FIELDNOTES

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Doing What Comes Naturally

THE "FLOODS" OF OCTOBER 1983

by H. Wesley Peirce and Peter L. Kresan

Figure 1. Raging waters of the brimful Santa Cruz River. Looking upstream to the south from St. Mary's Bridge. Photo taken on October 2, 1983 by Peter Kresan.

INTRODUCTION

Excerpts from *The Arizona Daily Star,* Tucson:

Sept. 10, 1887:
About 2 o'clock yesterday morning, it started to rain hard and poured unceasingly until after daylight, flooding many parts of the city and causing great loss to railroad east and west of Tucson. . . . Mr. Hancock's apiary was two feet under water. . . . Mr. Wetmore told a *Star* man yesterday that there was 9.5 feet of water in the river and that trees and other articles were floating with the current at a very brisk rate. . . .

Dec. 23, 1914:
WORST FLOOD FOR GENERATIONS. . . . LOSS OF SEVERAL LIVES UP THE VALLEY. . . . BELOW MARANA AND CORTARO, TRACK OF MAIN LINE INUNDATED FOR ABOUT 4 FEET; 25 MILES OF TRACK WASHED OUT. . . . TWO PEOPLE BELIEVED DROWNED AT SAHUARITA; 25 PEOPLE MAROONED ON HOUSETOPS AND WINDMILLS. . . .

Dec. 24, 1965:
FLOOD PERIL CONTINUES AS SEWERS WASH OUT; STATE ASSISTANCE SOUGHT. . . . FLOWING WELLS AREA STUNNED BY WILD RILLITO. The roiled, brown waters of the flooding Rillito Creek tore into two trailer parks in the Flowing Wells area yesterday, demolishing two trailers. Residents bitterly termed it a disaster and scorned public officials for apathy about their plights. . . .

Dec. 31, 1965:
RUNOFF CRISIS REPEATS ITSELF. Rain and rapidly melting snow in the Catalinas swelled the Rillito River again yesterday. . . .

Excerpts from *The Tucson Citizen:*

Oct. 3, 1983:
FLOODS RAM TUCSON. . . . ROARING RIVERS EAT AWAY BRIDGES, HOMES. . . . MARANA IS SUBMERGED; RESIDENTS EVACUATED. . . . HOMES, LIFE POSSESSIONS SWALLOWED BY SANTA CRUZ. . . . 4,000 ARIZONANS EVACUATED IN FACE OF MASSIVE FLOODS. . . .

Oct. 4, 1983:
ONLY TWO IN MARANA HAD FLOOD INSURANCE. Only two national flood insurance policies were issued in the Marana area before flooding inundated the whole area, because town officials "didn't believe it floods there," a flood insurance official said. . . .

RIVERS' CURVES FIGHT CITY'S STRAIGHT LINES. . . . Where the rains had collided with roads, houses, and power lines, the flood ripped, swallowed, and snapped. . . .

Excerpts from *The Arizona Daily Star,* Tucson:

Oct. 17, 1983:
THE FLOOD OF '83 — A SPECIAL REPORT:

THE BIG ONE. This was the flood we'll remember. This was the flood our children and grandchildren will be told about time and again as we warn of the awful power of the area's normally dry rivers. At least 10,000 Arizonans were at least temporarily homeless when flood dangers forced evacuation of entire communities. Other areas were cut off for days as the rivers toppled bridges and blocked roads. . . .

CLIFTON'S BEST PREPARATIONS FAILED. Clifton knows floods. . . . Most of the city's 4,200 residents were evacuated. Over 600 homes and 86 of Clifton's 126 businesses were damaged severely. . . .

LOSSES TOTAL HUNDREDS OF MILLIONS. . . .

If experience is a great teacher, then repetitious experience should be doubly effective as an educator. Teaching is ineffective, however, if the pupils aren't paying attention. In October 1983, nature taught many Arizonans a lesson that they will not soon forget. Certainly, the natural events that occurred during that time inspired many questions, and questions inevitably must precede answers. Local reaction varied from one of tragedy among those who were directly affected to one of glee among those who enjoyed watching nature "do its thing," even at the expense of humankind. Engineers learned a great deal and are already applying their newly acquired experiences and insights.

The dynamics of the hydrologic event can be analyzed in detail and are probably among the easiest aspects of the event to discuss. There would be no concern about the event itself, however, were there not direct social, economic, and political impacts and implications. Where there is an interface with human activity, some natural earth processes can be both hazardous and damaging. In the desert country of southern Arizona, processes associated with water runoff are the dominant natural hazard.

The events of October 1983 provide the incentive for this brief and basic review of the nature of the runoff hazard in this desert region. Although all of the examples are from the Tucson area, the principles involved are generally applicable to other desert regions.

DYNAMICS OF DESERT RIVERS

The network of natural drainageways in the desert country of southern Arizona is exceedingly intricate. The integrated network is a part of the larger Gila and Colorado River systems, which are naturally designed to carry surface waters toward the Sea of Cortez. Although most of the network occupies valleys and foothills, the headwaters are in the higher reaches of adjacent mountain ranges. Many of these ranges are a mile or so higher than the desert valleys and are, therefore, subjected to much higher precipitation rates. The excess precipitation in the mountains is conveyed to the valleys, where drainages are naturally enlarged to accommodate the total flow.

Within an integrated drainage network, the size of any particular flow or runoff event is proportional to the area receiving precipitation. Only at times of regional rainfall is it possible to activate all of the existing drainages. Such was the case in October 1983. Regionally, the land surface had been well-wetted by previous rains; then, in 2 days, aided by tropical storm Octavo, about 6 inches of rain fell. More rain fell in the mountains, swelling waterways even further.

Those who witnessed one or more of the major drainages in action were reminded of the frightening power of rushing, roily water (Figure 1). A flow rate of 25,000 cubic-feet-per-second (estimated for Rillito Creek) is about equivalent to an 800-ton mass moving past a given point each second. (An 800-ton mass weighs more than *two* 747 Jumbo Jets, which weigh 775,000 pounds each.)

A basic law of physics states that any mass, once in motion, will continue in a straight line until acted upon by an outside force. What happens when a mass of moving water is "asked" to flow around a bend in a channel? The only way the moving water can be made to turn is if the outside bank exerts enough force to redirect the flow. If the banks are relatively weak, as they tend to be in southern Arizona (Figures 2a-d), there will be a compromise: the river will continually "chew" at the bank in its effort to flow in a straight line, but will eventually turn in response to the resistance that the wasting bank will offer. This "chewing" causes banks at curves, and thus the curves themselves, to migrate downstream. The amount of land removed is a function of bank strength; radius of curvature; rate, amount, and duration of flow; etc.

There are, therefore, two measurements used to describe the extent of bank alteration: (1) the amount of straightening in the direction of river flow; and (2) the distance between old and new bank, measured perpendicular to the direction of flow. For the large historical runoff events, these measurements ranged from near zero to about 1,500 feet, and from near zero to about 600 feet, respectively, for a single bank. In other words, an area as large as 10 acres is known to have been transposed from riverbank to river bottom. Losses of up to 5 acres occurred at several sites along the Rillito last October.

The vulnerability of banks to destruction is also a function of geometric position at any given time. Like a cue ball, rapidly flowing water literally bounces from one side of a stream to the other, wherever there are curves in the channel. Unless they are adequately stabilized, these curves will not remain steadfast for long.

Flood vs. Flow Event

It is conceptually important to distinguish between flood and flow events in a desert region. Much confusion has arisen because of a lack of appreciation for the contrasting processes involved in these two types of runoff. A flood occurs when discharge exceeds the capacity of an active channel to contain the flow. In other words, a true flood refers to distinct overbank flow, called flood flow. If there is no flooding, the runoff event is simply a flow event. Flooding may locally occur, but elsewhere along the same drainage, runoff may be totally contained within well-defined banks. Flooding is an unusual flow condition, whereas confined flow is the norm.

Most of the damage to humankind within the Tucson metropolitan region has been done under *nonflood* conditions by the collapse and erosion of river banks, especially on the outside of meander bends.

If nonflood runoff alters banks enough to undercut "flood-protected" buildings, regulations that require construction above a certain elevation on a floodplain will not spare buildings from disaster. Many of the more dramatic pictures taken along Rillito Creek, Tanque Verde Wash, Pantano Wash, and the Santa Cruz River, on or after October 2, 1983, were related to nonflood bank-cutting and bank collapse (Figures 2a-d). Even so, adequate setback regulations have been slow in coming. In recent times, each new experience with severe nonflood runoff damage has led to more stringent setback regulations, especially in areas where there is inadequate bank protection. Because of the October 1983 experience, Pima County engineers now consider "inadequate" any bank protection that is not the relatively new soil-cement type. At the present time, 500-foot setbacks are required where banks are not protected by soil cement. A land user, however, can request a variance if the request is adequately supported by engineering studies. A 500-foot setback might seem large, but at selected times and places on Rillito Creek, bank erosion from a single runoff event has exceeded this amount.

Actual flooding did take place where channel capacity was not able to contain runoff. The Marana area was the most dramatic example. Marana is down-

Editor's Note: Related articles on desert-runoff hazards and flood-plain management have appeared in the following issues of *Fieldnotes*: Vol. 2, No. 3 (Sept. 1972); Vol. 5, No. 1 (March 1975); Vol. 10, No. 4 (Dec. 1980); and Vol. 11, No. 1 (March 1981). These issues are available from the Bureau for $2.00 ($1.00 covers postage and handling; $1.00 covers reproduction costs for the March 1975 issue, which is out-of-print).

NONFLOOD BANK-CUTTING AND BANK COLLAPSE

Figure 2a. Severe bank-cutting along the Santa Cruz River near I-19 and San Xavier Road. Looking northwest. Bridge segment nearest viewer collapsed when support washed out. Bridge in distance did *not* fail. Bank retreated from west end of bridge to present position. Distance between bank and midstream end of bridge is measure of amount of bank erosion that occurred. Photo taken on October 9, 1983 by Peter Kresan.

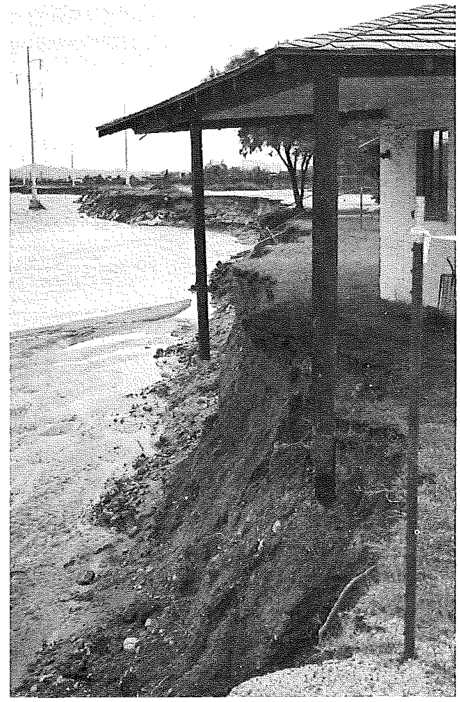

Figure 2b. Bank-cutting along north bank of Rillito Creek at N. 1st Avenue. Looking downstream. Photo by Peter Kresan.

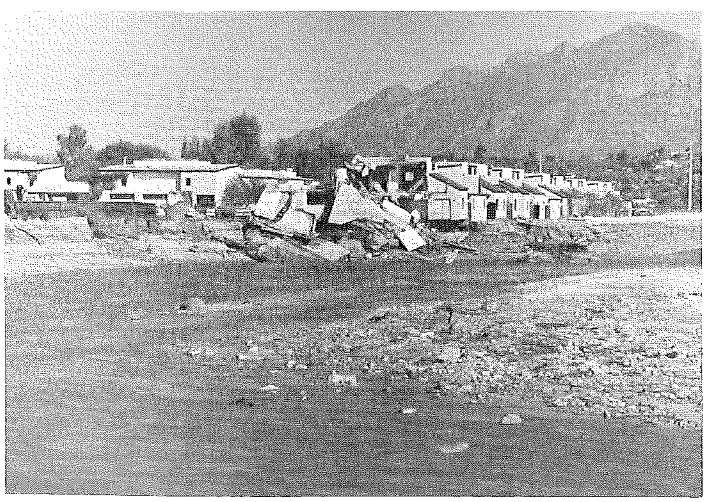

Figure 2c. Bank-cutting on outside of bend along Rillito Creek. Looking downstream near Prince and Country Club Roads. Photo by Tad Nichols.

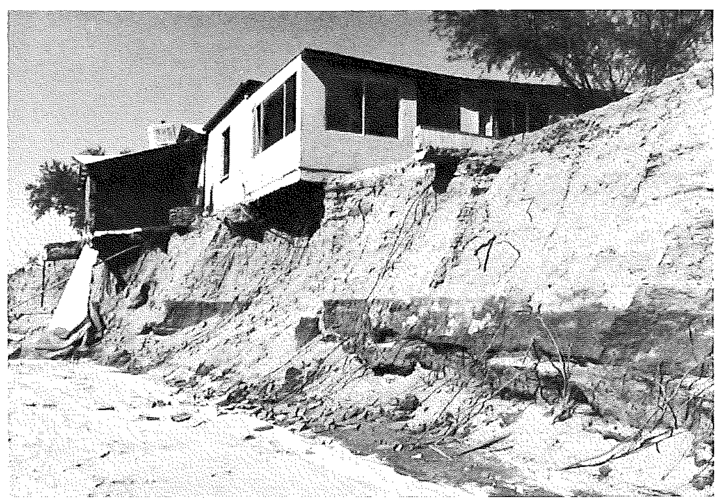

Figure 2d. Bank erosion along north bank of Rillito Creek. Looking downstream. Photo by Ken Matesich.

stream from the confluence of Rillito Creek and Canada del Oro with the Santa Cruz River. Water spread out laterally over a distance of 4 or 5 miles, causing a true flood. The channels through the city of Tucson, on the other hand, are deeply entrenched and barely managed to contain the October runoff within their banks. Nevertheless, this "saving grace" did not prevent the turbulent waters from damaging bridges, roads, buildings, vehicles, utility lines, crops, livestock, certain bank-protection devices, etc. (Figures 3a-d).

Because almost every drainageway in Arizona was activated by the rainfall from the large storm system, runoff effects were widespread. Small washes scoured their banks and bottoms, often finding things of man to damage (Figure 4).

When the Water Is Gone

After the last vestiges of runoff have seeped into the sand, vertical channel banks remain. That banks can migrate hundreds of feet during flow events is testimony to their lack of resistance. Banks fail because of undercutting and collapse, and this tendency does *not* disappear when the water does. Collapse of banks on the verge of failure could be triggered by any destabilizing mechanism. Vibrations of any sort, loading at the top by even one person, and undercutting by cave-making youngsters could cause a bank to collapse, with potentially tragic results (Figure 5).

There are many miles of banks along major drainages that course through the Tucson metropolitan area. Some of these banks are more than twice as high as two average-sized adults. Most were modified during October 1983 and left in various states of instability.

Consequently, when the water is gone, there is still reason for concern about dry drainages. Although they are in their normal state, dry drainageways continue to be hazardous to the unaware.

MISCELLANEOUS DAMAGE

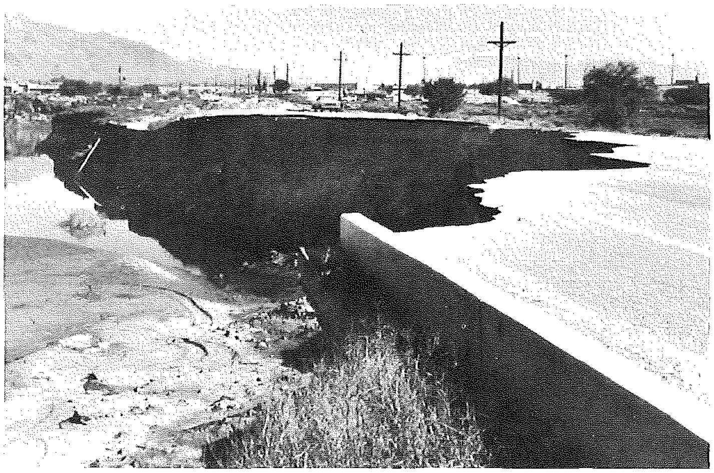

Figure 3a. Ina Road undercut by water from adjacent Santa Cruz River. Looking northeast. Photo by Ken Matesich.

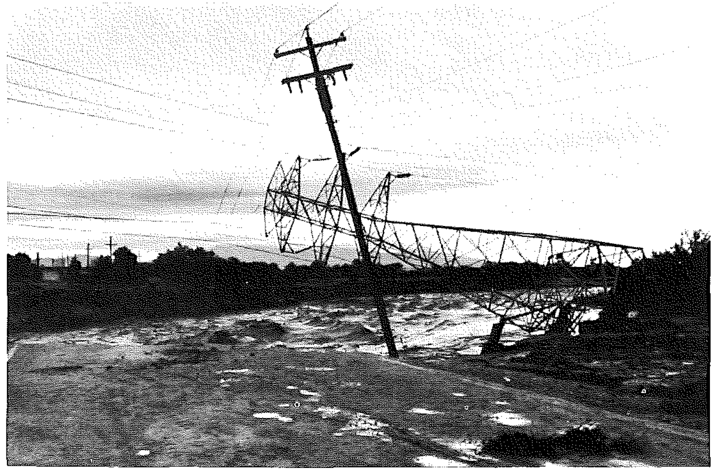

Figure 3b. Wipeout of bridge and utility tower at Sunset Road crossing of Santa Cruz River. Looking southeast. Photo taken on October 2, 1983 by Steve Reynolds.

Figure 3c. Same area as Figure 2d. Looking upstream at water well that was on left side of bank before erosion. Photo by Ken Matesich.

Figure 3d. Wipeout of northern approach to Dodge Boulevard Bridge over Rillito Creek. Looking south. Photo by Peter Kresan.

WHAT CAN BE LEARNED?

The events of October 1983 reinforced the belief that the worst regional runoff events tend to associate with the large tropical systems that invade the State during the fall months. Because these tropical systems can be repetitious, they can set the stage for large-scale runoff by first saturating the ground.

A general survey conducted by the authors revealed how fortunate many residents were that the next scheduled tropical storm failed to materialize in southern Arizona. Many buildings and objects, more numerous than those that were toppled, were poised for undermining when the flows of early October abated. Since then, the southern part of the State has been in a dry spell. This respite is buying time for the community to complete various repairs and add some protection prior to the anticipated summer rainy season.

Local residents might expect a future rash of aggravating maintenance work where utilities were buried along and beneath foothill washes several years ago. In some cases, various lines, buried until 1983, were uncovered by wash-bottom scour and broken at least three times in the latter half of the year (Figure 4). Many more lines are now closer to the surface because of erosion above them.

Considerable experience was gained about various methods of protecting banks. Almost anything will protect a bank, as long as the protective device is not tested too severely. A recently developed technique, which involves the use of soil cement, received its baptism in October. Except for minor problems, the technique tested well (Figures 6a and 6b). On the other hand, some of the more classic protective measures failed during the big October test (Figures 7a and 7b). For regulatory purposes, Pima County now recognizes only one type of bank protection: soil cement. Several soil-cement projects, funded by Federal monies, are underway at the places deemed to be most critical.

The October runoff event demonstrated how difficult it is to protect works of man that encroach upon major drainages. The largest drainages, such as Pantano Wash, Rillito Creek, and the Santa Cruz River, reached man-made structures that had been built many years ago. The runoff event was large, powerful, and persistent enough to cause hundreds of feet of lateral bank migration in several places. The areas where the soft banks would be cut away were predictable (Figure 8 with inset); the *size* and *power* of the runoff event, however, were *not* anticipated.

Because the channels, banks, and adjacent flood plains along major drainages are usually privately owned, it has not been possible to treat these systematically. A shopping-center owner can afford to invest more heavily in protection than can an average home or trailer-park owner. The result is "piecemealing," a condition that a raging flow of water will test in search of a weakness. Bank protection devices necessarily end at property boundaries, a situation that leaves the devices especially vulnerable at their points of termination. This is also true of soil cement. Water can erode the efficacy of any protective device if it gets behind the upstream end or overtops the structure (Figure 9). Selective application of soil cement is itself a form of "piecemealing" that will leave unprotected banks free to migrate (Figure 9). How this migration will eventually affect the protected parts remains to be seen.

SOME REMAINING QUESTIONS

Desert drainage systems are complex, interwoven, dynamic, and vital, characteristics that combine to test engineering and management skills. On the one hand, there is a demand to stabilize banks, especially around houses, businesses, and bridges that carry daily traffic. On the other hand, major drainages play a vital role in recharging the only indigenous water supply in southern Arizona: ground water. Replenishment of ground water depends on the maintenance of the sand "sponge" that usually occurs along drainage bottoms. What would cause the removal of this "sponge"? What would save it?

In the ideal solution to this two-sided problem, viable bank protection would be added *and* the necessary conditions for effective ground-water recharge would be maintained. Realization of this plan requires a basic understanding of the dynamics of the system, appropriate engineering techniques, and adequate financing. Appreciation and understanding of regional drainage dynamics is critical to the management of major drainages. Research into the cause-and-effect relationships within this drainage system should be encouraged and supported.

Proper management of drainageways involves several questions: What combinations of circumstances would cause channel-bottom scouring (removal of the important sand-gravel "sponge") or sand-gravel accumulation? How does urbanization of the desert floor affect these processes? Certainly the paving and development of square-mile-after-square-mile prevents transport of normal sediment loads to the major drainages. This leads to clear-water runoff, which, in turn, encourages scour (sediment transport) within the main drainages. If the banks of these drainages were totally protected, the most immediate sediment source would be the loose bottom materials that must be maintained to aid ground-water replenishment. Structural modifications would be required to prevent large drainages from scouring and to promote ground-water recharge. The enhancement of recharge should be a continuing goal of research.

Other questions concern the quantitative influence of urbanization on desert runoff. How does urbanization - paving, smoothing, packing, channeling, vegetative removal, etc. - affect runoff amounts and rates? Is the natural drainage system, at least near urban centers, being asked to carry a larger burden than it would otherwise? How does this increase in urbanization, over time, affect drainage predictability and planning for the future? How can urbanization of the Tucson Basin be planned to minimize the impact? Because of this evolving factor, how reliable are past studies and the regulations based upon them?

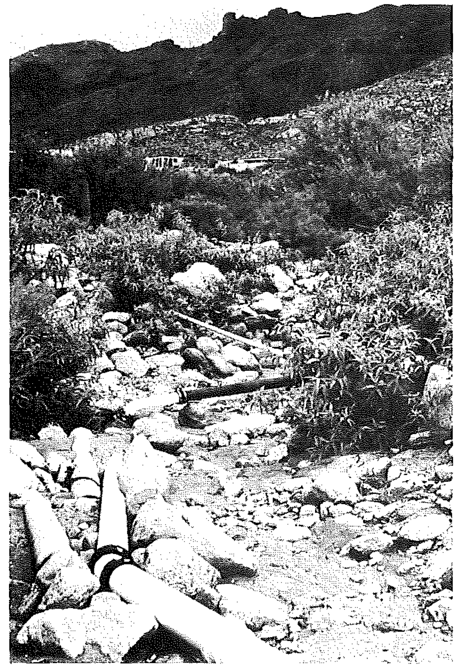

Figure 4. Sewer line, buried for 11 years, uncovered by erosion along bottom of Finger Rock Wash in foothills of Santa Catalina Mountains. Smaller pipe is natural gas line, also exposed by erosion. Looking upstream toward the northwest. Photo by H. Wesley Peirce.

THE FUTURE

Runoff in the Southwest desert is a natural process that is vital to life in general, but injurious in specific cases of encroachment. That the process will continue is assured. Because the frequency and severity of future events are unpredictable, it behooves citizens to look to themselves for protection by

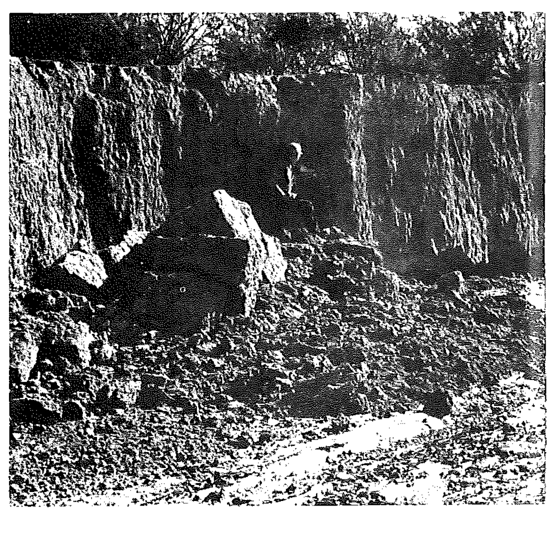

Figure 5. East bank of Pantano Wash collapsing after flow ceased. Scene depicts instability of banks and attendant hazard. Photo by H. Wesley Peirce.

SOIL-CEMENT BANK PROTECTION

Figure 6a. Same area as Figure 1 after passage of major flow. Right bank with railing is undamaged soil cement. Photo by Peter Kresan.

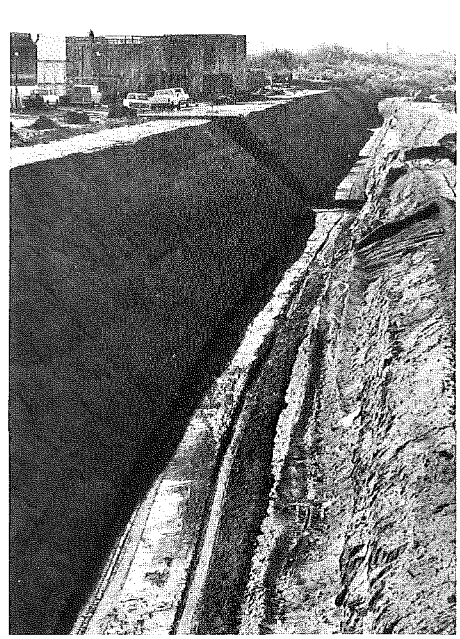

Figure 6b. Pantano Wash bank undergoing soil-cement process. Photo by Ken Matesich.

exercising judgment about things that they can directly control. Most adults have some say about where they choose to live. If one is aware of the general desert-water hazard, there should be no excuse for placing oneself in a grossly vulnerable situation.

There will be future damage to existing man-made structures that have been rendered vulnerable by virtue of their location and inadequate or nonexistent bank protection. On the other hand, because of the experiences of October 1983, the security of many bridges and associated features will be enhanced by better bank protection.

Building will continue near the major drainages where banks are judged to be adequately protected by soil cement. Although great faith is being placed in this form of bank protection, it remains to be seen whether nature, over time, will be able to significantly undo even these man-made attempts to control the natural flow of water toward the sea.

CONCLUSION

Damaging runoff in the deserts of southern Arizona is the rule rather than the exception. The region continues to grow in population and urbanization. It is only logical, therefore, for one to assume that damaging runoffs will occur in the future.

The consequences of large-scale runoffs range from minor harassments to tragic destruction. The "floods" of October 1983 resulted from pervasive tropical systems that affected much of Arizona. Although this natural event may have been the most costly ever inflicted on Arizona, it demonstrated what is possible. This message alone is invaluable; "forewarned *is* forearmed." More respect is already being given to the important drainages.

Because of the applicability of the laws of physics and geometry, there is no real mystery as to what a flowing mass of water will attempt to do and where it will do it. What are not predictable are the size and frequency of runoff

Figure 7a. Post in foreground marks position of bank-protection device prior to October 1983. South bank of Rillito Creek near N. 1st Avenue. Photo by Peter Kresan.

Figure 7b. Rock-and-wire-mesh bank-protection device breached and overtopped in October 1983. Looking north along Santa Cruz River from bridge at W. Grant Road. Photo by H. Wesley Peirce.

FAILED BANK PROTECTION

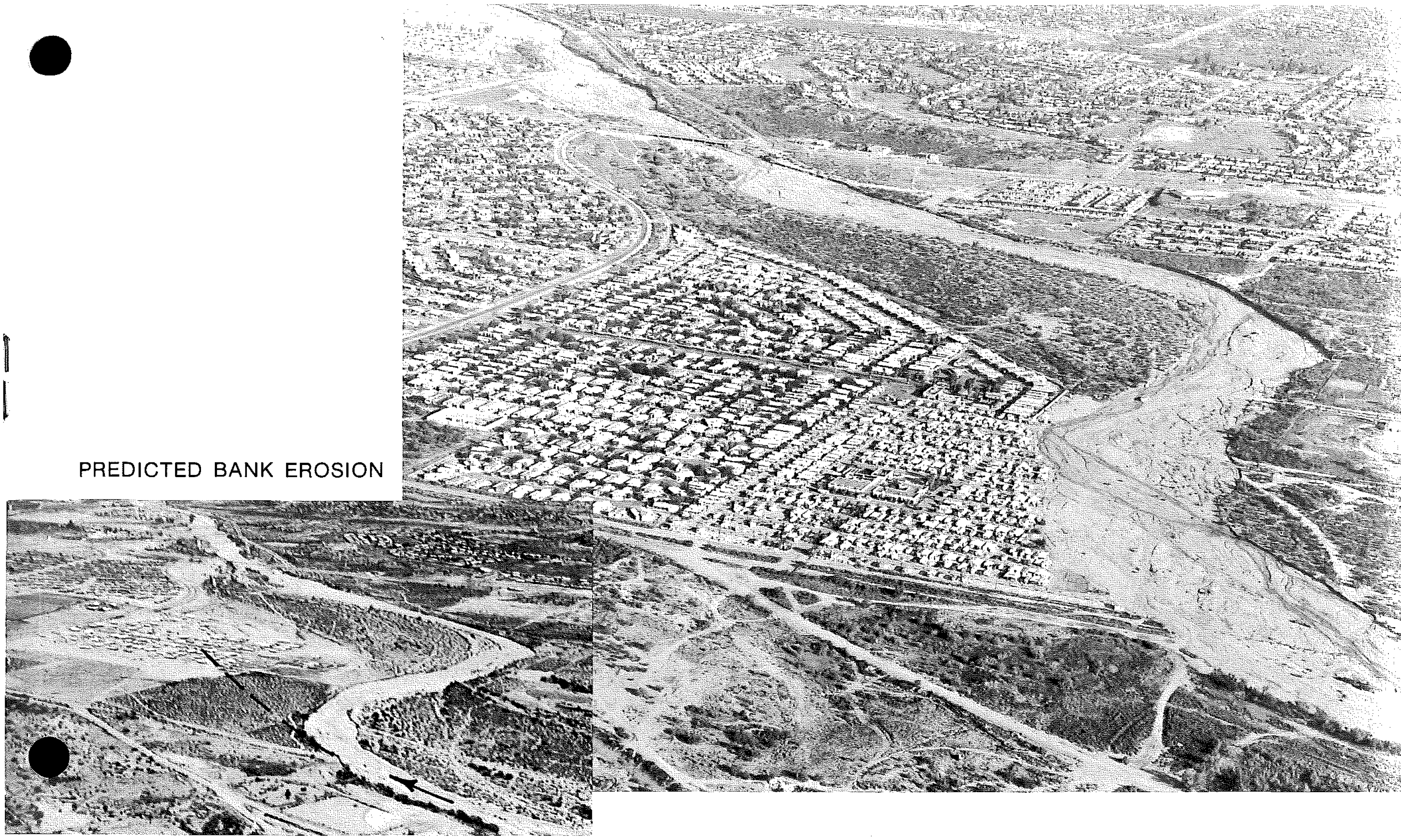

Figure 8. Bank-cutting at outside of bend along west bank of Pantano Wash, south of Golf Links Road. Photo taken on October 9, 1983 by Peter Kresan.

Inset: Same area as main photo, as seen in 1972. Dashed line indicates trend of future bank-cutting, as predicted in *Fieldnotes* in September 1972. Note erosion along predicted trend. Also note expansion of development toward wash. Photo by H. Wesley Peirce.

events for which a community should prepare itself. What constitutes preparedness? How much is enough? How much are citizens willing to spend on the uncertain future? One thing *does* seem certain, however: because of their experience with the October 1983 runoff, Arizonans will be willing to spend more than they otherwise would have. Oftentimes people have to see to believe. Crying wolf too often tends to lower a citizen's level of concern; *seeing* a wolf, on the other hand, heightens his or her awareness. Seeing the "wolf" of October generated enough support that Pima County voters approved a bond sale to redesign and repair the many highways and bridges that were damaged. Included will be bank protection mechanisms that will better withstand high flows, if they are properly designed and constructed.

As more channel control is sought to arrest bank collapse and migration, important questions will arise about the maintenance of stream-bottom stability, the potential for increased bank erosion along unprotected stretches, and the increased flood potential downstream from highly channelized sections. Major drainages are vital ecological factors: they are linked to the ground-water supply upon which much of southern Arizona depends. A raging torrent of water may appear unfriendly and in need of control; however, some of this torrent, if given the chance, will seep underground and help to restore the level of the water table. The trick to management of drainages is to exert control where necessary, but to encourage and maintain maximum recharge.

High banks continue to be unstable long after they have returned to their normal state of dryness. For wayfarers along the drainages, caution is the watchword, whether the drainages are wet or dry.

Figure 9. Bank collapse after Rillito Creek got behind upstream end of soil-cement protective device and undermined buildings. Flow is from bottom to top. There was no bank protection for buildings in lower left position. Near intersection of Prince and Country Club Roads. Photo taken on October 9, 1983 by Peter Kresan.

THE MOGOLLON ESCARPMENT

by
H. Wesley Peirce
Principal Geologist

Nontechnical Summary

The lateral extent and origin of the Mogollon Escarpment of central Arizona, familiar to many as the Mogollon Rim, are not common knowledge. In 1875, G.K. Gilbert recognized and described a regional physiographic escarpment, which he called the "Aubrey Cliffs," that extended from the Grand Wash Cliffs to Fort Apache. During the 108 years since then, however, geologists have not fully appreciated Gilbert's observations. As a geologic-geomorphic feature, the Mogollon Rim (Escarpment) of Peirce and others (1979) and the Aubrey Cliffs of Gilbert (1875) are identical. Young (1979, p. 28), recognizing the continuity of a portion of this feature, called it the "retreating Kaibab scarp."

"The Rim," or at least a portion of it in east-central Arizona, has long been used as a boundary to subdivide the western United States into major physiographic provinces. A review of these efforts reveals persisting inadequacies in the geologic rationales used to define and choose this boundary. The traditional effort to delineate an acceptable boundary between the Colorado Plateau Province and the Basin and Range Province in central Arizona appears to have been defeated by arbitrariness. The concept of transition seems useful. The Mogollon Escarpment, as defined here, is a geologically consistent feature to use as the physiographic boundary between the Colorado Plateau Province in the northeast and an expanded Transition Zone in the southwest. In turn, the Transition Zone—Basin and Range boundary is marked by a sharp contrast in structure and deformation.

The Mogollon Escarpment

The Mogollon (muh-ge-own) Escarpment of central Arizona is one of the State's spectacular natural attractions, especially when viewed from the rim of its precipitate cliffs. The name "Mogollon" was apparently derived from Juan Ignacio Flores Mogollon, a former Governor of New Mexico during the period 1712-1715 (Granger, 1960, p. 79). Several geographic features in western New Mexico embrace this name; it has also been extended to various features in Arizona. James (1917, p. 134) used the expression "so-called Mogollon Rim" to define an area that extended westward from the Mogollon Mountains of New Mexico to the Oak Creek region of central Arizona, in which he described ". . . a huge escarpment known as 'The Rim'" (p. 126). Contained in this simple phrase is a semantic technicality that must be explained before the discussion can proceed.

What are the meanings of "escarpment" and "rim"? In the quoted phrase, these words are intended to be interchangeable. "Rim" is more properly used, however, to describe an edge, the topographic top of an escarpment or cliff. The Rim Road, for example, follows the top of the escarpment. Although the distinction is seldom made, there can be *both* a Mogollon Escarpment *and* a Mogollon Rim. In this technical article, I will use the geomorphic term, "escarpment," rather than the commonly used term, "rim."

For convenience of discussion, the Mogollon Escarpment is divided into natural segments in this article. The most imposing section, of Zane Grey fame, is the Tonto segment between Payson on the west and Christopher Creek on the east (Figure 1). Here the top is 7,500-8,000 feet in elevation, and the escarpment averages more than 2,000 feet in height. The cliff face is rugged and generally inaccessible to humankind and the wingless. This south-facing escarpment marks the high edge of a planar plateau (Mogollon Plateau, Mesa, or Slope), which rises southward in response to a slight northeastward tilt of the underlying cliff-making strata. It is a jumping-off place par excellence. Sharp (1940, p. 65), referring to the Tonto segment, proclaimed:

> Here - is to be seen one of the finest examples of a retreating plateau escarpment ever mapped in the United States.

Further eastward, the Apache segment is more subdued and incised by long canyons carved by tributaries of the Salt River. Still further east, the classic escarpment zone is buried by volcanic rocks associated with the generally younger White Mountains volcanic field. Nevertheless, a "Mogollon Rim" is identified on topographic maps and Wilson (1965, p. 45) stated that the feature is manifested by volcanic rocks offset by as much as 2,000 feet along the Strayhorse fault. Although this could be called the White Mountains segment, I will not discuss it here.

To the northwest, the beautiful Sedona—Oak Creek Canyon country owes its scenic geologic attributes to both colorful rocks and landscape-forming processes that have been acting upon the Verde segment of the Mogollon Escarpment for more than 15 million years.

Between the Tonto and Verde segments is the north-trending Mormon segment that is dominated by a thick sequence of younger volcanic rocks, which are piled against, and thus obscure, the escarpment. Deep canyons proposed as wilderness areas gash the volcanic rocks headward, sometimes exposing a vertical sequence of lava flows 2,000 feet thick that abuts the ancestral escarpment.

The cumulative length of the Apache, Tonto, Mormon, and Verde segments is nearly 150 miles. It is this stretch that has frequently been called the "Mogollon Rim."

Extending the Escarpment

Defining the escarpment, as well as its age and origin, is essential to establishing its lateral continuity. The classic escarpment can be extended to the Grand Wash Cliffs another 125 miles to the northwest. Previous work by Peirce and others (1979) suggests that an ancestral cliff probably evolved during Oligocene time by fluvial entrenchment into thick, relatively soft, sedimentary rocks of Permian age. Erosional downcutting tended to parallel the regional northwest strike of Paleozoic strata that were slightly tilted toward the northeast. There were at least two episodes of tilting, subaerial exposure, and truncation of the stratal section. One preceded deposition of Upper Cretaceous marine strata and another preceded fluvial deposition of nonmarine Eocene-Oligocene Rim gravels. The escarpment is held up by resistant Permian cliffmakers that overlie the softer units. These cliffmakers include the Coconino Sandstone, the Toroweap Formation in some localities, and the Kaibab Limestone, which caps the western half of Arizona's portion of the Plateau country. In fact, the best way to find this escarpment zone is to locate the southernmost exposures of these units: they do not extend beyond the escarpment to the south. Although incised by canyons in several places, the Oligocene(?) escarpment, as evidenced by the geomorphic-stratigraphic position of Tertiary gravels and volcanics, has

Editor's Note: This article represents the second in a series of abbreviated technical reports designed to focus on a specific aspect of Arizona's geology or mineral resources. Readers' comments are encouraged.

retreated northward no more than 6-10 miles since its inception. If one assumes that inception occurred 25 million years ago, the maximum retreat rate would be 0.25-0.40 mile per million years.

When these criteria are applied, it is clear that northwest of the Verde segment the Aubrey Cliffs (present usage) near Seligman are a continuation of the Mogollon Escarpment geomorphic feature. Between these two segments, near Ash Fork, the subdued cliff has largely been obscured by erosion and a cover of post-Rim volcanic rocks. Similarly, the Shivwits segment on the extreme northwest is considered to be an extension of the Mogollon Escarpment; and, were it not for the breach by the Grand Canyon (and possibly by earlier drainages) along the Hurricane fault, the Shivwits segment would be continuous with the Aubrey segment. In Arizona, therefore, the Mogollon Escarpment ends at the Grand Wash Cliffs. The Grand Wash Cliffs, an eroded fault scarp, are controlled by the paralleling Grand Wash fault that truncates, and thus terminates in Arizona, the older Mogollon Escarpment (Figure 1). Defined in this way, the Mogollon Escarpment diagonally bisects central Arizona over a distance of 310 miles. The escarpment has, however, been segmented by later faulting, erosion, and volcanism, and in some places, has been enhanced by later faulting that parallels the escarpment trend.

Recognition of the basic statewide lateral continuity of this feature prompts a review of how it has been used to physiographically describe and subdivide Arizona.

Physiographic Subdivisions

This brief technical review and discussion of schemes for physiographically subdividing Arizona span the 108 years between 1875 and 1983. A clear evolution of geologic thought has been compromised by a literature containing words without diagrams, diagrams without words, unclear exposition, inconsistencies between rhetoric and diagrams, and a measure of arbitrariness that seems to shadow this subject. The problem, in a nutshell, is the geologic rationale for the placement of credible physiographic boundaries.

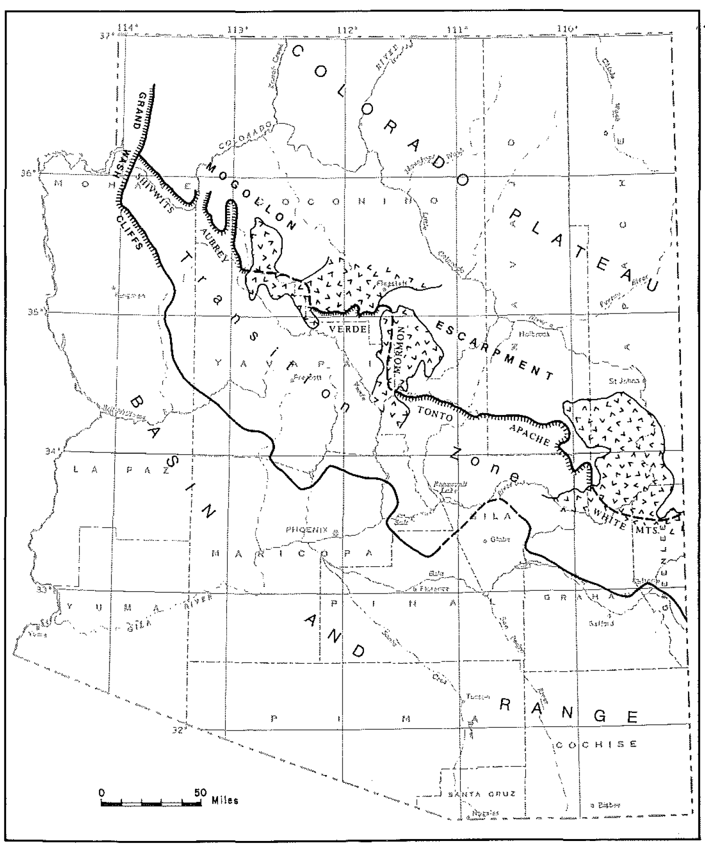

Figure 1. SUGGESTED BOUNDARIES OF PHYSIOGRAPHIC PROVINCES IN ARIZONA.

One of the clearest statements (which, unfortunately, lacks diagrams) that I have read regarding an Arizona physiographic boundary is by Gilbert (1875). By that time, all of the classic plateaus north of the Grand Canyon had been named by John Wesley Powell, geologist and pioneer explorer of the Colorado River. Gilbert had investigated much of the region south and east of the Grand Canyon and had defined a Colorado Plateau as being but one plateau in the larger Colorado Plateaus physiographic province. His newly defined plateau was bounded on the west by the southern Grand Wash Cliffs, on the east by the Colorado Chiquito (Little Colorado), and on the south by the Aubrey Cliffs. Gilbert stated that this plateau edge extended 240 miles from the mouth of Diamond Creek at the Grand Canyon to Fort Apache on the southeast. Gilbert also recognized the following: (1) that the southwestern edge of the Shivwits Plateau across the Grand Canyon to the northwest was a continuation of the Aubrey Cliffs; and (2) that much of this plateau edge, especially to the southeast, was a drainage divide between the Little Colorado and Gila systems. As defined, Gilbert's cliff trend extended all of the way to the Grand Wash Cliffs, the cliffs that form the western edge of the Shivwits Plateau. Gilbert called this trend the "Aubrey Cliffs," for the Aubrey Sandstone (Coconino Sandstone of today), which he recognized as being present in every cliff segment. I have come to recognize that the area that I am designating as the Mogollon Escarpment includes Young's Kaibab scarp (1979), and is precisely what Gilbert called the "Aubrey Cliffs," plus the Shivwits extension.

The first diagram of Arizona provinces is credited to Ransome (1903, p. 10). He commented that the provinces were "rudely" outlined and that the diagram was designed only to provide a setting for his specific study of the Globe copper district. He defined three regions: (1) Plateau on the northeast; (2) Mountain through central Arizona; and (3) Desert on the southwest (Figure 2). Ransome noted that his physiographic presentation was largely a compilation of the works of others. Although he cited only Gilbert's Aubrey Cliffs as a guide in defining a boundary for the Plateau region, Ransome's "rude" diagram notably did not follow Gilbert's Aubrey Cliffs in northwestern Arizona, especially the Aubrey and Shivwits segments defined in this article. That he intended to follow them is suggested in this statement (p. 16): "The Mountain region and the Desert region are both included in the Basin Range system of Gilbert." This statement affirms that Gilbert recognized only the single boundary (Aubrey Cliffs) as the division between the two major provinces. I have no explanation for the way in which Ransome positioned the Plateau boundary in northwestern Arizona, other than this: perhaps he simply disagreed with Gilbert and did not say so. There may also have been some casualness involved in Ransome's designations, as implied in his use of the word, "rude."

Lee (1908) cited Ransome (1904) for the Plateau, Mountain, and Desert regions and proceeded to discuss (p. 13) the Plateau boundary in his limited area of investigation:

> The Grand Wash Cliffs, extending from Colorado River to Music Mountain, a distance of about 50 miles, is composed of crystalline rock at the base, overlain by the sedimentary formation of the Plateau region. At Music Mountain this escarpment divides, the lower or crystalline part continuing southward under the names of the Cottonwood and Aquarius Cliffs and forming the edge of the Truxton Plateau, while the upper or sedimentary part recedes to the east, under the name of the Yampai Cliffs.

Lee's limited segment of the Plateau boundary consists of the Grand Wash Cliffs and the Yampai Cliffs, which recede to the east. It is this deviation from the structurally controlled Grand Wash Cliffs that subsequently plagues most attempts to

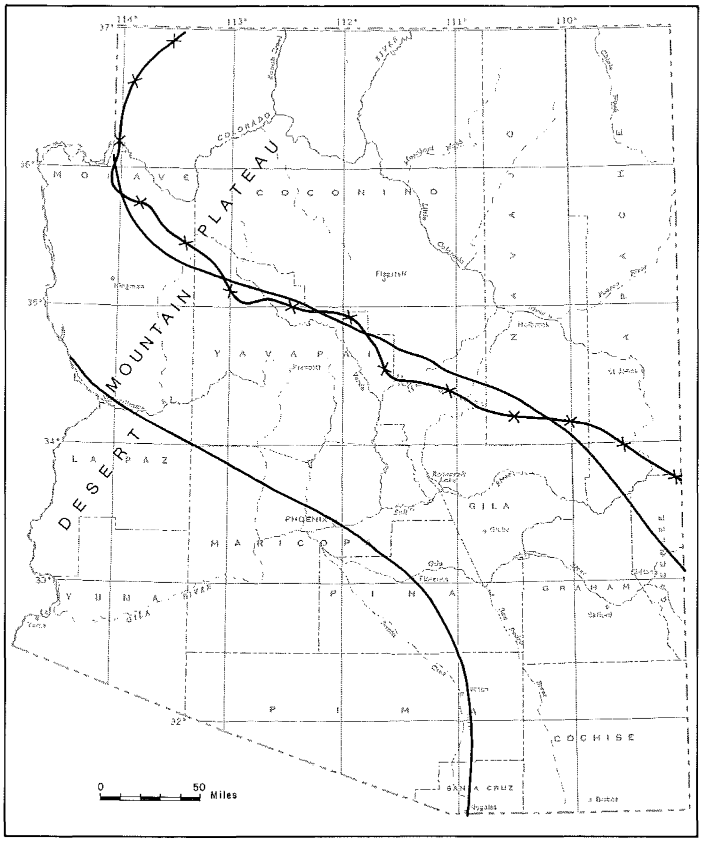

Figure 2. PHYSIOGRAPHIC SUBDIVISIONS OF ARIZONA BY RANSOME (1903) AND FENNEMAN (1931).

Ransome (1903). Two solid lines create three subdivisions: (1) Plateau; (2) Mountain; and (3) Desert regions.

Fenneman (1931). One line with *x*'s creates two subdivisions: (1) Colorado Plateau on the northeast; and (2) Basin and Range on the southwest.

delineate a boundary between the two provinces. The point of deviation geologically represents the intersection of two entirely different trends: (1) an older grain that represents the regional northwest strike; and (2) a younger north-trending fault zone, along which there have been thousands of feet of relative, down-to-the-west, stratigraphic throw.

Two publications by Fenneman (1916, 1931) are the most frequently cited physiographic references for the western United States. His maps show a single boundary across Arizona, which divides the State into two classic provinces (Figure 2). In describing northwestern Arizona, Fenneman cited Lee (1908) and specifically mentioned the cliff alignment followed there: southern Grand Wash Cliffs, Yampai Cliffs, Juniper Mountains, and Black Mesa. From Black Mesa, he moved over to the Verde segment, and from there he followed the traditional boundary along the escarpment to the southeast. Fenneman, however, also seemed to recognize the existence of Gilbert's Aubrey Cliffs, as evidenced in this idle comment (1931, p. 382):

> From the Grand Wash Cliffs on the west to this locality (Camp Apache), the Aubrey Cliffs are bold even if locally notched.

I can only surmise that, like Ransome, Fenneman chose not to follow these cliffs northwest from the Verde segment, preferring instead to piece together the more southerly alignment suggested, in part, by Lee.

Hunt (1956, p. 3) followed the general boundary of Fenneman in his map and labeled the Plateau boundary the "Mogollon Rim." He did not discuss a geologic rationale for this boundary, preferring to leave the matter to Fenneman.

As I've suggested, this popular boundary between the Colorado Plateau Province and the Basin and Range Province embraces a range of geologic-geomorphic settings. It runs the gamut from strong structural disruption to no discernible structures, and from low cliffs supported by lowermost Paleozoic strata on the west to high cliffs supported by uppermost Paleozoic strata on the east. In my opinion, this boundary, especially between the Verde and Grand Wash segments, has very little geologic integrity for a boundary designed to delineate two major provinces of the southwestern United States.

Heindl and Lance (1960, p. 12) thought that these older schemes left something to be desired, and after reviewing the literature, proposed another scheme based upon a structural concept. Their single-line boundary was established, in part, on the idea that flat-lying strata are characteristic of the Plateau Province and that these strata extend south of the traditional boundary. No part of the "Mogollon Rim," viewed merely as a retreating escarpment, should therefore serve as a structural boundary; it is but a *part* of the Plateau (Figure 3).

The suggested boundary of Heindl and Lance inherits the basic aspects of delineations that preceded it, especially in the northwest. Here again, the Grand Wash Cliffs structural zone is followed in extreme northwestern Arizona, and is then abandoned in favor of the base of slightly northeast-dipping, lower Paleozoic strata that strike southeastward across central Arizona. In other words, the boundary is based more upon a concept of relatively undeformed, erosional remnants than it is upon distinctive physiographic features. For this reason, the line is impractical; this is also probably why this scheme has not found general acceptance.

Hayes (1969, p. 36) suggested a more radical version. Although he subdivided the two major provinces into sections, he drew the basic boundary further south than did previous workers (Figure 3). This particular line, regardless of how the subdivisions are designated, is more natural than most; and, at least from central Arizona to the northwest, it is a sound geologic boundary because it is a logical southward continuation of the Grand Wash Cliffs structural trend. Hayes utilized the classic "Mogollon Rim" only as a section boundary within the Plateau. Northwest of the Verde region, this section boundary is dashed and follows some of the lower Paleozoic cliff segments; it does not follow the true geomorphic escarpment to its natural conclusion at the Grand Wash Cliffs. Hayes's scheme places most of the Mountain region of central Arizona within his "Tonto section" of the Plateau Province. His concern is in structure, and not in the surficial manifestations of the Plateau.

Wilson and Moore (1959, p. 90) were the first to formalize the concept of "transition" in central Arizona by defining a "Transition Zone" (Figure 3). They recognized that a sharp boundary between the major provinces prevails in northwestern Arizona (Grand Wash Cliffs), but doesn't prevail in central Arizona. Their Transition Zone delineates a small area south of the Mogollon Escarpment, wherein "the strata" tend to be relatively flat. The north boundary is, in part, the "Mogollon Rim," and the south boundary tends to follow the erosional pinch-out of the base of Paleozoic strata. It is this south boundary of Wilson and Moore that Heindl and Lance (1960) focused upon in designing their scheme. As already suggested, this south boundary seems, fundamentally, to be without significant geologic merit as a physiographic province boundary.

The only satisfactory approach to this central Arizona boundary problem seems to be the designation of an expanded region of transition. In general, much of central Arizona is mountainous and is commonly called the Central Mountain Belt. A word like "transition," however, has the advantage of being noncommital with regard to a particular topographic style. The region of transition might contain relatively shallow fault-bounded basins, small plateaus, mountains, nearly flat-lying strata, various types of ore deposits, etc.

The scheme that I suggest, like all the others mentioned,

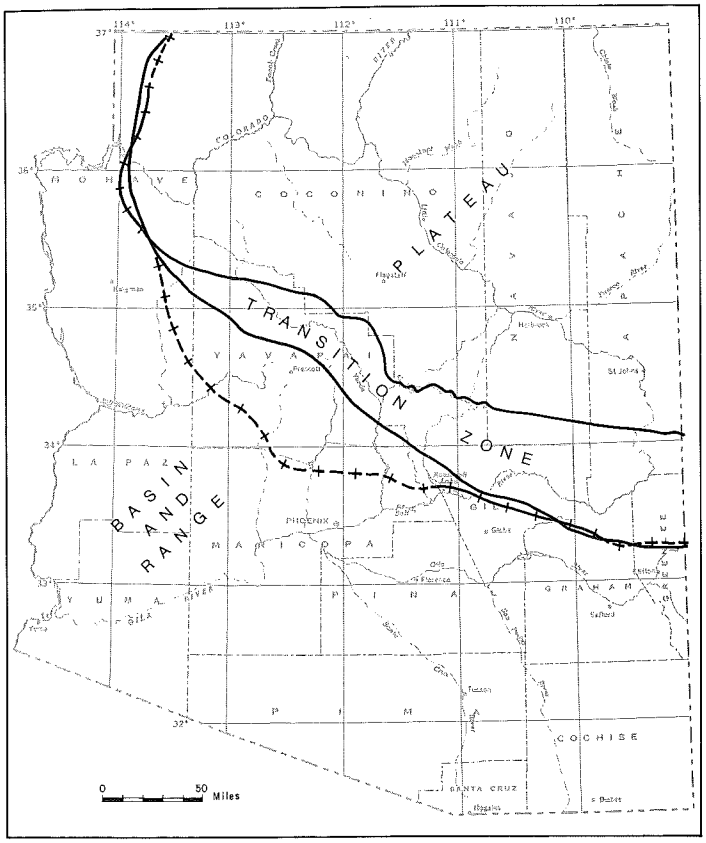

Figure 3. PHYSIOGRAPHIC SUBDIVISIONS OF ARIZONA BY WILSON AND MOORE (1959), HEINDL AND LANCE (1960), AND HAYES (1969).

Wilson and Moore (1959). Two solid lines create three subdivisions: (1) Plateau; (2) Transition Zone; and (3) Basin and Range. One solid line in northwestern Arizona eliminates Transition Zone at Grand Wash Cliffs.

Heindl and Lance (1960). Westernmost and southernmost plain lines of Wilson and Moore (1959) called boundary between Plateau Province and Basin and Range Province.

Hayes (1969). One line with crosses creates two subdivisions: (1) Colorado Plateau; and (2) Basin and Range.

recognizes one sharp structural boundary — north of the Grand Canyon — that separates the Plateau Province and the Basin and Range Province. The northern boundary of the Transition Zone follows the Aubrey Cliffs of Gilbert (1875), the Mogollon Rim of Peirce and others (1979), or the Kaibab scarp of Young (1979, 1982). The southern boundary of the Transition Zone (northern boundary of the Basin and Range Province) follows Hayes's (1969) boundary between the provinces, with some modifications in eastern Arizona.

I anticipate that the greatest controversy about this boundary delineation will result from the placing of the Hualapai Plateau and the last 80-mile leg of the Grand Canyon in the Transition Zone, and not in the Plateau proper. This, however, is but a small segment within the overall scheme; to create an exception for it would compromise the logic that leads to its inclusion within the Transition Zone.

The Mogollon Escarpment, south of which the upper Paleozoic cliffmakers are absent, marks the beginning of a relatively rapid structural rise to the south, which resulted in the erosional removal of the entire Paleozoic section and an unknown amount of Precambrian crystalline rock. Preserved remnants of probable Eocene Rim gravel, containing boulder-sized clasts of Precambrian rocks, occur along the Apache, Verde, and Aubrey segments. Relative to this gravel, the escarpment marks a depositional area, south of which the structure once rose comparatively rapidly into mountainous source-terrain of unknown heights. The Mogollon Escarpment is, therefore, more than just a receding escarpment of a planar plateau that once extended a full complement of Paleozoic rocks an indefinite distance to the south. Subsequent structural reversal within the Transition Zone (Peirce, unpublished work), including the Hualapai Plateau (Young, 1982), is another factor that suggests that the region herein designated as the Transition Zone has been less structurally stable than has the adjacent Plateau Province. The Mogollon Escarpment, therefore, marks the approximate position of a structural hinge. The Transition Zone, in the scheme that I suggest, includes the country south of the Permian cliffmakers that is covered by lower Paleozoic strata commonly assigned to the Plateau Province of other workers.

All told, the variable and complex topography south of the Mogollon Escarpment is the sum of a complex geologic history that has yet to be deciphered in detail, a history unrecorded in the Plateau proper. There seems to be little merit in attempting to delineate a single-line boundary between the Colorado Plateau Province and the Basin and Range Province in central Arizona. It is my opinion, however, that the Mogollon Escarpment is a definable geologic feature that is as well-suited as any for use as a boundary between the Colorado Plateau physiographic province and an expanded, central-Arizona zone-of-transition. The dominant structural change occurs between the Transition Zone and the Basin and Range Province south of the mouth of the Grand Canyon; and between the Colorado Plateau Province and the Basin and Range Province north of the Grand Canyon (Figure 1).

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As most of you already know, the *Fieldnotes* mailing list has recently been updated. The list has primarily been compiled from information that readers provided on the forms that appeared in the Fall 1983 and Winter 1983 issues. Because the blank form appeared in two issues, some of you may have sent in two forms to guarantee a place on our mailing list. We, in turn, may have inadvertently added your name twice. If you are receiving two or more copies of *Fieldnotes*, but one would suffice, please send us the mailing labels from *all* copies, so that we can eliminate the superfluous entries and retain the most accurate entry. This "trimming of the fat" will help us to maintain the free-subscription status of *Fieldnotes.*

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PUBLICATIONS

Geologic Map of Arizona (Map 13), E.D. Wilson and others, 1969 (reprinted 1984), scale 1:500,000. Limited supply available from the Bureau. ($6.60, plus $2.00 for shipping and handling.)

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