TECTONICS OF THE SAN JUAN BASIN AND SURROUNDING AREAS

VINCENT C. KELLEY
University of New Mexico, Albuquerque, N. M.

The San Juan Basin lies in the southeastern part of the Colorado Plateau and comprises approximately the eastern half of the Navajo physiographic section. The Basin is a roughly circular depression located mostly in the northwestern corner of New Mexico, but extends slightly into southwestern Colorado. The lowland part of the basin, including much of the Chaco slope, embraces 15-20 thousand square miles and is underlain by 25-30 thousand cubic miles of sedimentary materials above the Precambrian basement. It is bounded on the east principally by the Nacimiento uplift and Archuleta arch; on the north by the San Juan dome; on the west by the Hogback monocline and the Four Corners platform; and on the south, rather arbitrarily, by the Chaco slope. By a broader concept the Basin is often considered to extend southward to the Zuni uplift, in which case the Chaco slope is only a subdivision. The San Juan Basin is also commonly considered to extend southwestward across the Chaco slope and the Gallup sag to the foot of the Defiance uplift. The Central basin part (Kelley, 1950, p. 102), bounded by the rimming monoclines and the Chaco slope is about 100 miles in diameter. The trough of the basin is arcuate to the north and lies well to the north of center and near the New Mexico-Colorado state line (Fig. 1). The average negative structural relief is nearly 5000 feet, but the structural relief against the San Juan dome is about 20,000 feet and against the Nacimiento uplift about 14,000 feet. Inasmuch as the Basin is largely defined by its rims and bordering tetonic elements, these as well as the Central basin are described in order.

FOUR CORNERS PLATFORM

The Four Corners platform, bounding the San Juan Basin on the northwest, is a northeasterly trending intermediate structure, some 110 miles long and 20-40 miles wide[1]. Its boundaries are sharply defined along the Defiance, Red Rock, and Hogback monoclines but elsewhere the boundaries with the Blanding basin, Paradox fold and fault belt (Kelley, 1955, fig. 5), and San Juan dome are poorly defined and arbitrary. The platform does not rise topographically above the Basin, but structurally it is 2500-4000 feet above the adjoining part of the Basin. The overall structural relief on the platform is nearly 4000 feet, being higher toward its northern and southern ends. It is lowest near its middle along the San Juan River where there is a broad sag extending from the Blanding basin to the Hogback monocline. Most of the gentle folds on the platform parallel its northeasterly trend although in the southern part some trend northerly or northwesterly (Beaumont, 1954).

RED ROCK BENCH

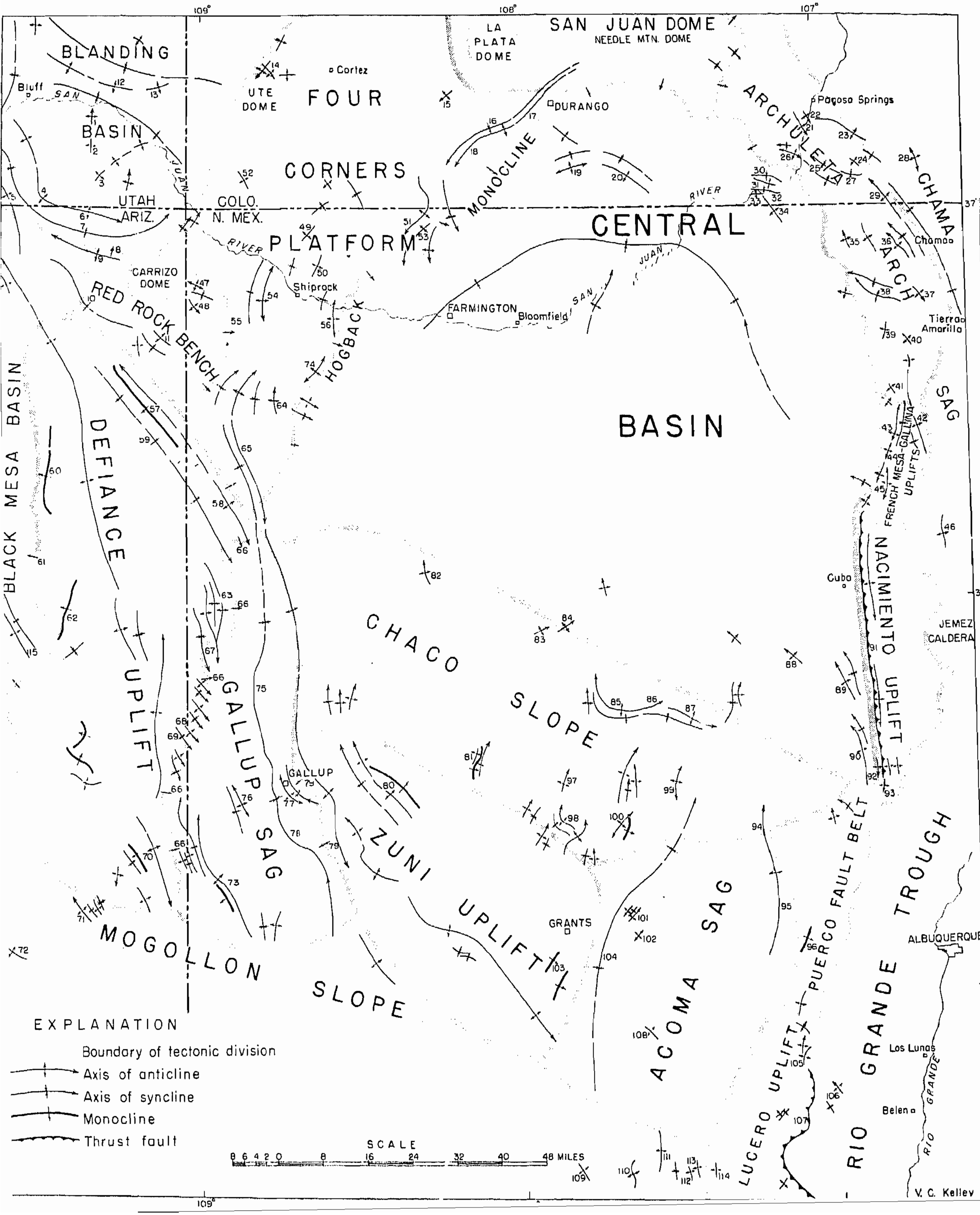
The Red Rock structural bench has been previously considered as part of the Four Corners platform (Kelley, 1955, fig. 5). In a sense, however, it is a northern salient from the Defiance uplift. It is bounded on the north and east by the Rattlesnake and Red Rock monoclines (fig. 1). Its southern boundary is chosen near the top of the Lukachukai monocline. The Carrizo intrusive dome occupies a considerable part of the northern portion of the bench, and a narrow sag modified by smaller folds intervenes between the dome and the Lukachukai monoclinal upwarp to the south. The Red Rock bench rises nearly 3000 feet structurally above the Four Corners platform to the north and east, but in general is very little lower than the Defiance uplift to the southwest.

DEFIANCE UPLIFT

The Defiance uplift is a northerly trending asymmetrical fold, steeper on the east, about 100 miles long and 30 miles wide, and is the De Chelly upwarp of Gregory (1917, p. 111-112). The maximum structural relief is about 8000 feet. The crest of the uplift is formed of several staggered axes. The principal rise of the uplift was accomplished along the Defiance monocline, which forms much of the eastern boundary. The Defiance monocline is remarkable for its sinuosity, being crossed by numerous southeasterly plunging noses and chutes. The principal one of these is the Todilto anticline near the eastern salient of the uplift where the northerly trend of the uplift turns northwesterly and parallels the Lukachukai monocline. A few small monoclines (Sheep Creek, Chinle, and Rock Mesa) are present along the western border, but generally that flank is part of a broad regional inclination into the Black Mesa basin and the average dip is only 2°-3°. Dips along the Defiance monocline range from about 30 degrees to vertical.

The Defiance uplift is the most irregular on the Colorado Plateau, a situation which may have resulted from the interplay of several differently oriented stress systems in and surrounding the uplift. Regionally the northerly trending sinuous monocline is aligned with the Hogback monocline, but the latter essentially dies out as it approaches the uplift. The Defiance monocline turns sharply northwestward and loses its sinuosity as it continues along the Toadlena anticline. The choice of the northeastern boundary of the uplift becomes a problem, that is, whether to include or exclude the Lukachukai warp. Some of the form of the Defiance uplift may be influenced by structure

[1]Most of the following descriptions of the separate tetonic elements such as this one are adapted and modified from a report to be published soon by the U. S. Atomic Energy Commission: "Fracture systems and tetonic elements of the Colorado Plateau" by V. C. Kelley and N. J. Clinton.



109°
108°
107°
37°
36
SAN JUAN DOME
NEEDLE MTN. DOME
LA PLATA DOME
BLANDING
Bluff
SAN
BASIN
UTE DOME
Cortez
FOUR
CORNERS
DURANGO
ARCHULETA
Pagosa Springs
CHAMA
ARCH
Chama
UTAH
ARIZ.
COLO.
N. MEX.
JUAN
RIVER
PLATFORM
CENTRAL
MONOCLINE
CARRIZO DOME
RED ROCK BENCH
Shiprock
HOGBACK
FARMINGTON
Bloomfield
SAN JUAN
Tierra Amarilla
SAG
BLACK MESA BASIN
DEFIANCE
UPLIFT
BASIN
FRENCH MESA-GALLINA UPLIFTS
NACIMIENTO
UPLIFT
Cubo
JEMEZ CALDERA
CHACO
SLOPE
GALLUP
SAG
GALLUP
ZUNI
UPLIFT
GRANTS
ACOMA
SAG
PUERCO FAULT BELT
RIO GRANDE TROUGH
ALBUQUERQUE
LUCERO UPLIFT
Los Lunas
Belen
RIO GRANDE
MOGOLLON
SLOPE
EXPLANATION
Boundary of tectonic division
Axis of anticline
Axis of syncline
Monocline
Thrust fault
SCALE
8 6 4 2 0 8 16 24 32 40 48 MILES
V. C. Kelley

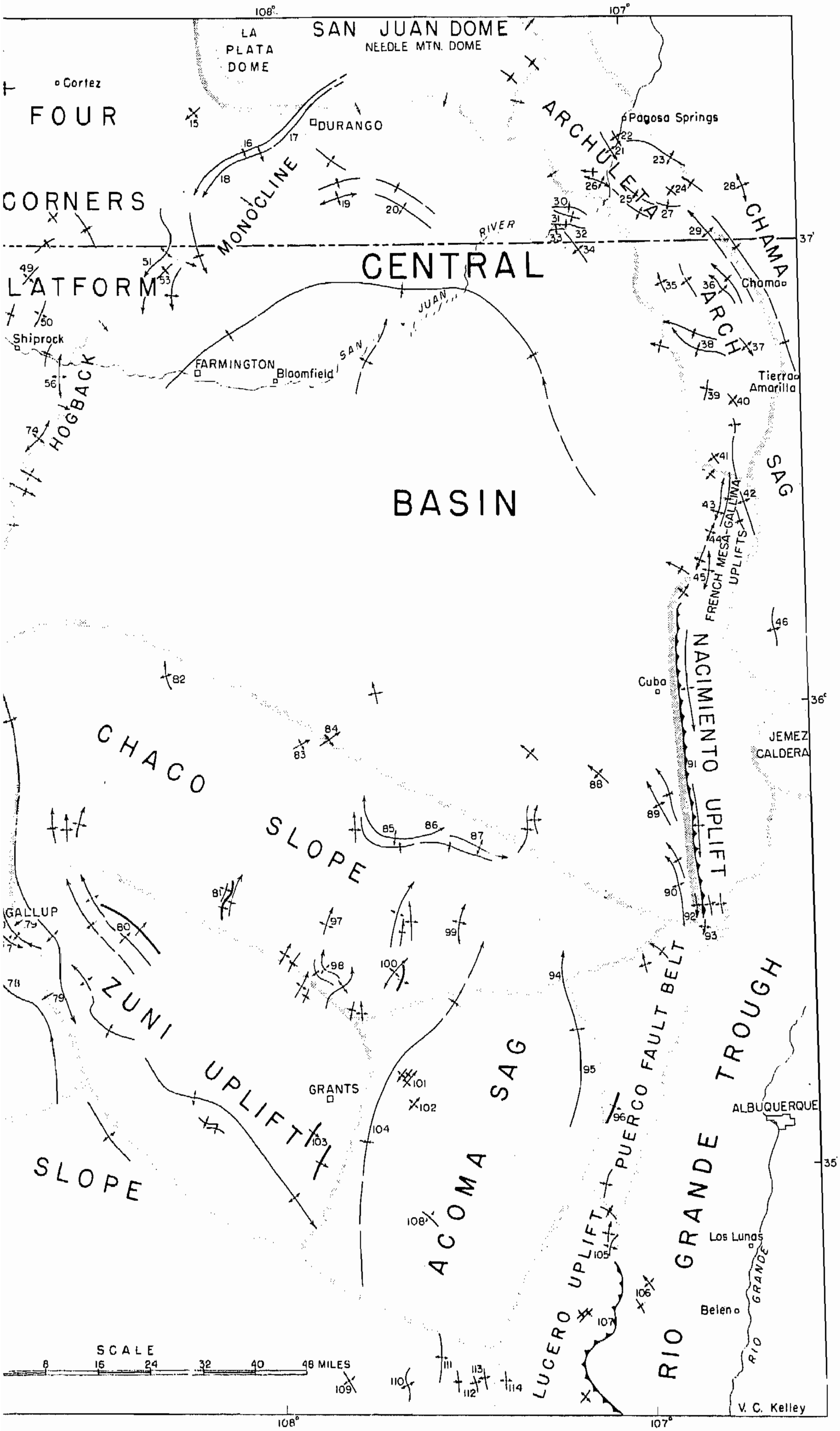


Figure 1 Tectonic map of San Juan Basin and adjacent areas.

NUMERICAL INDEX OF STRUCTURES

1. North Desert Creek anticline
2. South Desert Creek anticline
3. White Mesa anticline
4. Boundary Butte anticline
5. Water Creek anticline
6. Red Mesa anticline
7. Tshush syncline
8. Rattlesnake monocline
9. Toh Atin anticline
10. Red Rock syncline
11. Black Rock anticline
12. Aneth anticline
13. Hovenweep anticline
14. McElmo anticline
15. Thompsons anticline
16. Perrins syncline
17. Durango anticline
18. Red Mesa anticline
19. Bondad anticline
20. Ignacio anticline
21. Sunetha anticline
22. Stinking Springs anticline
23. Blue Creek anticline
24. Boone Creek anticline
25. Klutter Mountains syncline
26. Newton Mesa anticline
27. Coyote syncline
28. Gramps anticline
29. Chromo anticline
30. Round Meadow syncline
31. Cat Creek anticline
32. Gato syncline
33. Comodo anticline
34. Barello anticline
35. Monero anticline
36. Azotea anticline
37. Willow Creek anticline
38. Horselake anticline
39. Dulce anticline
40. North El Vado anticline
41. South El Vado anticline
42. Rio Chama anticline
43. Gallina anticline
44. Rio Gallina anticline
45. French Mesa anticline
46. Coyote anticline
47. Beclabito anticline
48. Syracuse anticline
49. North Chimney Rock anticline
50. South Chimney Rock anticline
51. Barker Creek anticline
52. Mancos Creek anticline
53. Southern Ute anticline
54. Rattlesnake anticline
55. Red Rock monocline
56. Hogback anticline
57. Lukachukai monocline
58. Toadlena anticline
59. Chuska syncline
60. Sheep Creek monocline
61. Chinle monocline
62. Rock Mesa monocline
63. Todilto Park anticline
64. Tacito anticline
65. Beautiful Mountain anticline
66. Defiance monocline
67. Zilditlai syncline
68. Window Rock anticline
69. Window Rock syncline
70. Black Creek monocline
71. Chambers anticline
72. Navajo anticline
73. Pinon Springs anticline
74. Table Mesa anticline
75. Nakaibito syncline
76. Torrivio anticline
77. Gallup anticline
78. Allison syncline
79. Nutria monocline
80. Pinedale anticline
81. Smith Lake anticline
82. Stoney Butte anticline
83. Smith Ranch anticline
84. Red Mountain anticline
85. Hospah anticline
86. Carica anticline
87. Chico anticline
88. Penistaja anticline
89. La Ventana anticline
90. Rio Salado anticline
91. Nacimiento fault
92. San Ysidro anticline
93. Tierra Amarilla anticline
94. Guadalupe anticline
95. Santa Rosa anticline
96. Ignacio monocline
97. Walker anticline
98. Ambrosia Lake anticline
99. Miguel Creek anticline
100. San Mateo anticline
101. Rinconada anticline
102. San Fidel anticline
103. San Rafael monocline
104. McCartys (Mt Taylor) syncline
105. Lucero anticline
106. Gabaldon anticline
107. Comanche fault
108. Acoma anticline
109. Cow Springs anticline
110. Red Lake anticline
111. Upper Red Lake anticline
112. Payne anticline
113. Miller anticline
114. Lawson anticline
115. Beautiful Valley anticline

ALPHABETICAL INDEX OF STRUCTURES

of the Paleozoic Defiance-Zuni positive, but most of it appears to be independent, and the echelon cross bowings of the Defiance monocline appear to result from some Laramide right-lateral shift during the uplifting.

GALLUP SAG

The Gallup sag is a narrow embayment extending southward from the San Juan Basin betwen the Zuni and Defiance uplifts. It is about 70 miles long and 8-28 miles wide. It is bounded sharply by the sinuous Defiance monocline on the west and the Nutria monocline along part of its eastern margin (Howell, 1875, fig. 121). It plunges into the central San Juan Basin across the Chaco slope to the north and fades imperceptibly into the low-dipping Mogollon slope to the south. The northern half of the sag is narrowed by the abrupt eastward shift of the Defiance monocline at the Todilto Park anticline, and the boundary on the east with the Chaco slope is chosen along a rather low, vague northward continuation of the Zuni axis to a possible connection with the Beautiful Mountain anticline located within the Four Corners platform. The trough of the sag, the Allison-Nakaibito syncline, is nearer to the eastern (Zuni) side and its eastern limb is shorter and of slightly less structural relief than its western limb. It plunges northward at about 60 feet per mile. The rather flattish bottom of the sag is modified by several short anticlines and synclines that strike roughly north-northwesterly (Sears, 1925, pl. 1). The largest of these, the Piñon Springs anticline, strongly modifies the southwestern part of the sag (Darton, 1925, pl. 52).

ZUNI UPLIFT

The Zuni uplift lies along the southern side of the San Juan Basin between Gallup and Grants, New Mexico. It is a northwesterly trending, doubly plunging, asymmetrical uplift, with steeper flank to the southwest (Darton, 1928, p. 138-148). Its length is about 55 miles and its maximum width is about 20 miles at its middle section. The structural relief is at least 5000 feet (Kelley, 1955, fig. 2). The uplift is bounded sharply by the Nutria monocline along the northwestern part of its southwestern flank and locally by small lesser monoclinal flexures along the northern and eastern edges (fig. 2). The crest of the uplift is curved and staggered. Faulting has also contributed to its irregularity. Several high-angle faults have considerably modified the structure, and in this respect the uplift differs from others of similar size on the Plateau. Throws on the principal faults range from a few hundred feet to more than a thousand feet (Kelley, 1955, fig. 2).

CHACO SLOPE

The Chaco slope is a somewhat arbitrarily defined structural subdivision of the larger San Juan Basin. It is a strip of low, northerly, regional dip some 110 miles in length and 30-40 miles in width, extending across the southern part of the San Juan Basin (Kelley, 1950, p. 102). The length is roughly parallel to the general strike of the slope and the width is in the direction of the regional dip. The over-all regional dip is about one degree and the structural relief is nearly 2500 feet. Along the south side near the Zuni uplift the dip is commonly several degrees, or locally even steeper, whereas to the north the beds are nearly flat. Along the northern edge the dips may again steepen slightly near the Cliff House sandstone cuesta and where the Chaco slope merges with the Central basin. The eastern part of the Chaco slope includes part of the McCartys or Mount Taylor syncline and it merges imperceptibly with the Acoma sag to the south.

In addition to the broad gentle flexes which parallel the strike of the slope there are a number of small plunging anticlines and small elliptical domes such as Smith Lake, Ambrosia Lake, San Mateo, and Miguel Creek (Sears, 1934, pl. 18). Several of these are asymmetrical and steeper to the east. Associated with these folds are numerous small high-angle faults which range in strike from northerly to easterly.

ACOMA SAG

The Acoma sag or embayment (Kelley, 1951, p. 125) lies largely between the Zuni and Lucero uplifts and is a part of a general structural embayment that extends southward from the Chaco slope and the Central basin. As with the Gallup sag there is little real structural demarcation to the north or the south.

The sag as outlined is about 25 miles wide and 50 miles long. McCartys syncline lies along the west side of the embayment and may be considered as the trough of the sag. Over all the sag plunges very gently northward and is strongly asymmetrical with a relatively steep short western limb, which is also the eastern flank of the Zuni uplift. A few very gentle, small anticlines and synclines are widely spaced in the southern part, and in the vicinity of Mount Taylor there are a few small domes partly covered by basalt flows. Although some of these domes are earlier in their origin than the late Tertiary basalt flows, the San Fidel dome appears to be younger as the flow is also deformed (Mohar, 1956, pl. 3).

LUCERO UPLIFT

The Lucero uplift is a small north-trending structural division located at the southeastern corner of the Colorado Plateau. It is 7-12 miles wide and 40 miles long, and is part of the Eastern Rockies deformed belt adjoining the west side of the great Rio Grande depression. It trends about N. 10° E. and is strongly asymmetrical to the east. Its crest in the central part is essentially at the large Comanche fault belt which forms the eastern front of the uplift. The north and south ends of the uplift terminate by plunging, which is considerably complicated by high-angle, north-trending normal faults. The western limb is gentle, with dips of 5°-10° westerly, whereas the eastern limb is sharply flexed downward into the fault zone. Although the topographic relief of the eastern escarpment is only a few hundred feet, stratigraphic relations supported by a deep well (Humble's Santa Fe No. 1, Sec. 18, T 6N, R 1W; TD 12,691') in the Rio Grande depression a short distance to the east indicate that the over-all throw into the depression is nearly 20,000 feet.

Overturning is present along the eastern base, and Kelley and Wood (1946) have interpreted the bounding structure as a thrust fault: Recently Duschatko (1953, p. 38-40) has suggested that the apparent thrusting and overturning along the eastern boundary may be in part the product of normal faulting of a west-facing earlier monocline and in part a Quaternary landsliding type of gravity adjustment.

PUERCO FAULT BELT

The Puerco fault belt borders the Rio Grande depression between the westward-tilted Lucero uplift on the south and the eastward-tilted Nacimiento uplift on the north. It is 7-22 miles wide and about 35 miles long. The northern part is mostly west of the southern end of the Nacimiento uplift and dies out irregularly into the Central basin. It is characterized by closely spaced normal faults trending N. 25°-30° E. Most of these faults are downthrown to the west, although several are downthrown to the east and form small horsts and grabens. A few of the faults dip westerly at angles as low as 45°. Although most of the faults have throws of only tens or hundreds of feet, a few have one or two thousand feet of throw. Mostly the beds dip easterly, but the structural decline in that direction is repeatedly nullified by upthrow across the faults in the same direction. The eastern boundary is largely obscured by overlapping late Tertiary beds, but in several places a major fault may be found with large downthrow into the Rio Grande depression. The western boundary of the belt trends northeasterly to northwesterly in a smooth curve concave westward along which the faults terminate in echelon. A more detailed description of the faults is given by Hunt (1936, p. 63-66). The more highly faulted part of the belt has been considered a part of the Basin and Range Province. Although it certainly possesses more structural relationship to the Rio Grande depression than most of the Colorado Plateau, the low dips in much of the belt make its structural separation from the Plateau problematical.

NACIMIENTO UPLIFT

The Nacimiento uplift lies along the eastern side of the San Juan Basin. It is about 50 miles long and 8-10 miles wide. The uplift is part of the western chain of uplifts of the Eastern Rockies. To the south the uplift dies out into the western margin of the Rio Grande depression. On the north the uplift is terminated at the west-northwesterly trending San Pedro Mountain fault, north of which are the smaller French Mesa and Gallina uplifts. To the east the Nacimiento uplift descends gradually into the broad Jemez structural bench which underlies the Quaternary and Tertiary Jemez volcanics (Bandelier tuff and Chicoma group).

The uplift is sharply defined on the west along the Nacimiento fault zone which extends almost due north with little or no curving for the full length of the range (Renick, 1931, p. 71-72). Overturning of beds on the downthrown (basin) side and low eastward dip of the fault are largely confined to the northern half of the range. In the southern part the fault, where exposed, is nearly vertical. Although the uplift is clearly of Laramide inception, it is nevertheless possible that some of the uplift and high-angle faulting may be late Tertiary in age. In the southern part of the uplift, a few miles east of the Nacimiento fault, several normal faults of the Rio Grande depression type (Jemez fault) step the uplift down to the east (Wood and Northrop, 1946).

FRENCH MESA AND GALLINA UPLIFTS

The French Mesa and Gallina uplifts lie in order northward from the Nacimiento uplift and form a connection with the Archuleta arch to the north. Together with the latter feature they constitute a narrow barrier between the large San Juan Basin to the west and the small Chama sag to the east. The combined length of the two uplifts is about 24 miles, and they are 4-6 miles wide. A small subsidiary elliptical anticline (Rio Gallina) intervenes between the two larger uplifts. The elevation of these structures is nearly 4,000 feet less than that of the Nacimiento uplift to the south and about 1,000 feet higher than that of the Archuleta arch to the north.

The long Nacimiento fault may be followed northward from the Nacimiento uplift with greatly diminished throw along the crests of the French Mesa and Gallina uplifts where it has been termed the Gallina fault (Lookingbill, 1955, p. 42). The Nacimiento fault appears to reverse its dip somewhere near the southern end of the French Mesa uplift, for the Gallina fault dips steeply westward and the western side along the crest of the Gallina uplift is upthrust as much as 800 feet (op. cit., p. 51). The French Mesa uplift is asymmetrical to the west, and the Gallina uplift to the east.

ARCHULETA ARCH

The structural feature here called the Archuleta arch has been referred to as the Archuleta anticlinorium (Wood, Kelley, and MacAlpin, 1948). It lies along a northeastern side of the San Juan Basin and forms a low structural divide between the basin and the narrow downwarp of the Chama-San Juan sag (Kelley, 1955a, p. 23). As part of the San Juan Basin rim the arch connects the San Juan dome to the northwest with the Gallina-French Mesa-Nacimiento uplifts to the south. It is about 75 miles long and 6-16 miles wide. The general arch is modified by numerous short folds and faults and is transected in its middle part by the northerly trending Archuleta dike swarm. In general, the small folds are staggered irregularly across the arch. The Azotea and Chromo anticlines are essentialy parallel to the general axis of the arch, but others, as the Horselake (Dane, 1948) and Newton Mesa anticlines, are diagonal. The faults are also irregularly distributed, and although several are nearly parallel to the trend of the arch, there are others that are oblique in both directions. The sharply flexed and locally faulted northern limb of the Horselake anticline is one of the principal modifications of the arch. The N. 70° W. trend of these and associated structures continues westward across the San Juan Basin toward the Ignacio anticline in the form of prominent joint sets in the Animas and San Jose formations.

SAN JUAN DOME

The San Juan dome is a roughly circular uplift of complex nature and geologic history (Cross and Larsen, 1935, p. 110-113) which lies north of the deepest part of the San Juan Basin. A great array of Precambrian, Paleozoic, and Mesozoic rocks is exposed within the uplift and was involved in the doming. Surmounting the dome are great piles of acidic volcanic rocks of middle and late Tertiary age and these have been modified by much faulting and some tilting or doming. The highest part of the multiple uplifts is the Needle Mountain dome, whose Precambrian peaks rise to as much as 14,084 feet. On the basis of extrapolation of the normal stratigraphic section above these peaks a structural relief against the bottom of the San Juan Basin of about 20,000 feet has been shown (Kelley, 1955, fig. 2). In addition to the several Precambrian periods of deformation, disturbances are known to have locally affected the region of the San Juan dome in late Paleozoic, Triassic, and Jurassic times. However, most of the present structural uplift was probably produced during Laramide time, although considerable doming has been postulated for late Pliocene time (Atwood and Mather, 1932, p. 21).

CENTRAL BASIN

The Central basin or San Juan Basin proper roughly coincides with the closing structural contour which, for the top of the Triassic Chinle formation is about 2200 feet (Kelley, 1955, fig. 2), and for the Cretaceous Dakota sandstone about 3300 feet. On the west, north, and east sides the Central basin is rimmed by a series of continuous hogbacks that are commonly and most typically Mesaverde sandstone beds. The length of this rimming flexure is about 260 miles. On the south, however, the basin is without sharp structural boundary. Even if the Chaco slope is included within the basin, the boundary is still without structural definition on the flank of the Zuni uplift. The southern boundary with the Chaco slope has been roughly selected by connecting the southern terminations of the rimming monoclinal flexure. This connection more or less parallels the structure contours and happens to correspond closely to the escarpment of the Cliff House sandstone cuesta. The rather remarkable straightness of this escarpment along the south side of the basin suggests some subtle structural control such as a slight steepening of the dip in the cuesta or a fractural zone parallel to the escarpment but in the Menefee beds just to the south.

The rimming flexure is irregularly sinuous and ranges greatly in its height and width. Thus along the west side the flexure is 2000-3000 feet in structural height, 1½-4 miles wide, and in many places nearly an ideal monocline. The steep limb averages about 35° of dip. Along the northern side east of Durango the flex rises more or less uniformly up the San Juan dome with dips of 15°-20° through a width of 15-20 miles. Along the northeastern side, bordering the Archuleta arch, the flexing somewhat resembles that along the western side although for the most part the flex is of lower dip and wider. Along the Nacimiento uplift the rimming flex assumes its most severe form where it is either overturned or flexed up steeply into the Nacimiento fault. Thus, there is much heterogeneity of the rim with regard to form and magnitude of deformation. The basin is most strongly asymmetrical north to south, but is also asymmetrical to some extent in almost any direction.

ORIGIN OF THE BASIN

Although the San Juan Basin may have its form and tectonic evolution controlled in a few places by ancient disturbances, notably those of late Paleozoic time, it is predominantly a Laramide feature. Burton (1955, p. 88) indicated a northern source for Dakota beds in the northern part of the basin, but this source area appears to have largely disappeared during Mancos and Mesaverde times. Zapp (1949), Silver (1950, p. 112), and Baltz (1953, p. 83-84) all concluded that a northeastern source of sediment may have reappeared in Pictured Cliffs (Montanan) time, thus suggesting at least a northwesterly trending sag along the present site of the basin. More definite rise of areas north of the basin is suggested by "new" detrital material appearing in the upper part of the Fruitland and younger beds (Barnes, Baltz, and Hayes, 1954) along the northern rim of the basin. A late Montanan age has been assigned by Reeside (1924, p. 24) to the Fruitland and Kirtland beds. Reeside (1924, p. 51) long ago postulated a northern source for the late Cretaceous-Paleocene McDermott and Animas beds although at that time he considered them to be Eocene ? (pl. 2). The best preservation of the unconformable, overstepping, and intertonguing relations of the several late Cretaceous and early Tertiary units that shed light on the nature and timing of the rise of the basin rim near Bridgetimber Mountain southwest of Durango. These relations have been excellently illustrated by Baltz (1953, fig. 6) and are shown here in Figure 2. From this it may be seen that along the northwestern side of the basin the monoclinal flex began during early Animas (late Cretaceout) time and culminated in late Animas (Paleocene) time. The cross section further shows that some flexing continued during and following San Jose (Eocene) time. The early flexing involved both the foot and head of the monocline whereas the later flexing did not; instead, the later growth appears to involve only the head of the monocline. This is indicated by the absence of bending of the San Juan beds above the original synclinal bend. The synclinal bend

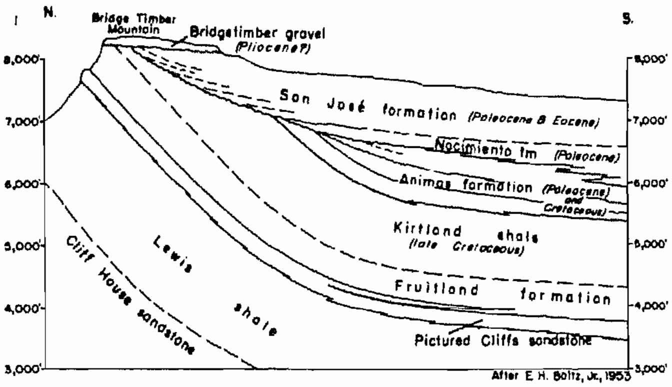


Figure 2. Diagrammatic cross section showing overstepping stratigraphic relations along the hogback monocline near Bridgetimber Mountain.

in the San Jose is more than two miles west of that of the McDermott. The mechanical action of bending during Eocene time resulted in widening and increasing the height of the monocline, but not steepening it except near the head. These relations might be taken to indicate that the Four Corners platform rose rather than that the Central basin subsided, and that if there is a fault in the basement over which the near surface beds are draped it is more likely to be a gravity one than a thrust.

Similar overstepping relationships have been found along the north and east sides of the Central basin, all of which suggest a late Cretaceous and early Tertiary age for the basin. Some subsidence occurred, however, during or after San Jose (Eocene) deposition for along the east side of the basin opposite the northern end of the Nacimiento uplift these beds are turned up as much as 80° (Renick, 1931, pl. 1). It appears, therefore, that the rimming action around the basin was not simultaneous and that the basin form is the result in part of the deformations of the bordering uplifts. Within the Central basin there are small folds and these are more common in the Animas, as at Ignacio, Bondad, and Cat Creek, than in the San Jose. Although this may be due to the fact that the Animas outcrops are nearer to the rim than the San Jose, it also is possible that some mild folding affected the Animas and Nacimiento beds prior to the deposition of the San Jose beds. Therefore, in the central part of the basin there may be pre-San Jose folds that are not expressed in the San Jose beds.

The Animas, Nacimiento, and San Jose beds are now largely present only within the Central basin. However, during early and middle Tertiary times they have extended considerably beyond the present confines of the Central basin especially across the platforms, slopes, and lower parts of some of the early formed bordering uplifts. Thus, San Jose equivalents may have extended across the Four Corners platform, parts of the San Juan dome (Irving, 1904, p. 75), Chaco slope, Archuleta arch, Acoma sag, etc. Long ago Gregory (1917, p. 81) suggested that the Chuska sandstone was an outlier of the Wasatch (San Jose) formation which at that time included the Nacimiento beds. These overlapping extensions would, of course, have been thinner in most places than in the Central basin. It is also possible that many of the rimming tectonic elements may have been slightly developed during most of Montanan time and that sedimentary units as old as the Pictured Cliffs sandstone may have thinned and locally overstepped one another toward such features as the Zuni and Defiance uplifts as well as the Four Corners platform.

Some of the mechanisms that may have acted during the development of the San Juan Basin have been discussed earlier (Kelley, 1950, 1951) and at that time it was concluded that basin mechanics of the type postulated by Thom (1943) were not important in the deformation of the San Juan Basin. Rather it was concluded that the Basin was mostly a byproduct of surrounding positive deformations, especially of the uplifts. This is an easy concept to embrace owing to the fact that along the eastern and western sides the Basin does not rise gradually toward the uplift, but instead the deformation is abrupt into the adjoining uplifts. On the other hand, some suggestion that the Basin was "active" rather than passive in its formation lies in its great asymmetry in the northerly direction. Thus, the basin floor is tilted northward and its deepest part generally adjoins the greater uplift in the San Juan dome as though they were counterparts of a single mechanism at depth. This also resulted in a sort of rotational shift along the Hogback monocline because, although the Four Corners platform behind the monocline is flattish, the foot of the monocline descends northward. These features make it appear that some basining negative force must have operated at depth even though basin mechanics and basin folding of an origin suggested by Thom may not have been important. It appears, therefore, that the San Juan Basin is a byproduct feature in its southern part, but perhaps a feature of active origin in the northern part. Perhaps one may generalize from this concerning nearly all Rocky Mountain basins. In the case of the extramontane basins such as those of the Colorado Plateau or the High Plains, individual basins may be either or both active and passive in their origin. Thus, the San Juan, Piceance, and Uinta basins experienced their own subsidence whether the adjoining uplifts were specifically active or not. The Denver-Julesburg and Powder River basins are probably also of this category. On the other hand, such basins as Black Mesa, Kaiparowits, Henry, and Blanding are by-products of adjacent active uplifting. Basin mechanics is essentially unimportant in either of the above types and probably only

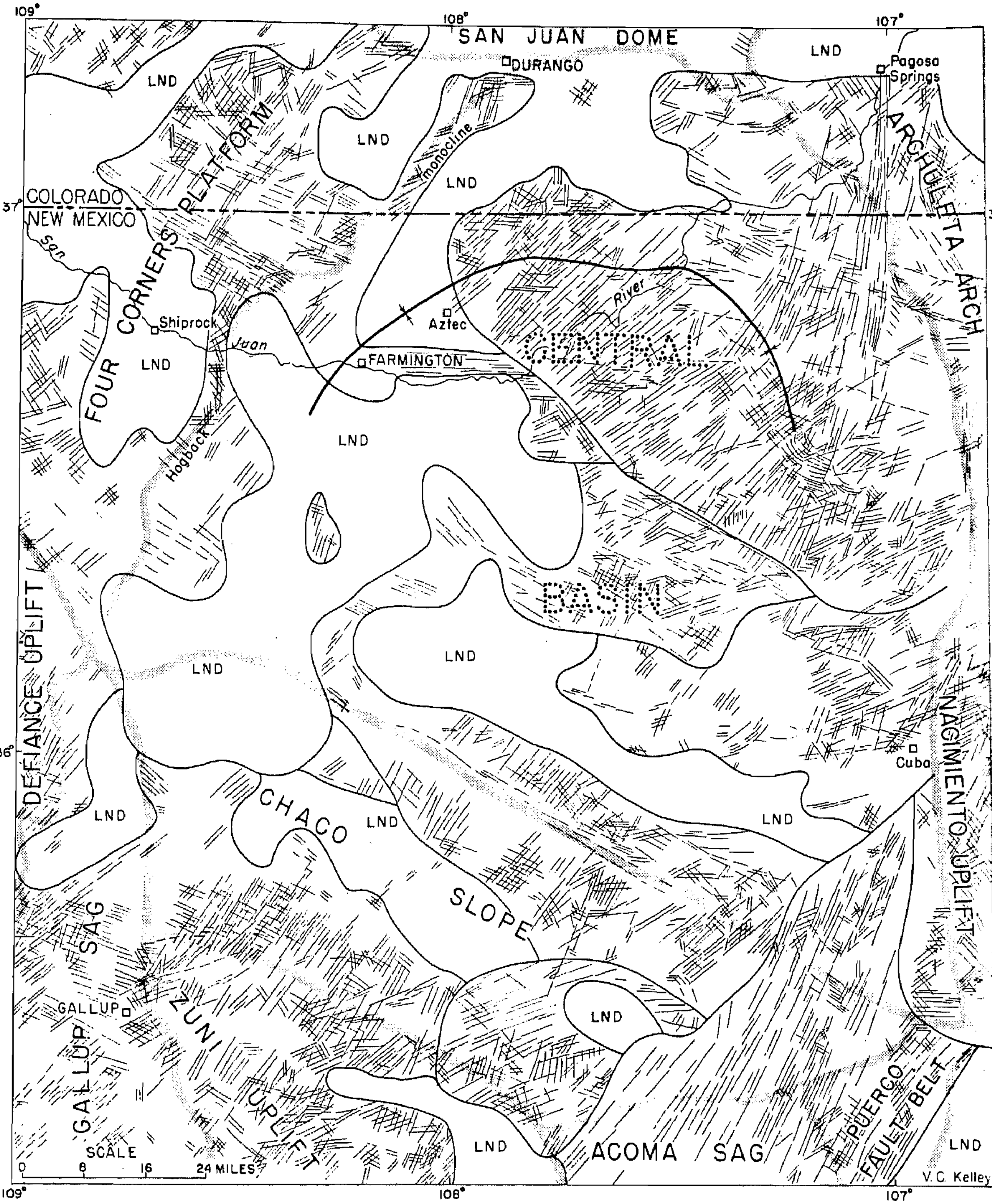


Figure 3. Diagrammatic map of the fracture systems of the San Juan Basin and surrounding areas. Only the principle sets are shown and the relative length of the lines roughly indicates the dominance and persistency of the sets. Areas of little or no data, LND. Division into sectors of different orientation and dominance of sets is somewhat arbitrary and done chiefly as an aid to study of the map.

becomes important in the intermontane basins such as the Big Horn Basin in Wyoming where basin deformation is more advanced than in the extramontane regions. Where basins are both passive and active in their derivation, the matter of relative timing between basin and uplift activity enters into the problem. Although this may be difficult to determine, the following proposition may be useful for analysis of the problem. If uplifts indent or protrude an otherwise smooth basin outline, the basin, in that part at least, may be older than the uplift or passive in its development; and vice versa, if uplifts terminate at a basin without indentation, then the basin may be younger than the uplift and/or active in its formation.

In view of the recent reported occurrences of oil production in the San Juan Basin from fracture reservoirs a few observations concerning the regional joint systems may be timely. Figure 3 shows sectors of different dominance of fracture systems. This has been generalized into sectors from a more detailed map. The only purpose of outlining the sectors is to attempt to point out broad and irregular differences among dominant sets of joints and surface linears. It is difficult to deduce logically the significance of the over-all pattern. The sets that strike northeasterly to north-northeasterly are prevalent. They are most strikingly so in the northeastern sector where sets converge somewhat toward Pagosa Springs, in the southeastern part, notably in the Acoma sag and Puerco fault belt, and in the southwesterly part in the Defiance uplift, Gallup sag, Zuni uplift, and Chaco slope. Northwesterly trending sets are next in abundance, and although they are widely distributed, their dominance appears to follow a wide band across the southern part of the Central Basin from the southern part of the Nacimiento uplift to the Four Corners platform. Too much emphasis should not be placed on the dominance of "northeast" and "northwest" directions. Actually there is wide divergence either way from these two directions, and in fact there is probably as much deviation from the northeast and northwest as there is from north and west. We are so accustomed to emphasizing the principal compass directions that deviations from these tend to be overemphasized. The over-all deviation of direction of joint sets from one pair of right-angle compass directions may be essentially as great as for any other pair. In many localities there are several directions of fracture sets and the angular variation between any two sets is considerable, perhaps 15°-75° as a rough approximation. Furthermore, the directions of the two most prominent joint sets change significantly within short distances, often abruptly across a fault, sharp fold axis, or sheeted zone. This aspect is not readily shown on the generalized diagram of Figure 3, but is more commonly present and is readily noted on more detailed joint maps. In general, heterogeneity is the rule and this must be remembered in all efforts to analyze fracture systems in terms of stress fields. The recognition of such heterogeneity should not be discouraging and one should not "average" or try to make regularity where none should exist. In view of the great variation in the orientations and dimensions of the folds and faults, to say nothing of the great variations of dimension and strength of the numerous rock units, it would be very odd indeed if the fracture systems revealed much regularity. It is also noteworthy that there is very little consistent geometric regularity or coincidence between fracture systems and the form of the various folds. Prominent fracture sets commonly extend from uplift to basin with little or no change in attitude. Many joints or joint sets may have been formed shortly after the deposition and burial of sedimentary units. They probably continued to form during numerous later times, especially at times and places of flexing and faulting, provided that the already existing joints could not serve in the necessary mechanical accommodations. It is a grave error to assume that all the joints observed in an uplift, basin, monocline, or along a fault are the brittle results of that particular episode of deformation.

One may ask in view of the above statements whether it is worth while to map joints at all. The answer is that one can never be sure until the data are collected and analyzed locally, but with the proper knowledge of their orientation within the regional tectonic framework. Perhaps more emphasis should be placed upon sheeted zones, linears due to alignment of numerous short fractures, subtle boundaries of change in orientation of sets (sectors), and the variation of the acute angles between the principal sets. The systematic mapping and study of joints is just beginning and much more collection of data is needed.

In a mining district, mapping of veins would not be discontinued because their orientations or irregularities were not understood. In an oil province joints may be "veins" for oil and gas as well as water. Here as in mining geology, intersections, changes in attitude, increased permeability locally in the walls, local shattering near a sheeted zone, etc., all may aid in concentration of the "vein" matter. Shattered intersections of two or more sets may have served as channelways for the fluids, and if oil was being transported by water escaping upward in a basin, it might be segregated from the water in the smaller or tighter fractures adjoining the channelway of water movement. Thus, in searching for oil in fractures, all "anomalies" in the fracture system, such as marked intersections, increased number of joints, abrupt changes in strike, variation of angles of intersection of sets, axes of bending such as monoclines, terraces, or bowings, where beds commonly are more fractured, and radial or circular fracture arrangements. Where exposures are poor, straight or regular stream or valley directions that are unrelated to strike of weak beds or known slopes of older erosion surfaces may be controlled by a concentration of fractures.

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