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Breccia pipe and geologic map of the southwestern Hualapai Indian Reservation and vicinity, Arizona

by

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INTRODUCTION

The map area encompasses approximately 420 sq mi of the southwestern part of the Hualapai Indian Reservation, along with minor amounts of Bureau of Land Management, State land and some private land that border the southwestern Reservation boundary. The map area lies within that part of the southwestern Colorado Plateau physiographic province that is dissected by the Colorado River where the river has created the western Grand Canyon and its system of plateaus and tributary canyons. All of the map area is within Mohave County, Arizona and most lies on the Hualapai Plateau (fig. 1).

The Colorado River of the Grand Canyon separates the Hualapai Plateau from the Sanup and Shivwits Plateaus (north of the river); it is bounded on the south and west by the Music Mountains, and by Peach Springs canyon on the east. The Hualapai Plateau is an irregular-shaped plateau of low relief; it is dissected by several deep tributary canyons to the Colorado River, most notably, Spencer, Meriwhitica, Milkweed, Peach Springs and Quartermaster canyons (fig. 2). The Music Mountains are bounded on the west by the Grand Wash Cliffs (visible on the western edge of the map), and mark the physiographic break between the Colorado Plateau and the Basin and Range provinces.

Elevations of the map area range from about 1,400 ft at the mouth of Travertine Canyon (northeast corner of map) to 6,697 ft in the Music Mountains (northwest edge of map), a maximum relief of about 5,300 ft. The average elevation of the Hualapai Plateau is about 5,000 ft.

The Hualapai Plateau is underlain by nearly horizontally bedded Paleozoic rocks that have a regional dip of about 2° to the northeast. The Paleozoic rocks have been eroded below the base of the Mississippian Redwall Limestone throughout most of the map area, although the Mississippian and lower Pennsylvanian rocks do cover the north-central and eastern corner.

Thousands of solution-collapse breccia pipes are found on the Hualapai Indian Reservation and adjacent areas in northwestern Arizona (Billingsley and others, 1986; Billingsley and Huntoon, 1983; Huntoon and Billingsley, 1981, 1982; Wenrich and others 1986a, 1987). The breccia pipes are genetically and temporally distinct from more modern karst features also found in the Grand Canyon region: (1) Collapses into space created by dissolution of gypsum within the Permian Kaibab and Toroweap formations, and (2) Collapses resulting from a modern system of caves in any of the Paleozoic carbonate section. The modern collapse features in the second group are referred to here as sinkholes. The breccia pipes originated through collapse of sedimentary strata into dissolution caverns in the Mississippian Redwall Limestone. The initial dissolution cavities in the Redwall were the product of a regionally extensive paleokarst that developed to various depths in the lower Paleozoic carbonate section during late Mississippian time when the Redwall Limestone cropped out as a surface of low relief. The pipes stoped upward from the Redwall through the upper Paleozoic section and into lower Mesozoic strata as additional space was created through dissolution of limestone and carbonate cement of wall rocks and downdropped clasts. A typical breccia pipe in the Grand Canyon region is approximately 300 feet in diameter and extends upward as much as 2,000 feet. The stoping process brecciated the rock, resulting in a breccia core between pipe walls that generally abut against horizontally bedded, undisturbed strata (Wenrich and others, 1986b; Van Gosen and Wenrich, 1989). The breccia pipes were formed prior to 200 Ma, the U-Pb age

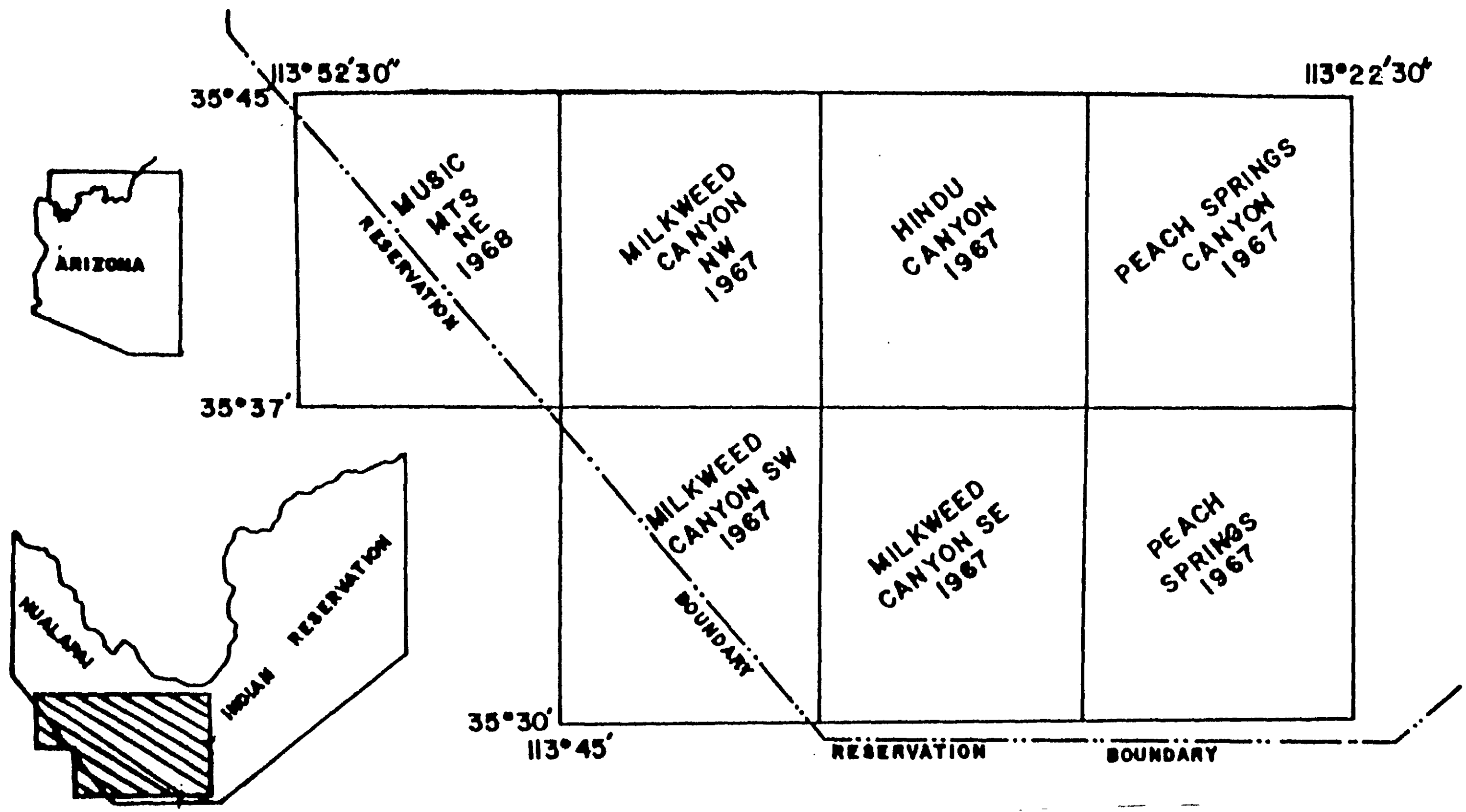


Figure 1--Location map of quadrangles mapped for the southeastern Hualapai Indian Reservation, Arizona (all quadrangles are 7-1/2 minute scale, 1:24,000.

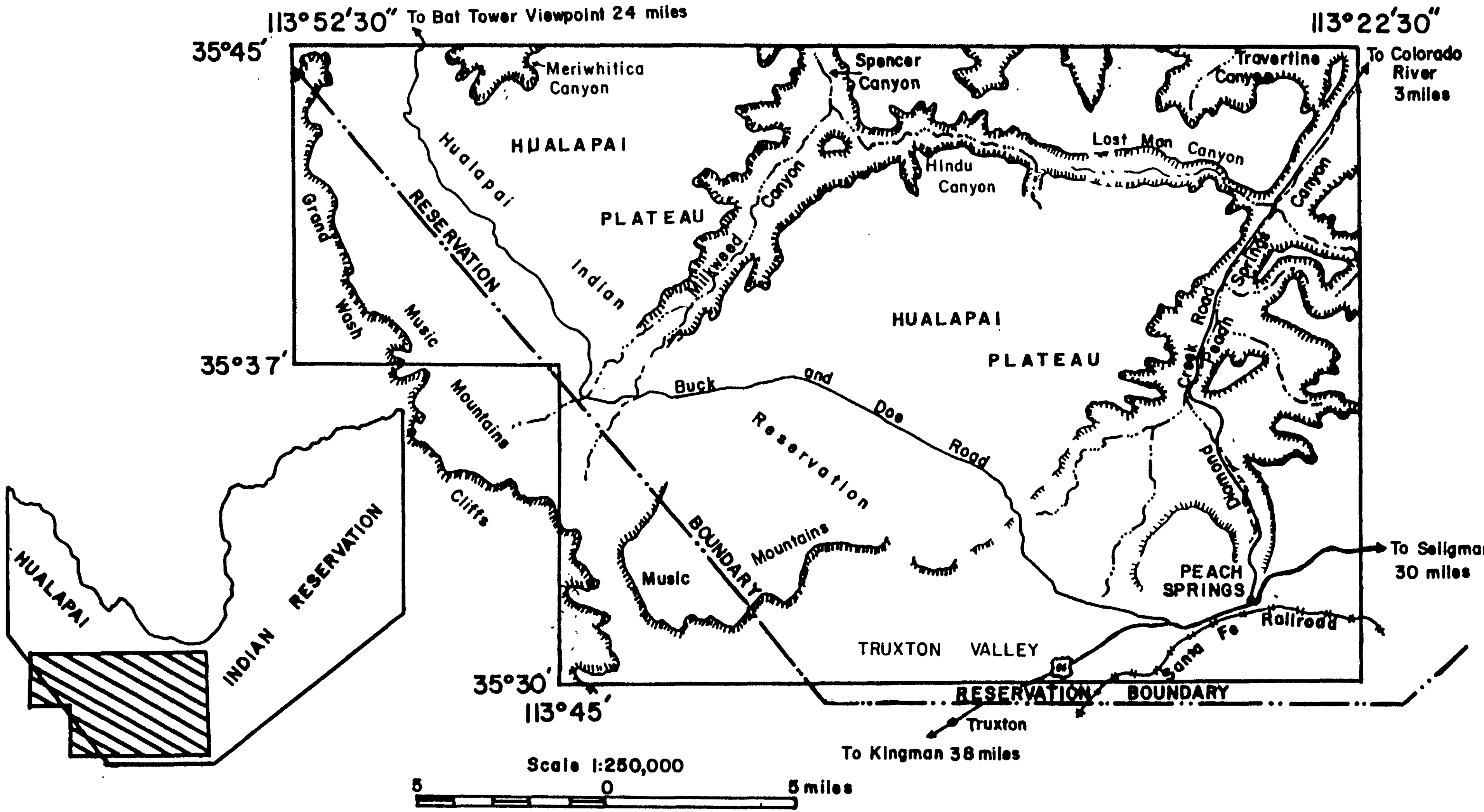


Figure 2--Geographic map of the southwestern part of the Hualapai Indian Reservation, Arizona.

determination (Ludwig and Simmons, 1988) on uraninite from orebodies within several of these breccia pipes. Some breccia cores are overlain by unbrecciated, infolded strata--referred to here as a collapse feature because from the plateau surface it is rarely possible to determine whether this collapse is due to an underlying breccia pipe or to the more modern, shallow-rooted, dissolution.

A significant number of the pipes in the Grand Canyon region contain U-mineralized rock, as well as anomalous concentrations of Ag, Co, Cu, Mo, Ni, Pb, and Zn. On the Hualapai Reservation, 857 confirmed and suspected breccia pipes have been mapped; of these approximately 8% show surface expression of mineralized rock, either recognizable Cu-bearing minerals (most notably malachite, azurite, or brochantite) or gamma radiation in excess of 2.5 times background.

Despite periods of depressed uranium prices, the breccia pipes have commanded considerable exploration activity in the 1980's because of their high-grade uranium deposits. Mining activity in breccia pipes of the Grand Canyon region of northern Arizona began during the nineteenth century, although at that time production was primarily for Cu with minor production of Ag, Pb, and Zn. It was not until 1951 that uranium was first recognized in the breccia pipes. During the period 1956-1969, the Orphan mine yielded 4.26 million lb of U_3O_8 (Chenoweth, 1986). In addition to uranium, 6.68 million lb of Cu, 107,000 oz of Ag, and 3400 lb of V_2O_5 were recovered from the ore (Chenoweth, 1986). Between 1980-1986 four breccia pipes were mined for uranium in northern Arizona with an average grade of 0.65% U_3O_8 (Mathisen, 1987) and production ranging from 1-7 million lbs of U_3O_8 per pipe (I.W. Mathisen, personal communication, 1988).

On the southwest part of the reservation (this map) only 66 confirmed and suspected breccia pipes and 2 sink holes have been mapped. Only 7 of these emitted gamma radiation in excess of 2.5 times background and no Cu-bearing minerals were observed. Because breccia pipes bottom in the Redwall Limestone the sparcity of pipes on this part of the reservation can be attributed to the erosion below the base of the Redwall Limestone of most of this part of the Hualapai Plateau. Consequently, the economic potential for uranium-rich orebodies on this part of the Hualapai Reservation is poor.

This report includes two plates, one showing the geology and breccia pipes/collapse features (plate 1), and the other showing only the breccia pipes/collapse features, their respective pipe number, and category (plate 2). All pipes in the mineralized category were sampled, and petrographic, mineralogic, and geochemical studies are in progress. Initial mapping of the pipes and sinkholes was done on 1:24,000 color aerial photographs. Each feature mapped was surveyed by helicopter or 4-wheel drive vehicle. Only where breccia was observed has the feature been referred to as a "breccia pipe"; all others are referred to as collapse features because shallow-rooted dissolution could not be eliminated as their genesis. The boundaries of all breccia pipes/collapse features on this map have been accurately mapped to scale (plate 2). Radiometric traverses were made across all but a few of the pipes/collapse features and sinkholes. Pipes/collapse features not field checked are in the Redwall Limestone and have little economic potential.

This research was funded by the Bureau of Indian Affairs in cooperation with the Hualapai Tribe in the hope that it would stimulate mining interest on Hualapai lands and would result in additional income for the Hualapai people. The entire 1,550 sq mi Hualapai Reservation has been mapped geologically at a scale of 1:48,000 and divided into 4 separate map areas: northeast (Wenrich and others, 1986a), southeast (Billingsley and others, 1986), northwest (Wenrich and others, 1987), and southwest (this map).

GEOLOGIC SETTING

The oldest exposed rocks in the map area are Precambrian granites, schists, and gneisses that crop out in Milkweed, Travertine, and Peach Springs Canyons and southwest slopes of the Music Mountains (fig. 2). The metamorphic Precambrian rocks are mostly of middle to upper(?) amphibolite facies (Clark, M.D., 1976). Pegmatite dikes also occur, mainly in the Milkweed Canyon area. The Precambrian basement in the Hualapai Plateau area is unconformabably overlain by an eroded Paleozoic section.

Exposed in canyon walls and on the Hualapai Plateau are Paleozoic sandstones, shales, and limestones ranging from Early Cambrian to Late Pennsylvanian in age. The most widely exposed Paleozoic units are the Cambrian, Devonian, and Mississippian rocks which are partly covered by Cenozoic deposits. Strata of Ordovician and Silurian age are not present in the area. Their anticipated position in the section is marked by a regional disconformity that separates rocks of Cambrian and Devonian age.

The beveled surface of the Hualapai plateau was eroded during and after the Laramide Orogeny (Late Cretaceous to Eocene time, Young, 1985, 1987, 1989). The erosional valleys were partly filled with Tertiary and Quaternary sediments and volcanic rocks. The Cenozoic deposits are informally described by Young (1966, 1970, 1979), Young and Brennan (1974), Gray (1959), and Twenter (1962). The oldest Cenozoic deposits in the map area are the Music Mountain Conglomerate and Hindu Fanglomerate of Young (1966, p. 24). Along with the Westwater Formation and the Buck and Doe Conglomerate (Young, 1966, p. 28) these deposits occupy the floors of eroded Tertiary valleys in Milkweed, Hindu, Lost Man, and Peach Springs Canyons (fig. 2). All of these Cenozoic sediments are mapped here as undivided Tertiary sediments (Paleocene? to Miocene).

Deposits overlying the volcanic rocks are considered to be Middle Miocene, Pliocene, and younger (Young, 1966, 1989; Twenter, 1962). These extensive gravel deposits contain mixed Precambrian, Paleozoic, and local volcanic clasts from reworking of older gravel deposits and local erosion of Paleozoic strata. These deposits are locally found in abandoned tributary drainages, as well as blanketing divides on the Hualapai Plateau, and are widespread between Milkweed and Peach Springs Canyons (Willow Springs Formation of Young, 1966).

Where detailed stratigraphy is clearly exposed in eastern tributaries to Peach Springs Canyon (Young, 1966; Young and Brennan, 1974) the basal conglomerates (pre-Miocene) appear to be correlative with the Robbers Roost and Frazier Wells Gravels located east of the map area (described by Koons, 1948, 1964; Billingsley and others, 1986). These two units are similar in lithology to the pre-Miocene conglomerates on the Hualapai Plateau.

A rhyolite tuff in Peach Springs Canyon was dated at 18.3 Ma (Middle Miocene) by Damon (1966, p. 28), and was named the Peach Springs Tuff by Young and Brennan (1974, p. 84). The tuff is sandwiched between basalt flows in Milkweed, Peach Springs, and upper Meriwhitica Canyons. Other isolated basalt flows are not in contact with the tuff. The Peach Springs Tuff is combined with overlying and underlying basalt flows and all are mapped as Tertiary volcanic deposits undivided. Most, if not all of the volcanic deposits overlie the Tertiary "undivided sediments" in this report.

STRUCTURAL GEOLOGY

Tectonic Overview

The tectonic history of the southwestern part of the Colorado Plateau can be subdivided into five broad episodes: (1) The Precambrian interval involved a complex succession of crustal accretion, subsidence and sedimentation, and finally uplift accompanied by extensional tectonism that produced a deeply eroded metamorphic complex. (2) Paleozoic through Cretaceous time was characterized by about 8,000 to 13,000 feet of net regional subsidence and comparable sediment aggradation. (3) The Laramide orogeny, herein used to include Late Cretaceous through Eocene events, resulted in north-northeast crustal compression and regional uplift, which was accompanied by widespread erosion. (4) Regional uplift, erosion, and widespread deposition continued after the Laramide orogeny, but the tectonic regime was transformed in Miocene time into one of east-west regional extension. (5) Erosion has produced the modern Grand Canyon during the past five million years. The dramatic topographic relief associated with the Grand Canyon led to the development of localized gravity tectonic features including large landslides, localized gravity-glide detachments, and valley anticlines.

The Hualapai Reservation contains a remarkable record of reactivated faulting caused by successive stress regimes imposed on the crust. Large displacement, north-, northeast-, and northwest-trending normal faults with offsets measured in thousands of feet dominated the late Precambrian structural setting in the region. The Paleozoic and younger rocks are deformed by superimposed Laramide monoclines that are cored by reverse faults, as well as Late Cenozoic normal faults. The Laramide monoclines are crustal-shortening features that generally overlie re-activated Precambrian normal faults; the sense of motion was reversed on these faults during Laramide compression. The principal Late Cenozoic normal faults also followed reactivated Precambrian trends (Walcott, 1890: Huntoon, 1974); however, east-west extension in the region has also produced many new normal faults and complexities in pre-existing fault zones. Normal faulting has continued in the region until very recently and has resulted in the development of extensional basins, mainly to the east of this map area. Faulted Quaternary alluvium and Miocene volcanic rocks are common along the Hurricane and Toroweap faults in the eastern part of the Hualapai Reservation.

Cenozoic Uplift and Erosion

No tectonic activity in the Hualapai Reservation since the close of Precambrian time has been as great as the regional uplift that took place during Late Cretaceous and early Cenozoic time. Vertical uplift along the southwestern margin of the plateau has been between 2 and 3 miles since Cretaceous sedimentation ceased. More than 3,000 feet of uplift at the Grand Wash Cliffs near Lake Mead may have occurred in the last 5 million years (Lucchitta, 1979). Individual offsets along the largest faults and monoclines within the plateau are spatially restricted and relatively modest in comparison.

The primary result of the uplift has been erosion. It is possible that a minimum of a mile of rock was stripped from the surface of the Hualapai Plateau during Laramide (Late Cretaceous-Eocene) time. Drainage then was toward the northeast across what is now the Colorado Plateau margin (Young, 1982, 1985). The large volumes of Cretaceous(?) or older rocks eroded from the region between Late Cretaceous and Oligocene time were transported northeastward across the Hualapai Reservation into Utah by a system of pre-Colorado River streams incised on the Hualapai Plateau but shallowing to the north (Young, 1982, 1987).

As extensional stresses supplanted compression following Laramide orogenesis, the southwestern margin of the Colorado Plateau became topographically and structurally differentiated from the Basin and Range Province to the south and west (Young and Brennan, 1974; Young, 1987). Northward drainage had been completely severed or buried by Miocene time. The westward draining Colorado River became entrenched through the area in Pliocene(?) time (Young and Brennan, 1974; Young, 1989). Continued uplift of the region probably resulted in the excavation of the Grand Canyon by the Colorado River to a depth of 3,500 ft below the surface of the Hualapai Plateau by the end of Pliocene time.

Laramide Monoclines

The Laramide monoclines developed in response to a stress regime in which the maximum principal stress was horizontal and oriented east-northeast (Reches, 1978). The compression resulted in minor crustal shortening through a series of east-dipping monoclines having sinuous, but generally northerly trends (Davis, 1978). The principal monocline in the map area is the Meriwhitica monocline (Huntoon, 1981). Laramide offset across this fold was down to the east, a maximum of about 1,000 ft. Most segments of the monoclines developed over single, reactivated, west-dipping Precambrian faults. As reverse motion occurred along the basement faults, the faults propagated variable distances upward into the Paleozoic section as the Paleozoic sediments simultaneously folded forming the monocline. Well-exposed outcrops of underlying basement rocks along the Meriwhitica monocline in Milkweed Canyon have provided evidence for horizontal compression as the causative mechanism for emplacement of Laramide monoclines in the Grand Canyon region (Huntoon, 1981). Typical monocline geometry is shown on Figure 3. The anticlinal and synclinal fold axes within the Paleozoic strata converge with depth on the underlying fault. The Paleozoic sediments become more steeply folded with depth and are overturned against the fault at the base of the Paleozoic section.

The sinuosity of the monoclines results from selective reactivation of different segments of Precambrian faults, where the dip and strike of the reactivated segment was favorably oriented to accommodate Laramide strain in the basement rocks (Huntoon, 1981). Abrupt changes in strike and branching of monoclines reveals the locations of intersecting Precambrian faults in the underlying basement.

The southern termini of the east-dipping Meriwhitica, Horse Flat, and Hurricane monoclines occur in this map area (see Plate 1). The Hurricane monocline does not occur in Peach Springs Canyon, having died out immediately to the north of this map. Minor eastward dips found in the southernmost Paleozoic exposures along the west wall in Peach Springs Canyon may have developed in response to subsidence associated with Late Tertiary extension across the Hurricane fault. However, it is also possible that the "up-to-the west" sense of displacement along the older monocline may have continued southward along the present fault zone (without folding) where the Paleozoic

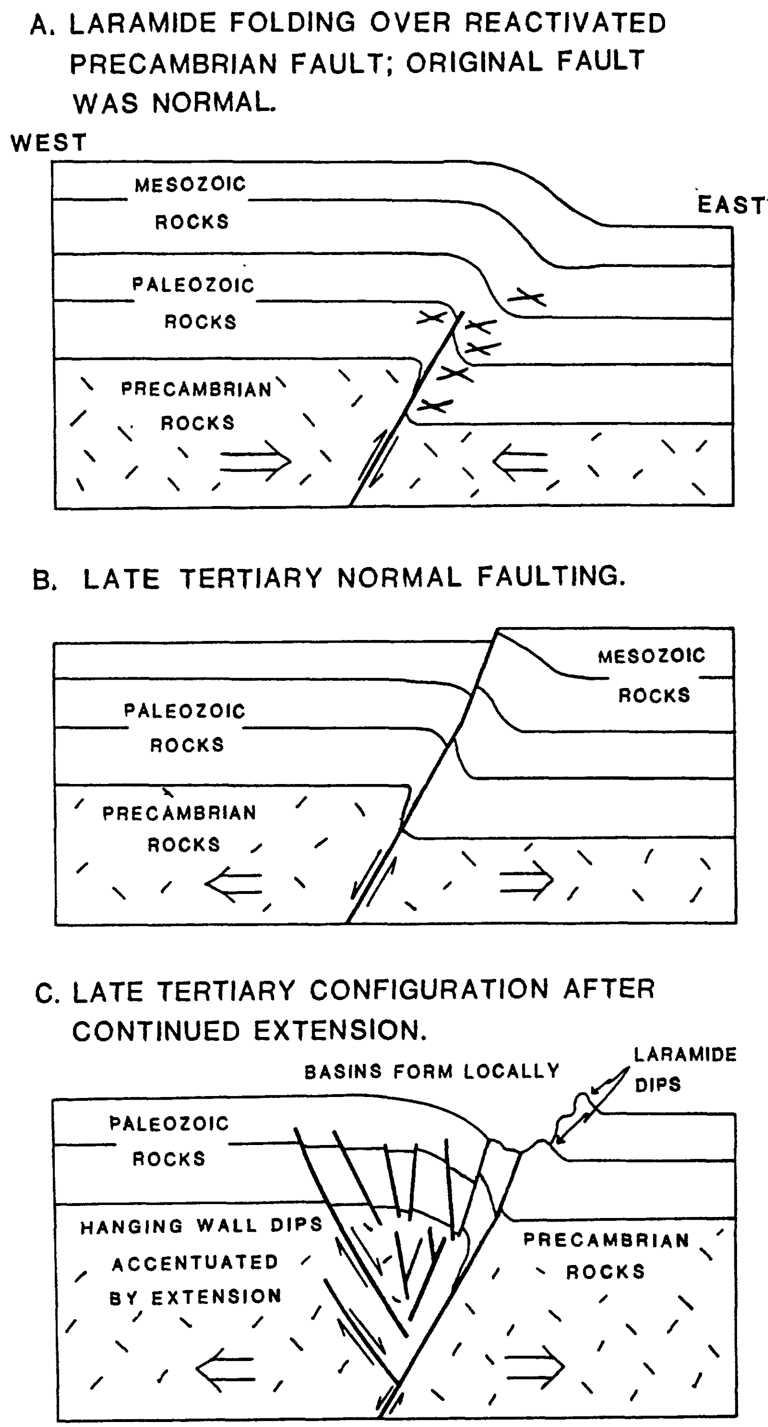


Figure 3--Structural cartoon of a cross-section showing the stages in the development of a typical western Grand Canyon monocline (such as along the Hurricane Fault Zone), Arizona. Small crosses in figure 3a are low angle conjugate thrust faults. Notice on Plate 1 that the Hurricane monocline does not extend from the north into this map area, but was apparently eroded or not emplaced (Huntoon, 1989, p. 80).

rocks have been thinned by erosion.

The west-trending segment of the Meriwhitica fold that lies to the west of Milkweed Canyon links two north-striking, high-angle, west-dipping, Precambrian faults that were reactivated during the Laramide. The linking, west-trending segment was not underlain by a pre-existing Precambrian fault, so the Laramide fault that developed under this segment caused deformation of previously unfaulted basement rocks. The result was a 30-degree west-dipping thrust fault in the basement rocks. The dip of this fault, coupled with numerous nearby small-scale conjugate thrust faults in both the Precambrian and Paleozoic sections, was used by Huntoon (1981) to deduce a horizontal orientation for the maximum principal stress tensors during monoclinal emplacement.

Young (1979, p. 34) makes a case for recurrent Eocene(?) deformation along the Meriwhitica monocline and at Peach Springs (also see fission track ages of Naeser et al., 1989). He described lacustrine limestones in a Laramide paleocanyon, presently being reexcavated as Milkweed Canyon, where the limestone facies are restricted to the upthrown blocks upstream from the anticlinal axes of the monoclines. He concluded that renewed folding or tilting caused the anticlinal hinges to rise sufficiently to pond water in the channel on the hanging wall blocks. If this interpretation is valid, these Eocene(?) limestones record the latest episode of monoclinal deformation known in the Grand Canyon region.

The Cenozoic rocks which bury the Paleozoic rocks in Truxton Valley south of Peach Springs Canyon obscure evidence for a southwestern segment of the Hurricane monocline. Such a fold might exist under the Cenozoic rocks in Truxton Valley (fig. 2). Truxton Valley is a broad, early Tertiary, erosional embayment along the largest valley eroded through the margin of the Colorado Plateau and continuing into Peach Springs Canyon (Young and Brennan, 1974). Erosion of this magnitude implies the presence of a structurally weak zone in early Tertiary time, such as a Laramide fault or monocline. Unfortunately insufficient data is available from the drillholes that have penetrated deep enough in Truxton Valley to verify the nature of the existing structural relations. A collinear Precambrian fault structure reappears from under Tertiary gravels at the south edge of the Truxton Valley (Beard, 1985).

Late Cenozoic Faulting

A horizontal, east-west, extensional-tectonic-stress regime was imposed on the southwestern Colorado Plateau following Laramide compression. Minor Cenozoic faulting on the Hualapai Plateau in the map area appears to have commenced after deposition of the Miocene Peach Springs Tuff because offsets of the tuff are essentially the same as offsets of the underlying Paleozoic rocks along the faults in areas to the east of this map. Extension resulted in normal faulting within the plateau, and tectonic differentiation of the plateau from the adjacent Basin and Range Province to the south and west.

Hurricane Fault Zone

An extensive record of recurrent movement exists along the Hurricane fault zone, summarized as (1) Precambrian normal faulting of unknown complexity, (2) probable minor hinging of the fault zone during regional Paleozoic and Mesozoic subsidence and sedimentation, (3) Laramide reverse faulting to produce the east-dipping Hurricane monocline north of this map area, and (4) late Cenozoic recurrent, west-down normal faulting. Much of the evidence for these events occurs north of this map area. However early Tertiary arkoses (Young, 1982, 1987, 1989) and the Miocene Peach Springs Tuff (Young and Brennan, 1974) are faulted in Peach Springs Canyon with displacements apparently equal to those of the underlying Paleozoic rocks. These outcrop relationships appear to imply that Tertiary extension across the Hurricane fault took place entirely after deposition of the Peach Springs Tuff in this region. Exposures of the Hurricane fault in Precambrian basement rocks along the Colorado River immediately north of this map reveal that the Tertiary normal displacement resulted from reactivation of a pre-existing Precambrian fault. Late Cenozoic displacement, west-down, across the Hurricane fault diminishes from almost 1,000 feet to less than 200 feet from north to south across this map.

EARLY TERTIARY PALEOGEOGRAPHIC RECONSTRUCTIONS

North-draining pre-Colorado River paleocanyons are well preserved in several locations from the level of the Laramide erosion surface, which is bevelled across the Redwall Limestone and older carbonate units in this map area, down into the Precambrian rocks. The drainages are partially filled by remnants of formerly more extensive Laramide and post-Laramide sedimentary and volcanic deposits (Young, 1966, 1982, 1989). The earliest of these deposits is a series of deeply weathered arkoses containing Precambrian clasts derived from sources to the south and west of the present edge of the Colorado Plateau. These distinctive red arkoses are characterized by pebble imbrications that reveal contemporaneous northward flow in the major Laramide canyons.

The longest and most prominent of the paleocanyons on this map is a channel that strikes northeast-southwest through Milkweed, Hindu, and Lost Man canyons to a point where it joins Peach Springs Canyon as a hanging valley (fig. 2). A similar deeply incised channel, which formerly drained the area south of Truxton Valley, is best preserved in two prominent re-excavated meander loops on the east side of Peach Springs Canyon. The youngest(?) paleocanyon is Peach Springs Canyon wherein remnants of the early Tertiary arkoses are found at present stream levels on both the downthrown and upthrown blocks of the Hurricane fault. The variable elevations of the Laramide arkoses, and record of abandonment of canyons and meander cutoffs, reveal a long and complex record of incision and sedimentation during and following Laramide uplift in the region, possibly associated with reversals of movement along the Hurricane fault.

In order for such streams to flow northward through Peach Springs Canyon, the regional dip in early Tertiary time had to be between 1/2 and 1 degree greater than at present in order for the stream to clear the north rim of the Grand Canyon (Young and Brennan, 1974). It is implied from the linearity of Peach Springs Canyon (paralleling the Hurricane fault) that fractures existed along the strike of the canyon, despite the fact that the Hurricane monocline was not strongly developed in this reach and there is no evidence preserved for early Tertiary displacement along the Hurricane fault. The record of recurrent tectonism along the Hurricane fault provides a ready but hypothetical solution to this dilemma. The Precambrian Hurricane fault probably served as a structural hinge between the blocks that it separates. Minor flexing across this hinge in Laramide and pre-Laramide time would readily increase joint densities in the Paleozoic rocks but not necessarily cause measurable displacements. As Peach Springs Canyon eroded in late

Laramide time, the increased jointing along the Hurricane lineament allowed for the alignment of drainage along Peach Springs Canyon. Although speculative, this scenario is viable based on known Laramide monoclinal folding along the zone to the north, and erosion of the Truxton embayment to the south in early Tertiary time, both of which reveal the presence of probable fracturing and subsequent erosion along the zone at those locations.

During Laramide time, the Mogollon Rim -- defined as the erosional escarpment comprised of cliffs developed in the Permian section (Pierce, 1984),--occupied a position to the north of this map area approximately along or slightly north of the present canyon of the Colorado River. The escarpment was breached to the northeast by the early Tertiary drainage system. Apparent back tilting of the Colorado Plateau, down to the southwest, during Late Oligocene or Miocene time, and tectonic differentiation between the Colorado Plateau and Basin-Range provinces in Miocene time, apparently led to the abandonment of the early Tertiary channels. The westward flowing Colorado River system became established here in the beginning of Pliocene time (Young and Brennan, 1974).

BRECCIA PIPES

Introduction

The southwestern part of the Hualapai Reservation contains few breccia pipes relative to other parts of the Reservation. This map contains only 66 breccia pipes and collapse features in contrast to 224 on the northwest map (Wenrich and others, 1987), 218 on the southeast map (Billingsley and others, 1986), and 347 on the northeast map (Wenrich, Billingsley, and Huntoon, 1986) for a total of 857 breccia pipes and collapse features mapped on the Hualapai Reservation. The paucity of pipes in the southwestern map area can be attributed to the depth of erosion of the Hualapai Plateau. As can be seen on Plate 1, most of the Redwall Limestone, in which the breccia pipes bottom, has been stripped from the Plateau surface. Remnants of the Mississippian Redwall Limestone and overlying Surprise Canyon, along with Lower Pennsylvanian Supai Group formations, are found only in the northern part of this map, where the 66 breccia pipe/collapse features cluster.

Although rock exposure is excellent on the Hualapai Plateau, the massive bedding of the Redwall Limestone makes it difficult to recognize the inward-dipping beds that reveal collapse features. Thus, some breccia pipes/collapse features may remain unmapped. In addition to the 66 breccia pipe/collapse features, there are 2 sink holes within the map area--one is exposed in the Devonian Temple Butte Formation and the other in the Cambrian Muav Limestone. They are both less than 50 feet in diameter, are bounded by vertical walls, contain angular blocks of rubble on their floors, and therefore, are believed to be recent.

Of the 66 collapse features on this map 7 emit surface gamma radiation in excess of 2.5 times background. No surface exposure of copper, lead, or zinc minerals was observed in any feature found on the Hualapai Plateau. Detailed discussions on the general mineralogy, geochemistry, and origin of the breccia pipes can be found in Wenrich (1985, 1986) and Wenrich and Sutphin (1989). Further breccia pipes discussions in this report will be restricted to those pertinent to the southwestern portion of the Hualapai Reservation.

All 66 breccia pipe/collapse features are located in formations older than the Permian, and are therefore clearly not related to the gypsum collapses located within the Permian Toroweap and Kaibab formations (such gypsum collapses are discussed in Wenrich, Billingsley, and Van Gosen, 1986). With the exception of 3 of the 66 features (discussed below), they are by our definition breccia pipes because they bottom in the Redwall Limestone. Nevertheless, we have retained the terminology applied to the other maps and refer to those without exposed breccia as collapse features. All mapped circular features have been placed into categories based on physical characteristics (see the collapse feature explanation on Plate 2) such as: (1) the presence of concentrically inward-dipping beds, (2) altered rocks (specifically, bleached and limonite-stained), (3) brecciated rock, (4) mineralized rock, and (5) circular vegetal or topographic anomalies. Clasts ranging in size from millimeters to boulders, inbedded within a fine grained sandstone matrix, comprise the brecciated rock; the clasts are always rock that has been dropped from an overlying stratigraphic horizon. Because the breccia pipes have probably undergone considerable flushing by ground water solutions and/or brines, the matrix is generally comprised of finely disaggregated sand grains recemented with minor carbonate cement.

Delineating the exact outline of the breccia pipe in the field is difficult unless the breccia column itself is exposed. Such exposure is not uncommon along the cliffs of the Grand Canyon and its tributaries, but is rare on the adjacent plateaus. Because the brecciated column of rock within each pipe abuts against generally well-stratified, relatively undeformed sedimentary rock, the plane demarking this contact is referred to here as the ring fracture. More properly, it should be termed the inner ring fracture, as the stratified sedimentary rock surrounding the breccia column commonly contains a series of concentric ring fractures (Verbeek and others, 1988), although these are not as well defined as the inner ring fracture. Because the inner ring fracture is well exposed in less than half of the known collapse features on the Reservation, and in order to be consistent throughout the mapped area, the boundaries of the breccia pipes were mapped as the outermost extent of inward-dipping strata.

Devonian and Cambrian Collapse Features

Although no "breccia pipes" have been observed to extend below the base of the Whitmore Wash Member of the Redwall Limestone, 3 similar looking features were observed in this map area below the Redwall and 15 in the area contained on the northwest map; all lie along the rim of Meriwhitica Canyon. The 3 such collapse features shown on this map are all exposed within the Muav Limestone. Two of these three features, #722 and #724, merely show inward-dipping beds (category C2--plate 2), while the third shows some alteration along with the inward-dipping beds (category C1--plate 2). On the northwest map 7 of the 15 features contain collapse breccia (Wenrich and others, 1987).

Apparently, collapse into Cambrian and Devonian limestone caves did occur, although such collapse must not have been extensive as its occurrence is restricted to the Meriwhitica Canyon area. Unfortunately, in the case of all 18 (3--southwest map and 15--northwest map), the overlying strata have been removed, so whether any upward stoping into the overlying units occurred has not been conclusively determined, although such continued activity is not believed probable by the authors. The timing of these collapses is not known, but they are probably not related to the breccia pipes that host high-grade uranium deposits, because no breccia pipes have been observed to go below the base of the Redwall and no radioactive or mineralized rock has been located in the Cambrian or Devonian limestones.

Mineralized Breccia Pipes:

None of the 7 pipes that have been labeled as mineralized on this map (Plate 2) of the southwestern Hualapai Reservation contain exposed copper, lead, or zinc minerals. All of the pipes mapped as "mineralized" merely contain anomalous gamma radiation, and hence contain above background levels or uarniu. The anomalous gamma radiation reaches 3 times background in black shales of the Surprise Canyon Formation that lie within breccia pipes. Each of these "mineralized" pipes shows some limonite alteration and bleaching of downdropped strata of Watahomigi or Surprise Canyon Formation. The Surprise Canyon rocks generally have a higher background radiation than any other Paleozoic formation in the Grand Canyon area. Thus, these gamma-ray anomalies may be normal where Surprise Canyon rocks occur, although it is difficult to determine what "normal background" is for the Surprise Canyon Formation because it is frequently associated with breccia pipes. Pipe #756 contains large calcite rhombs and travertine in vugs and pipe #777 contains acicular and stalactitic calcite. In addition, #777 also contains abundant carbonaceous material.

These "mineralized" pipes have been stripped of all overlying strata down to the Watahomigi Formation. Hence, these pipes offer little potential for economic uranium deposits because all breccia pipes mined in the Grand Canyon region as of 1990 have their ore within the Permian and upper Pennsylvanian sandstones. In addition, the total volume of rock remaining in these pipes is probably insufficient to provide an economic orebody given the average grade of 0.65% U_3O_8 (Mathisen, 1987) for breccia pipe orebodies.

All of the 7 "mineralized" pipes but one sit along the west rim of Travertine Canyon (fig. 2). Four of these 7 pipes (#770, #771, #777, and #779) contain downdropped Surprise Canyon Formation, and in the other 3 (#756, #776, and # 781) only Watahomigi has been dropped down to the Redwall Limestone level. In pipe #777 the Surprise Canyon blocks have been downdropped at least 80 ft. Geochemical analyses were completed for surface samples collected from each of the "mineralized" pipes, and although many of the pipes emitted gamma radiation three times background at the surface, no sample from the southwestern part of the Hualapai Reservation exceeded 10 ppm uranium. Likewise most other metals that are commonly enriched in breccia pipes were present in low concentratons for all samples collected from these 7 "mineralized" pipes (values listed in ppm): Ag=<2, Cd=<2, Cu=<14, Co=<9, S=<200, and Se=<1. The only elements that show any anomalous values are as follows:

Element	Pipe #756	Pipe #770	Pipe #771	Pipe #779	Pipe #781
As		510 ppm	830 ppm		
Mo	62 ppm				
Ni	44	54	72		
Pb	34				
V		130	200		
Zn		140		130 ppm	150 ppm

Structural Control of Breccia Pipes:

Structural control of breccia pipe locations has been a topic of debate since Sutphin and Wenrich (1983) first suggested that many breccia pipes on the Marble Plateau (located about 100 miles to the east of this map area) were aligned and equally spaced. Wheeler (1986) made a statistical analysis of the pipes and determined that these alignments were indeed real. Nevertheless, such trends have not been obvious in other parts of northwestern Arizona, perhaps in part because of inadequate mapping. However, on the Hualapai Reservation where this map is the final product of detailed breccia pipe mapping, the NW and NE alignments of Sutphin and Wenrich (1983) were seldomly observed.

No obvious correlation exists between the locations or alignments of breccia pipes and the principal faults and folds which deform the Paleozoic host rocks in the map area. However, careful examination of the map reveals that populations of pipes tend to cluster in bands that follow or parallel existing fault trends or prominent lineaments. For example, one particularly strong alignment ("B1" on fig. 4) extends southwestward from Travertine Canyon, to the southeast of the unnamed normal fault with the same strike (plate 1).

A tracing was made from Plate 2 of breccia pipes in the northeastern corner of this map (where most pipes are clustered) to create figure 4a. Whereever 4 or more pipes were aligned, a straight line was drawn through them. Next a line was drawn through any alignment of 3 pipes which was parallel to one of the lines containing 4 pipes. From this process, 4 unique alignments resulted (directions A-D on figure 4a). Next, several lines were drawn parallel to lines D1 and D2 with a spacing between them that is equal to that between D1 and D2. A similar process was used with lines A1, A2, and A3.

Several of the alignments delineated in figure 4a are similar to those on the Marble Plateau (Sutphin and Wenrich, 1983; Sutphin, 1986) in that the pipes along them are equally spaced and some are aligned along northwest (alignments C1-C3) and northeast (alignments D1 and D2) trends. In contrast to these two trends, there are also some obvious E-W alignments of pipes on this map. Two pipe alignments shown on figure 4a are particularly distinctive: (1) the alignment labelled "A1" strikes east-west, directly through 5 breccia pipes that are spaced roughly 1,500 ft, or multiples of 1,500 ft, apart; and (2) Alignment "B1" strikes N55°E through 5 pipes that are spaced 5,500 to 6,000 ft apart. Lines B2 and B3 intersect 3 pipes each and trend parallel to B1. These pipes are also equally spaced. A study of joints in the Redwall Limestone by Roller (1989) showed that the oldest joint set in the Redwall is a N57°E set; this Redwall joint set orientation is remarkably similar to the N55°E "B" alignments.

The second oldest joint set in the Redwall is N55°W (Roller 1989). Lines C1, C2, and C3 (fig. 4a) strike N55°W and go through 4, 5, and 5 pipes respectively. Three other parallel striking lines extend through 9 additional pipes; these along with lines C1-C3 form alignments with equal distance between them. Lines D1 and D2 that strike N42°E, each extend through 5 pipes and are parallel to the Meriwhitica monocline and the faults near Milkweed Canyon. Notice that the series of parallel lines drawn to D1 and D2, with a spacing equal to that between D1 and D2, intersect lines B1, A1, and A2 at breccia pipes localities. Interestingly, the geometry of the intersection of these alignments explains both the 5,500 ft equal spacing of pipes in the A-alignment set and the 1,500 ft equal spacing between pipes on the B-alignment set (fig. 4a).

Although both Roller (1989) and Verbeek and others (1988) show that an E-W fracture set exists in the Redwall and younger strata, Verbeek and others (1988) have proved that it was not active until after the Pennsylvanian and

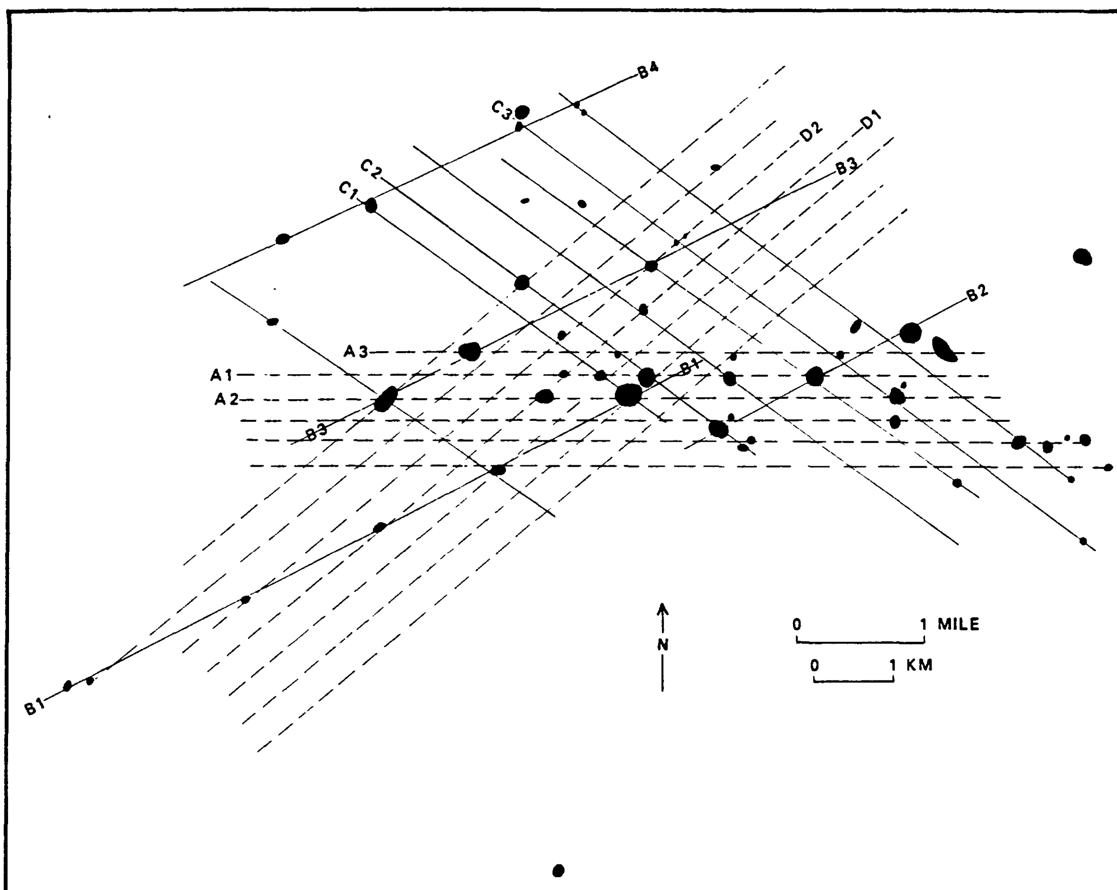


Figure 4a. Breccia pipe alignments in the northeastern corner of the southwestern Hualapai Indian Reservation. Line set A trends E-W, line set B trends N57°E, line set C trends N55°W, and line set D trends N42°E, which is parallel to parts of the Meriwhitica monocline and numerous other faults shown on Plate 1.

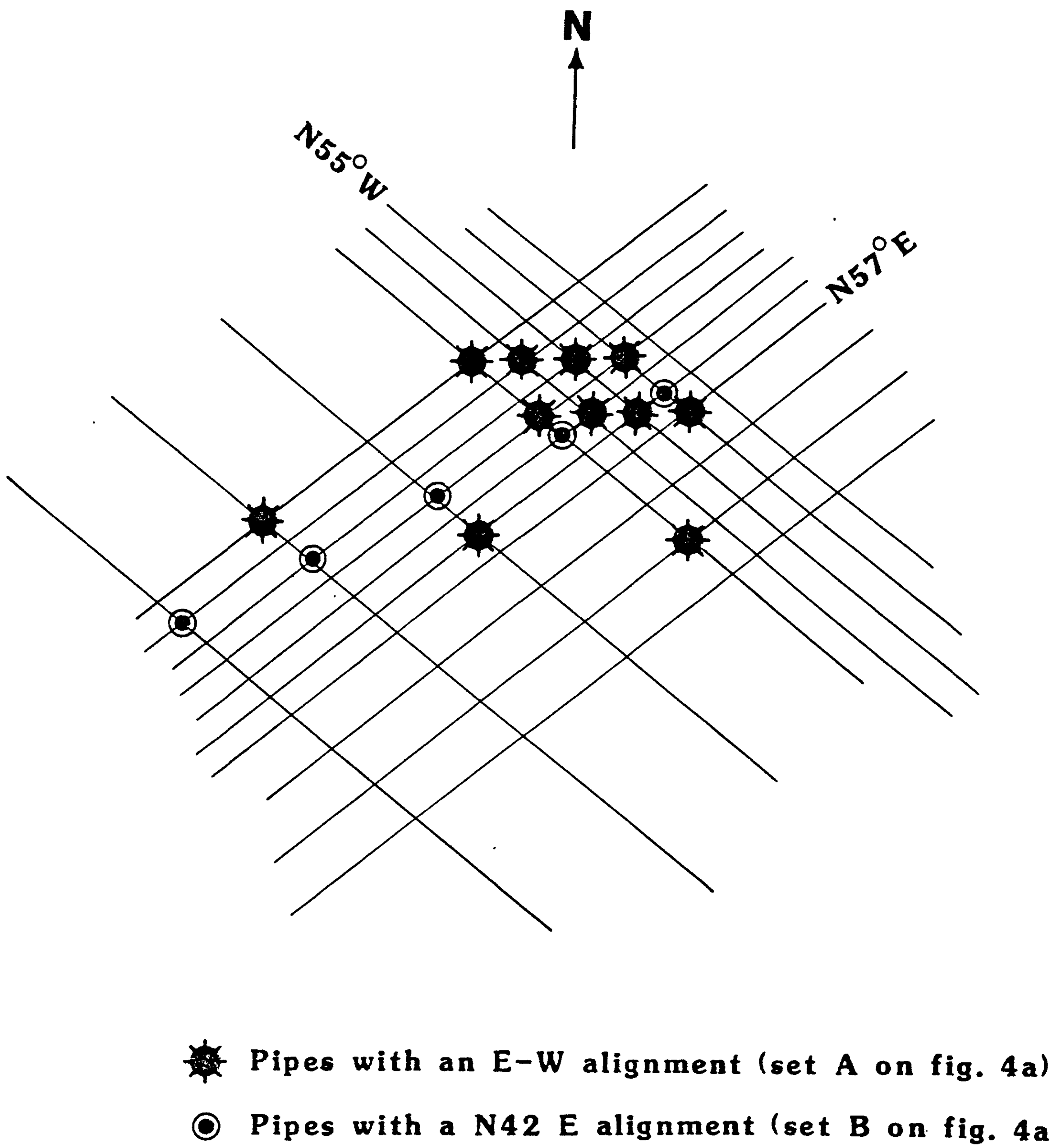


Figure 4b. Cartoon demonstrating that two nearly orthogonal joints sets (N55°W and N57°E) can create more than two trends of breccia pipe alignments. Note: (1) the E-W trend similar to the A set in fig. 4a, (2) the N42°E trend similar to the B set in fig. 4a, and (3) the N-S, N25°E, N25°W, etc. trends that are not developed in fig. 4a. Cartoon is modified from Verbeek (written commun., 1988) and Roller (1989, fig. 22).

Permian strata were deposited--in fact, not until after the breccia pipes were formed and mineralized (therefore the E-W set is younger than 200 Ma). The above "D" alignment set of N42°E was not a documented fracture trend within the rocks of the Hualapai Reservation during either the Roller (1989) or Verbeek and others (1988) studies. Yet, it is a direction followed by many of the Laramide faults and monoclines (see Plate 1), and a direction along which the Ridenour mine and 3 other mineralized pipes are aligned (discussed in Wenrich and others, 1986) northeast of this map area.

It is important to understand that 4 (A, B, C, and D) differently oriented breccia pipe alignments can be created by only two orthogonal (or nearly orthogonal) joint sets. Figure 4b shows a cartoon suggesting that when breccia pipes form at the intersection of N55°W- and N57°E-trending fractures, as suggested by Sutphin and Wenrich (1983), that multiple alignments of pipes, such as E-W and N42°E, also appear. Thus, these E-W alignments on the southwestern Hualapai Reservation plus the E-W alignment through Pinenut, Arizona 1, Lost Calf, Little Robinson, and June breccia pipes shown by Sutphin and Wenrich (1989) are real, as is the regular spacing of these pipes, although the breccia pipe locations are not due to any "structural control" along an E-W strike. They are due instead to the N55°W and N55°E joint sets in the Redwall Limestone that were described by Roller (1989). The N42°E pipe alignments (particularly alignment B1--fig. 4a) can occur with equally spaced pipes when the fracture spacing is regular. That is, the alignments with equally spaced pipes are dependant on the fracture spacing and if the fracture spacing becomes irregular so will the breccia pipe locations. Furthermore, if the pipes form at random fracture intersections rather than routinely along specific NW or NE fractures, then recognition of alignments becomes difficult and breccia pipe locations appear random, as they do on much of the Hualapai Reservation.

What causes the fracture spacing and the breccia pipe occurrences to become more regular in areas such as the Marble Plateau and the northeast part of this map area is still a mystery. It is interesting to note though, that both of these areas lie near the intersection of large monoclines, which presumably are an indication of an underlying junction in basement blocks. Also, the monoclines on the Marble Plateau (the Grandview, Coconino Point, and East Kaibab Monoclines) have orientations and shapes similar to those (the Horse Flat and Meriwhitica Monoclines) on the Hualapai Plateau (Wenrich and others, 1987).

Most of the brecciation and mineralization of the pipes in this area predates the oldest of the folds and faults which deform the Paleozoic host rocks, that is, late Paleozoic-Triassic pipe formation and mineralization predate Laramide and younger tectonism. The underlying Precambrian fault zones may have acted as structural hinges during the long Paleozoic through Cretaceous period of subsidence and sedimentation. Specifically, the pre-existing faults may not have produced sufficient displacement to appreciably deform the overlying Paleozoic and younger rocks, yet minor flexing along the Precambrian faults could have allowed for upward propagation of fractures into the overlying section. This would have increased the fracture densities in the brittle carbonate rocks (such as the Redwall) along the strikes of the underlying fault zones. Localized dissolution of the carbonates aided by joint-enhanced permeability would then have created ideal sites for the nucleation of future pipes.

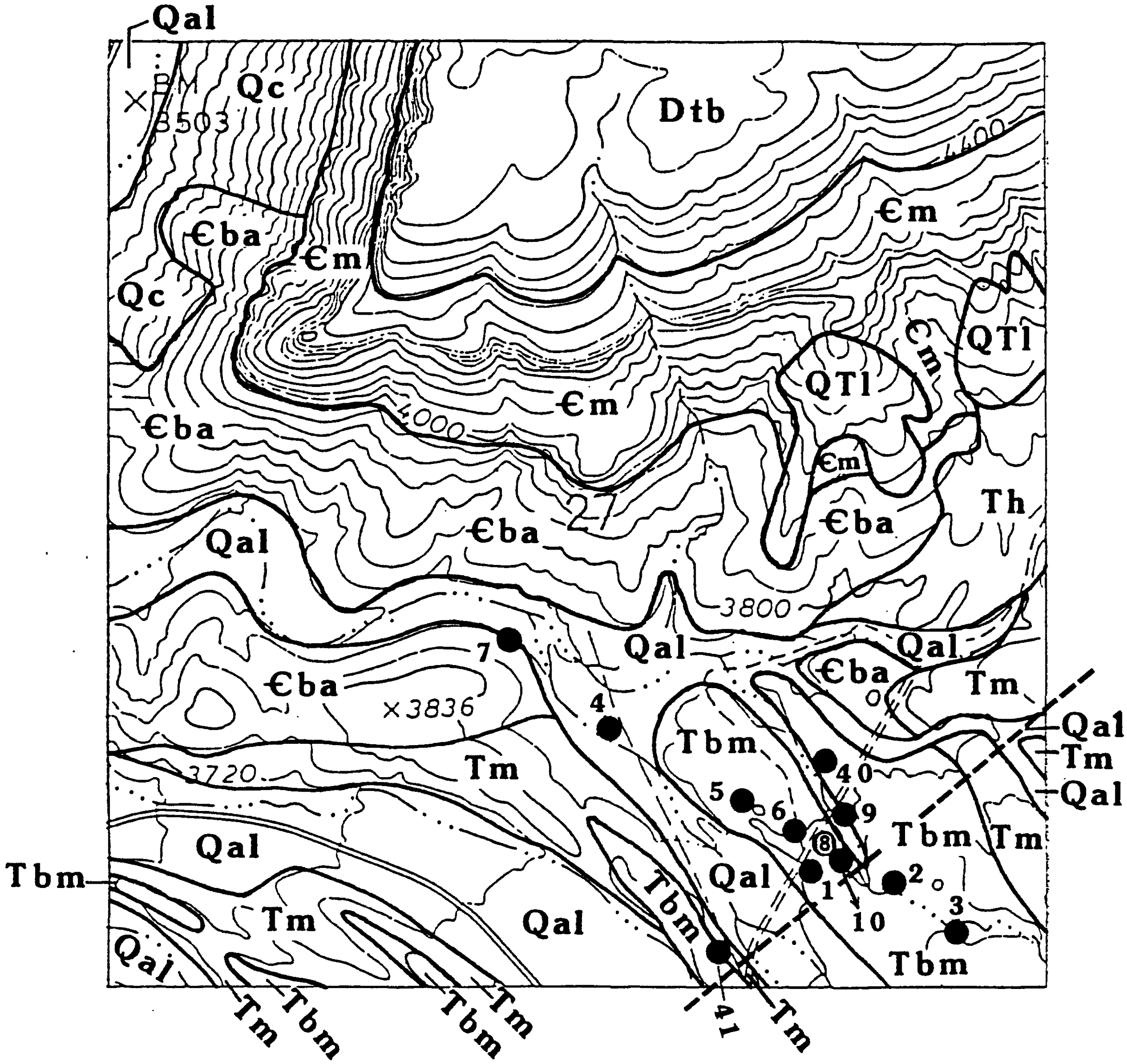
The entire process of pipe localization predates even the Laramide monoclines. Consequently the presence of pipe alignments along Laramide and post-Laramide structures simply serves notice that the Precambrian faults underlying and localizing those younger structures aided the upward propagation of fractures important for pipe formation. Such fracturing took place long before the basement faults were reactivated to such an extent that the overlying sediments failed through faulting or folding.

MULBERRY SPRINGS URANIUM MINERALIZATION

The Mulberry Springs prospect area is located east of Peach Springs Canyon, just west of Mulberry Springs in the southwest corner of the map. Tertiary sediments of the Buck and Doe Conglomerate, Music Mountain Conglomerate, and the Hindu Fanglomerate fill an ancient valley (Young, 1966). These Tertiary gravels lie directly on older landslide blocks composed of Cambrian Bright Angel Shale.

One mineral prospect was known prior to 1967 in this area, as it is shown on the Peach Springs 7-1/2' quadrangle. Western Nuclear Incorporated drilled 48 holes into the valley between 1976 and 1978; the lithologic and gamma-ray logs are on file in the Hualapai Tribal Office. The drill hole locations (T26N, R11W) are shown in figures 5a (section 27) and 5b (section 26). The gamma-ray anomalies are shown in three drill hole cross sections (fig. 6a-6c). Although the lithologic logs are rather sketchy, an approximate location demarking the Tertiary gravel-Bright Angel Shale contact was placed on figures 6a-6c. The highest gamma counts came from holes MS-24 and MS-17 reaching 850 cps (0.047% U_3O_8). Most holes had at least some intervals with gamma radiation between 100 and 200 cps, but for the most part there were no highly anomalous areas, and certainly no uranium concentrations were of interest in the 1980's uranium market.

The anomalous areas do not appear to be concentrated at the base of the Tertiary gravels just above the contact with the Bright Angel Shale as might be expected; uranium enrichments commonly occur above an aquiclude (a shale) at the base of a conglomerate (or gravel) where organic debris tends to accumulate. The highest concentrations, those above 400 cps, are all in the Tertiary gravels or landslide blocks, although figures 6a and 6b show many small anomalous zones in the range of 100-200 ppm, apparently located within the Bright Angel Shale beneath the landslide blocks and Tertiary gravels.



EXPLANATION

Qal Alluvial deposits (Holocene)
Qc Colluvium (Holocene and Pleistocene?)
QTl Landslides (Holocene, Pleistocene, and Pliocene?)
Tbm Buck and Doe Conglomerate, Milkweed Member (Miocene?)
Th Hindu Fanglomerate (Paleocene and Eocene?)
Tm Music Mountain Conglomerate (Paleocene and Eocene?)
Tl Landslides (Tertiary--exact age uncertain)
Dtb Temple Butte Formation (Upper and Middle? Devonian)
€m Muav Limestone (Middle Cambrian)
€ba Bright Angel Shale (Middle Cambrian)
● Drill hole location
— — — Approximate axis of Tertiary channel system

Figure 5a. Geologic map showing Western Nuclear, Inc. drill hole locations for T26N, R11W, Section 27 of the Peach Springs 7-½' quadrangle. The holes were drilled between 1976-1978; drill hole numbers are those shown on the map preceded by "MS-".

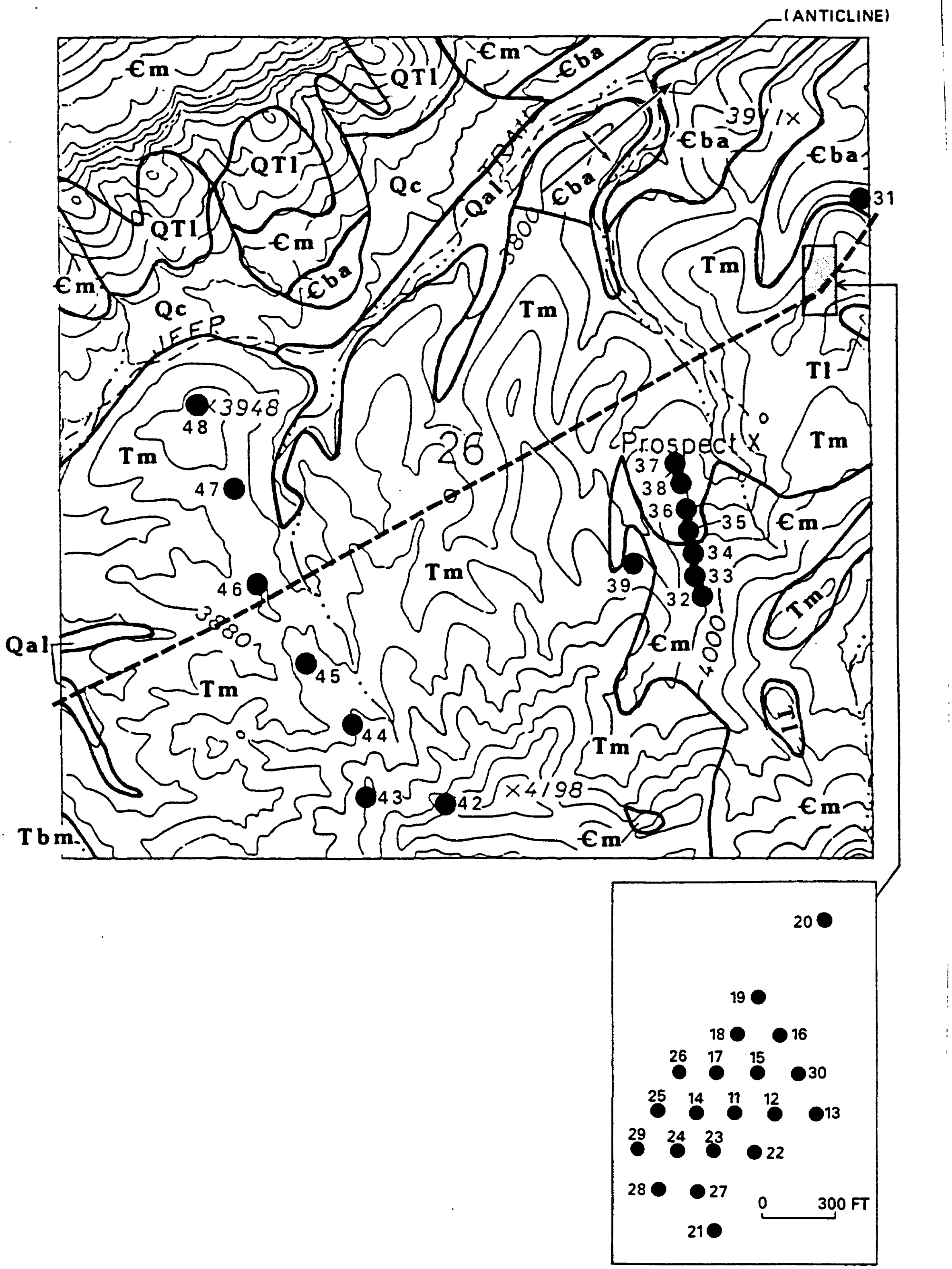


Figure 5b. Geologic map showing Western Nuclear, Inc. drill hole locations for T26N, R11 W, Section 26 of the Peach Springs 7-½' quadrangle. The holes were drilled between 1976-1978; drill hole numbers are those shown on the map preceded by "MS-".

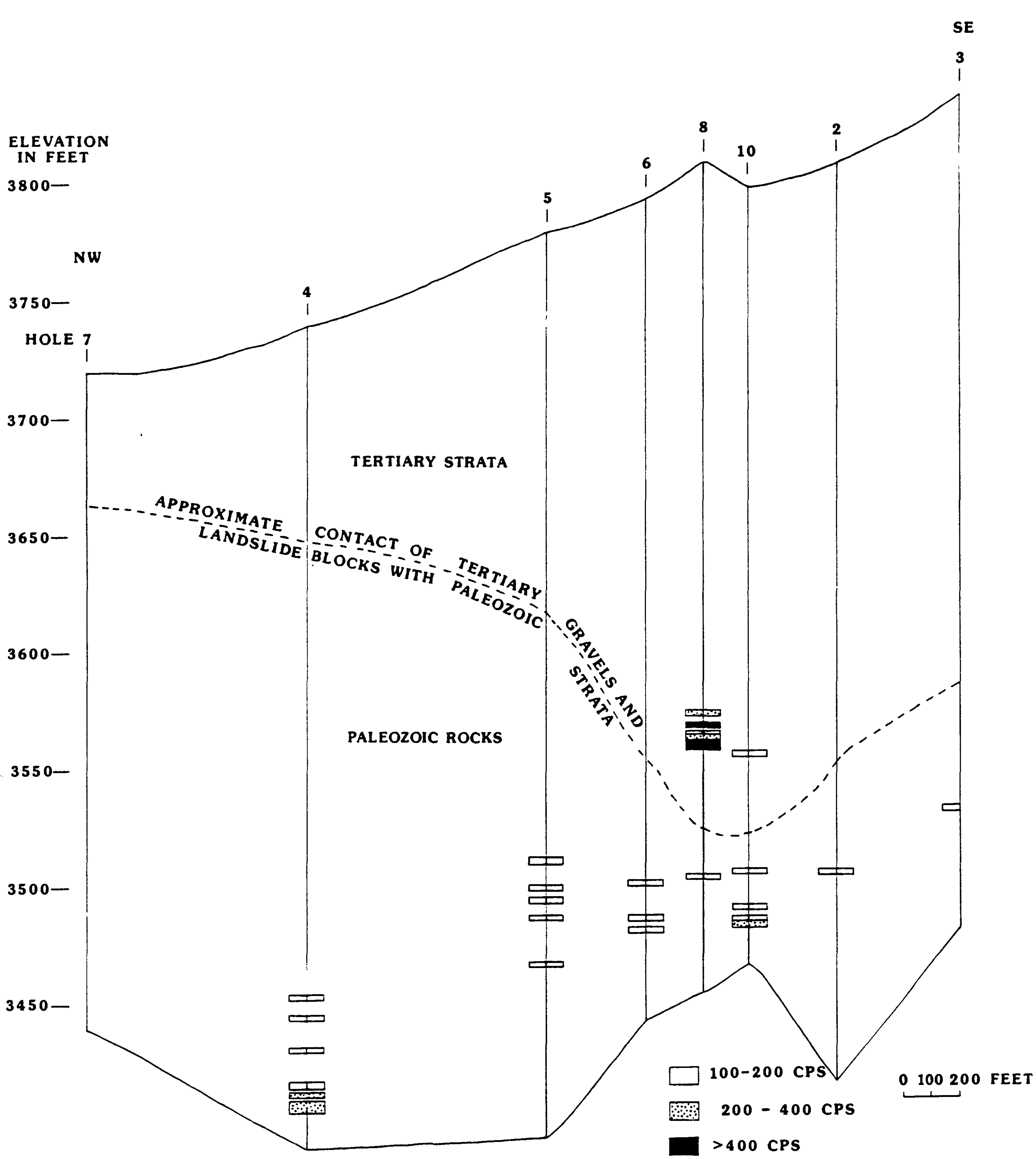


Figure 6a. Cross section of drill holes MS-7, MS-4, MS-5, MS-6, MS-8, MS-10, MS-2, and MS-3 showing intervals of anomalous gamma radiation and the approximate contact of the Tertiary gravels and landslide blocks with the Bright Angel Shale. Drill hole locations are shown in figure 5a.

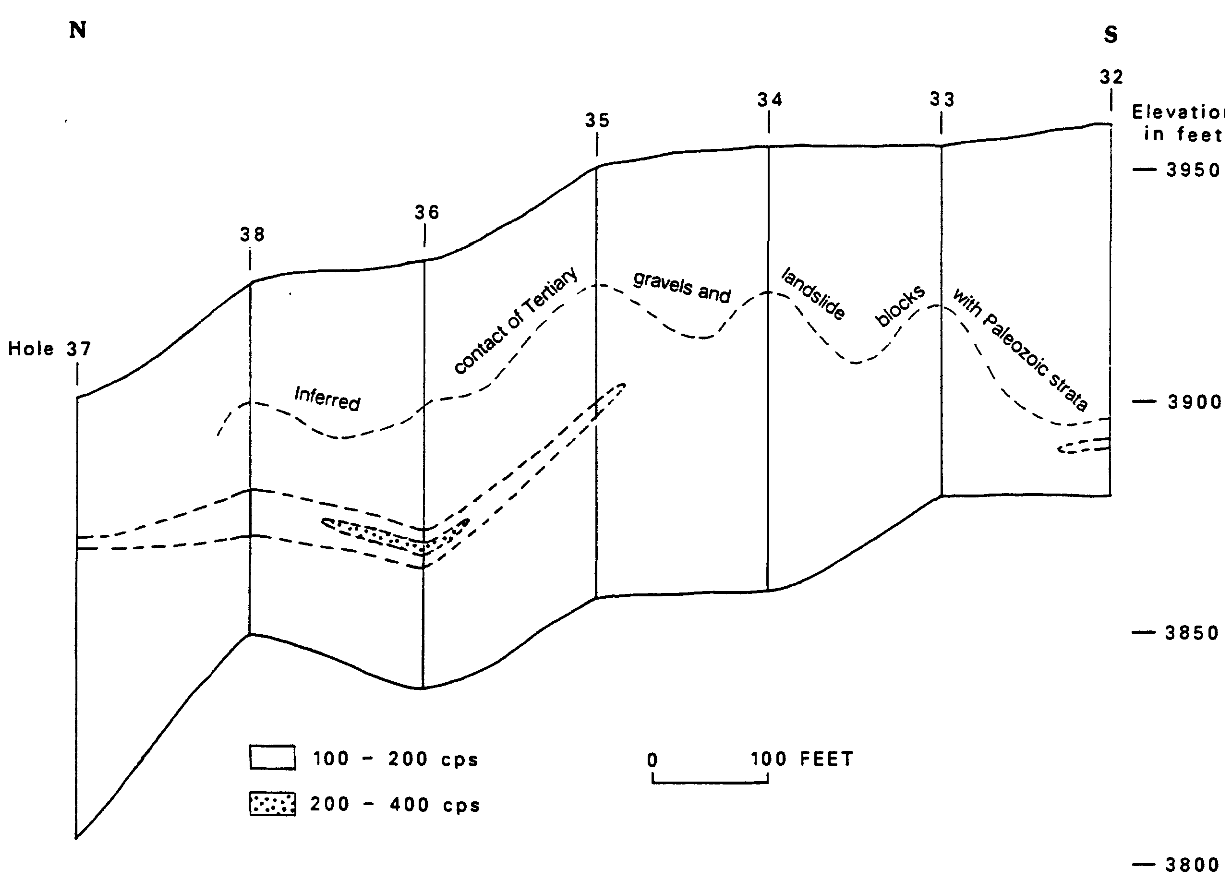


Figure 6b. Cross section of drill holes MS-37, MS-38, MS-36, MS-35, MS-34, MS-33, and MS-32 showing intervals of anomalous gamma radiation and the approximate contact of the Tertiary gravels and landslide blocks with the Bright Angel Shale. Drill hole locations are shown on figure 5b.

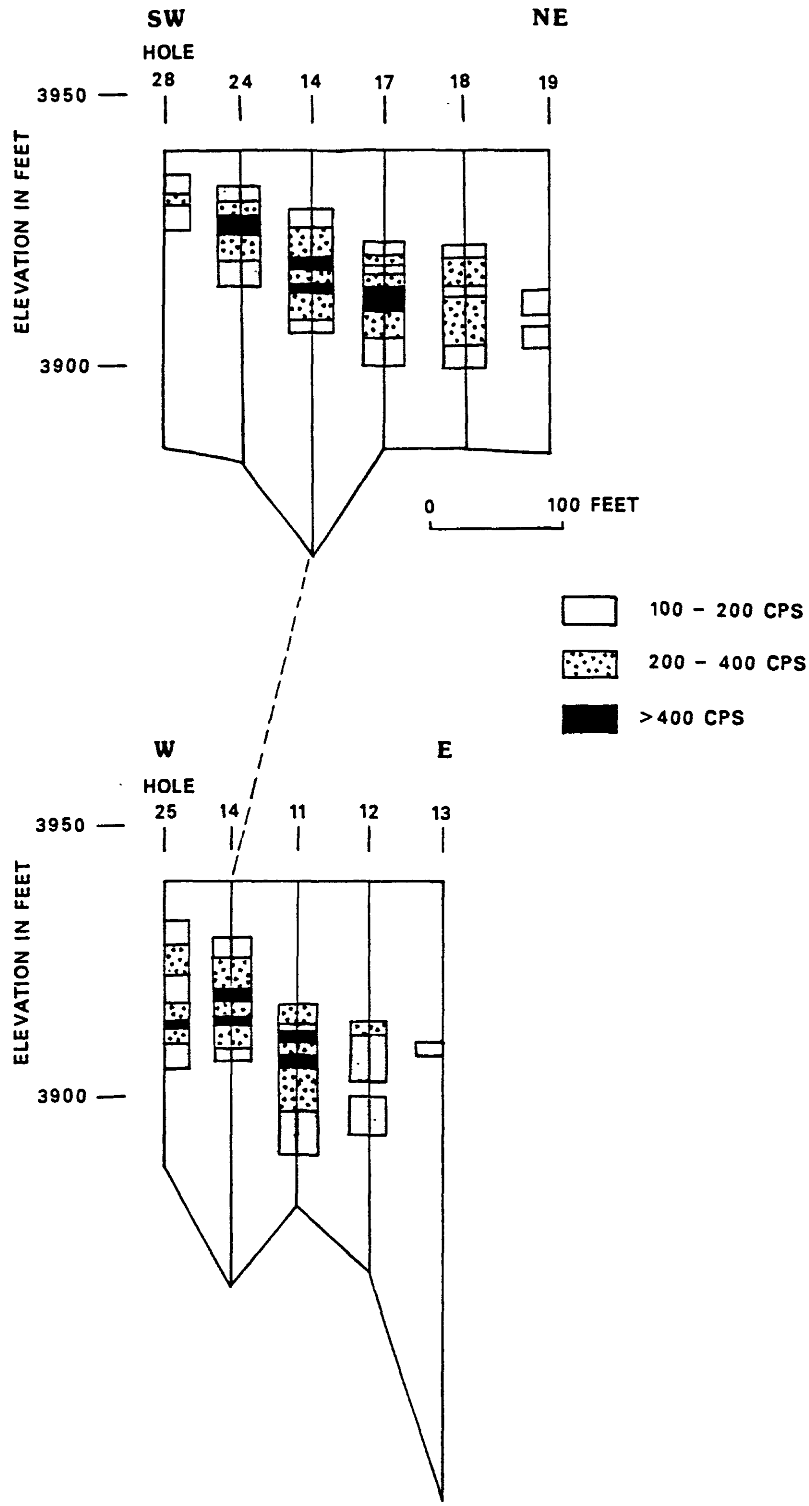


Figure 6c. Two cross sections, located at 60° and 120° to each other, of drill holes MS-28, MS-24, MS-14, MS-17, MS-18, MS-19 and MS-25, MS-14 (tie between the two sections), MS-11, MS-12, MS-13 showing intervals of anomalous gamma radiation. Drill hole locations are shown on figure 5b. All drill holes in these two sections are entirely within Tertiary gravels or landslide blocks.

DESCRIPTION OF MAP UNITS

Surficial and Volcanic Deposits

Qal **Alluvial deposits (Holocene)**--Unconsolidated fluvial deposits of silt, sand, and boulders; includes floodplain deposits. Faults shown as bounding alluvium do not offset the alluvium, instead, alluvium is banked against exhumed fault scarps

Qc **Colluvium (Holocene and Pleistocene?)**--Consists of brecciated rock fragments, boulders, gravel, sand and silt; partially consolidated with a gypsiferous or calcareous cement. Includes alluvial fan deposits. Intertongues with landslide debris. Locally includes reworked Cenozoic gravels on Hualapai Plateau. Faults shown as bounding colluvium do not offset the colluvium

Qt **Travertine deposits (Holocene and Pleistocene)**--Spring deposits of calcium carbonate with incorporated angular boulders, gravel, sand, and silt of adjacent talus deposits

QTl **Landslides (Holocene, Pleistocene, and Pliocene?)**--Unsorted and unconsolidated material; consists mainly of large blocks of Paleozoic sedimentary rock that have slid downward and rotated, presently dipping towards the base of the parent wall

QTg **Younger gravels, undivided (Miocene and Younger)**--Reworked Tg conglomerates, sand, gravel, and silt from older gravel and volcanic units; also consisting of locally derived Paleozoic clasts mixed and reworked with some Precambrian quartzite and volcanic (Miocene) clasts. Includes the Willow Springs Formation of Young (1966, p. 51). Clasts are matrix supported and cemented with calcium carbonate, commonly covered by thin colluvium and caliche. Thickness ranges from 20-200 ft

Ti **Intrusive volcanic rocks (Miocene and Pliocene)**--Alkali-olivine basalt and andesitic basalt dikes and plugs

Tv **Volcanic deposits undivided (Miocene and Pliocene)**--All surficial volcanic deposits on the Hualapai Plateau; includes the Peach Springs Tuff of Young and Brennan (1974, p. 84), basalt flows, agglomerate, and volcanic-bearing fluvial sediments. The Peach Springs Tuff is a gray welded rhyolitic ash-flow tuff, thin-bedded; locally the tuff includes volcanic pebbles of various lithologies. Dated at 18.3±0.6 m.y. (Damon, 1966, p. 28; Valentine and others, 1989). Thickness averages about 30 ft

Tc **Basaltic cinder deposits (Miocene)**--Basaltic, coarse-grained pyroclastic deposits near vent areas. Sometimes gradational with Buck and Doe Conglomerate; some derived from an unknown source to the west. Thickness unknown

Tg **Undifferentiated gravel deposits (Paleocene? through Miocene)**-- Mostly conglomerate, breccia, fanglomerate, with gravel, sand, silt, and limestone. Fills older canyons and valleys on the Hualapai Plateau. Includes the Music Mountain Conglomerate (Young, 1966, p. 24) composed of Precambrian clasts that intertongues with Paleozoic clast deposits of the Hindu Fangomerate (Young, 1966, p. 30); reddish to tan and white siltstone and limestone of the Westwater Formation of Young (1966, p. 32); and the Buck and Doe Conglomerate (Young, 1966, p. 36). Poor exposures make it difficult to distinguish the correct stratigraphic sequence in areas of low relief. The thickest deposits, up to several hundred feet, are in Milkweed, Hindu, Lost Man, and Peach Springs Canyons ranging from about 10-700 ft

Tp **Coarsely crystalline intrusive plutonic stock (Paleocene)**--Coarsely crystalline quartz-feldspar-hornblende-biotite-bearing pluton that intrudes Cambrian rocks on the Grand Wash Cliffs, northwest corner of map. Mapped by Young (1966) and dated at 65.5 m.y. by E.H. McKee (Young, 1979, p. 44). Unconformably overlain by Tv

Unconformity

Pwmw **Lower part of Supai Group: Manakacha and Watahomigi Formations undivided (Middle and Lower Pennsylvanian)**--

Manakacha Formation (Middle Pennsylvanian)--Reddish-brown, fine-grained, thick-bedded sandstone and shale interbedded with gray, medium-grained, cross-bedded dolomite and thin-bedded limestone; contains a few thin, red-brown shales. Largely removed by Cenozoic erosion. Forms a sequence of slopes and ledges up to 150 ft thick

Unconformity

Watahomigi Formation (Lower Pennsylvanian)--Purple-gray to gray, slope-forming, calcareous siltstone and fine-grained sandstone, interbedded with gray, ledge-forming, thin-to medium-bedded limestone containing red chert lenses. Includes a few thin-bedded conglomerates and thin-bedded limestone units near the base. A thick-bedded gray fossiliferous limestone ledge in the lower slope thickens westward and forms a small cliff. Average thickness is 180 ft

Unconformity

PMs **Surprise Canyon Formation (Lower Pennsylvanian(?) and Upper Mississippian)**--Consists of a basal ledge of chert pebble conglomerate, clasts supported with a dark red-brown to black iron-stained sandy matrix; a middle cliff-forming, yellowish-gray, coarsely crystalline, silty, crumbly, thin-bedded, fossiliferous limestone; an upper slope and ledge-forming, dark red-brown, thin-bedded, fine-grained siltstone and sandstone with laminated beds of silty limestone; deposited within paleo-caves and paleo-valleys eroded into the Redwall Limestone. Thickness ranges from a few feet to 75 ft; mostly removed by Cenozoic erosion on this map

Unconformity

Mr Redwall Limestone (Upper and Lower Mississippian)--From top to bottom, includes the Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members undivided. Redwall forms a shear cliff with a slight recess at the contact between the Horseshoe Mesa and Mooney Falls Members. All four members consist of a light-gray thick-bedded, aphanitic limestone and dolomite; contains marine fossils throughout. White chert bands are common in the Thunder Springs Member. Thickness ranges up to about 650 ft; mostly removed by Cenozoic erosion this map area

Unconformity

Dtb Temple Butte Formation (Upper and Middle? Devonian)--Dark-gray to purple-gray, medium-bedded dolomite, dolomitic sandstone and sandy limestone, interbedded with reddish-brown siltstone, and gray siltstone; forms a series of ledges averaging 400 ft thick; mostly removed by Cenozoic erosion

Unconformity

Tonto Group (Cambrian)

Cm Muav Limestone (Middle Cambrian)--Mottled gray and purple, thin-bedded, dolomitic limestone that weathers a rusty gray. Upper 450 ft includes a white to light gray sequence of dolomites (unclassified) that occur between Muav Limestone and Temple Butte Formation. Limestone ledges and small cliffs are separated by tongues of slope-forming green shale lithologically similar to underlying Bright Angel Shale. Lower contact with the Bright Angel Shale is at the base of the Rampart Cave Member of the Muav Limestone (McKee and Resser, 1945). Averages 600 to 750 ft thick; largely eroded by Cenozoic erosion

Cba Bright Angel Shale (Middle Cambrian)--Green and purplish-red fissile siltstone; interbedded with rusty-brown and dark gray dolomite tongues of the Muav Limestone in upper part; interbedded with light-brown to reddish-brown, coarse-grained, thin-bedded sandstone beds of Tapeats lithology in lower part. A very coarse-grained, purple-red sandstone (red-brown member of McKee, and Resser, 1945), forms a cliff at about the middle of the unit. Lower contact with the Tapeats Sandstone is arbitrarily placed at or near top of Tapeats Sandstone cliff. Forms a slope nearly 350 ft thick

Ct Tapeats Sandstone (Middle and Lower Cambrian)--Light-gray to light-brown, and red-purple, medium- to coarse-grained, medium-bedded sandstone to quartzite, and small pebble conglomerate. Has abundant low-angle cross-bedding and thin green-shale partings between beds in upper part; forms cliff that ranges in thickness from 50-200 ft

Unconformity

Vishnu Group (Older Precambrian) (Upper amphibolite facies)

pCgr Nonfoliated granitic plutons--Brown to light-red, holocrystalline, quartz-bearing granite plutons

pCgrb Foliated granitic plutons--Light colored, coarse-grained, plutonic granite with feldspar and mafic minerals

pCvs Mica schist--Mica and quartz; schistose foliation; mainly muscovite and biotite

pCva Mafic schist and amphibolite--Very fine grained, foliated, dark-colored minerals; amphibolite and plagioclase with little or no quartz

pCvm Paragneiss--Granular feldspar and quartz, alternating with lenticular micaceous layers and fine-grained amphibolite minerals

pCu Precambrian undivided--Brown to reddish-brown, holocrystalline, quartz-bearing, granite plutons; very fine-grained, foliated schist, gneiss, and quartz-feldspar pegmatites

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REFERENCES CITED

Anderson, R.E., 1979, Holocene faulting in the western Grand Canyon, Arizona, Discussion: Geological Society of America Bulletin, v. 90, p. 221-222.

Beard, L.S., 1985, Precambrian geology of the Cottonwood Cliffs area, Mohave County, Arizona: Unpublished MS thesis, Geology Department, University of Arizona, Tucson, 115 p., one map, scale 1:15,000.

Billingsley, G.H., and Huntoon, P.W., 1983, Geologic map of the Vulcan's Throne and vicinity, western Grand Canyon, Arizona: Grand Canyon Natural History Association, Grand Canyon, Arizona, scale 1:48,000.

Billingsley, G.H., Wenrich, K.J., and Huntoon, P.W., 1986, Breccia pipe and geologic map of the southeastern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458-B, 26 p., 2 plates, scale 1:48,000.

Chenoweth, W.L., 1986, The Orphan Lode mine, Grand Canyon, Arizona, a case history of a mineralized, collapse-breccia pipe: U.S. Geological Survey Open-File Report 86-510, 126 p.

Clark, M.D., 1976, The geology and petrochemistry of the Precambrian metamorphic rocks of the Grand Canyon, Arizona: Unpublished Ph.D. Thesis, University of Leicester, England, 216 p.

Damon, P.E., 1966, Correlation and chronology of ore deposits and volcanic rocks, Annual Progress Report No. COO-689-60 [Contract AT(11-1)-689] to Research Division, U.S. Atomic Energy Commission: Tucson, Ariz., Geochronology Laboratories, University of Arizona, 46 p.

Davis, G.H., 1978, Monocline fold pattern of the Colorado Plateau: Geological Society of America Memoir 151, p. 215-233.

Gray, R.S., 1959, Cenozoic geology of Hindu Canyon, Mohave County, Arizona: M.S. thesis, Univ. of Ariz., Tucson, 64 p.

Hamblin, W.K., 1965, Origin of reverse drag on the downthrown side of normal faults: Geological Society of America Bulletin, v. 76, p. 1145-1164.

Huntoon, P.W., 1974, Synopsis of Laramide and post-Laramide structural geology of the eastern Grand Canyon, Arizona, in Karlstrom, T.N.V., Swann, G.A., and Eastwood, R.L., eds., Geology of northern Arizona, with notes on archaeology and paleoclimate: Geological Society of America, Rocky Mountain Section, Guidebook for field trips, v. 27, pt. 1, Regional Studies, p. 317-335.

________1977, Relationship of tectonic structure to aquifer mechanics in the western Grand Canyon district, Arizona: Wyoming Water Resources Research Institute Water Resources Series 66, 51 p.

________1981, Grand Canyon monoclines, vertical uplift or horizontal compression?: Contributions to Geology, v. 19, p. 127-134.

________1989, Phanerozoic tectonism, Grand Canyon, Arizona: in Elston, D.P., Billingsley, G.H., and Young, R.A., eds., Geology of Grand Canyon, northern Arizona (with Colorado River Guides), 28th International Geological Congress Field trip guidebook T115/315, American Geophysical Union, Washington D.C. p. 76-89.

Huntoon, P.W., Billingsley, G.H., and Clark, M.D., 1981, Geologic map of the Hurricane Fault Zone and vicinity, western Grand Canyon, Arizona: Grand Canyon Natural History Association, Grand Canyon, Arizona, scale 1:48,000.

Huntoon, P.W., Billingsley, G.H., and Clark, M.D., 1982, Geologic map of the Lower Granite Gorge and vicinity, western Grand Canyon, Arizona: Grand Canyon Natural History Association, Grand Canyon, Arizona, scale 1:48,000.

Koons, D., 1964, Structure of the eastern Hualapai Indian Reservation, Arizona: Arizona Geological Society Digest, v. 7, p. 97-114.

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

Ludwig, K.R., and Simmons, K.R., 1988, Progress in U/Pb isotope studies of collapse-breccia pipes in the Grand Canyon region, northern Arizona: Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A139.

Mathisen, I.W., Jr., 1987, Arizona Strip breccia pipe program: Exploration, development, and production [abs.]: American Association of Petroleum Geologists Bulletin, v. 71/5, p. 590.

McKee, E.D., and Resser, C.E., 1945, Cambrian history of the Grand Canyon region: Washington, D.C., Carnegie Institute Publication 563, 232 p.

McKee, E.D., and Schenk, E.T., 1942, The lower canyon lavas and related features at Toroweap in Grand Canyon: Journal of Geomorphology, v. 5, p. 245-273.

Naeser, C.W., Duddy, I.R., Elston, D.P., Dumitru, T.A., and Green, P.F., 1989, Fission-track dating: Ages for Cambrian strata, and Laramide and post-middle Eocene cooling events from the Grand Canyon, Arizona; Fieldtrip Guidebook T115/315, 28th International Geological Congress: Washington, D.C., American Geophysical Union, p. 166-173.

Neilson, J.E., Lox, D.R., Dalrymple, G.B., and Glazner, A.F., in press, Age of the Peach Springs Tuff: Journal of Geophysical Research.

Peirce, H.W., 1984, The Mogollon Escarpment: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 14, no. 2, p. 8-11.

Reches, Z., 1978, Development of monoclines, part 1, structure of the Palisades Creek branch of the East Kaibab monocline, Grand Canyon, Arizona: Geological Society of America Memoir 151, p. 235-271.

Roller, J.A., 1989, Fracture history of the Redwall Limestone, lower Supai Group, and Tertiary units on the Hualapai Indian Reservation, northwestern Arizona: Additional data to Open-File Report 87-359: U.S. Geological Survey Open-File Report 89-463, 42 p.

Smith, R.B., and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the intermountain seismic belt: Geological Society of America Bulletin, v. 85, p. 1205-1218.

Sutphin, H.B., 1986, Occurrence and structural control of collapse features on the southern Marble Plateau, Coconino County, Arizona: Flagstaff, Ariz., Northern Arizona University M.S. thesis, 139 p.

Sutphin, H.B., and Wenrich, K.J., 1983, Structural control of breccia pipes on the southern Marble Plateau, Arizona: U.S. Geological Survey Open-File Report 83-908, 6 p., 2 plates, scale 1:50,000. (Superceeded by Sutphin, H.B., and Wenrich, K.J., 1988, Map showing structural control of breccia pipes on the southern Marble Plateau, north-central Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1778, 2 plates, scale 1:50,000.)

________1989, Map of locations of collapse-breccia pipes in the Grand Canyon region of Arizona: U.S. Geological Survey Open-File Report 89-550, 1 plate, scale 1:250,000.
Twenter, F.R., 1962, Geology and promising areas for groundwater development in the Hualapai Indian Reservation, Arizona: U.S. Geological Survey Water-Supply Paper 1576-A, p. 1-38.
Van Gosen, B.S., and Wenrich, K.J., 1989, Ground magnetometer surveys over known and suspected breccia pipes on the Coconino Plateau, northwestern Arizona: U.S. Geological Survey Bulletin 1683-C, p. 1-31.
Valentine, G.A., Buesch, D.C., and Fisher, R.V., 1989, Basal layered deposits of the Peach Springs Tuff, northwest Arizona, USA: Bulletin Volcano 51, p. 395-414.
Verbeek, E.R., Grout, M.A., and Van Gosen, B.S., 1988, Structural evolution of a Grand Canyon breccia pipe: The Ridenour copper-vanadium-uranium mine, Hualapai Indian Reservation, Coconino County, Arizona: U.S. Geological Survey Open-File Report 88-006, 75 p.
Walcott, C.D., 1890, Study of a line of displacement in the Grand Canyon of the Colorado in northern Arizona: Geological Society of America Bulletin, v. 1, p. 49-64.
Wenrich, K.J., 1985, Mineralization of breccia pipes in northern Arizona: Economic Geology, v. 80, no. 6, p. 1722-1735.
________1986, Geochemical exploration for mineralized breccia pipes in northern Arizona, U.S.A.: Applied Geochemistry, v. 1, no. 4, p. 469-485.
Wenrich, K.J., Billingsley, G.H., and Huntoon, P.W., 1986, Breccia pipe and geologic map of the northeastern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458-A, 29 p., 2 plates, scale 1:48,000.
________1987, Breccia pipe and geologic map of the northwestern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458-C, 32 p., 2 plates, scale 1:48,000.
Wenrich, K.J., Billingsley, G.H., and Van Gosen, B.S., 1986, The potential for breccia pipes in the National Tank area, Hualapai Indian Reservation, Arizona: U.S. Geological Survey Open-File Report 86-592-A, 45 p.
Wenrich, K.J., and Sutphin, H.B., 1989, Lithotectonic setting necessary for formation of a uranium rich, solution collapse breccia pipe province, Grand Canyon region, Arizona, in Metallogenesis of uranium deposits: Vienna, International Atomic Energy Agency Technical Committee Meeting, 9-12 March, 1987, IAEA-TC-542/20, p. 307-344 (Also released as U.S. Geological Survey Open-File Report 89-173, 33 p.).
Wheeler, R.L., 1986, Selecting reliable alignments of mapped points: Structural control of breccia pipes on the Marble Plateau, northern Arizona: Geological Society of America Abstracts with Programs, v 18, no. 5, p. 422.
Young, R.A., 1966, Cenozoic geology along the edge of the Colorado Plateau in northwestern Arizona: Washington University Ph.D. dissertation, 167 p.
________1970, Geomorphological implications of pre-Colorado and Colorado tributary drainage in the western Grand Canyon region: Plateau, v. 42, no. 3, p. 107-117.
________1979, Laramide deformation, erosion and plutonism along the southwestern margin of the Colorado Plateau: Tectonophysics, v. 61, nos. 1-3, p. 25- 47.

________1982, Paleogeomorphic evidence for the structural history of the Colorado Plateau margin in western Arizona, in Frost, E.G., and D.L. Martin, eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: Cordilleran Publishers, San Diego, California, p. 29-39.

________1985, Geomorphic evolution of the Colorado Plateau margin in west-central Arizona: A tectonic model to distinguish between the causes of rapid asymmetrical scarp retreat and scarp dissection, in Hack, J.T., and Morisawa, M., eds., Tectonic Geomorphology: Binghamton Symposium in Geomorphology, International Series 15, London, Allen and Urwin, p. 261- 278.

________1987, Landscape development during the Tertiary, in Colorado Plateau, in Graf, W.L., ed., Geomorphic systems of North America: Geological Society of America Centennial volume 2, p. 265-276.

________1989, Paleogene-Neogene deposits of western Grand Canyon, Arizona, in Elston, D.P., Billingsley, G.H, and Young, R.A., eds., Geology of Grand Canyon, northern Arizona; Fieldtrip Guidebook T115/315, 28th International Geological Congress: Washington, D.C., American Geophysical Union, p. 166-173.

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.