



Tectonics of the Black Mesa Basin region of Arizona

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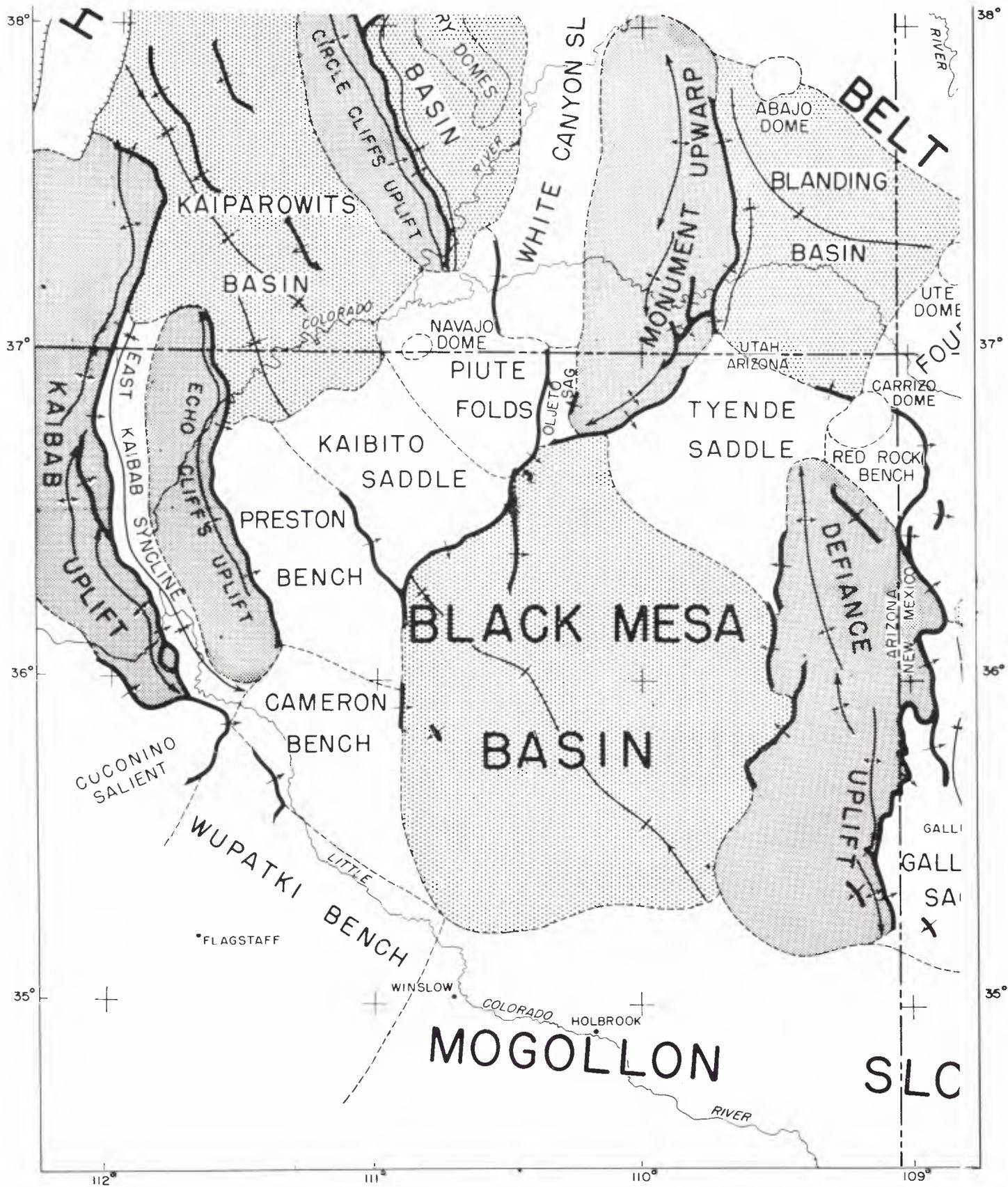


FIGURE 1. Index map of the tectonic divisions of the Black Mesa basin region.

TECTONICS OF THE BLACK MESA BASIN REGION OF ARIZONA

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In general, the region of the Black Mesa basin extends from the Kaibab uplift on the west to the Defiance uplift on the east and from about the Utah line on the north to the Mogollon Rim on the south. For the purposes of this paper the limits are indefinite on the one hand and arbitrary on the other. The field trip passes through only a small portion of the Black Mesa basin proper and continues into adjoining geologic divisions such as the Kaibab and Defiance uplifts that are clearly not a part of the basin. The region has been partitioned for purposes of structural description into a number of minor elements which surround the Black Mesa basin proper (Kelley, 1955a and Kelley and Clinton, in press). To many geologists engaged in stratigraphic studies and exploration all or parts of the surrounding minor structural divisions (fig. 1), such as the Preston and Cameron benches, the Tyende and Kaibito saddles, or the Mogollon slope, are within the broad confines or conception of the Black Mesa basin. To a considerable extent these lesser structural elements are only justifiable as conveniences in the description of the regional structure. Only along a part of the northwestern side of the restricted basin and locally along the eastern side can the boundaries be said to be clearly defined; elsewhere they are arbitrary for there is essentially imperceptible gradation into the surrounding divisions. The nature of these divisions and the reasons for making them are brought out in the following descriptions of the several lesser divisions as well as a few of the adjoining uplifts.

BLACK MESA BASIN

The restricted Black Mesa basin is a nearly circular downwarp some 90 miles in diameter. It is essentially equivalent to the Tusayan downwarp of Gregory (1917, p. 112). It is characterized by very low regional dips and shallow structural relief. Below the highest closing contour the relief is only about 500 feet. Long, broad, nearly parallel folds cross the basin in northwesterly directions. Many of these, with dips commonly of only one or two degrees, are scarcely noticeable without careful mapping. The deepest part of the basin is formed by the Black Mesa syncline which extends from the Kaibito saddle on the northwest to almost the southeastern boundary (see accompanying map by Doeringsfeld, Amuedo, and Ivey). Adjoining this syncline on the northeast is the long Cow Springs anticline which extends into the basin from the northwest south of the Organ Rock anticline. In the northeastern part of the basin the long, curving, Rim syncline and Black Mountain anticline form the northeastern edge of the major topographic feature, Black Mesa. The principal deformation in the southwestern part of the Basin parallels the curving Mount Beautiful anticline and Howell Mesa syncline. Although most of the folds within the basin are parallel and have northwesterly trends, the Big Mountain anticline, and the Oljeto syncline are northerly trending. Faults of any consequence are rare in the basin.

DEFIANCE UPLIFT

The Defiance uplift borders the Black Mesa basin on the east. It is a broad, north-trending asymmetrical fold about 30 miles wide and 100 miles long. It is equivalent to the De Chelly upwarp of Gregory (1917, p. 111-112).

The sinuous, locally steep, Defiance monocline forms the eastern limb, and the broad western limb is part of a low regional inclination into the Black Mesa basin. A few small monoclines (Sheep Creek, Chinle, and Rock Mesa) locally interrupt the western limb and in a general way these are followed in drawing the border between the uplift and the basin. The crest of the uplift appears to be formed by several staggered axes. In general most lesser folds on the uplift parallel each other and the general trend of the uplift.

TYENDE SADDLE

Tyende saddle bounds Black Mesa basin on the northeast and lies between the Monument upwarp to the northwest and the Defiance uplift to the southeast. Its boundaries are largely arbitrary and gradational except against the Comb monocline of the Monument upwarp. The saddle plunges into the Blanding basin on the northeast and into the Black Mesa basin on the southwest. The outline of the saddle is irregular, but in general it averages about 40 miles across. The saddle is broad and flat, and its over-all structural relief is less than 1000 feet. The lowest part is near the Comb monocline along the Tyende syncline (Witkind, Thaden, and Lough, 1952, fig. 4).

PIUTE FOLD BELT

The Piute fold belt, along with the Oljeto sag and the southern tip of the Monument upwarp, bound Black Mesa basin on the north. The belt consists of several northerly trending folds most of which are steeper to the east. The principal folds are the Organ Rock (fig. 2) and Balanced Rock anticlines. Their strong monoclinical eastern flanks are set in echelon toward the northwest and form also the eastern boundary of the belt. Folds in the western part of the belt are smaller, the principal linear flex being the long Rapids syncline, but the most pronounced fold is the Navajo dome (Kelley, 1955a, fig. 2). The nearly circular Navajo dome has been presumed by several geologists to be of laccolithic origin (Baker, 1936, p. 71-72), and Joesting (Written communication) points out that aerial magnetic traverses suggest the presence of igneous material beneath the dome. The dome has a radius of about three miles, and in that short distance possesses a minimum structural relief of nearly 2000 feet. It has no obvious elongation and it does not possess a ring syncline. It is difficult to ascribe other than an igneous origin for it.

KAIBITO SADDLE

Kaibito saddle bounds the Black Mesa basin on the northwest and is separated from the basin by the Cow Springs monocline, which lies along the northwest foot of Black Mesa. The saddle trends in a northwesterly direction and is about 40 miles long and 25 miles wide. Only parts of the southwestern and southeastern boundaries of the saddle along the Red Lake and Organ Rock monoclines are sharp. Elsewhere, the boundaries are gradational with the adjoining tectonic divisions. In general the saddle forms a saglike connection between the Black Mesa and Kaiparowits basins (fig. 1). Three northwesterly trending gentle folds, Black Mesa syncline, Cow Springs anticline, and Last Chance syncline (Kelley, 1955a) parallel the trend of the saddle.

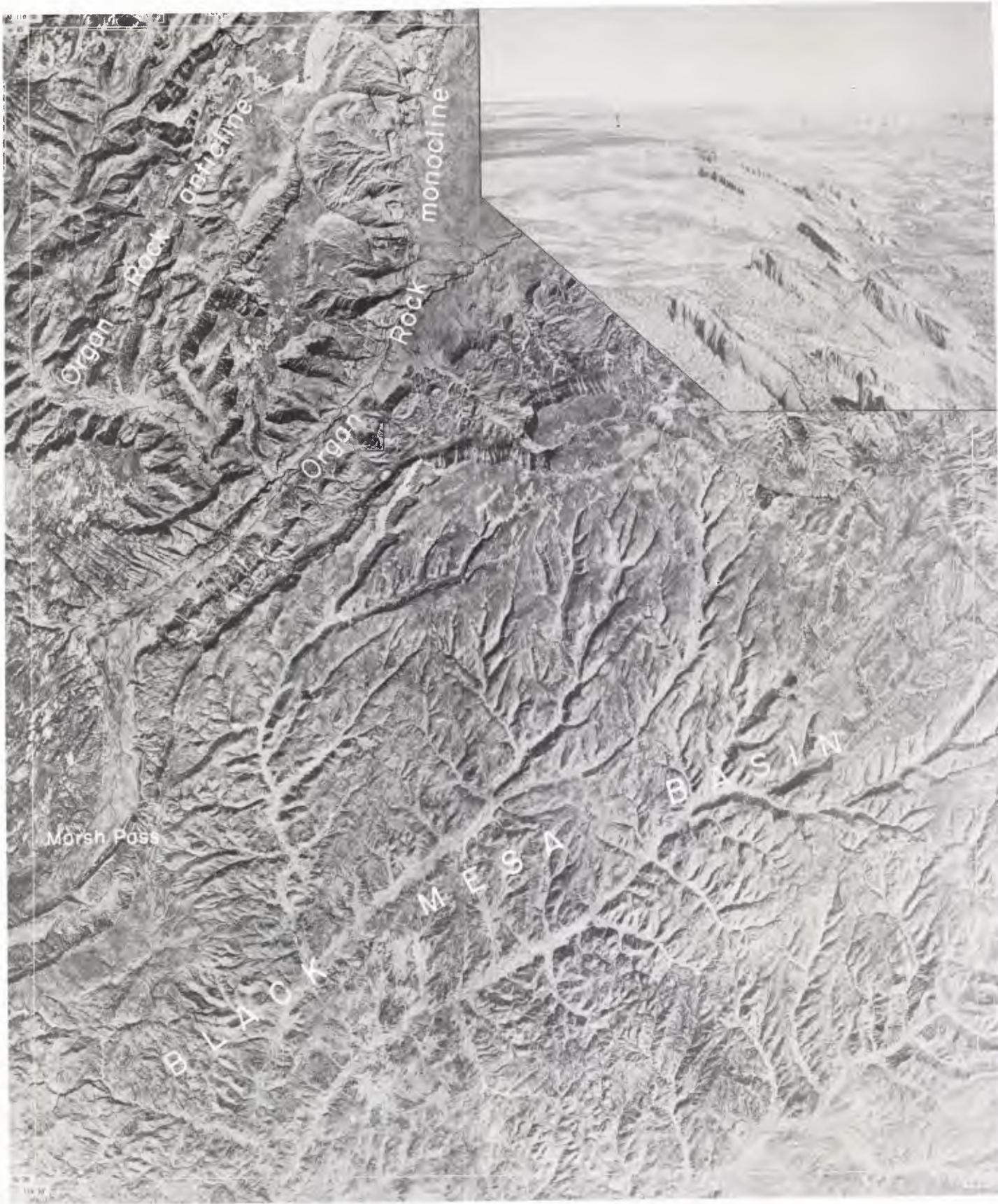


FIGURE 2. Aerial mosaic of 15-minute Arizona quadrangle A-35 showing the northern rim of Black Mesa basin near Marsh Pass at left. Curving Organ Rock monocline along left side. Inset is view north of the monocline near the northern edge of the quadrangle.

PRESTON BENCH

The Preston bench is a flat-lying segment some 65 miles long and 24 miles wide which together with the Kaibito saddle separates the Kaiparowits basin of southern Utah from the Black Mesa basin. It principally lies below the Echo Cliffs monocline on the west and above the Red Lake monocline, which separates it from the Kaibito saddle and Black Mesa basin on the east. There is no marked separation between the bench and the Kaiparowits basin or the Cameron bench. The over-all structural relief is not more than a few hundred feet. It is only mildly and broadly folded by the north-northwesterly trending Tuba City syncline and the Preston Mesa anticline, both of which in their northern parts plunge gently northward into the Kaiparowits basin. These folds, however, unlike those of Kaibito saddle to the east, do not extend southerly into Black Mesa basin. Numerous small faults lie along and nearly parallel the crest of the Preston Mesa anticline. These are displaced variously forming small grabens, horsts, or step faults. Along the northwestern border of the bench, between the Tuba City syncline and the Echo Cliffs monocline there are several northeasterly trending short faults and grabens that appear to be an extension of similar structures more common in the Echo Cliffs uplift to the west. Locally in the southern and southeastern parts of the bench there are faults of lesser prominence of northwesterly and westerly trends.

ECHO CLIFFS UPLIFT

The Echo Cliffs uplift is a long, narrow, north-trending anticline which is concavely arcuate, and asymmetrically steeper, to the east (Gregory, 1917, p. 114-115). It is approximately 80 miles long and 30 miles wide and plunges northward into the Kaiparowits basin and southward onto the Cameron bench. Only the eastern boundary of the uplift is sharp; all others are poorly defined and grade into basins or benches. Structural relief along the Echo Cliffs monocline is more than 2000 feet in the northern part and less than 1000 feet in the southern part.

The main Echo Cliffs crestal axis is curving and is offset westward in the southern part. Soap Creek syncline and the Vermilion anticline are long, very gentle folds that lie along the western flank and are more or less parallel with the main axis (Kelley, 1955a, fig. 2).

In a general way the Echo Cliffs uplift occupies a sort of intermediate structural step between the lower Preston bench to the east and the Kaibab uplift to the west. The narrow East Kaibab syncline intervenes between the uplifts.

Numerous northerly to northeasterly trending high-angle normal faults and small grabens cross the uplift in the central and southern parts.

KAIBAB UPLIFT

The Kaibab uplift is a northerly trending uplift some 125 miles long and 20-30 miles wide. It is asymmetrical and concave toward the east. The structural relief along the East Kaibab monocline is about 2000 feet in the southern part, 3000 feet in the central part, 4000 feet near the Utah line, and diminishes to vanish at its northern end. The southern end terminates against the Grandview monocline and the northern foot of the Coconino salient (fig. 3). The East Kaibab monocline is the type for monoclines and Powell in his early writings occasionally referred to other monoclines as "Kaibabs." In addition to being the type monocline it is characterized by much diversity of structure and geomorphology. The monocline splits in two places developing structural terraces. It is also broken

by one parallel (Butte) fault and several lesser oblique faults. The gently dipping western flank and crest of the uplift are broken by several northerly trending faults, especially in the middle and northern parts. Only the north-east-trending Bright Angel fault occurs in the southern part of the uplift. The throws on all the west flank and crestal faults never exceed a few hundred feet, which is in contrast with the 1700 feet of maximum throw of the Butte fault on the east flank.

Throughout much of the Kaibab uplift, except of course in the Grand Canyon, the surface generally follows the upper contact of the Kaibab limestone and the slopes generally parallel the dips of the monoclines and terraces. In the northern or Utah portion of the uplift, on the other hand, erosion has not penetrated as deeply and the monocline forms a series of hogbacks in Mesozoic formations.

COCONINO SALIENT

The structural Coconino salient is one of the most unusual and striking uplifts on the Plateau. The Coconino salient structure is a small protuberance (fig. 4) from the south end of the much larger Kaibab uplift. In detail the Coconino salient is formed by the intersection of the East Kaibab, Grand View, and Coconino monoclines (Kelley, 1955a, fig. 2), and, as roughly outlined by these features, trends northeasterly. The northeastern point is extremely abrupt with maximum dips on the monocline being vertical to slightly overturned and the structural relief is more than 2000 feet (Babenroth and Strahler, 1945, p. 113). To the southwest, on the other hand, the structure merges with the broad and only very slightly tilted structure of the general Grand Canyon section of the Plateau. The nearly hairpin-shaped monoclinical flex which outlines the salient is probably of Laramide age (Gregory and Moore, 1931, p. 131-132). It has been modified by possibly younger faults such as the Gray Mountain grabens (fig. 3) that cross the top in northerly, easterly, and northwesterly directions, the Mesa Butte graben which roughly parallels the Coconino monocline along the southeastern side, and an arcuate fault around Coconino Point. This last fault, as interpreted by Babenroth and Strahler (1945, pl. 2, fig. 2), is downthrown toward the uplift and has therefore somewhat reduced the original structural relief. Owing to the fact that the structural relief is greatest and steepest around the northeastern end, and that the deformation diminishes along the flanking monoclines toward the west and southwest, it appears that the structure may have resulted from the pushing of a deep-seated block north-eastward and upward between flanking shear zones that lie beneath the Grand View and Coconino monoclines (fig. 4). If this be the case, the principal northeastward shift in the basement rocks would have been beneath the Mesa Butte fault and Coconino monocline, and indeed, this may have been the principal accommodating tear along which the Kaibab uplift moved forward during its deformation. Therefore, the Mesa Butte fault may have right-lateral shift along it.

CAMERON BENCH

The Cameron bench is an irregular, roughly diamond-shaped division that generally lies between Black Mesa basin on the east and Coconino salient and Wupatki bench on the west and southwest (fig. 1). It trends northwesterly and averages about 50 miles long and 25 miles wide. The principal features that separate the Cameron bench from the surrounding divisions are the Coconino salient and the Black Point monocline on the west and the southern Red Lake monocline on the east. These bounding flexes

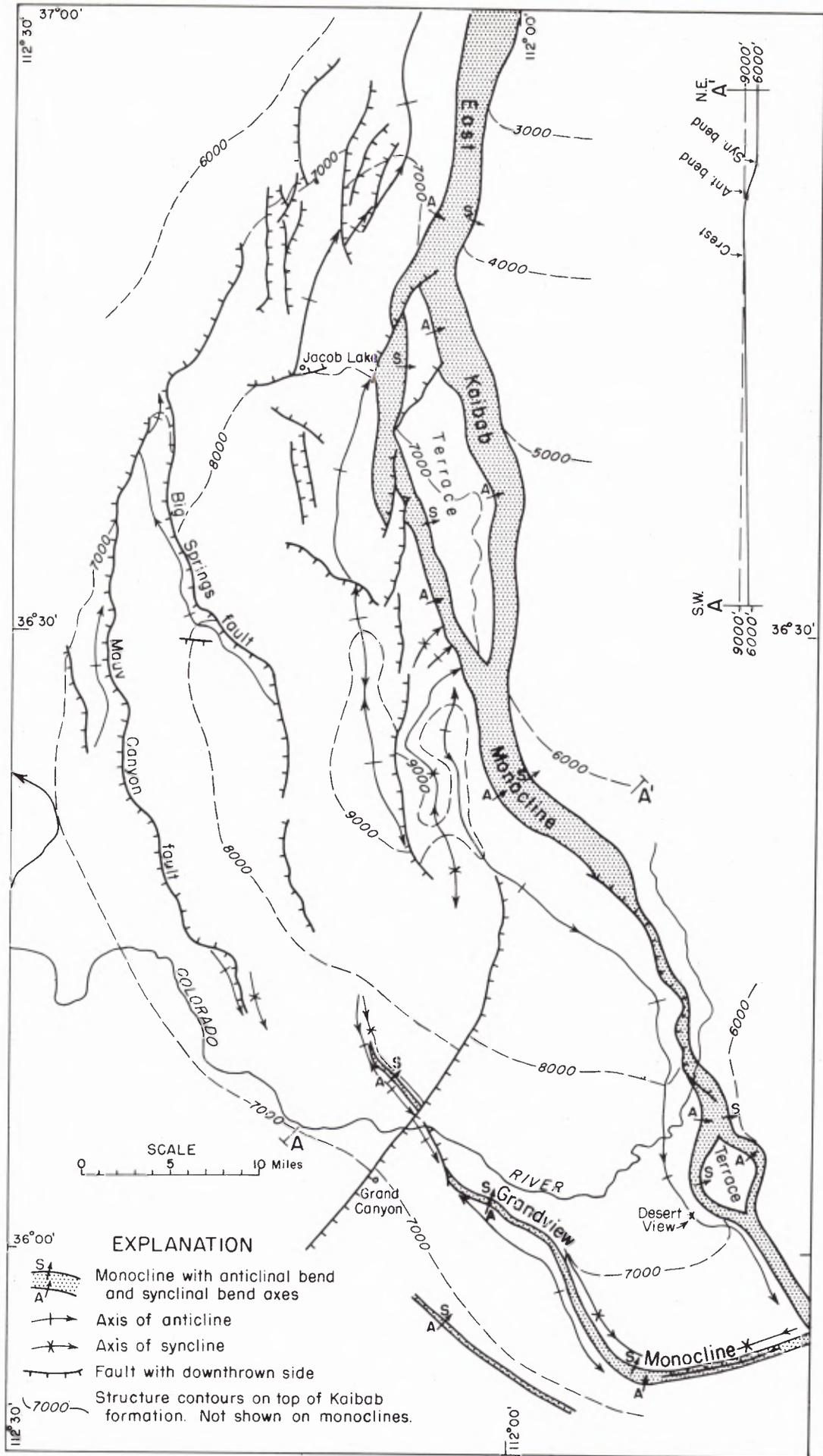


FIGURE 3. Kaibab uplift; adapted from Strahler, 1948.

are short in terms of the total length of the boundaries of the bench, and in most places there is no clear distinction between the bench and the adjacent tectonic divisions. The Cameron bench is essentially undeformed except for a very gentle regional dip toward the northeast. This dip may be as much as 2°-3° along the western side, but is less than 1° in the eastern part. The principal structural deformation takes the form of a few small grabens in the narrow western corner of the bench west of Cameron. The principal fault structure, the Cameron graben, has been shown by Reiche, (1937, p. 138) to be most likely Quaternary in age.

WUPATKI BENCH

The Wupatki bench lies between the Mogollon slope and the Coconino salient. It dips gently northeasterly and is about 60 miles long and 40 miles wide. The structural relief is more than 1500 feet. Only the northwestern limits are sharp along the Coconino and Black Point monoclines and the division between the bench and the Mogollon slope is for convenience. The gentle folding of the bench is dominated by the long northwesterly trending Tolchaco-Sunshine anticline.

Several hundred volcanic cones, which comprise the San Francisco centers, lie in the northwestern part of the bench northeast of Flagstaff, Arizona (Robinson, 1913 and Kelley, 1955a, fig. 2). Many of these cones are aligned in northwesterly, northeasterly, or easterly directions that are more or less parallel to the directions of prominent joint sets in the surrounding areas.

Numerous small faults and grabens, principally of northerly and northeasterly trends, are distributed across the Wupatki bench (Babenroth and Strahler, 1945, pl. 2).

MOGOLLON SLOPE

The Mogollon slope bounds the Black Mesa basin on the south and forms a wide southern border of the Colorado Plateau. Its primary characteristic is a gentle broad dip to the northeast (Darton, 1925, p. 202-204). It is about 200 miles long and 65 miles wide, trends west-northwesterly, and has a structural relief of 2000 feet. Only where the slope borders the Zuni and Defiance uplifts can a sharp demarcation be drawn.

The general trend of the fold axes on the Mogollon slope is northwesterly; however, some small folds south of the Black Mesa basin trend northeasterly. The western border of the Mogollon slope is modified by the Chevelon Creek-Holbrook buckle. This buckle is modified, in turn, by a cross-fault and the north-trending Richard Lake anticline.

Only a few faults are exposed on the Mogollon slope. The Atarque fault, along the Arizona-New Mexico border, is the largest. This northwest-trending fault is downthrown on the southwest side on the order of 2000 feet. A parallel fault with its downthrown side adjacent to the Atarque fault forms a narrow graben for a distance of about six miles in New Mexico. The Atarque fault is clearly the largest one within the southwestern part of the Colorado Plateau and it appears to be significant in the tectonic framework.

TECTONIC HISTORY AND ORIGIN

Little or nothing is known of the Precambrian tectonics of the region. However, before Cambrian time began the region must have been greatly deformed, uplifted, and deeply denuded to a lowland during a protracted period of stability which prevailed from late Precambrian well into Cambrian time. In the eastern and southern part of the region little or no Cambrian is present now, and it has

been presumed (McKee, 1951, p. 488, pl. 3) that the region was mostly positive through Silurian time. The trend of the positive was probably east-northeast. The tendency toward shoal and positive conditions continued during Devonian time except that the shore lines as indicated by the strike of the sedimentary wedge took a west-northwesterly trend (McKee, 1951, pl. 1). However, Huddle and Dobrovolsky (1952, p. 80) have deduced the possible existence of a "Granitic Holbrook Ridge" trending in a northeasterly direction between Holbrook and the Defiance uplift, and there may be other similar basement trends. During Mississippian time the hinge line between positive and negative tendencies took a northeasterly direction as the northwestern part of the region tilted slowly toward the Cordilleran geosyncline. During Pennsylvanian time a northwesterly positive trend may have been resumed, and even continued through Permian time. It should be realized that the data supporting the above statements are meager and certainly subject to several different interpretations. McKee's map (1951, pl. 2) shows essentially no Pennsylvanian strata beneath the central part of the Black Mesa basin. Brown and Lauth (1957, p. 80), on the other hand, interpret the presence of about 750 feet of Pennsylvanian strata. They also indicate a small basin in the Black Mesa area during Permian time whereas McKee infers a thinning in the form of an isopach nose in the same area. Kelley (1955a, p. 77) deduced a combined Permo-Pennsylvanian positive axis extending northwesterly across the basin. Several other unpublished interpretations have been made, but none of the interpretations made to date should be considered very definitive of past swelling or sagging in the area until more subsurface data are available. However, it does appear safe to conclude that for the Paleozoic as a whole the principal part of the region was a stable shelf with notable positive tendencies from time to time in relation to the surrounding area, except the Defiance uplift area.

During late Permian time the entire area was more or less tectonically stable and rising very slowly while some widespread stripping went on. During early Triassic time the region was tilted slightly westward (McKee, 1954, p. 23), and during late Triassic the region subsided continuously during the accumulation of nearly 2000 feet of floodplain materials. This subsidence may have continued through Jurassic time in the amount of 1000-2000 feet as aeolian and playa deposits accumulated. Thus, from Permian through Jurassic time the Black Mesa basin region subsided broadly on the order of about one mile without encroachment of the sea except in the western part during a relatively short time with the deposition of the Kaibab limestone. This rate of epeirogenic downwarping was approximately 10 times the rate of net subsidence during the previous Paleozoic time.

In late Jurassic time the region was broadly tilted northward on a hinge line that trended westerly across the southern part of the Black Mesa basin. From this line southward the gently upturned strata were broadly plicated down to the Permian. The rise by tilting appears to have amounted to as much as 2500 feet along the Mogollon Rim where Dakota beds rest upon Permian ones, and all the Triassic and Jurassic strata that intervene in the outcrops to the north are missing.

During Cretaceous time the entire region became a part of the Rocky Mountain geosyncline and subsided gradually until the basal beds of the sequence lay in the order of 4000 feet below sea level. This rate of geosynclinal



FIGURE 4. Aerial mosaic of 15-minute Arizona quadrangle A-96 showing the Coconino salient bounded by monoclines and faults. Inset is view southwest along Coconino monocline and Mesa Butte fault.

subsidence was on the order of 8 times that of the Permian to Jurassic subsidence and 40 times that of the previous interval. At present all but some 1500 feet of Cretaceous rocks have been eroded from the Black Mesa basin, the base of the Dakota in the center of the basin is about 5000 feet above sea level. In the San Juan Basin it is at about 2000 feet below sea level. Although some early Tertiary sediments may have spread across the Black Mesa basin area, it does not appear to have been an early Tertiary sedimentary basin. Most likely the entire area remained relatively high during Paleocene and Eocene times, contributing sediments to northern areas (Hunt, 1956, p. 76-79).

Most of the structural features of the Black Mesa basin region are probably the result of Laramide disturbances occurring in late Cretaceous or possibly earliest Tertiary times. Broad uplift with possibly some local tilting occurred during late Tertiary time. Brown (1956, p. 70) appears to believe that "the Defiance uplift has been a positive area since Pennsylvanian time, while the other uplifts surrounding the Black Mesa Basin are much younger (Laramide-Tertiary in age)." However, all Mesozoic formations are strongly and about equally deformed along flanks of the uplift and it therefore appears that the structural form as shown by contours on Kaibab, Chinle, or Dakota horizons are largely of Laramide deformation.

The principal evidence for the age of the folds of the region lies in the Kaibab uplift and the Kaiparowits basin, where late Cretaceous beds are folded and overlain by undeformed early Tertiary "Wasatch" beds in southern Utah. Elsewhere, the regional structures are covered by essentially untilted Miocene, Pliocene, or Quaternary volcanics; by the Pliocene Bidahochi formation; and by the Miocene (?) Chuska sandstone. Such pronounced folds as the Organ Rock, Echo Cliffs, and Comb monoclines have no direct stratigraphic means of dating them as Laramide. They have customarily been assigned to Laramide because of similarity to, or extension from, the folds where the relations are conclusive. For example, the Echo Cliffs monocline may be so dated because of its parallelism and proximity to the Kaibab monocline. The Last Chance syncline (Kelley 1955, fig. 2, no. 126) is well-dated as Laramide at its northern end, and it has been traced southeastward into the Black Mesa basin where its limbs involve the Organ Rock anticline. If it becomes reasonable to accept the Echo Cliffs monocline as Laramide then the Tuba City syncline at the foot of the monocline must also be Laramide and it, according to Doeringsfeld, Amuedo, and Ivey, continues southeastward into the French Springs syncline in the Black Mesa basin. One may progress in this manner, by extrapolation and reasoning by analogy, to most of the folds of the region, and not without some justification. Judicious caution should be exercised, however, for a long monocline or syncline well dated in one end may have been extended to another part during a later or earlier phase or period of deformation.

Although a Laramide age for most of the folds is generally accepted, Brown (1956, p. 70) reasoned that the shorter northeast-trending folds in the southern part of the basin between Holbrook and Winslow, are younger. Mc-

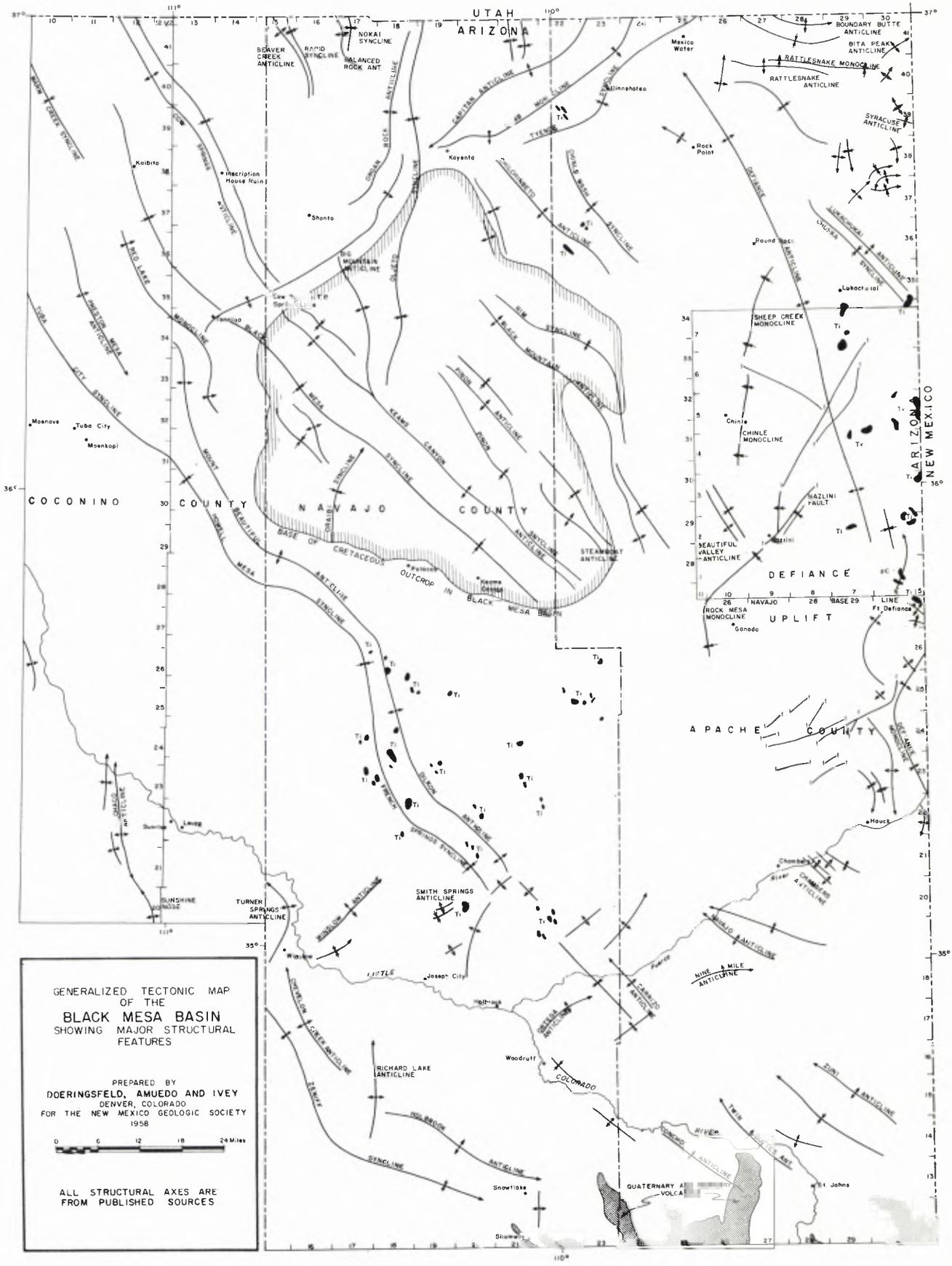
Cann (1938, p. 271-277) believed that west of the Zuni uplift on the Mogollon slope the present southwestward tilt of the Bidahochi beds was greater than its original dip thereby suggesting some late Pliocene or early Quaternary tilting. On the other hand, Repenning and Irwin (1954, p. 1825) believed that an easterly upward projection or Bidahochi beds of the Black Mesa basin to continuity with the Chuska sandstone atop the Defiance uplift was possible, and that tilting need not have been great.

From a regional point of view Black Mesa basin lies among a group of northerly trending uplifts, Defiance on the east, Monument and Piute folds on the north, and Echo Cliffs and Kaibab on the west. The Black Mesa basin folds, in turn, are a part of a wide belt of long, mild, northwesterly trending folds that extends from the Mogollon slope, south of the Defiance uplift, northwestward through the Kaiparowits basin, a distance of some 300 miles. The belt, furthermore, takes the form of an irregular long sag or open synclinorium whose trough is roughly formed, from northwest to southeast, by the Last Chance (Kelley, 1955, fig. 2), Warm Creek, and Black Mesa synclines and the downthrown side of the Atarque fault (Kelley, 1955a) south of the Zuni uplift. The southwestern side of the synclinorium is bounded by the Kaibab and Echo Cliffs uplifts, the Wupatki bench, and the Mogollon slope. The northeastern side is bounded by the Circle Cliffs, Monument, and Defiance uplifts together with the Piute folds. These, with the exception of the Circle Cliffs uplift, terminate obliquely against the synclinorium. On the southwest side, the Mogollon slope together with the southern parts of the Echo Cliffs and Kaibab uplifts parallel the trend of the synclinorium belt, but at the northern end, opposite the Circle Cliffs uplift, the Kaibab and Echo Cliffs uplifts obliquely intersect the synclinorium axes. It may be noted that the northwesterly trending synclinorium belt, of which Black Mesa basin is a part, is the most persistent trend of folds on the Colorado Plateau. It is in a sense a lineament which may be thought of as one of the tectonic splays from the Sierra Oriental far to the southeast and shows some expression in the way of deflections of the north-trending Basin and Range structures of Utah and Nevada (A.A.P.G. tectonic map of the United States). It may be noted that the Black Mesa-Kaiparowits synclinorium is not sharply separated from the adjoining northerly trending uplifts in that northwesterly folds lie to some extent between the uplifts. These two principal tectonic trends, northerly and northwesterly may be the product of two phases of Laramide deformation perhaps overlapping in part. If so, I am inclined to believe that the large and more prominent northerly trending uplifts formed first. The northwesterly trending folds of the synclinorium may have formed later by somewhat differently oriented exterior forces which may have modified the earlier uplifts to some extent just as the uplifts may have in themselves modified the more local stress fields.

In addition to the above two principal tectonic trends, there is a third lesser one of northeasterly trend. This takes the form of a sort of lineament of monoclines extending across the region from Coconino salient toward the San Juan dome in Colorado and including, on line, Coconino, Cow Springs, and the southern Comb monoclines.

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GENERALIZED TECTONIC MAP
OF THE
BLACK MESA BASIN
SHOWING MAJOR STRUCTURAL
FEATURES

PREPARED BY
DOERINGSFELD, AMUEDO AND IVEY
DENVER, COLORADO
FOR THE NEW MEXICO GEOLOGIC SOCIETY
1958

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ALL STRUCTURAL AXES ARE
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