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REGIONAL STRUCTURE OF THE SAN JUAN BASIN

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Introduction

The San Juan Basin is located in the northeastern part of the Colorado Plateau and is approximately the eastern half of the Navajo physiographic section of the Colorado Plateau Province. It is one of several large basins that are prominently interspersed or embayed into the ranges and chains of the great Rocky Mountain area between northern New Mexico and Canada. The San Juan Basin is in a sense a structural embayment of the Colorado Plateau into the southwestern edge of the Rocky Mountains.

The lowland part of the basin embraces 15-20 thousand square miles and is underlain by 25-30 thousand cubic miles of sedimentary materials above the pre-Cambrian basement. The northern and eastern rims are structurally complex. To the south the basin merges with a volcanic plateau and on the west the margin is locally complex but elsewhere merges with the western plateau.

The boundaries of the basin are in many places sharply defined whereas in other places the basin merges into adjoining depressions or uplifts. Several sub-basins, re-entrants, or embayments extend from the basin proper into the adjoining uplifts and plateaus.

Boundaries

The structural boundaries of the basin are diverse and differ markedly on all sides. They consist principally of (1) large elongate domal uplifts, (2) low structural platforms or arches, and (3) abrupt upthrusts.

On the northwest, laccolithic masses such as Carrizo, Ute, and La Plata Mountains are set upon a low, wide structural platform between the San Juan Basin, on the one hand, and Paradox and Sage Plain Basins on the other.

On the north, the southwestern part of the San Juan Mountains with its pre-Cambrian core rises abruptly from the basin.

On the northeast and east, a series of low, relatively narrow, linked, and en echelon structural arches rather incompletely separate the San Juan Basin from the shallow Chama Basin.

On the east, the most prominent structural boundary consists of the Nacimiento and San Pedro Uplifts which are thrust westward at moderate to steep angles over strata of the basin.

On the southeast, the long, gradual structural rise from the basin terminates at the highly fractured belt which marks the west side of the Rio Grande fault trough.

On the south, the principal structural boundary is the domal northwestward-trending Zuni Uplift. At the east end of this uplift the boundary is a low, wide divide along the axis of the southward-trending Mount Taylor syncline and the Acoma embayment.

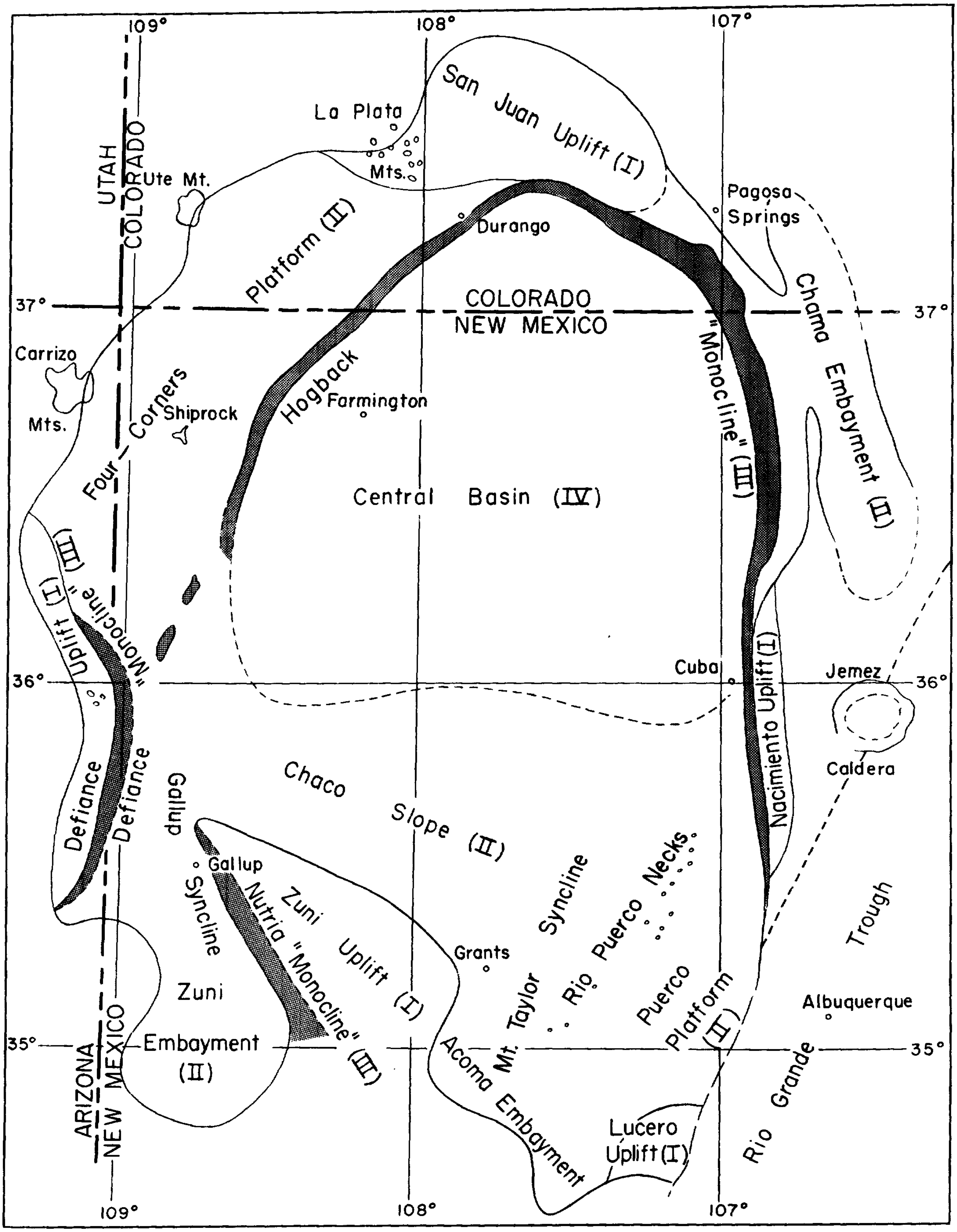
On the southwest, the northwestern end of the Zuni Uplift and the southern end of the domal Defiance Uplift form prominent structural boundaries to the basin. A long, narrow synclinal embayment termed the Gallup and Zuni Basins leads southward between the above uplifts.

On the west, the Defiance Uplift forms a pronounced structural barrier between the San Juan Basin and the Black Mesa Basin of Arizona.

The problems of the boundary of a basin are somewhat academic. However, the point that a basin includes its rim may be well taken, and hence, the above described major bounding structures are, on their inner halves at least, San Juan Basin structures. From another point of view, a structural basin is a set of nested basins consisting of the principal sedimentary units, the younger ones within the older. Thus the terms "Tertiary part of the basin", "Pictured Cliffs part of the basin", "Mesaverde part of the basin", or "Dakota part of the basin" are used. This results partly from the association of mineral resources with certain sedimentary units as for example the Fruitland coal basin or the Mesaverde coal basin. The concept of nested basins also results from the fact that some of the sedimentary units are basinal accumulations which more or less coincide with the structural basin.

The above stratigraphic approach to delineating the structural basin is supported by physiographers who may be influenced to define the limits of a structural basin at the separation between lowlands and uplands. Such a separation commonly coincides roughly with stratigraphy and the outcrop of the Dakota or some other resistant unit may be chosen. This coincidence between the rise to uplands and stratigraphy results most commonly where resistant beds are either abruptly flexed or faulted upward.

The stratigraphic choice of boundary and the concept of "nested basins" has structural basis



STRUCTURAL ELEMENTS OF THE SAN JUAN BASIN when it is realized that deformation may be confined or bounded by certain stratigraphic surfaces. Folding of beds by sliding across a broadly downwarping, relatively more competent, pre-Cambrian basement has been referred to as allochthonous. Folding of thin-bedded weak units between not too widely separated competent units is well known as drag or incompetent folding. It is possible that allochthonous folding has taken place above the basement in some basins where marked contrasts in beddedness and strengths occur within the sedimentary section. In the San Juan Basin, surfaces of allochthonous folding may occur, for example, at the top of the pre-Cambrian, Magdalena, or Entrada beds as well as others.

Finally, some are quick to point out that the most logical place to draw the boundary of a basin is, as with the analogous cases of a valley or physiographic basin, at the structural divide. This, however, appears to overemphasize tectonic importance of the basin and leaves little or no entity to the marginal uplifts.

Major Structural Elements

Four major structural elements may be delineated in the San Juan Basin, uplifts (I), structural platforms (II), "monoclines" (III), and the Central Basin (IV). Each of these elements is given a Roman numeral here and on the accompanying figure for the purpose of grouping.

The uplifts (I) include the Defiance, San Juan, Nacimiento, Lucero, and Zuni. Some of the principal features of these uplifts are shown in the following table.

Uplift	Trend	Length (in miles)	Width (in miles)	Structural Relief (in feet)	Steep Limb
Defiance	North	110	50	3, 500-6, 000	East
San Juan	Northwest	75	35	10, 000	South
Nacimiento	North	50	20	2, 000-8, 000	West
Lucero	North	30	14	2, 500	East
Zuni	Northwest	80	35	5, 500	Southwest

UPLIFTS BOUNDING THE SAN JUAN BASIN

The trends are either north or northwest; the lengths are slightly more than twice the widths; and the steep limbs face the basin in all except the Zuni Uplift.

The structural platforms (II) are relatively flat, wide, and low divide areas which alternate with the uplifts around the basin. They are as follows: Four-Corners, Chama, Puerco, Acoma, and Zuni. Most of the petroleum production to date has come from the platforms. Singly and doubly-plunging anticlines and synclines are distributed upon the platforms in irregular fashion. Their axes are mostly parallel to the structural contour of the basin. Some folds are oblique and a few are nearly normal to the regional contour of the basin. High-angle faults of irregular strike are especially numerous in the Chama and Puerco platforms on the east side of the basin. The throw on many of these faults is small in relation to their length.

The Chaco slope (II) is the southern part of the San Juan Basin that lies between the Central Basin to the north and the Zuni Uplift and Acoma-Puerco platforms to the south. In part it bears a regional relationship to the Central Basin that is similar to the platforms. It differs from them, however, in its more pronounced and continuous regional inclination toward the center of the basin and by the absence of a "monocline" separating it from the Central Basin.

The "monoclines" (III) are perhaps the most distinctive features of the basin. They are the Nutria "monocline" on the southwest side of the Zuni Uplift, the Defiance "monocline" on the east side of the Defiance Uplift, and the Hogback "monocline" which borders the Central Basin on all sides except the south. The Nutria and Defiance "monoclines", facing each other, bound the Zuni embayment. By some the Hogback "monocline" is considered to be the principal boundary of the San Juan Basin and the feature is so pronounced that it has the effect of at least marking a basin within a basin. No other basin in the plateau or mountain provinces, with the possible exception of the Powder River Basin of Wyoming, has such a long, continuous, and clearly marked "monoclinal" feature. In only a few places on the west side of the basin is the feature precisely a monocline. In most places the feature is a combination of an outer anticlinal bend and an inner synclinal bend. It is the steep flexure between these two axes that is designated as the "monocline" on the accompanying figure. In some places the dip of the upper limb of the anticlinal bend is only slightly less than that of the "monocline". It is common, however, for the inner limb of the synclinal bend to be quite flat or locally slightly reversed in direction of dip, but in many places it simply continues its basinward inclination only slightly less steep than the "monocline". The abrupt and nearly complete flattening of the inner limb is an especially noticeable feature of the structure. Along the Nacimiento thrust the "monocline" is associated only with the synclinal bend.

The Central Basin (IV), as designated on the accompanying diagram, is the floor or bottom of the basin. It lies inside the "monocline" by which it is bounded on all sides except the south. The Central Basin has a very long, low-dipping south limb and a relatively short north limb. The axis of the basin strikes northwesterly about through Governador. In terms of the "height" or top of the "monocline" the Central Basin has a depth of 2, 500-8, 000 feet. The outcropping rocks of the Central Basin area are largely the San Jose, Nacimiento, and Animas formations of early Tertiary age. Folds are fewer in the Central Basin than on the platform, and where present they are apt to be broad with gentle dips.

Tectonic Evolution

The pre-Cambrian history of the San Juan Basin is greatly obscured by the complexity of metamorphism and deformation impressed upon the rocks in pre-Cambrian and later time, by the deep erosion of the rocks in pre-Cambrian time, and by the subsequent widespread burial under Paleozoic, Mesozoic, and Cenozoic strata. Little or nothing is present in the outcrops to indicate that a pre-Cambrian basin was coincident with the site of the present basin. Furthermore, there is little to indicate from the thinly spread lower Paleozoic rocks that a depression at all resembling the present one had begun to form at that time.

During Pennsylvanian time, however, geanticlines began to form along the north, south, and east sides of the basin and sediments accumulated to a greater thickness in a northwesterly trending seaway more or less coincident with the present basin axis (Read and Wood, fig. 2). Recurrent uplift and minor deformation of the northern positive areas probably continued into Jurassic time. As successively younger strata lapped the older ones disconformities or even local angular unconformities were formed between beds on the flank of the uplift. Along the Piedra River on the north side of the basin the Entrada sandstone of Jurassic age covers a surface of erosion cut across upturned beds that range from Triassic to Pennsylvanian in age. The Pennsylvanian geanticline of the Zuni Uplift does not appear to have risen during Permian and Triassic times. It is possible, however, that activity similar to that along the northern belt may have occurred south of the Zuni Uplift during Triassic and Jurassic time. Supai beds of Permian age overlying pre-Cambrian quartzite in the Defiance Uplift suggest the possibility of crustal mobility in that area during early Permian as well as Pennsylvanian time. Wengerd elsewhere in this guidebook presents evidence of a sedimentary basin in the central area of the San Juan Basin in late Triassic time.

Recurrent rise continued in the region to the south of the present basin during Cretaceous time, and the region to the north of the basin again rose in very late Cretaceous time. Silver elsewhere in this guidebook indicates the presence of a small basin which probably developed in the western part of the present San Juan Basin area in Kirtland time. In fact, at this time the basin probably began to develop the first aspects of its present form. The rimming uplifts were accented, and the "monoclines" began to develop at the end of Cretaceous time. Locally, on several sides of the basin the lower as well as the upper beds of the Paleocene and Eocene rocks lap across plicated edges of late Cretaceous beds. In other places the Tertiary beds appear conformable with the uppermost Cretaceous strata in the monoclinal flexures. Uplift of the outer rim areas appears to have begun in very late Cretaceous time, continuing and spreading gradually to the inner rim of the basin through Eocene time when the Laramide orogeny culminated. Pre-Cambrian fragments first appear in abundance in the lower Tertiary beds and constitute evidence of the profoundness of the uplift, the vigor of erosion, and the relative thinness of the sedimentary cover along the axes of the uplifts.

In the San Juan, Brazos, and Nacimiento Uplifts, Oligocene and lower Miocene sediments and volcanic rocks rest upon a rather mature surface cut across all older rocks including wide areas of pre-Cambrian rock exposed in the cores of the earlier uplifts. These rocks and especially the volcanic piles on the north and east sides of the basin attained thicknesses up to several thousand feet through Pliocene time. According to Atwood and Mather (1932) a great peneplain (San Juan peneplain) developed across the domed and tilted San Juan volcanic pile by the end of Pliocene time. If this be so, it is a curious and puzzling fact that little or no product of this profound erosion of volcanic rocks is to be found in the San Juan Basin. The sedimentary counterparts of the great Miocene-Pliocene volcanic eruptions in the San Juan, Brazos, and Jemez Uplifts are, however, found in great quantity in the Rio Grande trough in the form of the Espinaso, Abiquiu, and Santa Fe formations. The San Juan Basin appears to have existed as a relatively high plateau-like feature which underwent erosion during much of Oligocene, Miocene, and Pliocene time. The whole area including the San

Juan volcanic pile may have been tilted east-northeastward and maturely eroded by the end of Pliocene time. The early Tertiary deformation along the east side of the basin may have involved only mild folding. The Nacimiento thrust probably did not develop until late Tertiary time.

The earliest Pleistocene glaciation in the San Juan Mountains reveals aspects of a non-mountainous terrain, whereas the succeeding Durango and Wisconsin stages were under mountainous conditions. This evidence is taken to indicate an uplift of the San Juan Mountains in Pleistocene time.

The point of this review of the depositional and erosional history of the San Juan Basin is that it reveals the tectonic history. From the lithology and stratigraphic relations of the sedimentary rocks in the San Juan Mountains and along the ancient Uncompahgre geanticline, it may be observed that the belt was mobile during a long interval of time and the stratigraphic record shows signs of regeneration during nine periods since pre-Cambrian time as follows:

(1) lower Paleozoic (?)
(2) Pennsylvanian
(3) Permian
(4) Triassic
(5) Jurassic (?)
(6) Late Cretaceous
(7) Early Tertiary
(8) Late Tertiary
(9) Pleistocene

In an analysis of the mechanics of deformation of the San Juan Basin, or many other Rocky Mountain basins for that matter, it is a mistake to consider the problem as though the region had suddenly been placed under deformation in Laramide or some such time. The San Juan Basin has had a long tectonic evolution which is reflected in its sedimentary record. The principal mobile axes developed northwesterly trends on the north and south sides of the basin as early as Paleozoic time. Although the evidence is not directly forthcoming it is possible that the direction and mobility may have been inherited from the pre-Cambrian terrane. The swing to a southerly direction of the mobile uplift axis on the east side of the basin is an influence of the late Paleozoic north-northeasterly trends of the mobile axes in the north-central part of the state (See Read and Wood 1947, fig. 2).

The late Paleozoic and early Mesozoic lines of mobility together with the form and composition of the sedimentary units exerted a strong influence upon the Cenozoic deformation. The early Cenozoic deformation appears to have rather largely outlined the present basin form. Modification of the basin by north-northeasterly trending faults along the southeast margin is the result of late Tertiary rifting which was associated with the development of the Rio Grande trough. The strong tangential compressive forces which existed during the late Tertiary rifting in the Rio Grande trough probably converted an early Tertiary asymmetrical fold on the east side of the basin into the Nacimiento thrust.

The details of deformation in the platforms and flanks of the uplifts are the result of complex "splitting" and deflection of the large forces as they moved the major structural yield units such as the uplifts with their irregular and diverse cores. It is difficult, of course, to satisfactorily orient the major forces, and whereas they may have been east-west in early Tertiary time, they may have been northerly in late Tertiary time. Either of these major forces may have given rise to secondary and tertiary directions as they motivated the major yield units.

One of the principal secondary forces set up during basinal downwarp is tangential to the rim and it results in shrinkage of the perimeter of the basin. As downwarping proceeds the outer parts of the beds are "pulled" toward the center of the basin and therefore must occupy a smaller area. One would expect radial fold axes from this action, and they are indeed present, especially in basins that approach circularity, such as the San Juan. On the other hand, tangential fold axes (parallel to the rim) result from either a push from a rising and expanding uplift or from differential confinement of the strata in the flanks of the uplift area. Both may work together. Upthrusts of basement or other competent masses may furnish an abutment against which basin sedimentary units move differentially up the flanks of the basin with respect to the underlying units. If an upthrust confinement is formed, the differential movement in the sedimentary units tends to fold the upper units somewhat more than the lower ones. Theoretically at least, the differential movement results in a decollement and the formation of allochthonous folds which terminate abruptly on a lower unit or "floor" of less crowded and possibly more competent rock.

In addition to confinement by upthrusts, confinement to the differential up-dip movement in younger units results from pinchouts, overlaps, and local unconformities all of which are common in the beds along the flanks of old geanticlines. Buckling or warping of the confined strata and overlying beds may result.

A characteristic feature of San Juan Basin structure is an apparent localization if not a concentration of folds "behind" or just outside the Hogback "monocline". If the "monocline" results largely from vertical force, this localization becomes difficult to understand. If, on the other hand, the "monocline" is the result of inward directed forces from the uplifts, the development of folds on the platforms "behind" the "monocline" is easier to understand. Some possibility exists that the Hogback "monocline" on the west side of the basin overlies a steep outward-dipping thrust at depth. From another point of view the Hogback "monocline" may represent the early deformational stage and the Nacimiento thrust the late stage. Additional mapping at the north end of the Nacimiento thrust may demonstrate what is already suggested there, that the thrust passes gradually on the surface and at depth into the "monocline" which bounds the Chama platform on the west. The structures along the east side are undoubtedly the result of several deformations.

The cause and mechanics of formation of intermontane basins are rather imperfectly known or understood. One of the fundamental questions is whether the activating forces of basin formation arise within the basin or in the bounding uplifts. Fanshawe (1947, p. 180) envisions that the uplifts are the result of deformation initiated in the basin and that the uplift structures are the "by-product" of competition between adjacent basins. Aside from the relative nature of the movement between the uplifts and the basin, it is important to recall that both have been elevated on a broad regional base on the order of about one mile since late Cretaceous time. In view of the marginal thrust faults on the east and the inward facing "monoclines" it appears more likely that the basin results from the crowding action of the uplifts and platforms under horizontal compressure forces.

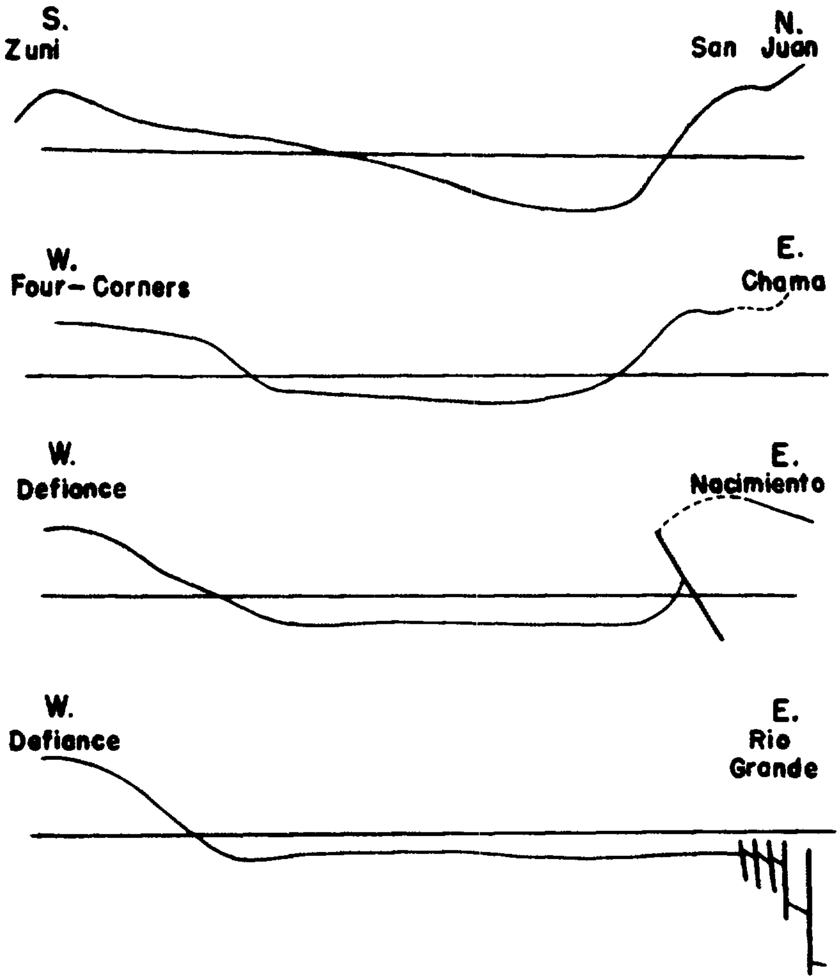
Most of the large basins of the Rocky Mountain area probably have a similar tectonic evolution. They differ in shape and detail principally because of differences in early history, thicknesses and character of the sedimentary units, and degree of deformation. Aside from the somewhat greater thickness of the sedimentary prism in the Bighorn Basin, which certainly played a role in the contrast, the principal difference is probably in the degree of deformation. At an earlier time the Bighorn Basin may have resembled the San Juan Basin of the present. The San Juan Basin and the Powder River Basin are much more nearly in the same stage of deformation.

In summary, the tectonic evolution of the San Juan Basin began at least as early as late Paleozoic time. The northern or Uncompahgre geanticline was regenerated repeatedly whereas the southern geanticline in the area of the Zuni and Defiance Uplifts were probably much less active. The modern aspect of the structural basin began in late Cretaceous or very early Tertiary time. It appears probable that the present structural elements including the domal uplifts, the platforms, and the "monoclines" developed by middle Tertiary time. Some broad eastward tilting may have taken place along the north and east sides of the basin in late Tertiary time. Fracturing of the eastern margin of the basin accompanied the rifting that gave rise to the Rio Grande trough in late (Pliocene) Tertiary time. The Nacimiento thrust may have developed at this time, and other sides of the basin may have been rejuvenated at this time.

The San Juan Basin is a result of geologically slow growth along mobile belts. The early formed arches controlled the subsequent deformation which culminated in early Tertiary time. The deforming mobile rims widened and progressively encroached upon the depressed undeformed basin residuum during early Tertiary time. The basin area is a sag resulting from the upward bulge and outward spread of the deforming mobile belt. As the basinal beds were crowded into a smaller downwarping area tangential compression in the peripheral area tended to develop radial folds. These, however, were masked by folds tangential to the basin which result from relatively greater confinement of successively younger sedimentary units in the basin.

From the regional analyses of the tectonic evolution of the basin certain general observations may be made concerning local structures.

(1) Owing to the long history of deformation, intensity of folds, and hence closure, may increase with depth.
(2) On the other hand, allochthonous type folds may bottom above the pre-Cambrian in some places along the flanks of the basin.
(3) Although basin deformation tends to develop radial and tangential folds the influence of older Paleozoic trends has resulted in a dominance of fold axes that are northwest and north in direction. Northeast trends are uncommon.
(4) Folds outside the "monocline" are more apt to be tangential and result in doubly plunging anticlines where crossed by radial axes.
(5) Folds inside the "monocline" are more apt to be radial and result in noses except for folds immediately at the base of the "monocline".
(6) Folds may diminish in intensity with increasing distance inward from the "monocline".
(7) The "monocline" may be a guide to traps if it passes into a thrust fault at depth.
(8) Buried tangential folds may be more numerous along the flanks of the ancient highlands.
(9) Porosity wedge belts occur marginal to the ancient highlands and where basinward plunging radial folds cross these belts "stratitecto" (combination) traps may result.



DIAGRAMMATIC STRUCTURAL PROFILES OF THE BASIN

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NOTES

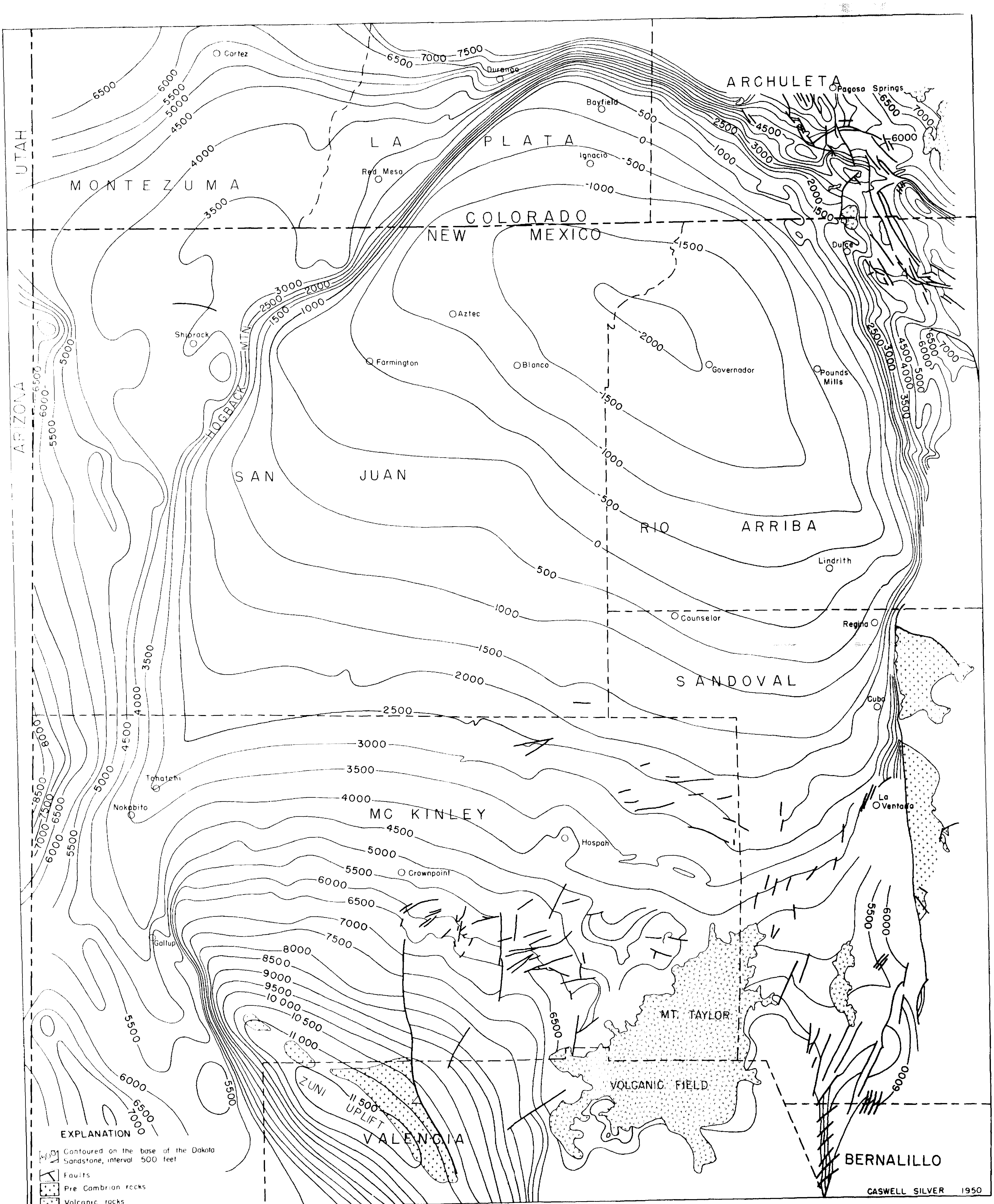

FIG. 6. MAP SHOWING STRUCTURE OF THE SAN JUAN BASIN, NEW MEXICO AND COLORADO

IN PART AFTER SEARS, J. D., HUNT, C. B., DANE, C. H., WOOD, G. H., ZAPP, A. D., AND OTHERS WITH ADDITIONS AND MODIFICATIONS BY CASWELL SILVER, 1950