Mexican species, now extinct in Arizona, than to the modern desert tortoise of the region (McCord, 1982). The same now-extinct form has been recovered form buried sands along the Salt River near Phoenix (McCord, pers. comm., 1984).

Haynes (1968), in a detailed stratigraphic investigation of Late Pleistocene beds in the upper San Pedro Valley, noted a curious series of isolated exposures of fine-grained deposits, his Boquillas formation, usually 20-100 m above river level from Naco to north of Redington, with a strangely consistent two-part stratigraphy (a lower olive-colored clay and an upper white marl with ostracod and snail remains), with radiocarbon dates between 30,000 and 12,000 years B.P. At the time, he proposed that the Boquillas beds represented a shore line of a lake (his Fig. 1) for which little other evidence existed. Although the lake's existence in late Pleistocene time followed by a slight regional northward tilt of the whole valley (to explain the present slight northerly dip to the level of Boquillas outcrops) is highly improbable, no other explanation has since been proposed to explain the accordancy of these beds. It is possible that the beds represent paludal or spring-fed deposition at or near the edge of an elevated floodplain level of the San Pedro in late Pleistocene (last 100,000 years?) time, followed by river entrenchment to the modern level. Most pediment gravel caps and inset terraces within the aerial bounds of Haynes' "lake" are late Pleistocene age, and likely younger than 100-200,000 years. So his "lake" boundary may represent the wedge-shaped volume of material removed since the existence of the floodplain at the Boquillas level.

Johnson and Miller (1980), working in the Parker-Blythe reach of the lower Colorado River, suggested two periods of major aggradation and two of degradation since Bouse Formation deposition, and prior to the most recent

period of incision starting at least 80,000 years ago that produced the three lowest stream terraces. The first major aggradation took place pre-3.3 m.y. and was followed by at least 700 ft. of downcutting prior to the second aggradation that took place between 700,000 and 200,000 years ago. The latest period of incision has produced more than 300 feet of relief, with major terraces at 40, 70, and 140 feet above present river level. Some of the sediments deposited by the last aggradation are probably related to the Chemchuevis formation discussed in some detail in the Lake Mead area by Longwell (1936). Bell and others (1978) describe the Chemchuevis formation as usually less than 60 m thick and predominantly laminar-bedded silt, sand, and clay. Preliminary age brackets suggest 100,000-200,000 years for dated sections.

Late Pleistocene Record at Willcox Playa

Present-day Willcox Playa at an elevation of 1,260 m (4,135 ft.) asl was the site of Pluvial Lake Cochise (Schreiber, 1978), the only Pleistocene Lake generally recognized in Arizona. Beach ridge topography suggests the pluvial lake was 18 x 32 km in size and up to 11-13 m deep. Pollen studies by Martin (1963) from a 43-m core near the Playa center suggest the upper 23 m with abundant Pinus pollen represents a cool-wet Wisconsin climate, the next 6-m interval the Sangamon Interglacial, and the bottom 14 m older pluvial times. The top of the Wisconsin pollen zone was C-14 dated at 20,000 years B.P. Cameron (1971), working with ostracods from the core, noted evidence for a permanent body of water represented in the upper 15 m of core, and repeated wetting and drying of the lake below the 15-m interval. Long (1966) concluded that the lake was depositing a green clay and marl between 30,000 and 13,000 years B>P>, a dried phase with playa-edge channel cutting and off-lake alluviation between 13,000 and 11,000 years B.P., and the last phase of lacustrine sedimentation represented by an upper green clay between 11,500 and 10,500 years B.P. Since that time, some playa deposits have deflated from the surface, and sand dunes formed north of the playa. See Figure 3A for data.

Based upon sedimentation rates of muds in Searles Lake, California (Smith, 1979, p. 75) of between 18 and 38 years/cm, with a best average of 28-30 years/cm, the Willcox core could represent between 80,000 and 160,000 years of deposition, with the best average of 125,000 years. Because of the relative runoff characteristics in these two areas (Searles having received more during pluvial times), this time at Willcox may be considered a minimum.

The nearest pluvial lake to Willcox is the Animas Playa in New Mexico (Fleischauer and Stone, 1982). Its highest shoreline is at an elevation of 1,280 m (4,190 ft.) with the lake occupying 390 km^2 (150 $mi.^2$) when full. Thus far, no absolute lake chronology has been established. Morrison (1965, 1984) suggests early-middle Pleistocene lakes existed in the upper Gila and Duncan valleys, whose shorelines are now found at elevations between 1,130 and 1,340 m (3,710-4,400 ft.). This hypothesis needs to be examined closely since this author feels that the bedrock dams to these areas had been breached by the Gila River prior to Pliocene time, as already outlined. The elevation of the bedrock dam at the present site of Coolidge Dam cannot easily have been above about 1,000 m, which is 130-340 m below, and tens of kilometers downstream

from, Morrison's study areas. Morrison's hypothesis demands the breaching of the dam, the denudation of the valley, and the construction of all inset Pleistocene terraces along with the complete removal of all shoreline features in the Coolidge Dam area, since lake time.

Pleistocene Glaciation

Montaine Pleistocene glaciation is recognized on the San Francisco Peaks (Sharp, 1942; Pewe and Updike, 1976; Updike and Pewe, 1974), on the White Mountains (Merrill and Pewe, 1977); and periglacial deposits (solifluction lobes, protalus ramparts, remnant rock glaciers) have been described on Kendrick peak, San Francisco Peaks (Barsch and Updike, 1971), in the Chuska Mountains near Roof Butte (Blagbrough, 1971), and noted on Escudillo Mountain (Barsch and Updike) and in the Santa Catalina and possibly Santa Rita Mountains by Brackenridge and Scarborough (1977). The studies at higher elevations in Arizona have concluded the Pleistocene glacial snowline was at an elevation of about 3,380 m (11,100 ft.), but, as shown in Table ?, toes of valley glaciers extended down to 2,560 m (8,400 ft.) in the Interior Valley of the San Francisco Peaks, and 2,800 m (9,200 ft.) in the White Mountains. Barsch and Updike found rock glacier remnants as low as 2,480 m (8,150 ft.) on the northeast slope of Kendrick Peak. Blagbrough suggests nivation hollows in the Chuskas extend down to 2,590 m (8,500 ft.) on northeast slopes. Brackenridge and Scarborough found three nivation cirques, several solifluction lobes, and one possible moraine on the northeast flank of the Catalinas between 2,740 and 2,440 m (9,000-8,200 ft.) elevation, and one nitch glacier or nivation hollow at 2,610-2,530 m (8,550-8,300 ft.) elevation on Mt. Hopkins in the Santa Ritas. Barsch and Updike note that the northern Arizona and central New Mexico data suggest that Wisconsinan rock glaciers and other periglacial phenomena existed at elevations depressed 600-900 m below the Wisconsinan snowline at elevations of 2,250-2,820 m (8,280-9,250 ft.).

Akers (1964) recognized glaciofluvial outwash in the Springerville area as thick as 30 m, presumably derived from the Purcell-Smith Cienega events in the White Mountains.

Integration of Southern Arizona Drainage System

At several points along the modern regional drainage system there is evidence of its antiquity. There is good evidence in the Lake Mead-Grand Wash trough area that the through-flowing aspect of the Colorado River course was established only after 5.9 m.y. ago, that the lower Colorado River gorge between Pierce Ferry and Temple Bar has been incised 925 m (3,030 ft.), 815 m (2,670 ft.) of which occurred between 5.9 and 3.8 m.y. ago, shortly following the deposition of the Hualapai Limestone, and only 110 m (360 ft.) of channel entrenchment in that area since 3.8 m.y. (Damon and others, 1978; Shafiqullah and others, 1980; Lucchitta, 1972, 1979). Downstream, some considerable fraction of the Bouse Formation was deposited post 5.5 m.y. age (see section on Bouse Fm.). Possibly, some earlier part of Bouse Formation deposition overlapped in time with the Hualapai Limestone. Based on these age dates, it appears that most of the downcutting of the Colorado River around Lake Mead (and in the Grand Canyon?) was contemporaneous with the Bouse estuary; this

contention is supported by the Bouse faunal evidence of Smith (1970). Remember also that Hopi Lake on the Navajo Reservation apparently dried up sometime around 6-5 m.y. ago, possibly due to this same incision carried upstream along the Little Colorado River. When Hopi Lake dried, there need not have been cataclysmic flooding since that region is semi-arid and the cutting of the Grand Canyon during the establishment of the new low base level took some period of time.

Within the Gila River drainage, Gila River gravels underlie a 6 m.y. old basalt flow near Gillespie Dam, Gila Bend area, but they only overlie an 8.9 m.y. basalt flow near Florence that caps fine-grained interior-basin deposits (Shafiqullah and others, 1980, text and age date #141). Both dated basalts outcrops very near the river channel, and very near modern river grade. So it appears that the modern Gila River was essentially in place and near grade before 6 m.y. ago, but possibly not before 8.9 m.y. ago. Therefore, it is likely that the modern Gila River drainage also emptied into the Bouse estuary and/or its predecessor, the upper Miocene marine transgression noted in the Yuma area by Eberly and Stanley (1978). It is not clear how far northeast along the Gila trough (Yuma-Gila Bend interval) either of these marine-estuarine environments extended. Metzger (1968, p. 135), citing Ross (1923), suggests that subsurface clay beds in the Gila trough extending to the Gila Bend area may be part of the Bouse embayment, as pictured in Figure 1. See Miller (1981) for a sketch of a very large possible southern Arizona Bouse embayment, probably too extensive to be supported by available evidence.

Farther upstream around San Carlos, a remnant of a 7.5 m.y. old basalt remnant at Bucket Mountain projects to about 120-200 m (~650 ft) above modern river grade, while the 1 m.y. old Peridot Mesa flow lies 60 m (200 ft.) above the present channel of the San Carlos River that grades to the Gila River 14 km downstream (Shafiqullah and others, 1980, #145 and 156). Hence, the Gila River between Florence and San Carlos must have been locked into its present course for the last 6 m.y., and downcut about 200 m since 7 m.y., and 60 m since 1 m.y.

The origin of the southwest-flowing transverse (across mountain block) segments of major streams in Arizona is a puzzling aspect of drainage integration, as noted by Melton (1960) and McKee and others (1967). It is tempting to call upon an antecedence to explain their origin, as did Melton, particularly in light of the early Tertiary northeast-flowing stream history known for central Arizona. The alternative origin for transverse segments would hypothesize that they are not antecedent, but are subsequent to Basin and Range mountain making and would represent spill-over points between basins filled literally to mountain divides by early-phase basin fill and lakes. This scenario appears untenable since it would require enormous depths of water or thickness of early-stage basin fill that must have been removed down to modern river grades before Pliocene time (see Cooley, 1968 for a variation of this theme). This author prefers a delicately balanced antecedent model to explain the positioning of the major southwest-directed transverse stream segments, especially for difficult cases such as the Gila River between Coolidge Dam and Winkleman. In this case it is most probable that an antecedent river course existed (flow direction not specified) whose path was probably laid out

following mid-Tertiary volcanic time, and was slowly locked into place during river incision that accompanied Basin and Range faulting. The facies relationships of the Big Dome Formation near Winkleman suggest that a southwest-flowing proto-Gila River existed in Big Dome time that deposited alluvial fans containing clasts of Williamson Canyon volcanics that are found only in the upstream direction to the northeast (Krieger et al., 1974). A corollary to this hypothesis is that Gila River Valley basin fill and major tributary deposits were continually graded to the developing river course whose overall southwest direction was determined by the regional topographic outcome of Basin and Range faulting and whose gradient was controlled by the rate at which it incised through the Gila River gorge. Thus, ponded deposits along the Gila River system represent transient times when the Gila River did not maintain enough power to incise its downstream gorge at a rate commensurate with the rate of Basin and Range mountain uplifts; hence the term "delicately balanced", above. This overall model suggests that transverse stream segments are the best clues we have regarding drainage directions before the Basin and Range disturbance. The Salt River course with a definite history of older northeast flow above Roosevelt Reservoir has apparently suffered a "piano key" back rotation that imposed an exact opposite slope to the old channel, that the new river exploited. As Melton (1960) asked, how regional a phenomenon was this, particularly in terms of the transverse southwest-flowing stream segments?

The history of other transverse stream segments have their own unique aspects. For example, Aravaipa Creek occupies a transverse gorge through a structural low point in the Galiuro Mountains. The 21 m.y. old Apsey Conglomerate blanket atop the Galiuro Mountains (Krieger, 1968, 1969) is preserved both north and south of Aravaipa gorge, but bears no facies evidence of having been deposited under the influence of an ancestral Aravaipa Creek. Hence the Aravaipa drainage is entirely younger than 21 m.y. Aravaipa Creek probably represents the San Pedro River baselevel capturing the uppermost Aravaipa-to-Willcox Playa drainage across the Galiuro crest within the last million years or so. This followed a basin fill high stand in Aravaipa Valley in early Pleistocene time that was clearly graded to Willcox Playa, since the high-level surface remnants that completely surround the north end of Aravaipa Valley all lie on a gentle south-dipping surface graded to nearly the present level of Willcox Playa.

A fascinating biological control exists relative to the antiquity of regional stream integration in the Southwest. As reported by Miller (1981), various species of the desert pupfishes (Cyprinodon sp.) exist today in aquatic pockets in now-isolated springs within major drainage systems of Chihuahua, Sonora, Texas, New Mexico, Arizona, Nevada, and east-central California. Drainage systems involved include the Owens, Mojave, Gila, Rio Grande, Rio Sonora, and Rio Yaqui. Different varieties of the fish, ranging in length between 2 and 10 cm. exist under often precarious conditions of water availability, temperature, and salinity throughout the region. The pupfish are known not to be strong swimmers, and would have had a hard time migrating upstream in fast-moving streams. However, their amazing tolerance to changing salinity conditions allows them to live in fresh water and salt water conditions, such as in estuaries and lagoons, within a single lifetime,

allowing for a good potential of regional migration under appropriate conditions. Even with their wide modern distribution, all available evidence seems to point to their derivation from ancestral forms found along the coastal waters of the Gulf of Mexico (Mark Jennings, UofA, pers. comm., 1984). However, the oldest record within the cordillera of their presence is from a single fossil from the Death Valley area from beds described as "late Miocene" in age (7-5 m.y.?) As well, certain varieties (C. radiosus in Death Valley; C. macularius at Anza-Borrego Park and Quitobaquito Springs) may have been "in place" (introduced into a drainage) since sometime in the Pliocene or perhaps earlier, based upon geologic evidence cited by Miller concerning the existance of Pliocene and Pleistocene pluvial lakes, waterways, and presumed perennial drainages (see Miller's discussion). Of particular interest here is that some members of the group must have been able at one time to cross the continental divide in order to be found now in drainages west of the Divide. And they must have done it sometime in the late Miocene and/or Pliocene, at a time when fully integrated drainages were already present. (Could they, alternately, have swam around Mexico through the flooded straits of Panama?) It would be interesting to identify possible cross-over points for this migration. There may have been one or more cross-over points; points could have existed between the Rio Grande and Gila systems, or they could have been farther south in Mexico.

Basin Dissection

Areas of the State that have undergone significant stream entrenchment, basin dissection, and pediment stripping are illustrated in Figure 8d of Menges (1983). Available evidence (Johnson and others, 1975); McFadden, 1981; Menges and McFadden, 1981) suggests this degradation in southeastern Arizona is no older than about one m.y., and may have been initiated somewhat later. This forces a voluminous Pleistocene denudation in valleys along the main southern Arizona streams, espically in areas of mountainous central Arizona like the Tonto Basin. Here, basin fill high stands now sit nearly 500 m above the valley floor (near 3600 ft asl along the north side of Salome Creek, compared to 2100 ft asl for the level of Lake Roosevelt).

Preliminary Th-U dating of pedogenic caliche nodules in terrace-capping soils along the lower Colorado River by Ku and others (1979) suggests ages of four prominent Pleistocene terraces of >350,000; 180,000; 100,000 and 60,000 years. They suggest that the age estimates should be considered minimum, and so lower Colorado River downcutting has been ongoing for at least 0.35 m.y. based on this estimate. However, the oldest terrace set is noted by them to lack representation of a 1.2 m.y. old basalt found upstream in the Grand Canyon in contrast to the younger terraces; hence suggesting a pre-1.2 m.y. age for the oldest terrace.

Basin dissection along the Rio Grande River in southern New Mexico and west Texas occurred mostly between 0.5 and 0.4 m.y. ago (based on presence of Perlette "o" ash in pre-dissection sediments) following an analogous basin level high stand called the La Mesa Surface around El Paso. The dissection is attributed by Seager and others (1984) to a downstream integration of the river and subsequent base level fall that quickly worked northward.

It seems likely that the dissection commenced along the lower Colorado River and downstream reaches of major trunk streams and gradually headcut upstream, since upstream areas have progressively shallower entrenchment. The question of the relative importance of tectonics, climate, sea level lowering, and stream captures (regional integration) as causal factors of basin dissection is still debated. Menges and McFadden (1981) suggest that "integration of formerly closed or partially closed local basin drainages to the externally drained Gila River regional network (is) the most probable triggering mechanism for basin dissection", although they suggest that regional Pliocene-Quaternary tectonic uplifts have possibly affected some regional base-level falls of streams and aided the process. Regional geomorphic evidence in central Arizona given by Menges (1983) and Pewe (1978) suggests a neotectonic uplift of the southwestern margin of the Colorado Plateau with respect to the Gila Low region around Phoenix. Also, it should be noted that the 10.5 m.y. old basalt above the Luke salt body has since been buried by 244 m (800 ft.) of basin fill, whereas similar-aged basalts throughout southwestern Arizona now sit atop mesas that lie 50-150 m above a generally denuded landscape (Shafiqullah and others, 1980). This is interpreted to indicate a post-10 m.y. subsidence in the Phoenix area, and an uplift in the Parker-Yuma-Cabeza Prieta region, relative to the regional grade of the Gila River. These observations suggest that the Gila Low has subsided relative to most surrounding areas since the late Miocene that certainly could cause upstream incision. Lucchitta (1979) cites evidence for progressive northward post-5.5 m.y. absolute uplift along most of the lower Colorado River region north of Yuma, based upon the estuarine Bouse marlstone datum, amounting to a maximum uplift of 1050 m (3,440 ft.) north of Needles. This observation adds support to the contention that crustal warping does exist in the region. Cooley's (1968, p. 77) observations and Pewe's downstream-convergent terraces in the Phoenix area may well indicate that the Gila Low subsidence has continued into late Pleistocene time, since it seems unlikely that the upstream projection into the Tonto Basin of the Sawik terrace level at hundreds of meters above river level can be solely attributed to climatic perturbation. This relative subsidence of the Gila Low could well be the trigger for basin dissection in valleys along the major streams above the Phoenix region.

Figure 1 Selected Tertiary lacustrine, paludal, estuarine, and playa environments in Arizona. See legend for ages of units.

Mogollon Rim, generalized

Colorado Plateau deposits

1 minimum extent of Eocene lake hypothesized by Young (1982)

2 possible extent of Hopi Lake (late Miocene-Pliocene) see text.

3 Rose Well-Frazier Well gravels (Koons, 1964)

4 rim gravels of Peirce and others (1979)

5 Eager Formation of Sirrine (1950)

6 Chuska Sandstone of Gregory (1917) and Wright (1954)

G Gila Low of Peirce (1976)

exposed or documented lacustrine, paludal, or playa strata of late Miocene-Pliocene age (upper Gila Group rocks)

B Bouse estuary (L. Miocene-Pliocene)

large evaporite masses of probable mid-Miocene age. Halite at Red Lake (R), halite and anhydrite at Luke (L) and Picacho (P).

M possible extent of early-middle Oligocene lakebeds represented by Mineta, Pantano Fms., etc.

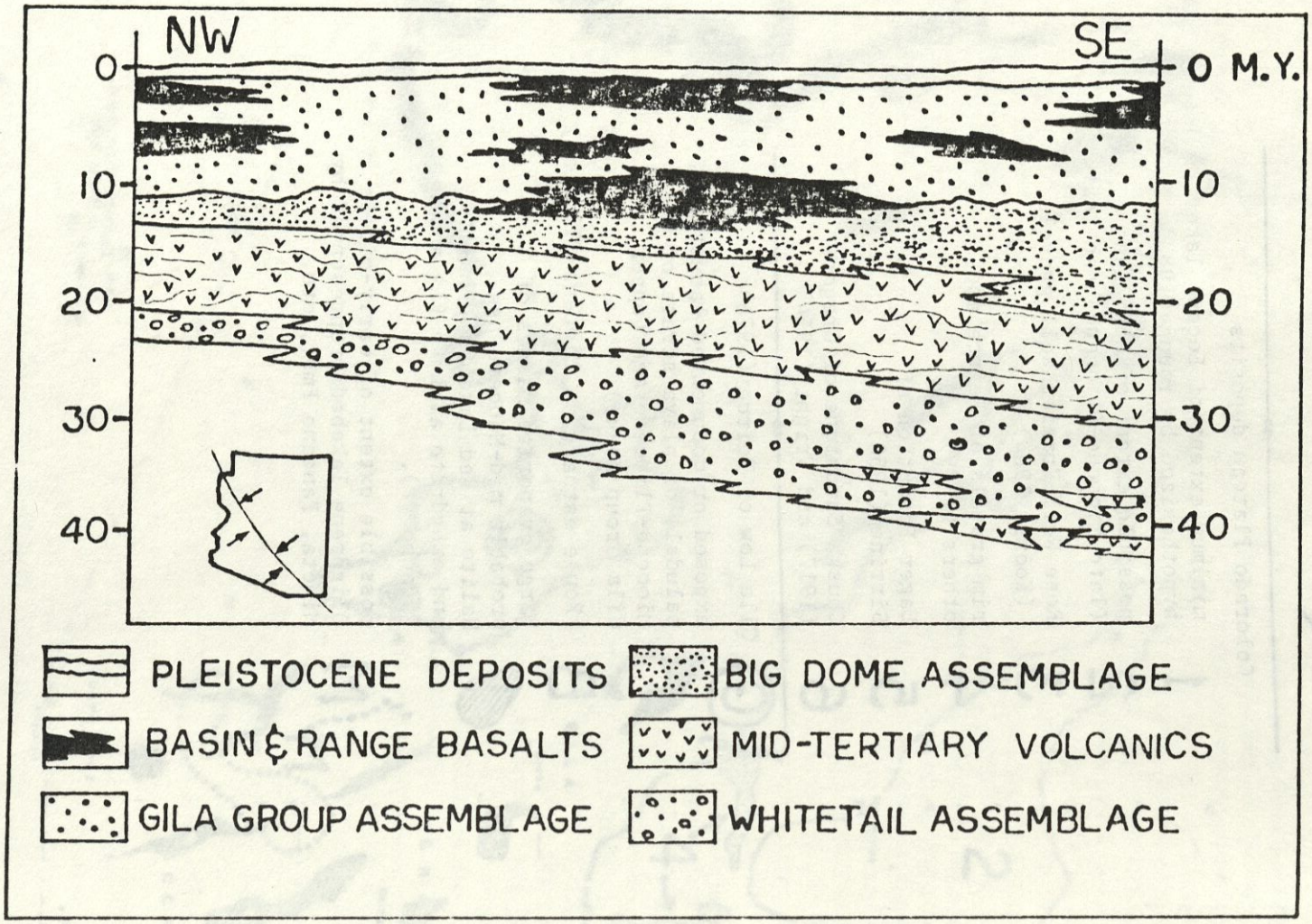

Figure 2. Age of Cenozoic sedimentary assemblages in the Basin and Range province of Arizona, generalized from Scarborough and Wilt (1979). The small inset state map shows the general line of cross-section. The figure indicates the general time-transgressive nature of the older assemblages and unconformities.

Figure 3. Diagramatic east-west cross-section through the Big Sandy Valley, positioned just south of Wikieup, looking north. The Big Dome Assemblage strata dip uniformly eastward where seen throughout the valley. These beds were deformed and beveled by a pediment (P1) that is post-12 m.y. old (age of upper volcanic flow in Big Dome rocks) and pre-Hemphillian (age of fine-grained Gila Group rocks, called the Big Sandy Formation) in age. Pediment P2 is late Pliocene-early Pleistocene age, and is overlain by pediment gravels and inset terraces, not shown. Lower volcanics here are probably 18-22 m.y. old. This style of deformation and Gila Group deposition imply a pre-Basin and Range rotational faulting event that shapes the basin and prepares it for Gila Group sedimentation. Other Arizona basins displaying this assymetric cross-sectional geometry include the Walnut Grove valley, Tonto Basin, Grand Wash trough, and the lower San Pedro Valley.

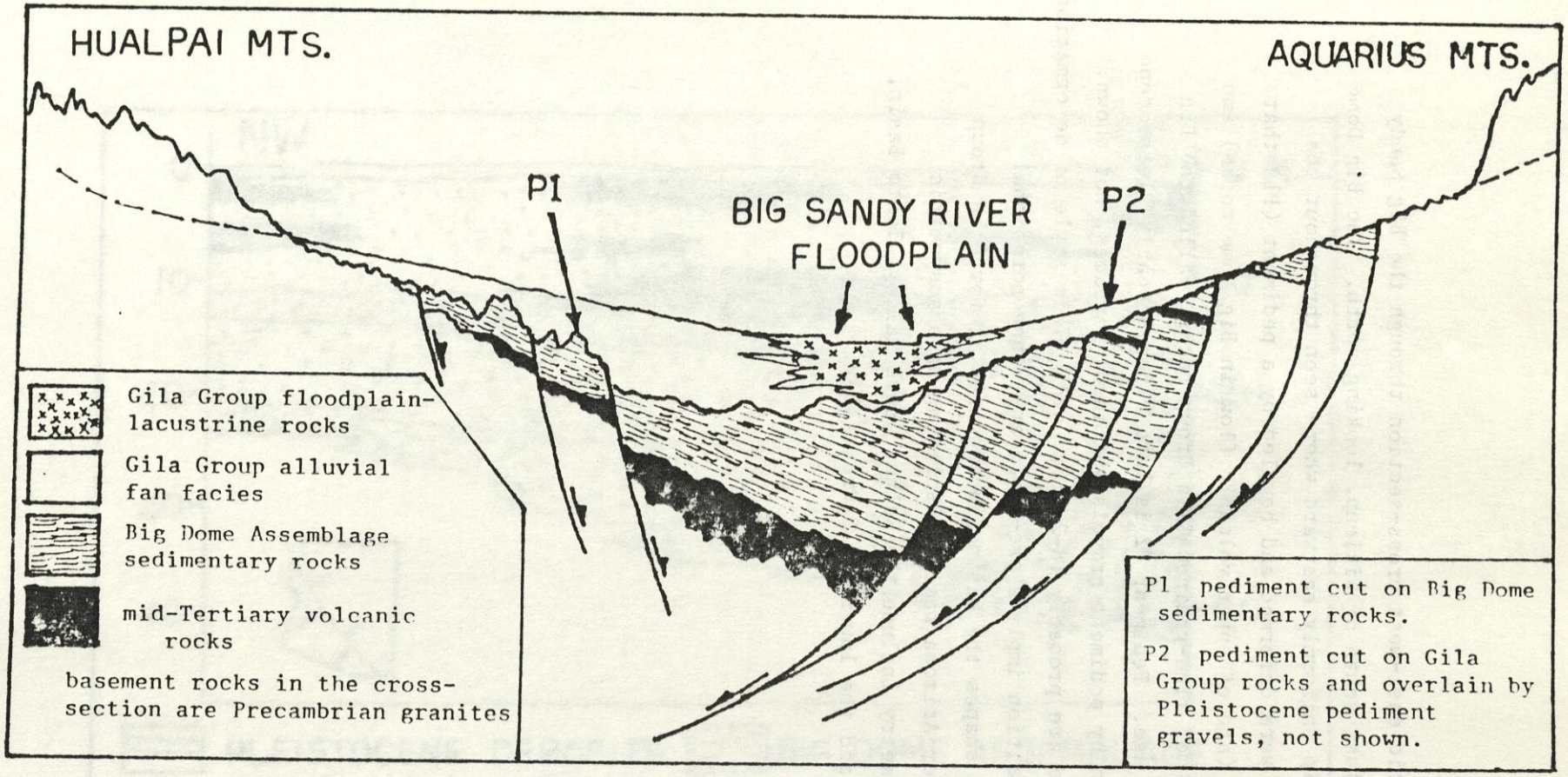
HUALPAI MTS.
AQUARIUS MTS.
P1
BIG SANDY RIVER
FLOODPLAIN
P2
Gila Group floodplain-lacustrine rocks
Gila Group alluvial fan facies
Big Dome Assemblage sedimentary rocks
mid-Tertiary volcanic rocks
basement rocks in the cross-section are Precambrian granites
P1 pediment cut on Big Dome sedimentary rocks.
P2 pediment cut on Gila Group rocks and overlain by Pleistocene pediment gravels, not shown.

FIGURE 3A LEGEND. GEOCHEMISTRY AND PALYNOLOGY OF A 140 FT. CORE FROM WILLCOX PLAYA.

Data from Long (1966), Martin (1963), and Cameron (1971)

1a depth in feet

1b Cameron's ostracod zonation (see column 2)

I series of temporary lakes, many ostracod-barren, generally highly saline
II longer-lived lakes, generally low salinity
III a permanent, alkaline lake; mesotrophic

1c Martin's 1963 pollen zonation

1 (1-6 ft) recently oxidized zone
2 (6-12 ft) 95-99% pine pollen (contains 3 C^{14} ages of 20-23,000 yBP; see below)
3 (12-47 ft) increase of grass, decrease of pine
4 (47-69 ft) decreasing pine with fluctuations; increased grasses
5 (69-140 ft) large changes; occassional zones with high grasses

Martin (1963) interprets high pine pollen zones to be cool-wet (pluvial) times, and poor pollen preservation or high grass pollen counts to be interpluvial. He suggests zones 1-4 (above 77 ft) to represent the Wisconsin pluvial event, and zone 5 (69-96 ft) to be the Sangamon interglacial, and the zones below 96 ft to represent Illinoian time.

2 Cameron's ostracod zonation. Intervals shaded black were essentially barren of ostracods; white intervals contained ostracods; diagonal-lined zones were not sampled. Barren zones probably represent waters too alkaline or saline to support ostracods, or times when lakes were very temporary or seasoned inconsistently with ostracod growth.

3 Eh values, showing the entire envelope range and smoothed fluctuations

4 Ph values, showing the entire envelope range and smoothed fluctuations

5 relative pollen percentages, summed to 100%

a: Picea-Abies-Pseudotsuga (Spruce-Fir-Douglas Fir)
b: Pinus sp.
c: Quercus sp. (oaks)
d: Artemesia sp. (sagebrush)
e: Gramineae (grasses)
f: Juniperus sp. (junipers)
g: solid black is Sarcobatus (greasewood); open line is all Cheno-Ams

C^{14} ages from Long (1966)

2 ft down - 8615 ± 110 yBP
6 ft down - >20,000 yBP
8 ft down - 23,000 ± 500 yBP
9 ft down - 22,000 ± 500 yBP

Long suggests the lake was full 30-13,000 yBP, depositing a "lower green clay unit", and a marl. He suggests the marl formed between 25,000 and 13,000 yBP during a "warm, moist climate". 13,000 - 11,000 yBP represented a period of alluviation north of the playa and channel cutting east of the playa. 11,500 - 10,500 yBP represented a short pluvial during which time the lake level rose to near the beach ridge top, and a thin upper green clay was deposited.

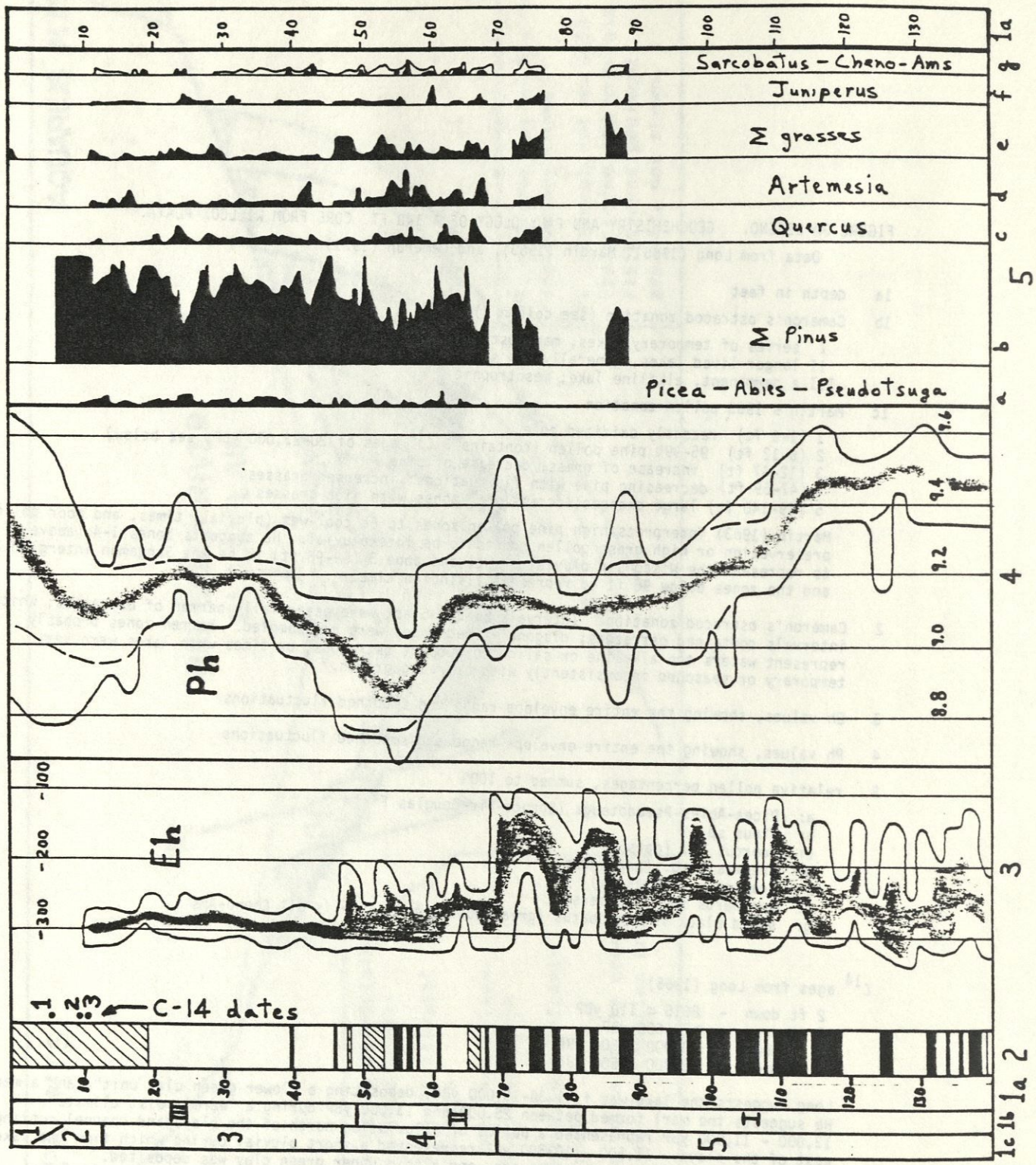
Sarcobatus - Cheno-Ams
Juniperus
M grasses
Artemesia
Quercus
M Pinus
Picea - Abies - Pseudotsuga
Ph
Eh
C-14 dates

Figure 3A

Figure 4

Teran Basin sequence of the southern Galiuro Mts., correlated to the Mineta Formation by Grover (1982). View looks northward. The main ridge-forming light-colored units in the view are limestones and shales. The entire mid-Tertiary package dips easterly, as does the lower part of the conformably capping Galiuro Volcanics, at the right edge of the photo. The sedimentary strata generally progress from a lower fanglomerate unit, upward through the lacustrine units, and through floodplain sands and gravels that contain white tuff marker beds, into the capping lower Galiuro Volcanics, in this area represented by a series of basaltic andesites with a K/Ar age of 27 m.y. (Scarborough and Wilt, 1979). The steep eastward dip on the strata decreases upward through the thick volcanic section, to less than 5° for uppermost volcanic units. This implies progressive tilting (due to listric fault effects?) for a period of time representing essentially post-Mineta through early to mid-volcanic time, a time probably correlative with the "unroofing" and "refrigeration" of the Santa Catalina-Rincon-Tortolita metamorphic core complex mountains. A very similiar timing argument applies to the type Mineta Formation across the valley to the west (Scarborough and Wilt, 1979).

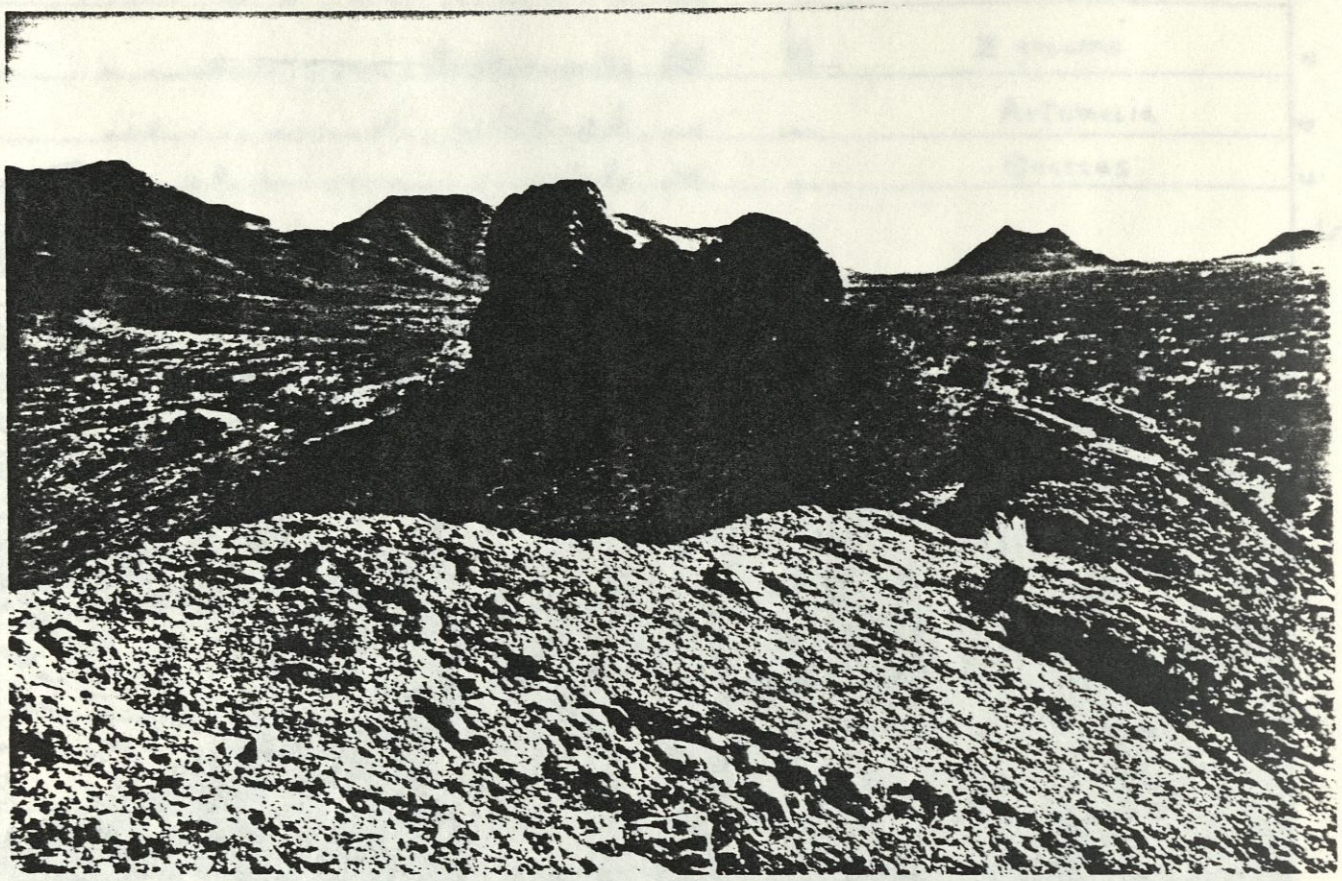

Figure 5

Locomotive Fanglomerate at Ajo, of Gilluly (1946). The red-brown colored sedimentary section contains less than 5% sandstone and shale lenses (concentrated near the top of the section), and consists generally of a thick (8000+ ft.) sequence of debris flows and coarse-grained fluvial sandy gravels; clasts range in diameter from one foot to as large as seven feet. The sediments are overlain by some andesite lapilli tuff horizons, and then a volcanic section dominated by basaltic andesites, termed the Ajo Volcanics by Gilluly. Eberly and Stanley report a 25 m.y. K/Ar age for one of these flows. The entire stratified sequence is deformed, dipping about 50° to the southwest (view in the photo is southerly). Detachment and allied listric faulting are probable causes of the deformation, since an entirely allochthonous, SW tilted section in one area is floored by a flat horzontal fault, and underlain by Precambrian gneiss (Gilluly, 1946, p. 36).

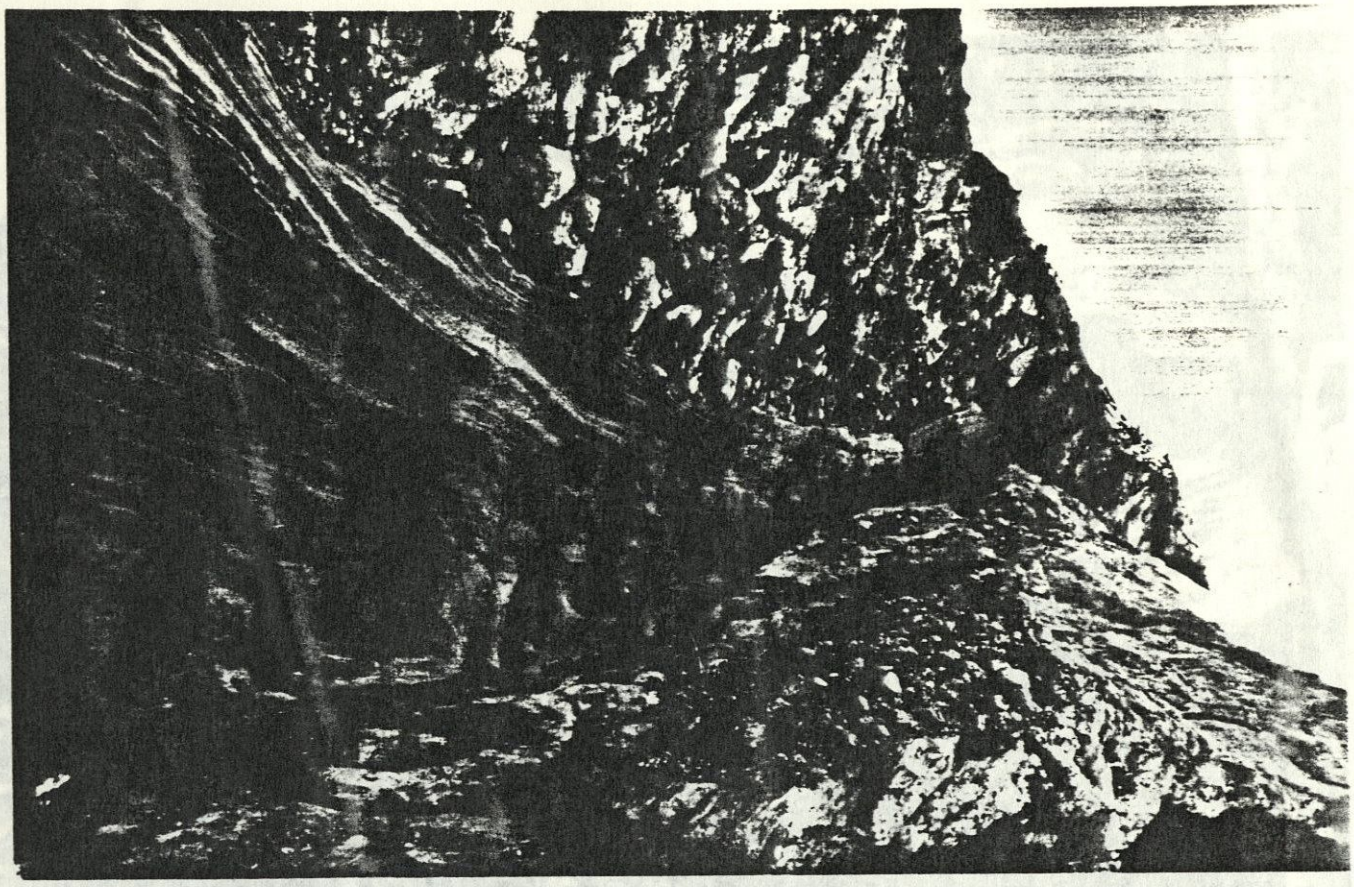

Figure 6

Sil Murk Formation, north of Gila Bend (Heindl and Armstrong, 1963). View looks northwest at the contact between the basal aeolian sandstone member and the overlying fanglomerate member. The formation in this area has been tectonically deformed into southwesterly dip attitudes. The aeolian sandstone approaches 500 ft. in thickness, is brick-red in color, and contains pebble horizons at some contacts between cross-bed sets. The fanglomerate unit is up to 1400 ft. thick, and is in turn overlain by a 200 ft. thick volcanic member from which Eberly and Stanley obtained a 27 m.y. K/Ar age date. A northwest-trending fault offsets the basal units to the west on the southwestern block. The aeolian member grades downward to a thin granitic pebble and cobble conglomerate that rests depositionally on Precambrian granites of the Maricopa batholith. The basal contact dips steeply to the southwest, and may have been tectonically deformed by rotation of the entire Tertiary section and underlying crystalline rocks.

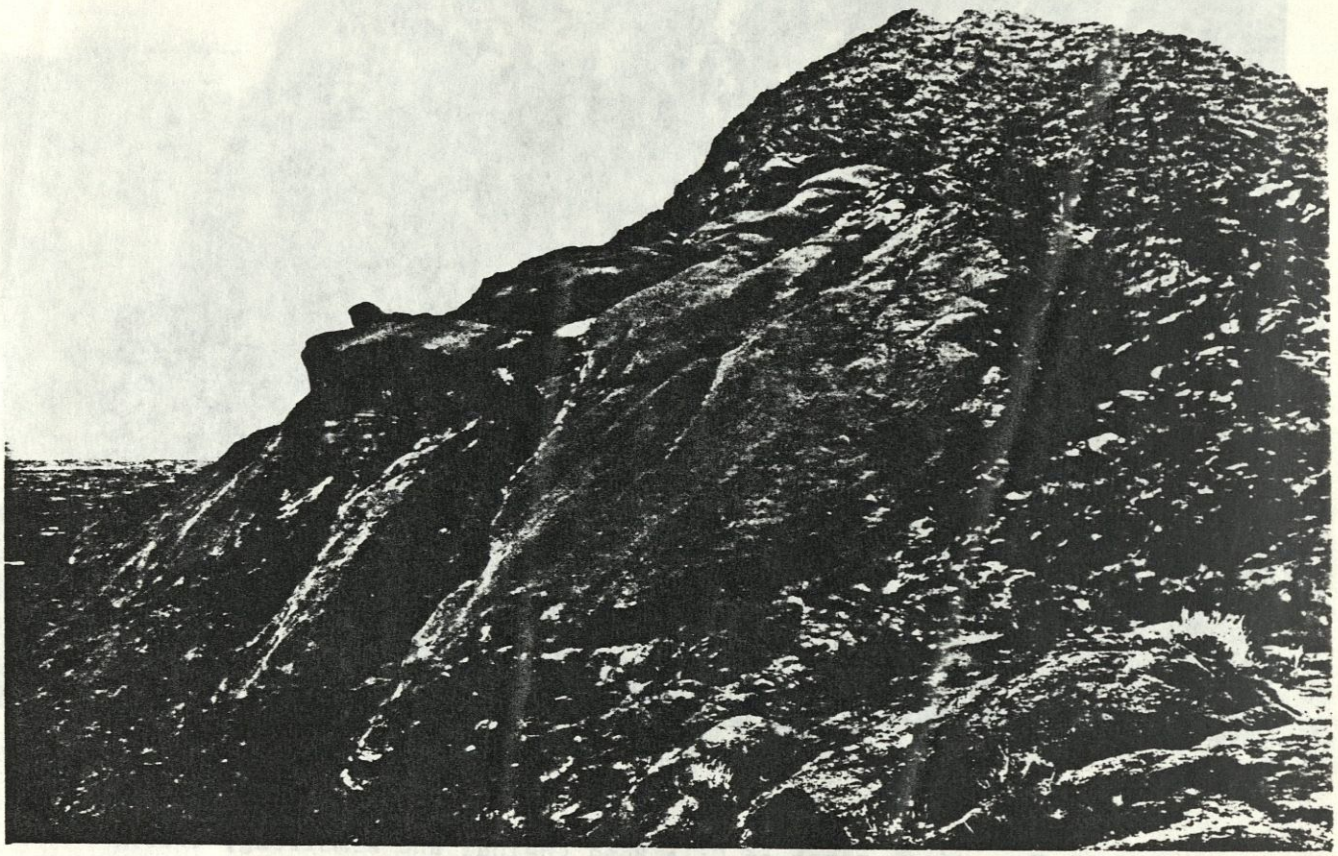

Figure 7

Depositional contact of redbeds against the northwest flank of Camelback Mountain, near Phoenix. Red-brown colored grussy sedimentary rocks here apparently still retain original depositional dips relative to their source terrain, a granitic highland still partially represented by Camelback Mountain. Since the redbeds are most likely Miocene in age, the present-day relief is inherited from that time. Similiar "fossil relief" conditions can be seen at the base of the redbeds just northeast of Mt. McDowell (Red Mountain), and near the Blue Point picnic area, near the confluence of the Salt and Verde Rivers. The condition this author judges to be "fossil relief" is based mostly upon field observations of situations where no tectonic rotation within a terrain is necessary or obvious.

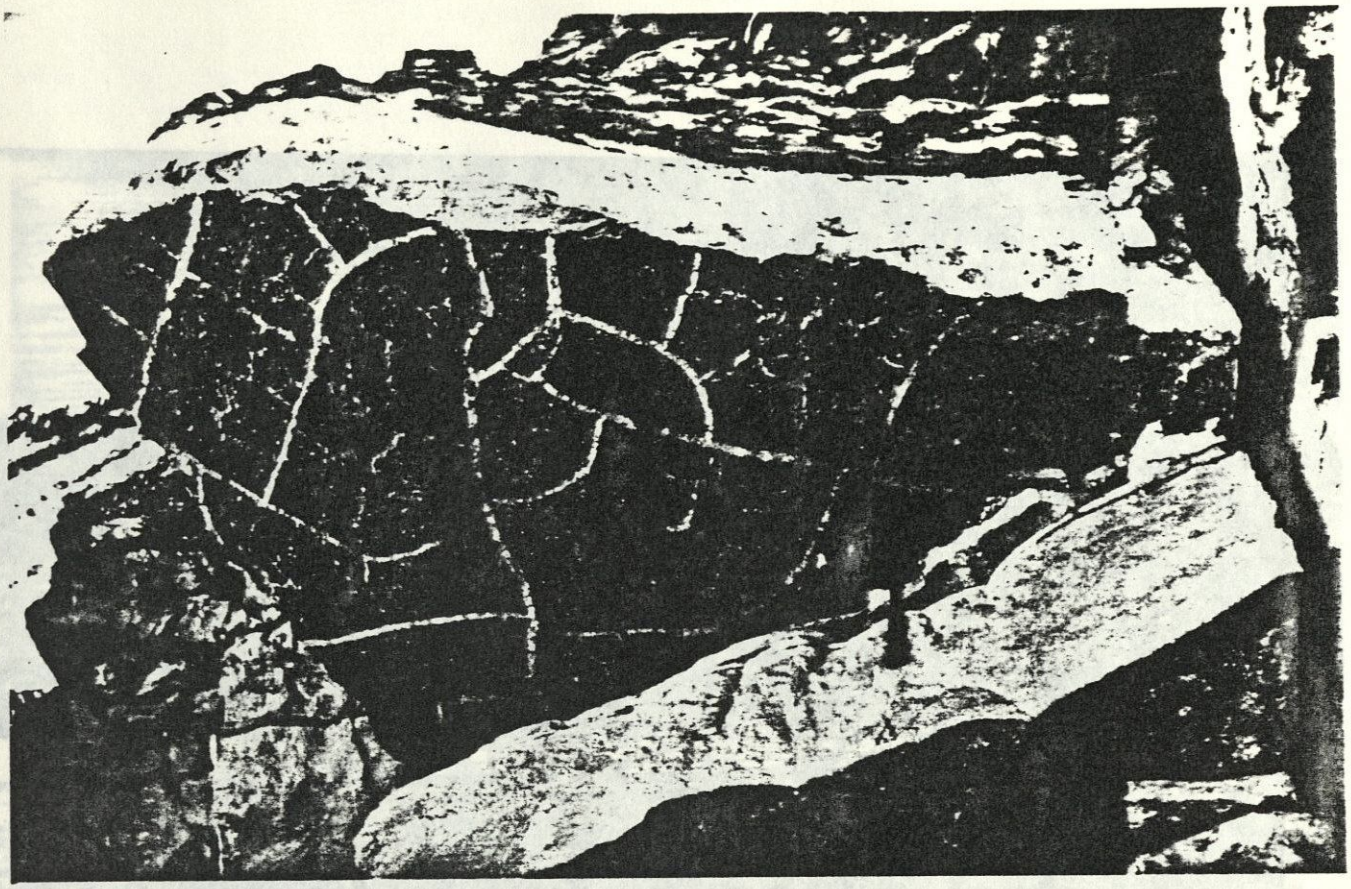

Figure 8

Mudcracked horizon in a mudstone bed of the Papago Park Formation, exposed northwest of the football stadium of ASU, near the south bank of the Salt River. These floodplain and conglomeratic alluvial fan sedimentary rocks conformably underlie a 17 m.y. old basaltic andesite that caps the hill (Scarborough and Wilt, 1979). The section here dips steeply southeast, and must have been rotated to its present attitude post-17 m.y. ago. This deformational interval is probably "upper plate" effects related to detachment above the South Mountains metamorphic core complex (Reynolds UofA PhD thesis, 1982).

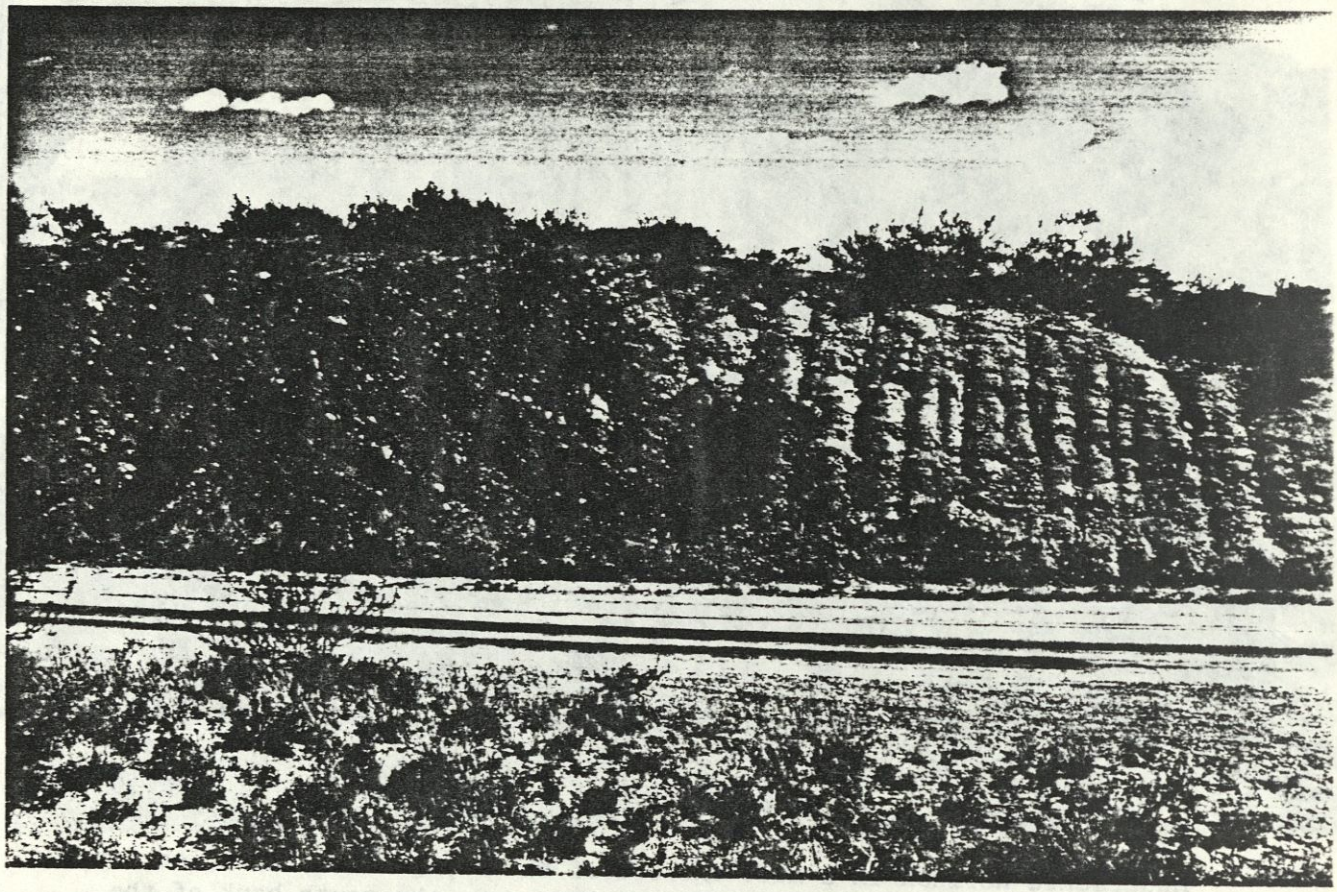

Figure 9

Lapout of Gila Group fanglomerates against darker-colored mid-Tertiary redbeds, along Highway 83, north of the drainage divide at the north end of the Sonoita basin. The Gila Group rocks here retain original depositional dips to the south, and are graded to fluvial and paludal sediments deposited in the central and southern Sonoita Valley, generally north of the town of Sonoita. Paleomagnetic dating results from the fine-grained materials indicate they are Pliocene in age (Menges, 1981). The Gila Group rocks in the photo are light gray colored, in contrast to the red-brown coloration of the clayey older sediments, that are most likely related to the Pantano and/or older Rillito Beds farther north. A curious thin layer of pebbles and cobbles at the interface of the two units in the photo are totally covered with a stain of chemically precipitated manganese oxides. Away from the contact, no staining is obvious on the particles in either of the units. Similiar staining effects, probably diagenetic in nature, are seen in terrace gravels in the southern Sonoita basin and around Patagonia, including some roadcuts of the highway where infiltration of the manganese oxides (confirmed by chemical analysis) has acted as a cement in the gravels.

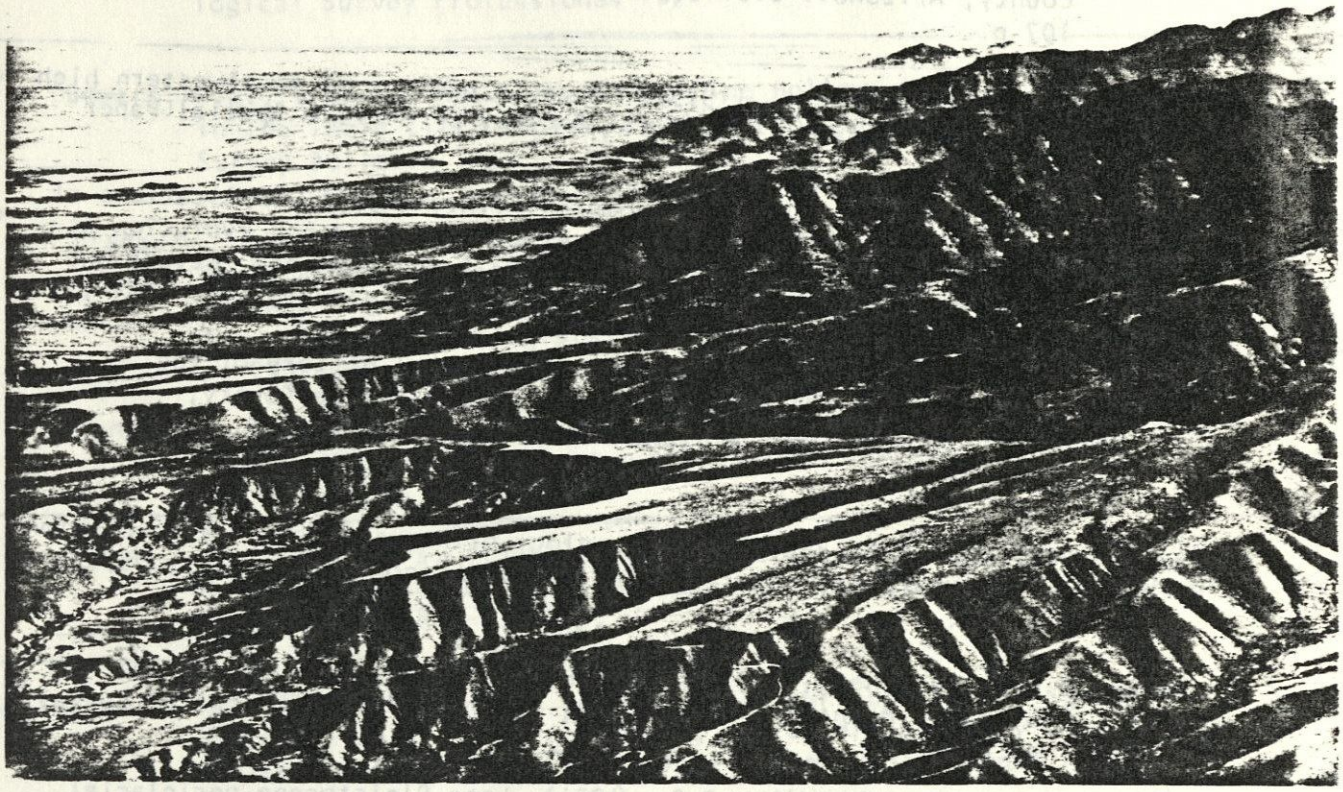

Figure 10

Aerial view of the Frye Mesa alluvial fan remnant along the northern flank of the Pinaleno Mountains, southwest of Safford. View looks eastward. Metamorphic crystalline rocks of the mountains are covered with darker colored vegetation beyond the fan. The fan surface is capped by a thick relict paliargid soil, indicative of perhaps a million years or more in age. Along the erosional escarpment at the edge of the preserved fan, one can see (in the field) the valleyward-dipping fanglomerates grade rapidly into horzontally-bedded fine grained materials deposited on the Gila River floodplain during late Pliocene and early Pleistocene valley aggradation. Since that time, the Gila River has downcut in an episodic manner so as to have produced two lower level extensive pediment terrace sets, exposed throughout the valley. The denudation of the valley has probably lowered the river level by 100 to 150 meters, and left the bulk of the alluvial fan perched as an erosional remnant. The stream that fed the fan has migrated to the far east edge of the fan (visible in photo) and downcut through the sediments, and is now cutting into crystalline bedrock at the mountain front.

References

Agenbroad, L.D., (1967), Cenozoic stratigraphy and paleo-hydrology of the Redington-San Manuel area, San Pedro Valley, Arizona: University of Arizona (Tucson) unpublished PhD thesis, 111 p.

Akers, J.P., (1964), Geology and ground water in the central part of Apache county, Arizona: U.S. Geological Survey Water Supply Paper 1771, 107 p.

Anderson, J.J., and others, (1975), Cenozoic geology of southwestern high plateaus of Utah: Geological Society of America Special Paper 160, 88 p.

Anderson, R.E., Zoback, M.L., and Thompson, G.A., (1983), Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range province, Nevada and Utah: Geological Society of America Bulletin, v. 94, p. 1055-72.

Balcer, R.A., (1984), Stratigraphy and depositional history of the Pantano Formation (Oligocene - Early Miocene), Pima County, Arizona. University of Arizona unpublished M.S. thesis (Tucson), 107 p.

Banks, N.G., and others, (1972), Chronology ofintrusion and ore deposition at Ray, Arizona: Part I, K/Ar ages: Economic Geology, v. 67, p. 864-878.

Banks, N.G., and others, (1977), Reconnaissance geologic map of the Tortolita Mountains Quadrangle, Arizona: U.S. Geological Survey map MF-864.

Barsch, Dietrich, and Updike, R.G., (1971), Late Pleistocene periglacial geomorphology (rock glaciers and blockfields) at Kendrick Peak, northern Arizona: Arizona Geological Society Digest, v. 9, p. 225-244.

Baskin, J.A., (1975), Small vertebrates of the Bidahochi Formation, White Cone, northeastern Arizona: University of Arizona (Tucson) unpublished M.S. thesis.

Bell, J.W., Ku, T.L., and Kukla, G.J., (1978), Chemehuevi Formation of Nevada, Arizona, and California: an examination of its distribution, facies, and age (abstract): Geological Society of America abstracts, v. 10, no. 3, p. 95.

Berry, R.C., (1976), Mid-Tertiary volcanic history and petrology of the White Mountain volcanic province, southeastern Arizona: Princeton University unpublished PhD thesis, 317 p.

Blacet, P.M., and Miller, S.T., (1978), Reconnaissance geologic maps of the Jackson Mountain quadrangle, Graham County, Arizona: U.S. Geological Survey map MF-939, scale 1:62,500.

Blagbrough, J.W., (1971), Large nivation hollows in the Chuska Mountains, northeastern Arizona: Plateau, v. 44, p. 52-59.

Blair, W.N., (1978), Gulf of California in Leak Mead area of Arizona and Nevada during late Miocene time: American Association of Petroleum Geologists Bulletin, v. 62, p. 1159-1170.

Blair, W.N., and Armstrong, A.K., (1979), Hualapai Limestone member of the Muddy Creek Formation: The youngest deposit predating the Grand Canyon, southeastern Nevada and northwestern Arizona: U.S. Geological Survey Professional Paper 1111, 14 p.

Bowers, W.E., (1972), The Canaan Peak, Pine Hollow, and Wasatch Formations in the Table Cliff region, Garfield county, Utah: U.S. Geological Survey Bulletin 1331-B, 39 p.

Bradbury, J.P., and Blair, W.N., (1979), Paleoecology of the upper Miocene Hualapai Limestone Member of the Muddy Creek Formation, northwestern Arizona. in Basin and Range Symposium volume of Rocky Mountain Association of Geologists, G.W. Newman and H.D. Goode, (editors), p. 293-303.

Brennan, D.J., (1957), Geological reconnaissance of Cienega Valley, Pima County, Arizona: University of Arizona (Tucson) unpublished PhD thesis, 53 p.

Brown, S.G., and others, (1966), Water resources of Fort Huachuca Military Reservation, southeastern Arizona: U.S. Geological Survey Water-Supply Paper 1819-D, 57 p.

Bryan, Kirk, (1956), Map of the physiographic surfaces in the Benson Quadrangle, Arizona. in Gilluly, J., General Geology of central Cochise County, : U.S. Geological Survey Professional Paper 281, plate 10.

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

Cameron, S.P., (1971), Ostracodes of pluvial Lake Cochise, Cochise county, southeastern Arizona: Arizona State University (Tempe) unpublished M.S. thesis, 65 p.

Childs, O.E., (1948), Geomorphology of the valley of the Little Colorado River, Arizona: Geological Society of America Bulletin, v. 59, p. 353-388.

Chapin, C.E., and Cather, S.M., (1981), Eocene tectonics and sedimentation in the Colorado Plateau - Rocky Mountain area: Arizona Geological Society digest, v. 14, p. 173-198.

Clay, D.W., (1960), Late Cenozoic stratigraphy in the Dry Mountain area, Graham County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 68 p.

Clay, D.W., (1970, Stratigraphy and petrology of the Mineta Formation, Pima and Cochise Counties, Arizona: University of Arizona (Tucson) unpublished PhD thesis, 183 p.

Coney, P.J., (1978), Plate tectonic setting of southeastern Arizona. in New Mexico Geological Society Guidebook No. 29 (Land of Cochise), p. 285-290.

Coney, P.J., and Reynolds, S.J., (1977), Cordilleran Benioff Zones: Nature, v. 270, p. 403-406.

Cooley, M.E., (1958), Physiography of the Black Mesa basin area, Arizona: New Mexico Geological Society Guidebook 9 (Black Mesa Basin), p. 146-149.

Cooley, M.E., (1962a), Geomorphology and the age of volcanic rocks in northeastern Arizona: Arizona Geological Society digest 5, p. 97-115.

Cooley, M.E., (1962b), Late Pleistocene and recent erosion and alluviation in parts of the Colorado River System, Arizona and Utah: U.S. Geological Survey Professional Paper 450-B, p. 48-50.

Cooley, M.E., (1968), Some notes on the late Cenozoic drainage patterns in southeastern Arizona and southwestern New Mexico: Arizona Geological Society Guidebook 3, 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, 29 p. plus 1:1,000,000 scale map.

Cooley, M.E., and Akers, J.P., (1961), Ancient erosional cycles of the Little Colorado River, Arizona and New Mexico: U.S. Geological Survey Professional Paper 424-C, p. 244-248.

Cooley, M.E., and Davidson, E.S., (1963), The Mogollon Highlands - their influence on Mesozoic and Cenozoic erosion and sedimentation: Arizona Geological Society digest, v. 6, p. 7-36.

Cooley, M.E., and others, (1969), Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico and Utah: U.S. Geological Survey Professional Paper 521-A, 61 p.

Cooper, J.R., (1960), Some geologic features of the Pima Mining districts, Pima County, Arizona: U.S. Geological Survey Bulletin 1112-C, 101 p.

Cooper, J.R., and Silver, L.T., (1964), Geology and ore deposits of the Dragoon Quadrangle, Cochise County, Arizona: U.S. Geological Survey Professional Paper 416.

Cornwall, H.R., Banks, N.G., and Phillips, C.H., (1971), Geologic map of the Sonora Quadrangle, Pinal and Gila Counties, Arizona: U.S. Geological Survey map GQ-1021.

Creasey, S.C., (1967), General geology of the Mammoth Quadrangle, Pinal County, Arizona: U.S. Geological Survey Bulletin 1218, 94 p.

Damon, P.E., and Bickerman, Michael, (1964), K/Ar dating of post-Laramide plutonic and volcanic rocks within the Basin and Range province of southeastern Arizona and adjacent areas: Arizona Geological Society digest, v. 7, p. 63-78.

Damon, P.E., and Mauger, R.L., (1966), Epeirogeny-orogeny viewed from the Basin and Range province: Society of Mining Engineers Transactions, v. 235, p. 99-112.

Damon, P.E., and Shafiqullah, M., (1981), Evidence for Oligocene deserts in Arizona (abstract): Arizona-Nevada Academy of Science, 25th annual meeting.

Damon, P.E., Shafiquallah, M., and Leventhal, J.S., (1974), K/Ar chronology for the San Francisco volcanic field and rate of erosion of the Little Colorado River: Geological Society of America Guidebook to the Geology of Northern Arizona, Part I, p. 221-235.

Damon, P.E., Shafiqullah, M., and Scarborough, R.B., (1978), Revised chronology for critical stages in the evolution of the lower Colorado River (abstract), Geological Society of America Abstracts with Programs, v. 10, n.3, p. 101-102.

Davidson, E.S., (1960), Geology of the eastern part of the Safford Basin, Graham County, Arizona: Arizona Geological Society digest, v. 3, p. 123-126.

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

Davis, G.H., and Hardy, J.J. Jr., (1981), The Eagle Pass detachment, southeastern Arizona: product of mid-Miocene listric (?) normal faulting in the southern Basin and Range: Geological Society of America Bulletin, v. 92, part 1, p. 749-762.

Davis, W.M., (1930), The Peacock Range, Arizona: Geological Society of America Bulletin, v. 41, p. 293-313.

Drewes, Harald, (1972), Cenozoic rocks of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 746, 66 p.

Drewes, Harald, (1981), Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 96 p.

Eaton, J.E., (1932), Decline of Great Basin, southwestern United States: American Association of Petroleum Geologists Bulletin, v. 16, p. 1-49.

Eaton, G.P., Peterson, D.L., and Schumann, H.H., (1972), Geophysical, Geohydrological, and geochemical reconnaissance of the Luke Salt body, central Arizona: U.S. Geological Survey Professional Paper 753, 28 p.

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

Ellis, R.W., (1935), Glaciation in New Mexico: University of New Mexico Bulletin, No. 276, Geological Series, v. 5, No.1, 31 p.

Elston, W.E., and others, (1973), Tertiary volcanic rocks, Mogollon-Datil Province, New Mexico, and surrounding regions: K/Ar dates, patterns of eruption, and periods of mineralization: Geological Society of America Bulletin, v. 84, p. 2259-2274.

Elston, W.E., and Northrop, S.A. (editors), (1976), Cenozoic volcanism in southwestern New Mexico: New Mexico Geological Society Special Publication No. 5, 151 p.

Elston, D.P., and others, (1974), Miocene-Pliocene volcanism in the Hackberry Mountain area and evolution of the Verde Valley, north-central Arizona: Geological Society of America field guide "Geology of Northern Arizona", part II, p. 602-610.

Epis, R.C., and Chapin, C.E., (1975), Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains. in Curtis, B.F. (editor), Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 45-74.

Everenden, J.F., Savage, D.E., Curtis, G.H., (1964), Potassium-argon dates and the Cenozoic mammalian chronology of North America: American Journal of Science, v. 262, pl 145-198.

Faulds, J.E., (1984), Cneozoic evolution of part of the Transition Zone, Gila County, east-central Arizona. Geoscience Daze abstract volume for March 1984 meeting; University of Arizona Geoscience Department, p. 10 (M.S. thesis research in progress).

Finnell, T.L., (1966), Geologic map of the Cibecue Quadrangle, Navajo County, Arizona: U.S. Geological Survey map GQ-545.

Finnell, T.L., (1970), Pantano Formation: U.S. Geological Survey Bulletin 1294-A, p. 35-36.

Fleischauer, H.L., and Stone, W.J., (1982), Quaternary geology of Lake Animas, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 174, 23 p.

Gassaway, J.S., (1977), Reconnaissance study of Cenozoic geology in west-central Arizona: San Diego State University unpublished M.S. thesis, 120 p.

Gastil, G., Morgan, G.J., and Krammenacher, D., (1981), The tectonic history of Peninsular California and adjacent Mexico. in Ernst, W.G. (editor), the Geotectonic Development of California, Prentice-Hall, p. 284-305.

Gilbert, G.K., (1875), Report on the geology of portions of New Mexico and Arizona; U.S. Geographic and Geologic Surveys West of the 100th Meridian, volume 3, p. 503-567.

Gilluly, James, (1946), The Ajo mining district, Arizona: U.S. Geological Survey Professional Paper 209, 112 p.

Gray, R.S., (1965), Late Cenozoic sediments in the San Pedro Valley near St. David, Arizona: University of Arizona (Tucson) unpublished PhD thesis, 198 p. See also related article in Journal of Sedimentary Petrology, v. 37, no. 3., p. 774-789.

Gregory, H.E., (1917), Geology of the Navajo country; a reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 93, 161 p.

Gilbert, C.M., and Reynolds, M.W., (1973), Character and chronology of basin development, western margin of the Basin and Range province: Geological Society of America Bulletin, v. 84, p. 2489-2510.

Gresens, R.L., (1981), Extension of the Telluride erosion surface to Washington State, and its regional and tectonic significance: Tectonophysics, v. 79, p. 145-164.

Grimm, J.P., (1978), Cenozoic pisolitic limestones in Pima and Cochise Counties, Arizona: University of Arizona (Tucson) unpublished M.S. thesis.

Grover, J.A., (1982), The geology of Teran Basin, Cochise County, Arizona, University of Arizona unpublished M.S. thesis (Tucson), 73 p.

Hack, J.T., (1942), Sedimentation and volcanism in the Hopi Buttes, Arizona: Geological Society of America Bulletin, v. 53, p. 335-372.

Harbour, Jerry, (1966), Stratigraphy and sedimentology of the upper Safford Basin sediments: University of Arizona (Tucson) unpublished PhD thesis, 242 p.

Harsbarger, J.W., Repenning, C.A., and Irwin, J.H., (1957), Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country (Colorado Plateau): U.S. Geological Survey Professional Paper 291, 74 p.

Haxel, Gordon, and others, (1978), Reconnaissance geologic map of the Comobabi Quadrangle, Pima county, Arizona: U.S. Geological Survey map MF-964, scale 1:62,500.

Hayes, P.T., and Raup, R.B., (1968), Geologic map of Huachuca and Mustang Mountains, southeastern Arizona: U.S. Geological Survey map I-509.

Haynes, C.V., Jr., (1968), Preliminary report on the late Quaternary geology of the San Pedro Valley, Arizona: Arizona Geological Society Guidebook No. 3, p. 79-96.

Heindl, L.A., (1952), Gila Conglomerate: Arizona Geological Society Guidebook No. 1, p. 113-116.

Heindl, L.A., (1954), Cenozoic alluvial deposits in the upper Gila River drainage basin, Arizona and New Mexico (abstract): Geological Society of America Bulletin, v. 65, no. 12, p. 1262.

Heindl, L.A., (1958), Cenozoic alluvial deposits of the upper Gila River area, New Mexico and Arizona: University of Arizona (Tucson) unpublished PhD thesis, 249 p.

Heindl, L.A., (1959), Stratigraphic relationships of the Whitetail and Gila Conglomerates near Ray, Arizona (abstract): Geological Society of America Bulletin, v. 70, p. 1724-1725.

Heindl, L.A., (1960), Cenozoic geology of the Papago Indian Reservation, Pima, Maricopa, and Pinal Counties, Arizona: Arizona Geological Society digest, v. 3, p. 31-34.

Heindl, L.A., (1962), Cenozoic geology of Arizona - a 1960 resume: Arizona Geological Society digest, v. 5, p. 9-23.

Heindl, L.A., (1962), Should the term "Gila Conglomerate" be abandoned?: Arizona Geological Society digest, v. 5, p. 73-88.

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

Heindl, L.A., and Armstrong, C.A., (1963), Geology and ground water conditions in the Gila Bend Indian Reservation, Maricopa County, Arizona: U.S. Geological Survey Water Supply Paper 1647-A, 48 p.

Hunt, C.B., (1956), Cenozoic history of the Colorado Plateau: U.S. Geological Survey Professional Paper 279, 99 p.

Hunt, C.B., (1969), Geologic history of the Colorado River: U.S. Geological Survey Professional Paper 669-D, p. 59-130.

Hunt, C.B., (1976), Grand Canyon and the Colorado River, their geologic history. in Geology of the Grand Canyon, edited by W.J. Breed and Evelyn Rost: Museum of Northern Arizona and Grand Canyon Natural History Association, p. 129-141.

Imswiler, J.B., (1959), Structural geology of the Safford Peak area, Tucson Mountains, Pima County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 46 p.

Jacobs, L.L., III, (1973), Small mammals of the Quiburis Formation, southeastern Arizona: University of Arizona (Tucson) unpublished M.S. thesis,

Johnson, Carl, and Miller, Darryl, (1980), Late Cenozoic alluvial history of the lower Colorado River. in Fife, D.L., and Brown, A.R. (editors), Geology and Mineral Wealth of the California Desert: South Coast Geological Society, Santa Ana, p. 441-446.

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

Keith, S.B., (1981), personal communication. Magmachem Associates, Inc., Phoenix, AZ

Kiersch, G.A., and Keller, W.D., (1955), Bleaching clay deposits, Sanders-Defiance Plateau district, Navajo County, Arizona: Economic Geology, v. 50, p. 469-494.

Knechtel, M.M., (1936), Geologic relations of the Gila Conglomerate in southern Arizona: American Journal of Science, 5th Series, v. 31, p. 81-92.

Knechtel, M.M., (1938), Geology and ground water resources of the valley of Gila River and San Simon Creek, Graham County, Arizona: U.S. Geological Survey Water Supply Paper 796, p. 181-222.

Kokalis, P.G., (1971), Terraces of the lower Salt River Valley, Arizona: Arizona State University (Tempe) unpublished M.S. thesis, 103 p.

Koons, Donaldson, (1964), Structure of the eastern Hualapai Indian Reservation, Arizona: Arizona Geological Society digest, v. 7, p. 97-114.

Krieger, M.H., (1968), Geologic map of the Brandenburg Mountain Quadrangle, Pinal County, Arizona: U.S. Geological Survey map, GQ-668.

Krieger, M.H., (1977), Large landslides, composed of megabreccia, interbedded in Miocene basin deposits, southeastern Arizona: U.S. Geological Survey Professional Paper 1008, 25 p.

Krieger, M.H., (1979), Ash-flow tuffs of the Galiuro volcanics in the northern Galiuro Mountains, Pinal County, Arizona: U.S. Geological Survey Professional Paper 1104, 32 p.

Krieger, M.H., Cornwall, H.R., and Banks, N.G., (1974), Big Dome Formation and revised Tertiary stratigraphy in the Ray-San Manuel area, Arizona: U.S. Geological Survey Bulletin 1394-A.

Krieger, M.H., Johnson, M.G., and Bigsby, P.R., (1979), Mineral Resources of the Aravaipa Canyon Instant Study Area, Pinal and Graham Counties, Arizona: U.S. Geological Survey open-file report 79-291, 27 p.

Ku, Teh-Lung, and others, (1979), Th-U dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, southeastern California: Geological Society of America Bulletin, v. 90, part I, p. 1063-1073.

Ladd, T.W., (1975), Stratigraphy and petrology of the Quiburis Formation near Mammoth, Pinal county, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 103 p.

Lammers, G.E., (1970), The late Cenozoic Benson and Curtis Ranch faunas from the San Pedro Valley, Cochise County, Arizona: University of Arizona (Tucson) unpublished PhD thesis.

Lance, J.F., (1954), Age of the Bidahochi Formation, Arizona (abstract): Geological Society of America Bulletin, v. 65, p. 1276.

Lance, J.F., Downey, J.S., and Alford, Malcolm, (1962), Cenozoic sedimentary rocks of Tonto Basin: New Mexico Geological Society Guidebook No. 13, p. 98-99.

Lance, J.F., and Wood, P.A., (1958), New Miocene fossil locality from southwestern Arizona (abstract): Geological Society of America Bulletin, v. 69, no. 12, p. 1694.

Lasky, S.G., and Webber, B.N., (1949), Manganese resources of the Artillery Mountains region, Mohave County, Arizona: U.S. Geological Survey Bulletin 961.

Lehner, R.E., (1958), Geology of the Clarkdale Quadrangle, Arizona: U.S. Geological Survey Bulletin 1021-N, p. 511-592.

Lindgrey, S.H., (1982), Structural geology and tectonic evolution of the northeastern Rincon Mountains, Cochise and Pima Counties, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 202 p.

Lindsay, E.H., and Lundin, R.F., (1972), An Oligocene oreodont (Mammalia: Artiodactyla) from central Arizona: Journal of Paleontology, v. 46, p. 115-119.

Lindsay, Everett, (1978), Late Cenozoic vertebrate faunas, southeastern Arizona. in New Mexico Geological Society guidebook No. 29, "Land of Cochise", p. 269-276.

Link, M.H., (1980), Sedimentary facies and mineral deposits of the Miocene Barstow Formation, California. in Fife, D.L., and Brown, A.R. (editors), Geology and Mineral Wealth of the California Desert: South Coast Geological Society, Santa Ana, p. 191-203.

Livingston, D.E., Manger, R.L., and Damon, P.E., (1968), Geochronology of the emplacement, enrichment, and preservation of Arizona porphyry copper deposits: Economic Geology, v. 63, p. 30-36.

Longwell, C.R., (1936), Geology of the Boulder Reservoir floor: Geological Society of America Bulletin, v. 47, p. 1393-1476.

Lucas, S.G., and others, (1981), Eocene biostratigraphy of New Mexico: Geological Society of America Bulletin, v. 92, part 1, p. 951-967.

Lucchitta, Ivo, (1972), Early History of the Colorado River in the Basin and Range Province: Geological Society of America Bulletin, v. 83, p. 1933-1948.

Lucchitta, Ivo, (1979), Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region, Tectonophysics, v. 61, p. 63-95.

Lustig, L.K., (1966), The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona (discussion): Journal of Geology, v. 74, p. 95-102.

Marlowe, J.I., (1961), Late Cenozoic geology of the lower Safford Basin on the San Carlos Indian Reservation: University of Arizona (Tucson) unpublished PhD thesis, 184 p.

McCord, R.D., (1982), Fossil Gopherus from northern Yuma County, Arizona. in Brown, P.E. and Stone, C.L. (editors), Granite Reef: a study in desert archaeology: Arizona State University Anthropological Research Paper No. 28, Appendix D, p. 401-406.

McCord, R., (1983), personal communication. Geoscience Deparpment, University of Arizona, Tucson, AZ., 85721

MacFadden, B.J., Johnson, N.M., and Opdyke, N.D., (1979), Magnetic polarity stratigraphy of the Mio-Pliocene mammal-bearing Big Sandy Formation of western Arizona: Earth and Planetary Science Letters, v. 44, p. 349-364.

McFadden, L.D., (1981), Quaternary evolution of the Canada del Oro Valley, southeastern Arizona: Arizona Geological Society digest, v. 13, p. 13-20.

McKee, E.D., Wilson, R.F., Breed, W.J., and Breed, C.S. (editors), (1967), Evolution of the Colorado River in Arizona: published by Museum of Northern Arizona as Bulletin no. 44, 67 p.

McKee, E.H., and Anderson, C.A., (1971), Age and chemistry of Tertiary volcanic rocks in north-central Arizona and relation of the rocks to the Colorado Plateaus: Geological Society of America Bulletin, v. 82, p. 2767-2782.

McKee, E.H., and McKee, E.D., (1972), Pliocene uplift of the Grand Canyon region - time of drainage adjustment: Geological Society of America Bulletin, v. 83, p. 1923-1932.

Melton, M.A., (1960), Origin of the drainage in southeastern Arizona: Arizona Geological Society digest, v. 3, p. 113-122.

Melton, M.A., (1965), The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona: Journal of Geology, v. 73, no. 1, p. 1-38. See also related article in Journal of Geology, v. 73, no. 5, p. 715-729.

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

Menges, C.M., (1983), The neotectonic framework of Arizona: implications for the regional character of Basin-Range tectonism: Arizona Bureau of Geology and Mineral Technology open-file report 83-19, 109 p.

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

Menges, C.M., and Pearthree, P.A., (1983), Map of neotectonic (latest Pliocene-Quaternary) deformation in Arizona: Arizona Bureau of Geology and Mineral Technology open-file report 83-22.

Merrill, R.K., and Pewe, T.L., (1977), Late Cenozoic geology of the White Mountains, Arizona: Arizona Bureau of Geology and Mineral Technology Special Paper No. 1, 65 p.

Metzger, D.G., (1968), The Bouse Formation (Pliocene) of the Parker-Blythe-Cibola area, Arizona and California: U.S. Geological Survey Professional Paper 600-D, p. 126-136.

Miller, H.W., Jr., (1962), Cretaceous rocks of the Mogollon Rim in Arizona: New Mexico Geological Society Guidebook No. 13 (Mogollon Rim), p. 93-94.

Montgomery, E.L., (1963), Geology and groundwater investigations of the Tres Alamos dam site area of the San Pedro River, Cochise County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis.

Morrison, R.B., (1965), Geologic map of Duncan and Canador Peak Quadrangles, Arizona and New Mexico: U.S. Geological Survey map I-442.

Morrison, R.B., (1984), Pliocene/Quaternary geology, geomorphology, and tectonics of Arizona: Geological Society of America Special Paper (in press), edited by Dave Weide.

Naeser, C.W., (1971), Geochronology of the Navajo-Hopi diatremes, Four Corners area: Journal of Geophysical Research, v. 76, p. 4978-4985.

Nations, J.D., (1974), Paleontology, biostratigraphy and paleoecology of the Verde Formation of late Cenozoic age, north-central Arizona: Geological Society of America Rocky Mountain Section meeting guidebook "Geology of Northern Arizona," part II, p. 611-629.

Nations, J.D., and others, (1981), Paleontology, paleoecology, and depositional history of the Miocene-Pliocene Verde Formation, Yavapai County, Arizona: Arizona Geological Society digest, v. 13, p. 133-150.

Oppenheimer, J.M., and Sumner, J.S., (1981), Gravity modeling of the basins in the Basin and Range province, Arizona: Arizona Geological Society digest, v 13, p. 111-116, map scale 1:1,000,000.

Otton, J.R., (1978), Criteria for uranium deposition in the Date Creek basin and adjacent areas, west-central Arizona: U.S. Department of Energy open-file report GJBX-12(78), p. 101-110.

Otton, J.K., (1982), personal communication; U.S. Geological Survey, Branch of Energy Minerals, Denver, CO., 80225.

Pashley, E.F., Jr., (1966), Structure and stratigraphy of the central, northern, and eastern parts of the Tucson Basin, Arizona: Univeristy of Arizona (Tucson) unpublished PhD thesis.

Pederson, E.P., (1969), Sedimentology and stratigraphy of basin-fill sediments of the Payson Basin, Gila County, Arizona: Arizona State University (Tempe) unpublished M.S. thesis, 136 p.

Peirce, H.W., (1976), Tectonic significance of Basin and Range thick evaporite deposits: Arizona Geological Society digest, v. 10, p. 325-340.

Peirce, H.W., (1981), Major Arizona salt deposits: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 11, no. 4, p. 1-4.

Peirce, H.W., Damon, P.E., and Shafiqullah, M., (1979), An Oligocene (?) Colorado Plateau Edge in Arizona: Tectonophysics, v. 61, p. 1-24.

Peters, Dusty, (1979), The sedimentologic history of the sandstones of Tempe Butte, Arizona: Arizona State University (Tempe) unpublished M.S. thesis, 197 p.

Peterson, D.E., (1983), personal communication. Sergent, Hauskins, and Beckwith, consulting engineers, Phoenix, AZ. 85019.

Peterson, D.W., (1968), Zoned ash-flow sheet in the region around Superior, Arizona: Arizona Geological Society Guidebook No. 3, p. 215-222.

Pewe, T.L., (1978), Terraces of the lower Salt River valley in relation to the late Cenozoic history of the Phoenix Basin, Arizona: Arizona Bureau of Geology and Mineral Technology Special Paper No. 2, p. 1-13.

Pewe, T.L., and Updike, R.G., (1976), San Francisco Peaks, a guidebook to the Geology, Second edition, Museum of Northern Arizona, Flagstaff, 80 p.

Plafker, Lloyd, (1956), Geologic reconnaissance of the Cenozoic Walnut Grove basin, Yavapai County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 62 p.

Pridmore, C.L., and Craig, C., (1982), Upper plate structure and sedimentation of the Baker Peaks area, Yuma County, Arizona. in Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: Cordilleran Publishers, San Diego, CA, p. 551-559.

Ransome, F.L., (1903), Geology of the Globe copper district, Arizona: U.S. Geological Survey Professional Paper 12, 168 p.

Ransome, F.L., (1923), Description of the Ray Quadrangle, Arizona: U.S. Geological Survey Atlas Folio 217.

Ransome, F.L., (1925), Basin range structure at Jerome, Arizona: Science, new series, v. 61, p. 659-660.

Reagan, A.B., (1924), Stratigraphy of the Hopi Buttes volcanic field, Arizona: Pan-American Geologist, v. 41, p. 355-366.

Reed, C.A., (1950), Preliminary announcement of a new mammalian fossil locality in the Pliocene of Arizona: Plateau, v. 22, p. 75-77.

Repenning, C.A., and Irwin, J.H., (1954), Bidahochi Formation of Arizona and New Mexico: American Association of Petroleum Geologists Bulletin, v. 38, p. 1821-1826.

Repenning, C.A., Lance, J.F., and Irwin, J.H., (1958), Tertiary stratigraphy of the Navajo Country: New Mexico Geological Society Guidebook No. 9 (Black Mesa Basin), p. 123-129.

Ross, C.P., (1922), Geology of the lower Gila region, Arizona: U.S. Geological Survey Professional Paper 129-H, p. 183-197. See also USGS Water Supply Paper 498, 237 p., issued 1923.

Ross, C.P., (1925), Geology and ore deposits of the Aravaipa and Stanley mining districts, Graham County, Arizona: U.S. Geological Survey Bulletin 763, 120 p.

Rowley, P.D., and others, (1978), Age of structural differentiation between the Colorado Plateaus and Basin and Range provinces in southwestern Utah: Geology, v. 6., p. 51-55.

Rowley, P.D., and others, (1979), Cenozoic stratigraphy and structural framework of southwestern Utah: U.S. Geological Survey Professional Paper 1149.

Royse, C.F., Jr., and Barsch, Dietrich, (1971), Terraces and pediment-terraces in the Southwest: an interpretation: Geological Society of America Bulletin, v. 82, p. 3177-3182.

Sabins, F.F., Jr., (1957), Geology of the Cochise Head and western part of the Vanar Quadrangles, Arizona: Geological Society of America Bulletin, v. 68, p. 1315-1342.

Sabels, B.E., (1962), Mogollon Rim volcanism and geochronology: New Mexico Geological Society Guidebook No. 13, (Mogollon Rim), p. 100-107.

Scarborough, R.B., (1975), Chemistry and age of late Cenozoic air-fall ashes in southeastern Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 107 p. [abstract!

Scarborough, R.B., 1981a , Radioactive occurrences and uranium production in Arizona: U.S. Department of Energy open-file report GJBX-143(81), 297 p. (Hopi Buttes discussion pp. 51-53.)

Scarborough, R.B., (1981b), Reconnaissance geology of the Salt River from Roosevelt Dam to Granite Reef Dam, central Arizona: Arizona Bureau of Geology and Mineral Technology open-file report 81-30, 70 p. plus maps.

Scarborough, R.B., (1984), Cenozoic erosion and sedimentation in Arizona. Arizona Bureau of Geology and Mineral Technology open-file report 84-6, 90p.

Scarborough, R.B., Damon, P.E., and Shafiqullah, M., (1974), K/Ar age for a basalt from the volcanic member (unit 5) of the Bidahochi Formation (abstract): Geological Society of America abstracts, v. 6, no. 5, p. 472.

Scarborough, R.B., and Meader, N.G., (1983), Reconnaissance geology of the northern Plomosa Mountains, La Paz county, Arizona. in guide to fall, 1983 field trip sponsored by Arizona Geological Society, p. 1-35.

Scarborough, R.B., Menges, C.M., and Pearthree, P.A., (1983), Map of Basin and Range (post-15 m.y.a.) exposed faults, grabens, and basalt-dominated volcanism in Arizona: Arizona Bureau of Geology and Mineral Technology open-file report 83-21.

Scarborough, R.B., and Peirce, H.W., (1978), Late Cenozoic basins of Arizona, New Mexico Geological Society Guidebook No. 29, Land of Cochise, p. 253-260.

Scarborough, R.B., and Wilt, J.C., (1979), A study of uranium favorability of Cenozoic sedimentary rocks, Basin and Range province, Arizona: U.S. Geological Survey open-file report 79-1429, 101 p.

Schafer, J.P., and others, (1974), Field guide for the Black Mesa-Little Colorado River area, northeastern Arizona: Geological Society of America field guide "Geology of Northern Arizona," part II, p. 729-756.

Schmidt, E.A., (1971), A structural investigation of the northern Tortilla Mountains, Pinal County, Arizona: University of Arizona (Tucson) unpublished PhD thesis, 248 p.

Schreiber, J.F., Jr., (1978), Geology of the Willcox Playa, Cochise County, Arizona: New Mexico Geological Society Guidebook No. 29 (Land of Cochise), p. 277-282.

Seager, W.R., (1984), New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87-99.

Seff, Philip, (1962), Stratigraphic geology and depositional environments of the III Ranch area, Graham County, Arizona: University of Arizona (Tucson) unpublished PhD thesis, 171 p.

Sell, J.D., (1968), Correlation of some post-Laramide Tertiary units Globe (Gila County) to Gila Bend (Maricopa County), Arizona: Arizona Geological Society Guidebook No. 3, p. 69-74.

Shafiqullah, M., Damon, and others P.E., and Peirce, H.W., (1976), Late Cenozoic tectonic development of Arizona Basin and Range Province:(abstract): 25th International Geological Congress, Sydney; abstract volume #1, p. 99

Shafiqullah, M., and others, (1978), Mid-Tertiary magmatism in southeastern Arizona: New Mexico Geological Society Guidebook No. 29 (Land of Cochise), p. 231-242.

Shafiqullah, M., and others, (1980), K/Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society digest, v. 12, p. 201-260.

Sharp, R.P., (1942), Multiple Pleistocene glaciation on San Francisco Mountain, Arizona: Journal of Geology, v. 50, p. 481-503.

Sheppard, R.A., and Gude, A.J., (1972), Big Sandy Formation near Wikieup, Mohave County, Arizona: U.S. Geological Survey Bulletin 1354-C.

Sheppard, R.A., and Gude, A.J., (1973), Zeolites and associated anthigenic silicate minerals in tuffaceous rocks of the Big Sandy Formation, Mohave County, Arizona: U.S. Geological Survey Professional Paper 830.

Sherborne, J.E., and others, (1979), Major uranium discovery in volcanoclastic sediments, Basin and Range province, Yavapai County, Arizona: American Association of Petroleum Geologists Bulletin, v. 63, p. 621-646.

Sheridan, M.F., (1978), The Superstition Cauldron complex: Arizona Bureau of Geology and Mineral Technology Special Paper No. 2, p. 85-96.

Shoemaker, E.M., Roach, C.H., Byers, F.M., (1962), Diatremes and uranium deposits in the Hopi Buttes, Arizona: Geological Society of America Buddington volume, p. 327-355.

Simons, F.S., (1964), Geology of the Klondyke Quadrangle, Graham and Pinal Counties, Arizona: U.S. Geological Survey Professional Paper 461, 173 p.

1956 in bibli. 1956 in microfilm Sirrine, G.K., (1956), Geology of the Springerville-St. Johns area, Apache County, Arizona: University of Texas unpublished PhD thesis.

Smith, D.G., (1963), Pleistocene geology and geomorphology of the San Pedro River valley, Cochise County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 61 p.

Smith, P.B., (1970), New evidence for a Pliocene marine embayment along the lower Colorado River area, California and Arizona: Geological Society of America Bulletin, v. 81, p. 1411-1420.

Smith, W.J., (1967), Cenozoic stratigraphy near Redington, Pima County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis.

Stone, Claudia, and Witcher, J.C., (1983), Geothermal energy in Arizona (Final report); Arizona Bureau of Geology and Mineral Technology open-file report 83-12, 398 p.

Sutton, R.L., (1974), The geology of Hopi Buttes, Arizona: Geological Society of America field guide for Flagstaff meeting "Geology of Northern Arizona", part II, p. 647-671.

Teel, D.B., and Frost, E.G., (1982), Synorogenic evolution of the Copper Basin Formation in the eastern Whipple Mountains, San Bernardino county, California. in Frost, E.G., and Martin, D.L. (editors), Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: Cordilleran Publishers, San Diego, p. 275-285.

Tomida, Yukimitsu, (in progress), Evolution of Plio-Pleistocene mammals and correlation of fossil-bearing deposits, Gila and San Simon Drainages, southeastern Arizona: University of Arizona (Tucson) PhD thesis.

Trevena, A.S., (1979), Studies in sandstone petrology: origin of the Precambrian Mazatzal Quartzite and provenance of detrital feldspar: University of Utah unpublished PhD thesis. 390 p.

Tuan, Yi-Fu, (1954), Types of pediments in the San Pedro Valley region, Arizona: Association of Pacific Coast Geography Yearbook, v. 16, p. 17-24.

Tuan, Yi-Fu, (1959), Pediments in southeastern Arizona: University of California Publications in Geography, v. 13, 163 p.

Twenter, F.R., and Metzger, D.G., (1963), Geology and ground water in Verde Valley - the Mogollon Rim region, Arizona: U.S. Geological Survey Bulletin 1177, 132 p.

Updike, R.G., and Pewe, T.L., (1974), Glacial and pre-glacial deposits in the San Francisco Mountain area, northern Arizona. in Karlstrom, T.M.V., and others (editors), Geology of Northern Arizona: Geological Society of America guidebook, part II, p. 557-566.

Van Horn, W.L., (1957), Late Cenozoic beds in the upper Safford Valley, Graham County, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 108 p.

Wadell, J.S., (1972), Sedimentation and stratigraphy of the Verde Formation (Pliocene), Yavapai County, Arizona: Arizona State University (Tempe) unpublished M.S. thesis, 110 p.

Walker, T.R., (1967), Formation of red beds in modern and ancient deserts: Geological Society of America Bulletin, v. 78, p. 353-368.

Walker, T.R., and Honea, R.M., (1969), Iron content of modern deposits in the Sonoran Desert: a contribution to the origin of red beds: Geological Society of America Bulletin, v. 80, p. 535-544.

Weibel, W.L., (1981), Depositional history and geology of the Cloudburst Formation near Mammoth, Arizona: University of Arizona (Tucson) unpublished M.S. thesis, 81 p.

Wenrich-Verbeek, K.J., and Spirakis, C.S., (1982), National Uranium Resource Evaluation, Flagstaff Quadrangle: DOE open-file report PGJ/F-014(82).

Williams, Howel, (1936), Pliocene volcanoes of the Navajo-Hopi Country: Geological Society of America Bulletin, v. 47, p. 111-172.

Wilson, E.D., (1931), Marine Tertiary in Arizona: Science, v. 74, p. 567-568.

Wilt, J.C., and Scarborough, R.B., (1981), Cenozoic sediments, volcanics, and related uranium in the Basin and Range province, Arizona. in Goodell, P.C., and Waters, A.C. (editors), Uranium in volcanic and volcaniclastic rocks: American Association of Petroleum Geologists Studies in Geology no. 13, p. 123-144.

3 9001 02558 7547

Wood, P.A., (1962), Pleistocene fauna from 111 Ranch area, Graham County, Arizona: University of Arizona (Tucson) unpublished PhD thesis.

Wright, H.E., Jr., (1954), Problem of Tohatchi Formation, Chuska Mountains, Arizona-New Mexico: American Association of Petroleum Geologists Bulletin, v. 38, p. 1827-1836.

Wrucke, C.T., (1961), Paleozoic and Cenozoic rocks in the Alpine-Nutrioso area, Apache County, Arizona: U.S. Geological Survey Bulletin 1121-H, 26 p.

Yetman, R.P., (1974), The geology of Chiricahua National Monument: report prepared for the Monument, dated 15 March 1974, 33 p.

Young, R.A., (1982), Paleogeomorphic evidence for the structural history of the Colorado Plateau margin in western Arizona. in Frost, E.G. and Martin, D.L. (editors), Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: Cordilleran Publishers, San Diego, p. 29-40.

Young, R.A., and Brennan, W.J., (1974), Peach Springs Tuff: its bearing on structural evolution of the Colorado Plateau and Development of Cenozoic drainage in Mohave County Arizona: Geological Society of America Bulletin, v. 85, p. 83-90.

Young, R.A., and McKee, E.H., (1978), Early and middle Cenozoic drainage and erosion in west-central Arizona: Geological Society of America Bulletin, v. 89, p. 1745-1750.

Vice, D.H., (1974), The geology and petrography of the Babocomari Ranch area, Santa Cruz and Cochise Counties, Arizona: Arizona State University (Tempe) unpublished M.S. thesis, 152 p.

Zoback, M.L., Anderson, R.E., and Thompson, G.A., (1981), Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States. in Extensional Tectonics associated with convergent Plate boundaries, published by the Royal Society, London, p. 189-216.