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LATE CENOZOIC BASINS OF ARIZONA

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INTRODUCTION

After about one hundred years of geological research, it has become apparent that the physiography of the Basin and Range province is strongly related to a late Cenozoic relief-producing tectonic event. This event established a complex array of disconnected mountain ranges and rather broad, intervening valleys. However, the detailed relationships between modern physiography and Cenozoic structural events are just beginning to be understood. The purpose of this paper is to explore some of these relationships.

A few terms need to be defined. In this paper a temporal distinction will be made between "basin" and "valley." A basin is a feature that acted in the past as a center of deposition or a trapping mechanism for sediments, whereas a valley (bolson) is an extant, topographically low feature which is contained between adjacent mountains. Most of the modern valleys in southern Arizona are spatially related to basins produced during the late Cenozoic (fig. 1). The two features are thus related, as most valleys are topographic forms which owe their distribution to the position of earlier-formed late Cenozoic basins. Valleys are, however, always more extensive than basins because of pedimentation (erosion) of adjacent mountain blocks.

For the purpose of categorizing discrete Cenozoic geologic episodes, a name should be applied to the important tectonic event that was initiated during the late Miocene (14-6 m.y. ago). We shall call this event the "Basin and Range disturbance." "Basin fill" is the sedimentary group that was deposited in basins created by the Basin and Range disturbance. However, we exclude all deposits formed by relatively modern,

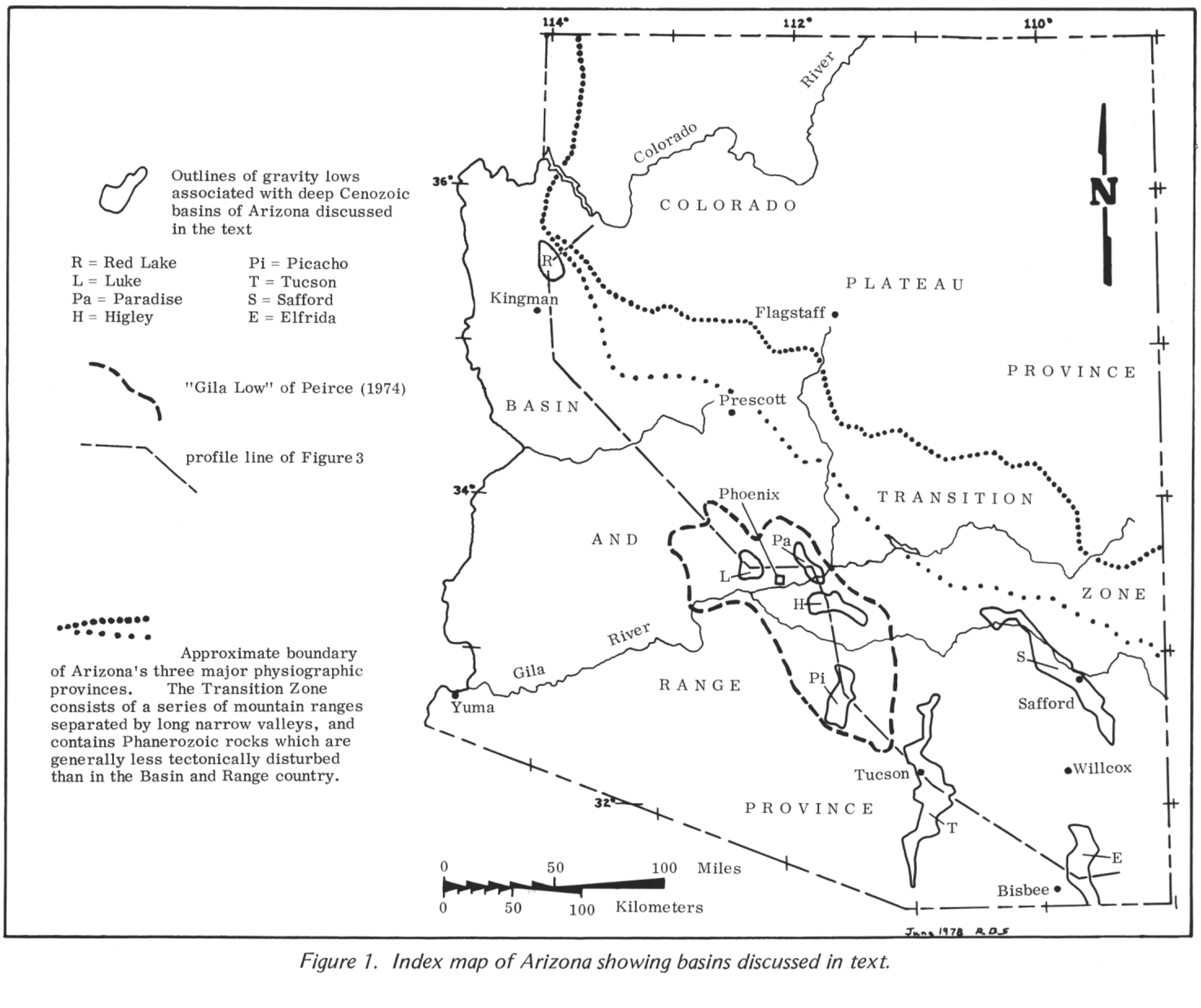

Figure 1. Index map of Arizona showing basins discussed in text.

integrated stream systems; these deposits are generally coarser-grained. It is likely that these latter materials are no older than Pleistocene.

GENERAL CENOZOIC HISTORY

The Cenozoic history of Arizona may be divided into four relatively well-defined events, each of which, within the scheme of Cordilleran geology, is related to certain large-scale and discrete tectonic-magmatic-stratigraphic events. They are: a) Eocene quiescence, b) massive late Oligocene-early Miocene, talc-alkaline volcanism and plutonism and associated sedimentation, c) the Basin and Range disturbance and associated late Miocene-Pliocene basin filling, and d) maximum filling of basins in middle Pleistocene followed by stream downcutting, development of terraces and valley unloading along the major rivers of the region.

Following the last stage of the Laramide orogeny, there appears to have been a time of magmatic and tectonic quiescence within Arizona, during most of the Eocene and early Oligocene, in which a generally low-relief surface of very large lateral extent was produced by subaerial erosion. This surface apparently was spread over much of the Cordillera (Livingston and others, 1968; Epis and Chapin, 1975). On the southern part of the Colorado plateau in Arizona, this surface is inferred to have been a north to northeastward sloping pediment that angularly truncated sediments as young as Upper Cretaceous and upon which rest "rim gravels" (McKee, 1951; Peirce and others, 1977). Within the Basin and Range portion of Arizona the continuity of the surface is more inferential because of later pervasive tectonism. The surface is believed to be represented by the tilted and highly faulted surface upon which rest the Whitetail Conglomerate (Ransome, 1903) and equivalents and scattered Oligocene volcanic rocks and sediments.

In Arizona the period 32-20 m.y. generally was a time of massive talc-alkaline volcanism and associated sedimentation (Superstition complex is an exception), part of volcanic event evidenced over most of the western United States and Mexico. Southern Arizona contains several large mid-Tertiary volcanic centers, including the Chiricahua Mountain volcanics (28-24 m.y.) (Marjaniemi, 1970), the Galiuro-Winchester mountains silicic and andesitic pile (29-22 m.y.) (Creasey and Krieger, 1978), the Superstition Mountains silicic center (29-15 m.y.) (Sheridan, 1978) and the White Mountains complex (36-20 m.y.), considered a part of the larger Mogollon-Datil Group (Elston and Northrop, 1976). Sediments formed at this time are frequently 5,000-10,000 ft-thick assemblages of fanglomcrates, fluvial overbank, and lacustrine beds which usually are found today at basin margins in fault contact with older rocks.

Within the time period 20-13 m.y., which essentially postdates the mid-Tertiary volcanic pulse but predates the Basin and Range disturbance, sedimentation and complicated tectonism were active. A series of tectonically disturbed fanglomerates has recently been identified that probably were both formed and deformed during this interval. These include the Rillito beds of Pashley (1966) in the northern Tucson basin, the Big Dome Formation, dated at 17-14 m.y. by K/Ar methods, near the Ray copper mine (Krieger and others, 1974) and the Nogales Formation of Simons (1974). These units display variable amounts of high-angle faulting and folding.

The tectonic picture and attendant volcanic style underwent an abrupt change in Arizona during the time range 15-10 m.y. ago (Damon and others, 1973; Eberly and Stanley, 1978; Peirce, 1978; Sheridan, 1978), when apparent large-scale, deep, pervasive fracturing resulted from an east-west directed, regional extensional field. The fracturing was manifested at the surface by generally north-south faults and was accompanied by volumetrically minor alkali flood basalts. This faulting created a series of irregularly shaped and only partially connected basins over the southwestern half of the state. These basins, created by the Basin and Range disturbance, and their contents are the subjects for the remainder of this discussion.

There seems to be a need to interject a note concerning terminology. The literature abounds with names such as "Basin and Range orogeny" and "Basin and Range disturbance" which at times have been carefully applied only to an event of block faulting as originally envisioned by Gilbert (1875), and which now appears to be no older than late Miocene in age (Wilson and Moore, 1959; Osmond, 1960). But frequently the terms have been applied in a more general sense to include many earlier Cenozoic tectonic events (Hayes, 1969; Elston and Northrop, 1976, p. 25-28; Loring, 1976; and others). We feel strongly that a restricted definition of the term within the Basin and Range country of Arizona is desirable, primarily because more general use of the term masks a whole series of temporally and spacially discrete geologic episodes, each of which requires a very special future attention. Furthermore, we think the name "Basin and Range" befits the obvious physiographic connotation of the causal tectonic event, as originally conceived by Gilbert, and therefore is the best descriptive term for that event. Also, we feel that the word "disturbance" better describes the manifestations of the episode than does "orogeny" because of the lack of recognized significant igneous activity and (or) regional compressive tectonics. We think it conceptually unproductive to attempt to extend the "Basin and Range disturbance" as far back in time as normal faulting can be recognized.

LATE CENOZOIC BASINS OF SOUTHERN ARIZONA

The understanding of the general character of Basin and Range basins is slowly improving with geophysical and deep-drilling projects (Davis, 1971; Sauck and others, 1971; Eaton and others, 1972; Aiken and Sumner, 1974; Budden, 1975; Goodoff, 1975; Bittson, 1976; Peirce, 1976; Robinson, 1976; Gass, 1977; Eberly and Stanley, 1978; Parker (in press); and other M.S. theses). Several statements may be made utilizing these data.

Although the general direction of elongation of basins is north to north-northwest in response to a proposed east-north-east to west-southwest regional extensional field initiated in late Miocene time, many 10 to 20 mi-long segments of subsurface basin boundaries and valley margins trend more northwesterly and northeasterly. The overall effect of this is a rather pronounced zig-zag pattern for most basins when viewed on a regional scale. Detailed mapping along certain Basin and Range faults (C. Menges, pers. comm.) gives the distinct impression that breakage in any small area simply followed the most susceptible pre-existing trends, many of which in southern Arizona were northwest- and northeast-directed.

Less than ten Arizona basins have been penetrated by deep drillholes, but this information is crucial to an understanding of basin stratigraphy and structure. The basins for which this information is known are shown on Figure 2, and summary information for these drill sites is presented in Table 1.

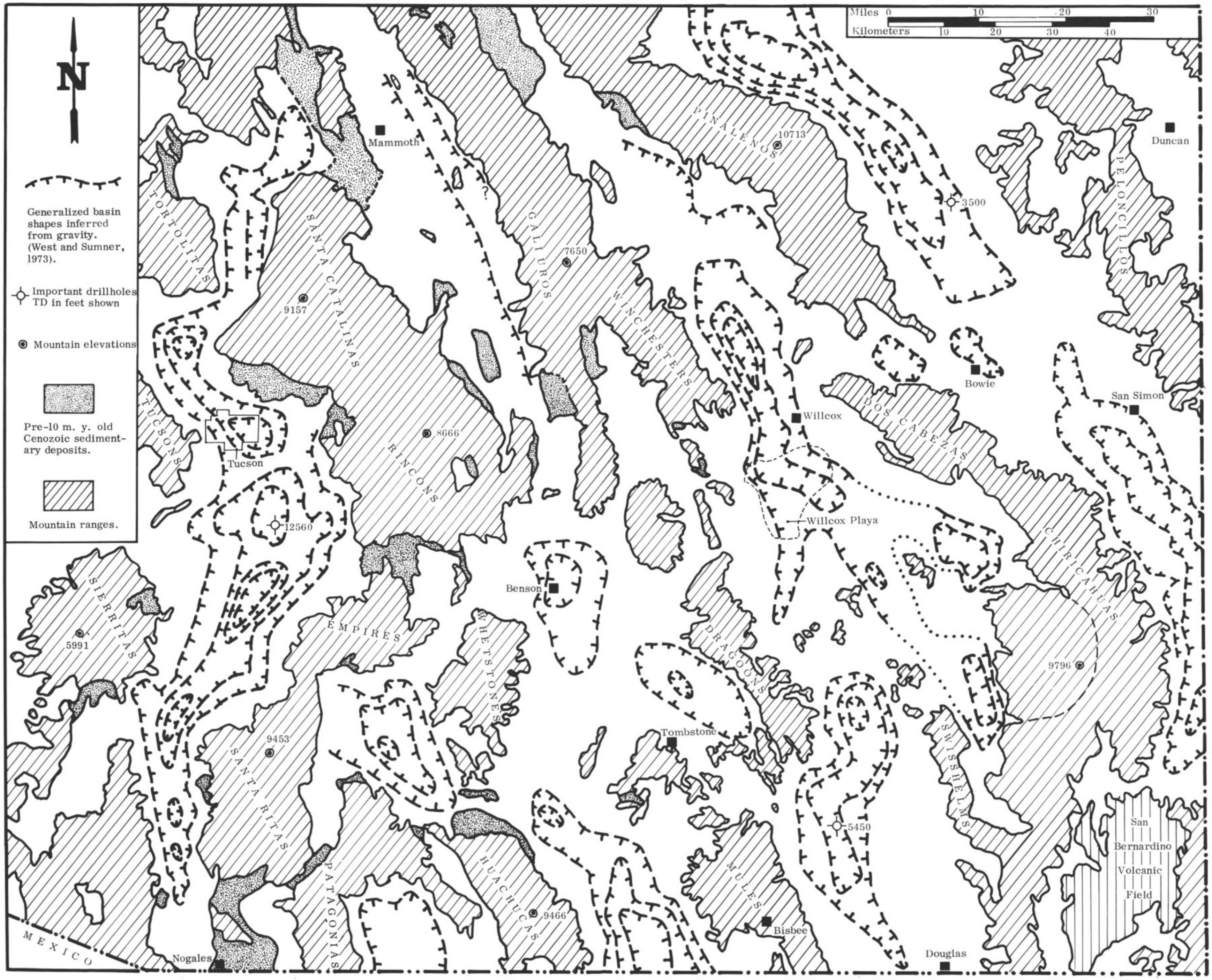

Figure 2. Basin shapes deduced from gravity studies for southeastern Arizona.

Table 1. Summary data for selected basins in Arizona.

Basin	TD of drillhole	elev. of BF base = below	elev. of BF top	BF thickness	evaporite thickness a= anhydrite g= gypsum h= halite	elev. of valley surface	elev. of surface outcrop reference point	estimated maximum stratigraphic separation on base of BF due to BRD
Elfrida	5450	+660	+4000	3340	------	+4260	Swisshelm Mts +7200	7650
Safford	3500	-270	------	------	600 g	+3230	Gila Mtns. +6000	6000
Tucson	12560	-4615	+1785	6400	------	+2885	Tucson Mtns. +4700	9200
Picacho	10180	-6740	+920	7660	5985 a	+1580	Picacho Mtns. +4500	11000
Paradise	5400	-2800	+360	3160	------	+1720	McDowell Mtns. +4070	7000
Higley	9250	-5200	+300	5500	------	+1340	Santan Mtns. +3000	8000
Luke	4470	-3380[2]	+1000	4380[1]	3600 h	+1100	White Tank Mtns. +4300	8000
Red Lake	5800	-3100	+2700	5800	4000 h	+2700	Grand Wash Clf. +6800	10000

BF = basin fill. BRD = Basin and Range disturbance. (1) Basin fill thickness of 10,000 feet estimated by gravity (Eaton, et. al., 1972). (2) -7400 foot elevation estimated by Eaton, et. al., (1972).

Elfrida basin, north of Douglas in Sulphur Springs Valley, has not been fully penetrated by drillholes, but one hole was drilled to a depth of 5,450 ft near the center of the basin. It penetrated, in ascending order above 1,850 ft of interbedded volcanic flows and claystones, 900 ft of claystones, 590 ft of conglomerate with minor claystone and sandstone, 1,500 ft of interbedded gypsum, claystone and minor sandstone, 400 ft of claystone with minor sandstone, and an uppermost 200 ft of conglomerate. All of the material above the volcanic flows and beneath the uppermost gravel cap is interpreted as basin fill (3,340 ft) and ranges in absolute elevation from 660 ft to 4,000 ft above sea level, assuming that the volcanics are pre-Basin and Range faulting in age. This is the highest basin in elevation known in Arizona.

The Tucson basin drillhole (Eberly and Stanley, 1978) contains 12,000 ft of inferred Cenozoic deposits above a pre-Eocene quartz monzonite, 6,050 ft of which are thought to represent basin fill. The drillhole section contains, in ascending order above quartz monzonite, 1,960 ft of reddish-brown clastics (which are analogous to deformed sediments in outcrop along the northwest flank of the Rincon Mountains), 2,850 ft of volcanic section with an uppermost K/Ar drillchip date of 11.6 m.y. (Damon and others, in preparation), 6,050 ft of fine-grained clastics that presumably represent the main mass of basin fill, and 1,100 ft of light reddish-brown sand and gravel which may correlate with the many thin Pleistocene pediment and stream gravels found throughout the region.

The volcanic section penetrated by the drillhole has younger K/Ar ages than the mid-Tertiary volcanic rocks in nearby outcrops, and may well represent younger volcanics that were faulted down and preserved beneath the basin but were eroded off adjacent mountain blocks. In this model Basin and Range faulting postdates 11.6 m.y. at this locality. This relatively young age for the Basin and Range disturbance may be compared with the 13.2 m.y. age on a flat-lying ash-flow remnant in the Roskruge Mountains (Bikerman, 1965) that has been postulated to be pre-Basin and Range faulting in age because it is a part of the mountain structural block. However, its implied presence at the bottom of the adjoining basin has not been confirmed. We now consider that the onset of the Basin and Range disturbance in southern Arizona postdates 12 m.y.

The Picacho basin drillhole contains 9,880 ft of inferred Cenozoic sediments above metamorphic rock dated at 26 m.y. by the K/Ar method (Eberly and Stanley, 1978). The metamorphic rock resembles gneiss which crops out in the Picacho Mountains 6 mi to the east. In a generalized fashion, in ascending order above the metamorphic rock are 210 ft of gneissic pebble conglomerate, 610 ft of dark-colored volcanic flows with K/Ar drillchip dates of 17 and 15 m.y. (Eberly and Stanley, 1978; Shafiqullah and others, 1976), 740 ft of volcanic-clast conglomerates, 5,985 ft of bedded anhydrite with minor shale, 1,675 ft of claystone with minor gypsum and anhydrite and 80 ft of halite near its base, and an uppermost 660 ft of gravel and sand. The evaporite and clastic interval between 660 and 8,320 ft is believed to represent basin fill, and was deposited after 15 m.y. according to the drillchip dates. The nearly 6,000 ft of anhydrite in this hole represents the thickest known evaporite sequence in Arizona, and perhaps the thickest anhydrite sequence in the world (Peirce, 1973). In addition, the bottom of fine-grained basin-fill rests at 6,740 ft below sea level, the lowest elevation basin floor known in the state (fig. 3).

Along with the thick anhydrite basin fill of the Picacho basin, two other Arizona basins are known to contain large amounts of halite. Luke basin near Phoenix (fig. 1) contains in

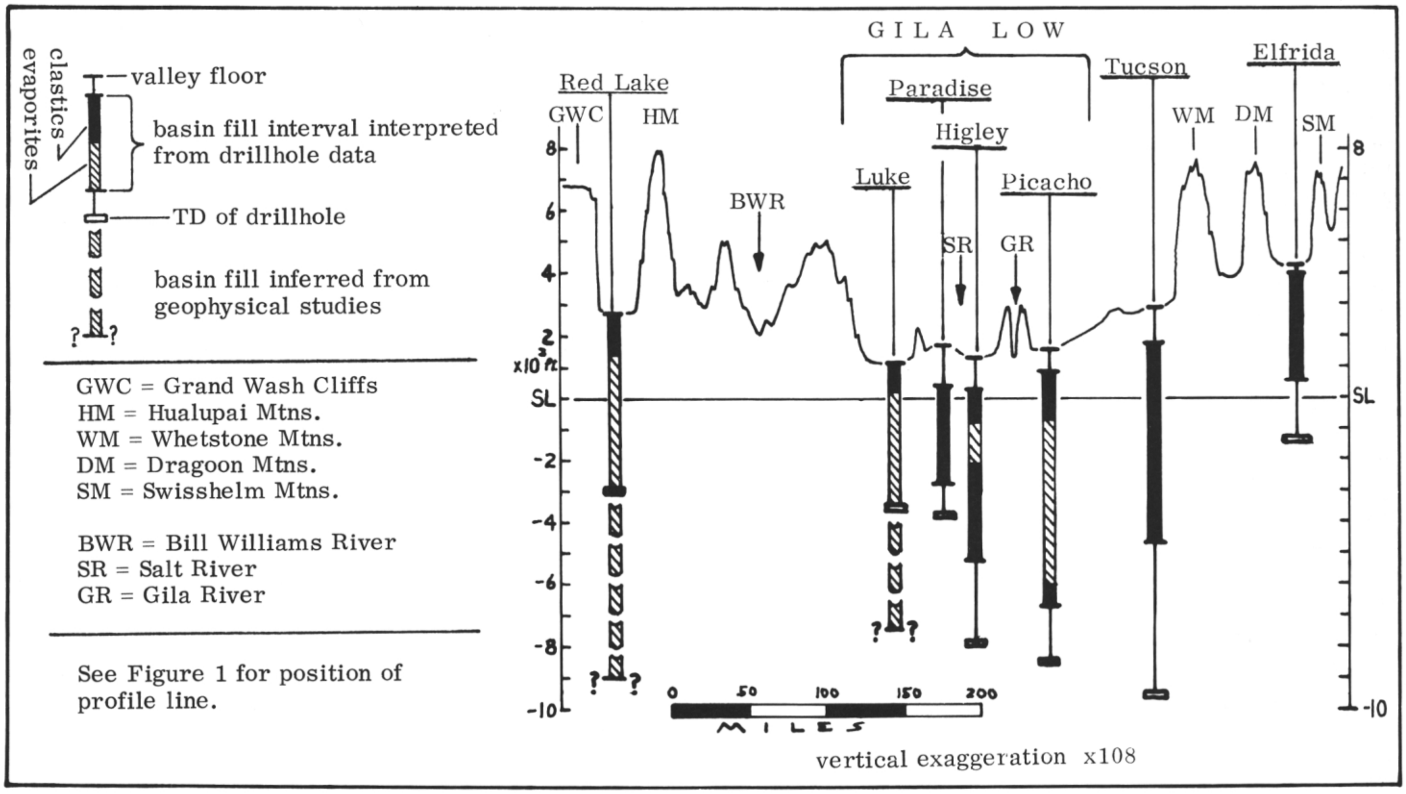

Figure 3. Profile showing structural positions of some Arizona basins.

one drillhole at least 3,600 ft of halite capped by 80 ft of anhydrite; both apparently have upwelled into a basalt flow which has been K/Ar dated from drillchips at 10 m.y. (Peirce, 1976). Eaton and others (1972) suggested the presence of 15 to 30 mi^3 of nonmarine halite in this basin, all of which could have been deposited by the present Gila, Salt and Verde River inputs of NaCI in roughly 20,000 years. Red Lake basin in the northwest corner of the state is also known to contain 4,000 ft of halite in one drillhole, and may have a volume of halite in excess of 100 mi^3 (Peirce, 1974).

Like Red Lake basin, the Willcox Playa area is still a closed basin, but has not yet been drilled to any great depth near its center. It lies within the southern confines of a gravity-deduced basin south of the Pinaleno Mountains (fig. 2). The Safford basin, another gravity low of large magnitude, lies just north of the Pinalenos, and at its southeastern extremity was found in a drillhole to contain at least 600 ft of bedded gypsum below an elevation of 330 ft above sea level. The full section of evaporite-basin fill in this region remains to be tested.

It is interesting to note that the siltstone-anhydrite-halite basin-fill deposits of the Tucson-Picacho-Luke basins, respectively, suggest some pattern of inter-basin connection of stream systems during basin-fill time (Peirce, 1976). Their spatial configuration is closely parallel to elements of today's drainage pattern in the same region. That there may also have been patterns of interbasin connection for the Lake Mead-Red Lake-Detrital valley area in the northwest corner of the state is suggested by Peirce (1974) on the basis of nearly equal elevations of tops of basin-fill evaporite sequences in those valleys. In attempting a regional picture of the pattern of drainage during basin-filling time, Peirce (1974) defined an area in central Arizona that he called the "Gila low," which is characterized by the presence of massive basin-fill evaporite deposits and by low elevation of tops of non-evaporite basin fill. The tops of basin fill are noted to rise in elevation progressively away from this area to the north, east and south, as does the modern drainage network (fig. 3). This suggests an orderly evolution of drainage from a regionally closed net of interconnected basins to the modern moderately well integrated, exteriorly draining system.

Bottoms of selected basin-fill sequences range in elevation from about 600 ft above sea level to about 6,800 ft below sea level. To what extent basin floors have subsided relative to sea level may be hinted at by noting what appears to be absolute subsidence to an elevation of 6,800 ft below sea level of the base of a "marine late Miocene" sequence in a Humble Oil (now Exxon) test well 20 mi southwest of Yuma (Eberly and Stanley, 1978). If other parts of the Basin and Range country behaved in the same manner, then amounts of absolute subsidence may approximate at least the thicknesses of basin fill deposits (Table 1) and hence may help to explain the magnitude of these thicknesses. Maximum values for stratigraphic throw across Basin and Range faults can only be estimated because of the difficulty of matching stratigraphic markers in drillholes with nearby surface exposures. Geologic relief in excess of actual basin-fill thicknesses is always present, and maximum determinable relief is always less than that which once prevailed. Caution is necessary in assessing the cause or causes of geologic relief between a basin and adjoining ranges, because all such relief is not necessarily just the result of faulting during the Basin and Range disturbance as defined here. However, our estimates of the magnitude of geologic relief assignable to such faulting is indicated in Table 1. These data suggest, for these basins, that vertical movement caused by faulting generally exceed 6,000 ft and range up to more than

11,000 ft. Stratigraphic separation of about 20,000 ft can be measured in the central part of the state for the base of Cenozoic deposits (the Eocene surface) between the southern edge of the Colorado Plateau and the Higley basin some 60 mi away. If one assumes a modest regional northeastward gradient on the Eocene surface at the time of Basin and Range foundering, the projected stratigraphic separation could be higher than this value by a factor of two. We are suggesting here that cumulative throws on Basin and Range faults could offset pre-faulting rock units by 30,000 ft or more, when measured from the southern edge of the Colorado Plateau to the area of the lowest basin floors within the "Gila low."

BASIN FILL

Sedimentologically and structurally, basin fill is differentiated from older deposits in that it: a) tends to retain original depositional dips, b) contains facies relationships largely consistent with present valley configurations, c) is tectonically deformed only locally, and d) rests upon an erosional surface which is cut upon rocks as young as early to middle Miocene within areas close to the mountain-piedmont junction (i.e., Ril I ito Surface of Pashley, 1966).

In the partially dissected valleys, the general nature of basin fill is a coarser-grained piedmont facies and a finer-grained valley-center facies. Older parts of the piedmont facies often are observed to be in fault and (or) depositional contact against range blocks. Lithologically, this coarse phase consists of bedded, sub-angular to sub-rounded cobble conglomerates with lenses and channel-fill pods of fluvial sand and unsorted, unbedded debris flows; the entire assemblage is here called fanglomerate. Depositional dips range from 3 to 7 degrees. Facies boundaries with the valley-center deposits usually are confined within a zone approximately 600 ft or less in width. The valley-center facies consists of either fluvial overbank or lacustrine deposits. Fluvial overbank facies are recognized as an assemblage of poor- to well-bedded sandy silts and silty sands which are horizontally bedded cross-valley but dip down valley rather parallel to present stream gradients; they contain sporadic admixtures of thin clay-rich beds, local gypsum beds (locale of Arizona's principal gypsum sources), and vitric-silicic air-fall ash beds. They also contain local ponded deposits which at times contain marginally recoverable quantities of diatomite (Peirce, 1969), along with green chert pods and fossiliferous green mudstones (for general descriptions, see Knechtel, 1938; Marlowe, 1961; Seff, 1962; Melton, 1965; Agenbroad, 1967; Sheppard and Gude, 1972; Ladd, 1975). Parts of several valleys contain more extensive beds of marly limestones, as near San Carlos (Davidson, 1961), or interlayered beds of green- and red-colored silty clays, as near Benson and St. David (Gray, 1965), which were laid down in what was probably a lacustrine to swampy environment. However, the overall depths of these lakes is perhaps not very great because of scattered occurrences of large mammal footprints and bone concentrations throughout the deposits (Lammers, 1970; Jacobs, 1973; Nations, 1974). The environments of deposition of the thicker evaporite deposits are not known, although it seems likely that large volumes of water were involved. In general, environments of deposition for all the fine-grained facies are summarized as "a series of local shallow playas or salt lake basins separated by large fan deposits," and containing diatoms originating from a saline, inland playa (Davis and Brooks, 1930), or, as shallow, slightly saline lacustrine conditions with occasional very sluggish movement of water through the valleys (Marlowe, 1961).

SUMMARY

Relative to the Colorado Plateau province, the basins of the Basin and Range province are downdropped. The maximum amount of downdrop (geologic relief) occurs between the Gila Low or central Arizona "sump" and the Mogollon Rim. Although unproven, it seems possible that the basins of central and southern Arizona actually have subsided relative to sea level.

The expression "plateau uplift" has been widely used in Arizona. In actuality, there seems to be more evidence in Arizona for a collapsing Basin and Range province than there is for a rising Colorado Plateau province, relative to sea level, during the late Miocene-Pliocene Basin and Range disturbance.

The special correspondence between present-day valleys and late Miocene basins (fig. 1) is a compelling reason to suspect that the valleys are an offspring of the Basin and Range disturbance. They have resulted from widening of the late Miocene basins due to pedimentation and burial of the basin bottoms by debris derived from mountain blocks. However, to what extent each individual basin may be called a graben, half graben or rhombochasm, is a pronouncement that must be made for each individual case.

The presence of sequences of non-marine siltstone, anhydrite and halite in separate but adjacent basins suggests the presence of one or more ultimately closed drainage net(s) of regional proportion during basin-fill time. Basins were connected by a series of spillways over bedrock shoulders, and stream systems delivered massive amounts of dissolved minerals to the area of the "Gila low," among others, where they were deposited by evaporation. Along the way, sluggish stream systems deposited mudstone-siltstone-minor evaporite sequences in various valley segments. A gradual evolution from a closed regional drainage pattern to today's moderately-well integrated, exterior system is indicated by all available data.

Evidence suggests the basin-making event was initiated during late Miocene time (15-10 m.y. ago). However, its termination is another matter. The encroachment of youngest, unfaulted basin fill upon erosion surfaces cut upon mountain blocks is an indication of diminished faulting in later basin-fill time. Generally, this upper basin fill may be as old as Pliocene or as young as mid-Pleistocene.

In our opinion, vertical tectonics have not been active in Arizona's Basin and Range province since mid-Pleistocene time except for a belt of vertically offset Pleistocene surfaces found within the southeastern part of the state in the San Pedro and Santa Cruz valleys. Zones of modern seismicity within Arizona (Sumner, 1976) are related in no simple way to either the belt of post-mid-Pleistocene offsets or to the position in space of the Basin and Range province.

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