



The Rio Grande rift, Part I: Modifications and additions

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1971, pp. 191-201. <https://doi.org/10.56577/FFC-22.191>

in:
San Luis Basin (Colorado), James, H. L.; [ed.], New Mexico Geological Society 22nd Annual Fall Field Conference Guidebook, 340 p. <https://doi.org/10.56577/FFC-22>

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THE RIO GRANDE RIFT, PART I: MODIFICATIONS AND ADDITIONS

by

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INTRODUCTION

The Rio Grande rift cleaves New Mexico in two and splits Colorado halfway up the middle. For about 600 miles, it provides the highest mountains and deepest intermontane basins of the territory it traverses. It is somewhat like a plowed furrow with raised shoulders and half full of soil (see fig. 1). Topographic relief ranges up to 8,000 feet and averages about 5,000 feet along the main basins. Bed-rock relief varies from several hundred feet in some of the smaller basins to a staggering 36,000 feet in the San Luis Basin. Thickness of alluvial fill ranges from 400 feet in the embryonic Estancia Basin to an estimated 30,000 feet in the San Luis Basin and probably averages at least 5,000 feet. Three-fourths of the population of New Mexico, plus the inhabitants of a number of communities in Colorado, Texas, and Chihuahua, live along this gigantic scar and derive much of their irrigable land and water supply from it.

Bryan (1938, p. 197, fig. 45; p. 198) coined the term "Rio Grande depression" to describe the series of basins followed by the Rio Grande from the San Luis Valley of Colorado through New Mexico to El Paso, Texas. Within this length, he outlined 8 structural basins (San Luis, Espanola, Santo Domingo, Albuquerque-Belen, Socorro, Engle, Rincon, or Las Palomas and Mesilla) separated from each other by canyons or constrictions and likened the Rio Grande to: ". . . a stream flowing from one sand-filled tub to another through narrow troughs" (op. cit., p. 198). Kelley (1952, 1954, 1956) described many structural details of the depression and discussed their regional tectonic setting. Much of our understanding of the rift has developed over a period of many years from stratigraphic, paleontologic and hydrologic investigations of the alluvial fill, from geomorphic studies of erosion surfaces and from geophysical profiles of the rift structure. So many researchers are involved that space does not permit a systematic review of their contributions; some of the more important papers are cited in the text.

The purpose of this paper is to examine the extent and boundaries of the rift and to propose modifications where necessary. The central portion of the rift is relatively distinct geomorphically, but the ends need some discussion and modification. In the following sections, evidence will be presented for adding the upper Arkansas graben at the north end, for including a number of small downwarps along the inflection line of the uplifted eastern border, for widening the rift south of the Albuquerque Basin into a series of parallel basins separated by intrarift horsts, for bifurcation of the rift along a weakly-developed, southwest-trending limb through the San Augustin Basin and for a

possible extension of the rift into the Los Muertos Basin of northern Chihuahua. Figure 2 shows the extent of the rift as visualized by the author and some of the features to be discussed later.

It was originally intended to center the paper around a series of observations about the rift and a model synthesized from them. However, in the process of writing the paper, it was realized: (1) that the characteristics of an object are somewhat dependent upon where the boundaries are placed and (2) that data from geological field work over the past decade suggests that a number of modifications should be made to the boundaries of the Rio Grande rift from those originally set forth by Bryan (1938) and Kelley (1952). To both modify the boundaries and derive the model would make this paper overly long, hence the project has been divided into two parts with the observations and the model to be published in a later paper. A brief abstract of Part II is included here to provide perspective for the boundary problems (and controversy for the field trip).

ABSTRACT OF PART II

Rifting began at least 18 million years ago as evidenced by the Middle and Late Miocene fossils in basal alluvial fill and by K-Ar dates on interbedded volcanic rocks. Concurrent volcanism has occurred mainly along the medial axis and west side of the rift; present hot spring activity (Summers, 1965) shows a similar distribution. Compared to other rift valleys, the alluvial fill in the Rio Grande depression was relatively free of interbedded volcanic rocks until about 5 million years ago when volcanism became more prominent. A histogram of published K-Ar dates, supplemented by archaeological dates and geomorphic estimates on very young flows, suggest that the rate of volcanism may be increasing. Lipman (1969) has recently demonstrated that primitive tholeiitic flood basalts were erupted in the Rio Grande rift near Taos while alkalic, crustally contaminated basalts were being erupted to either side. He suggested that high heat flow and an upward protrusion of the mantle beneath the rift may have allowed fractionation of basalt to take place at an unusually shallow depth. Renault (1970) has shown that basalts within the rift near Las Cruces and west of the rift near Grants are relatively undifferentiated compared to basalts east of the rift.

South of the upper Arkansas Valley, structural relief is greater along the east side of the rift. Precambrian and Paleozoic rocks generally comprise the uplifts to the east, whereas thick sections of Tertiary volcanic and sedimentary rocks form much of the western boundary. The

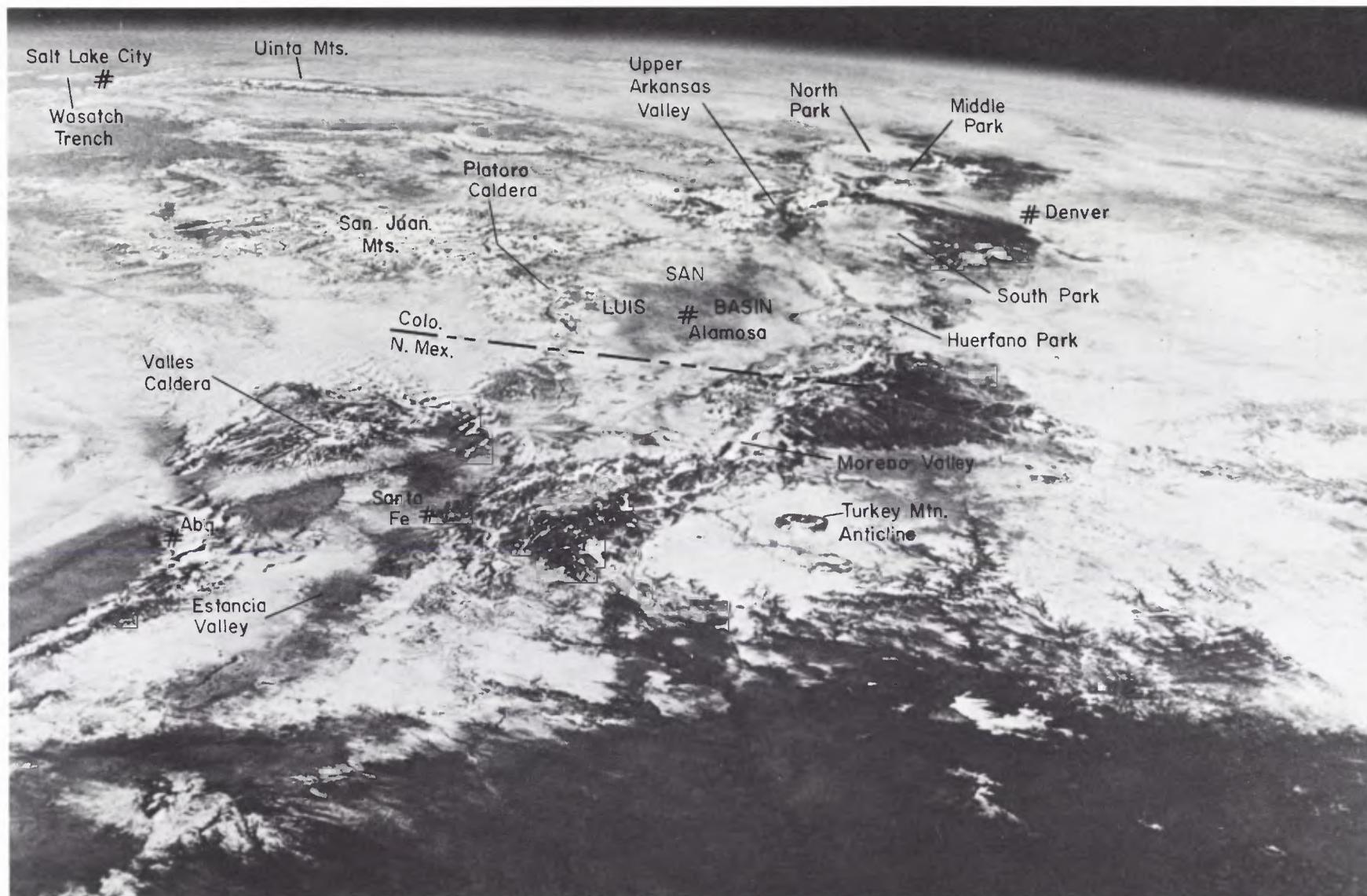


FIGURE 1.

Apollo 9 photograph looking NNW up the Rio Grande rift from an altitude of about 130 miles. To the north, the camera is looking directly up the narrow cleft of the upper Arkansas graben with the snow-covered Colorado Parks to the right. The Rio Grande rift bends to the SSW near Alamosa and trends diagonally to the left, leaving the field of view near the south end of the Albuquerque Basin. Note the Pleistocene Valles caldera on the west margin of the rift north of Albuquerque and the Estancia Basin east of Albuquerque. Sierra Blanca and the Tularosa Basin are just off the lower left corner. The Wasatch trench, which is part of a rift system bounding the west side of the Colorado Plateau in Utah and Arizona, is visible in the upper left corner. Photo courtesy of the National Aeronautics and Space Administration and the Bonanza Remote Sensing Project of the Colorado School of Mines and the Martin-Marietta Corporation.

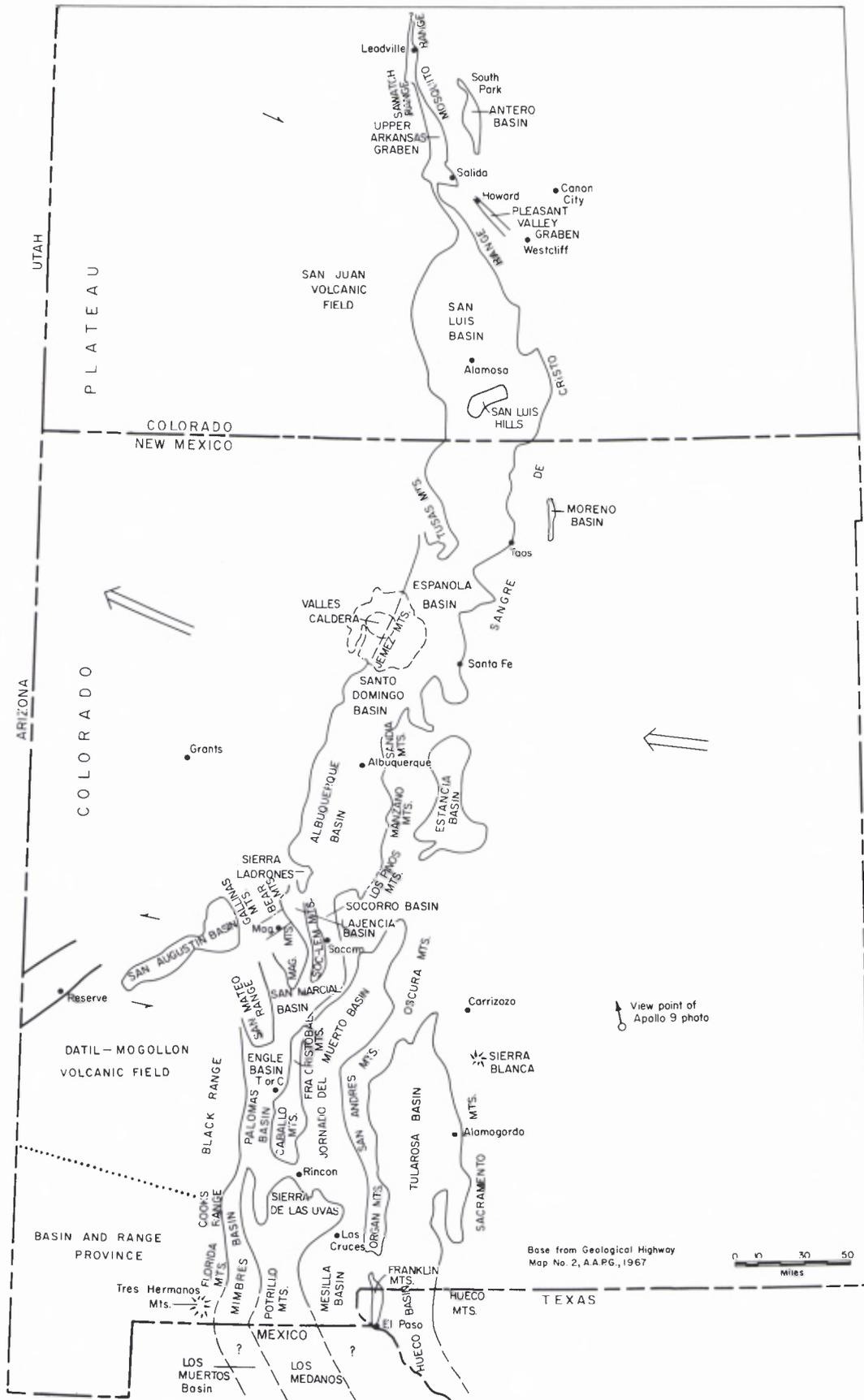


FIGURE 2.
Generalized map of the Rio Grande Rift.

southern Rocky Mountains were beveled by an erosion surface of moderately low relief in the Late Eocene; thus the disappearance of great thicknesses of Oligocene volcanic rocks across the rift must be ascribed to Late Tertiary uplift and erosion rather than to nondeposition. Assuming an average elevation of 2,000 feet for the erosion surface in Late Eocene time, minimum uplift was approximately 5,000 to 12,000 feet during Late Tertiary time for ranges east of the rift and minimum subsidence was 4,000 to 24,000 feet within the rift. Numerous fault scarps cut-

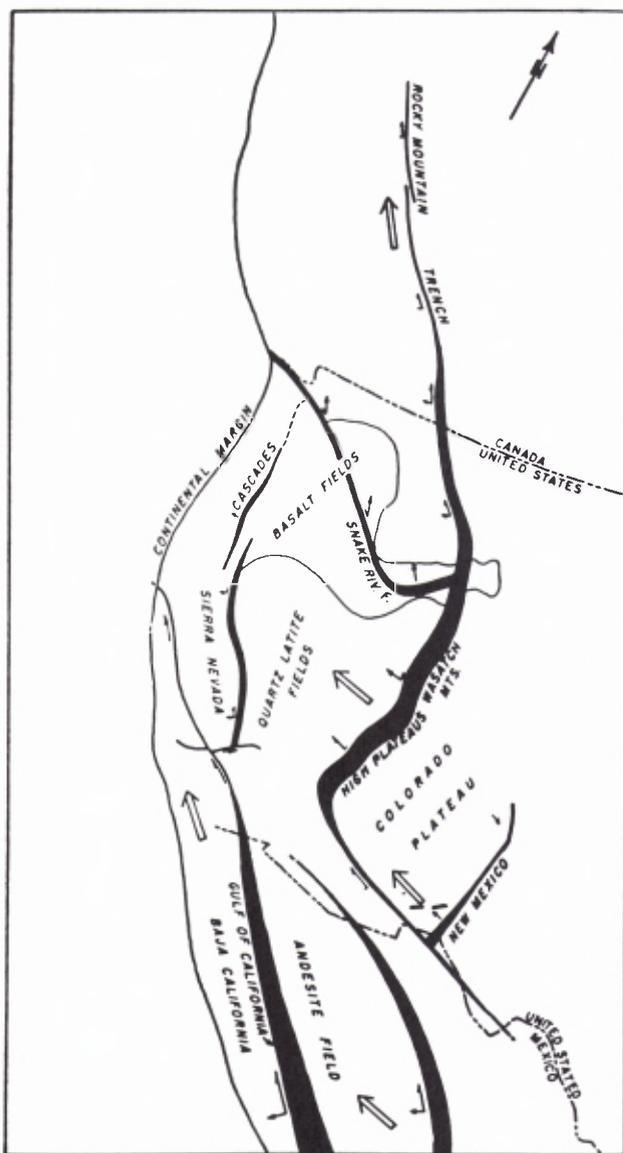


FIGURE 3.

Diagrammatic map exploring the concept of extension and drift affecting western North America. Black lines represent amount of expansion as if localized along a few separations. Small arrows represent apparent vectors of movement; large arrows the apparent resultant direction of the movement. From Eardley (1962, p. 510) with slight modifications along the Rio Grande rift.

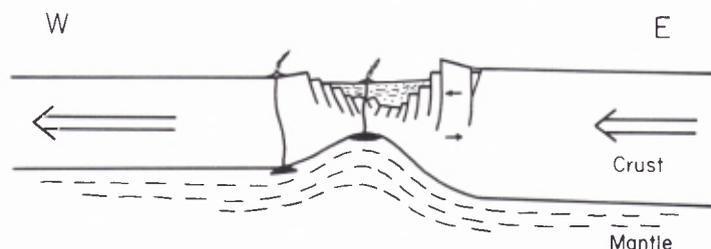


FIGURE 4.

Hypothetical cross-section of the Rio Grande rift. The large arrows indicate direction and relative rate of drift of continental plates. The small arrows indicate a force couple acting on the east shoulder of the rift. Freund (1965, p. 340) has experimentally produced a similar, but symmetric, model of the rifting and "necking" of sand above a convection current in a heavy fluid substratum.

ting alluvial fans and Pleistocene surfaces indicate that differential movement is continuing.

Synthesis of the above observations suggests the following model (see figs. 3 and 4): (1) the continental plate west of the rift is drifting faster than the continental interior (mantle convection may be pulling it over the East Pacific Rise in a "conveyor belt" manner similar to that suggested by Cook, 1962); resultant crustal attenuation formed the Basin and Range province and is splitting the Colorado Plateau block away from the interior; (2) the east side of the rift developed greater structural relief due to riding up of thicker crust onto an upward bulge of mantle material beneath the rift; (3) the west side of the rift is relatively subdued due to crustal stretching accompanied by abundant normal faulting and a tendency to pull the crust away from the mantle bulge beneath the rift; (4) stretching and normal faulting along the west side relieves subcrustal pressure and provides avenues for ascent of magmas and hydrothermal solutions; (5) longitudinal faults along the east side are relatively tight and un conducive to magmatism; westward drift of the interior block against the mantle bulge tends to rotate the fault planes to a near vertical position and may change the sense of movement from normal to reverse; (6) northwestward drift of the Colorado Plateau as suggested by Eardley (1962) causes a slight clockwise rotation against the north end of the rift which tends to keep it tight and relatively free of volcanism; this may also explain the unusually high upthrusting of the Sangre de Cristo horst along the east side of the San Luis Valley; (7) continued widening of the Rio Grande rift in New Mexico appears to be accelerating volcanism and may cause the rift to evolve into a lava-filled trough similar to the Snake River rift.

THE UPPER ARKANSAS GRABEN AND PROBLEMS OF THE NORTH END

North of the San Luis Basin of Colorado, a narrow, north-tapering, sharply defined trough extends for at least 60 miles to the continental divide north of Leadville (fig. 2). That this basin is a graben with a tectonic style similar

to the Basin and Range province has been recognized by workers in the Leadville area for many years. Emmons, Irving, and Loughlin (1927, p. 97) recognized that Lower Paleozoic strata in the Mosquito Range had undergone at least 8,000 feet of post-ore uplift relative to the same strata in the upper Arkansas Valley at Leadville. They discussed the relative merits of subsidence versus uplift and spoke of the similarity of this faulting to that in the Great Basin. Their cross-sections (pl. 12) show the same progressive stepping down of strata towards the valley axis by numerous longitudinal faults as is characteristic all along the rift. Tweto (1948, pl. 7) showed this structure very well on a cross-section of the upper Arkansas Valley at Leadville and labeled the valley a graben. Both sets of cross-sections show a progressive steepening of the fault planes towards the east boundary of the graben, which culminates in upthrusting of the crest of the Mosquito Range along reverse faults.

Gableman (1952, p. 1608-1609), in a very perceptive discussion based largely on geomorphology, projected the graben structure of the San Luis Valley northward up the Arkansas Valley to Leadville. In 1960, Van Alstine and Lewis (p. B245) described Early Pliocene fossils from a 500-foot section of alluvial fill exposed near Salida. The following year, Tweto (1961, p. B133) named the alluvial fill of the upper Arkansas Valley the Dry Union Formation for exposures near Leadville and showed their continuous distribution along the valley. He also presented evidence for recurrent faulting of unconsolidated sediments continuing into Holocene time; this phenomenon is a nearly universal characteristic of the Rio Grande rift. Chapin and Epis (1964, p. 158) presented evidence for downfaulting of Oligocene ash-flows by as much as 2,100 feet in the Browns Canyon area north of Salida. But the real breakthrough came in 1968 when R. E. Van Alstine (p. C158) demonstrated that the Arkansas and San Luis Valleys are connected by a structural trough containing Late Tertiary sediments. The trough crosses Poncha Pass west of U.S. Highway 285 and is not obvious from that route. In a later paper Van Alstine (1970, p. B46) extended the age of the Dry Union Formation to Late Miocene on the basis of vertebrate fossils identified by G. E. Lewis. On the basis of similarities in structural style, age of alluvial fill, alignment, and physical continuity, the upper Arkansas graben is clearly part of the Rio Grande rift.

How far the Rio Grande rift extends beyond Leadville is uncertain. Geomorphically, it appears to end at about the Continental Divide; however, as Tweto (1968, p. 566) has recently pointed out, scattered *en echelon* north-trending faults extend northward to near the Wyoming line and may be related to the rift. Kelley (1956, 1970) has postulated that the Rio Grande depression, the Colorado Parks, and the Laramie Basin are linked in a right-lateral *en echelon* system of intermontane troughs. However, the intermontane parks of Colorado are Laramide basins distinct in structural style and age of sedimentary deposits from the post-Laramide grabens of the rift (see summary by Tweto, 1968, p. 563, 566, 567). The contrast is especially sharp between South Park and the adjacent upper Arkansas Valley. South Park is a Laramide basin which

received at least 1,000 feet of andesitic extrusives of Paleocene age (57 m.y.) and 8,000 feet of arkosic conglomerates prior to folding and thrusting in the Late Paleocene or Early Eocene (Sawatzky, 1964, 1968). During the Late Eocene, South Park was beveled by a surface of low relief onto which Oligocene eruptive rocks and volcanic detritus from the adjacent Thirtynine Mile field (Epis and Chapin, 1968, p. 56) were emplaced. The only Late Tertiary sediments of appreciable thickness occur in the Antero syncline in the extreme southwest corner of the park. This small basin developed synchronously with the Rio Grande rift as a small subsidiary downwarp along the inflection line of its uplifted eastern shoulder and will be discussed in the following section. In contrast, the area now occupied by the upper Arkansas Basin was situated high on the flanks of the Sawatch anticline until the Miocene when subsidence accompanying regional uplift split the anticline to form a narrow, highly-elongate graben. Streams flowed eastward off the Sawatch anticline in the Late Eocene and were filled with ash-flow tuffs in the Oligocene; these paleovalleys and their volcanic rocks have been tilted to the west and downfaulted over 2,000 feet into the upper Arkansas graben (Chapin, Epis, and Lowell, 1970; Lowell, 1969, and this guidebook). The upper Arkansas Valley then received 500 to 2,000 feet of Late Tertiary sediments which are very similar to those of the Santa Fe Group in New Mexico. Thus, the upper Arkansas graben is the northward extension of the Rio Grande rift, not the Colorado Parks.

INFLECTION BASINS

The sharply uplifted and outward-tilted shoulders of the rift are generally 10 to 30 miles in width beyond which the structural slope is more gentle. The change in slope is rather sharp and marked by an inflection line along which numerous faults, small folds, and local downwarps occur. These smaller structures parallel the rift and were formed contemporaneously with it. They appear to be more abundant east of the rift, probably because of the greater uplift and tilting on that side. Four local downwarps, whose development can be demonstrated to be synchronous with the rift, are the Antero, Pleasant Valley, Moreno, and Estancia basins; others probably exist.

The Antero Basin

The Antero Basin of southwestern South Park is a north-to-northwest-trending syncline, which parallels the upper Arkansas graben about 10 miles east of its rim. Oligocene ash-flow tuffs and volcanoclastic sedimentary rocks of the Thirtynine Mile field have been folded as much as 28 degrees about the synclinal axis (De Voto, 1964, p. 124). Alluvial fan deposits of the Late Tertiary Trump and Wagontongue formations are as much as 700 feet thick in the southern part of the syncline; these beds dip 5 degrees or less (*op. cit.*). Vertebrate fossils from the Wagontongue Formation have been identified by C. L. Gazin (in Stark and others, 1949, p. 69) and by G. E. Lewis (in De Voto, 1961, p. 168) as species of Late Miocene or Early Pliocene age. Thus, formation of the Antero Basin was approxi-

mately synchronous with development of the upper Arkansas graben. No Late Tertiary folding or sedimentation has been found east of the Antero Basin in the area occupied by South Park and the Thirtynine Mile volcanic field.

The Pleasant Valley Graben

The Pleasant Valley graben parallels the east side of the Sangre de Cristo Range from the vicinity of Westcliff in the Wet Mountain Valley northwestward to Howard in the canyon of the Arkansas River. It is about 3 miles wide and at least 25 miles long; the southern extent is difficult to determine because of cover by alluvial fans extending eastward off the Sangre de Cristo Range. Near Hillside, Oligocene ash-flow tuffs of the Thirtynine Mile field dip 10 to 20 degrees southwestward into the graben; at Goat Creek on the Sangre de Cristo side of the graben the same tuffs dip 20 to 40 degrees northeastward (Karig, 1963; Chapin and Epis, 1964, p. 158). Downfaulted blocks of these ash-flows are exposed at Oak Creek and near Howard and are overlain by alluvium which Tweto (1961, p. B133) tentatively correlated with the Dry Union Formation of the upper Arkansas Valley. The ash-flow tuffs at Oak Creek are about 1,400 feet lower in elevation than outcrops of the same units along the north rim of the Arkansas Canyon and at Goat Creek on the east flank of the Sangre de Cristo Mountains. Glenn Scott and R. B. Taylor of the U.S. Geological Survey are currently studying this area and a more complete picture is forthcoming.

The Moreno Basin

The Moreno Basin is a north-trending topographic and structural depression about 16 miles long and 3 to 4 miles wide located between the Sangre de Cristo and Cimarron Ranges in northern New Mexico. It is parallel to, and about 15 miles east of, the Rio Grande rift in the Taos area. According to Ray and Smith (1941, p. 208), the Moreno Valley is genetically similar to the Rio Grande depression and was formed approximately contemporaneously with it. The valley is a northward-plunging syncline bounded on both sides by longitudinal faults. The faulting and folding occurred after the development of a mid-Tertiary surface of low relief upon which the Picuris Formation of pre-Santa Fe age (Cabot, 1938; Galusha and Blick, 1971, p. 370) was deposited. Coalescing alluvial fans deposited an estimated 1,000 feet (Ray and Smith, p. 191) of debris within the downwarp; remnants of this alluvium, as much as 440 feet thick (Clark, 1966, p. 62), underlie the present valley and are known as the Eagle Nest Formation (Ray and Smith, p. 190).

The Estancia Basin

The Estancia Basin parallels the Albuquerque Basin about 20 miles east of its rim. With dimensions of about 55 by 35 miles, the Estancia Basin is the largest of the inflection basins considered here. It is also the youngest and contains only 300 to 400 feet of alluvial fill of Late Pliocene to Pleistocene age overlain by 100 feet of lacustrine sediments (Smith, 1957, p. 38-39; Titus, 1969, p. 40-42).

Smith correlated the alluvial fill with the upper beds of the Santa Fe Group north of Galisteo Creek; he considered the alluvium to have been "deposited in a structural basin which formed as a result of mild downwarping related to late stages of the development of the adjacent Rio Grande trough" (op. cit., p. 38). An additional 400 feet of subsidence has occurred in Late Pleistocene time (Titus, p. 153). The Estancia Basin occurs on a line connecting the Santa Fe embayment with the north end of the Tularosa Basin. Considering the youthfulness of the Estancia Basin, its recent downwarping, and the eruption of very young basalts at the north end of the Tularosa Basin (the Carrizozo flows estimated by R. H. Weber, 1971, oral communication, to be in the vicinity of 1,500 to 2,000 years old), it seems possible that the Rio Grande rift may be in the process of straightening its course between Santa Fe and the Tularosa Basin. If so, Chupadera Mesa and the Los Pinos-Manzano-Sandia uplift may become intrarift horsts as the Estancia downwarp develops into a major basin. Eardley (1962, p. 399) has also included the Estancia Basin as part of the rift belt.

PARALLEL BASINS AND INTRARIFT HORSTS

South of the Albuquerque Basin, the Rio Grande rift broadens into a series of parallel basins separated by intrarift horsts. This widens the depression from an average of about 30 miles in the northern two-thirds to about 100 miles in the southern one-third. Kelley (1952) restricted the southern portion of the rift to the narrow depression along the eastern edge of the Mogollon Plateau formed by the Socorro, San Marcial, Engle, and Palomas basins and their interspersed constrictions. Elston (1970, fig. 2) has recently shown the Rio Grande rift bifurcating to the southwest to include a number of small grabens within and around the edges of the Mogollon Plateau. Since our views differ appreciably, I will attempt in the following paragraphs to justify widening the rift to include the La Jencia, eastern Mimbres, Jornada del Muerto, Tularosa and Hueco basins. The criteria will again be similarities in alignment, age, sedimentation, and tectonic style. In this case, one additional criteria will be used: that of comparison with other rift systems which show that the maximum uplift occurs along the raised shoulders which dip away from the depression (Freund, 1965; Illies, 1969; Saggerson and Baker, 1965).

The most obvious subdivision of a basin by intrarift horsting occurs in the Socorro-La Jencia Basin. Here, the Socorro-Lemitar Mountains form a north-northwest-trending horst which splits the basin into two semiparallel halves. Uplift of this horst and accompanying volcanism began during deposition of the Popotosa Formation, a basal unit of the Santa Fe Group, and has continued to the present (Bryan, 1938; Denny, 1940; Burton, 1971). Several thousand feet of Popotosa beds have been uplifted and exposed by erosion between Polvadera Mountain and the Sierra Ladrones to yield a rare glimpse of the early sedimentary record of the Rio Grande rift. Volcanic conglomerates and playa deposits of the Popotosa Formation presently crop out as high as 2,000 feet above Socorro on

the east face of Socorro Peak. Basaltic andesites, interbedded in the lower part of the Popotosa Formation and exposed along Silver Creek, have been dated at 16 million years (Weber, 1971, p. 34). They are overlain by playa deposits which have been intruded in the Socorro Peak volcanic center by rhyolitic domes and dikes. The Socorro Peak volcanism is Early Pliocene in age as indicated by K-Ar dates of 10.7 m.y. on a trachyandesite capping the peak (Weber, 1971, p. 41) and 11.7 m.y. on an intermediate dike in the adjacent Luis Lopez Manganese District (Willard, 1971). The Socorro Peak volcanism appears to have taken place largely, if not entirely, during the time span of the Popotosa Formation. Some domes were overlapped and buried by volcanic conglomerates which were later tilted and intruded by adjacent domes; flows interbedded with Popotosa beds have also been observed (Burton, 1971). Younger alluvium of the Santa Fe Group overlies the Popotosa Formation with angular unconformity; however, another period of relative uplift in the Late Pliocene or Early Pleistocene deformed the younger Santa Fe beds (Denny, 1940, p. 105; 1941, p. 259). High seismicity in the Socorro area (Sanford, 1963) and the presence of numerous Pleistocene and Holocene fault scarps (Budding and Topozada, 1970) indicate that movement is continuing.

The Socorro-Magdalena area is a complex junction between the main south-trending stem of the rift and a weakly developed southwest-trending limb along the San Augustin Plains. The Socorro constriction of Kelley (1952, p. 97) is due to intrarift horsting which produces an illusion that the rift has narrowed. The basin in which the Popotosa Formation accumulated was at least 25 to 30 miles wide prior to horsting. Outcrops of volcanic conglomerates and mudflow breccias, very similar to beds in the Popotosa Formation on the Socorro-Lemitar uplift, occur to the east in the Joyita Hills and to the west on the summit and both flanks of the Magdalena Range. As previously noted, the Socorro-Lemitar mountains now occupy the axis of the basin as evidenced by the uplifted playa deposits. The Magdalena Range is also an intrarift horst with about 3,000 to 5,000 feet of Late Tertiary uplift relative to other Popotosa outcrops. To the west of the Magdalena Range, the San Mateo uplift appears to have been formed by block faulting along the east side of the Rio Grande rift. The extensive block faulting of the San Mateo-Magdalena area may be related to the fact that this wedge-shaped area is bounded on both the north and south by rift structures.

The Tularosa-Hueco Basin

South of Socorro, the Rio Grande rift is made up of three parallel north-trending basins separated by intrarift horsts. On the west, the San Marcial, Engle, Palomas, and eastern Mimbres basins form a narrow trough along the edge of the Mogollon Plateau. A central basin formed by the Jornada del Muerto and Mesilla basins is separated from the San Marcial-Mimbres trough by an intrarift horst made up of the Caballo, Fra Cristobal, Sierra de Las Uvas, and Potrillo mountains. An eastern basin, formed by the Tularosa and Hueco basins, is separated from the cen-

tral basin by another intrarift horst formed by the Oscura, San Andres, Organ, and Franklin mountains. The Tularosa-Hueco Basin is bounded on the east by Sierra Blanca and the Sacramento and Hueco mountains which form the raised and outward-dipping eastern shoulder of the rift. Evidence to support inclusion of the above basins and horsts within the Rio Grande rift has become available largely in the last three or four years as a result of work published in the Border Stratigraphy Symposium (1969, Kottlowski and LeMone, eds.); the New Mexico Geological Society Guidebook of The Border Region (1969, Wengert, ed.), and several reports on the ground-water resources of the area.

Each of these basins contains a substantial thickness of Late Cenozoic alluvial fill. The greatest known thickness occurs in the Tularosa-Hueco Basin where Mattick (1967, p. D85) estimated 9,000 feet of alluvium (gravity and seismic data) east of the Franklin Mountains; McLean (1970, p. 17) reported 6,015 feet of alluvium in a well drilled east of the Organ Mountains. The Tularosa-Hueco Basin is more than 160 miles long and 20 to 35 miles wide. It deepens to the south and is markedly asymmetric; the thickest fill is along the west side, the center is elevated several thousand feet as a suballuvial horst and shallower troughs occur along the east side (McLean, 1970, fig. 5). On the east side of the basin, in the vicinity of Alamo-gordo, seismic and gravity data indicate more than 3,000 feet of alluvium (op. cit., p. 17); the western escarpment of the Sacramento Mountains rises abruptly from this trough with about 8,600 feet of bedrock relief for 12 miles. The western border of this basin is equally abrupt and with even greater bedrock relief. The basin post-dates the uplifted and deeply dissected Sierra Blanca volcanic field (Sierra Blanca syenites, 27-34 m.y., Kottlowski, Weber, and Willard, 1969) and contains Pleistocene lacustrine sediments of Lake Cabeza de Vaca (Strain, 1966) in the upper part of the alluvial fill. The Tularosa-Hueco Basin is undoubtedly one of the major fault troughs of the southwest and is similar in age, alignment, and sedimentation to other basins of the Rio Grande rift. Eardley (1962, p. 399) has previously suggested that the Tularosa Basin is associated tectonically with the Rio Grande depression and is part of the general rift belt. Further evidence may be seen in a topographic profile across the rift at this latitude. The maximum elevations occur on Sierra Blanca (12,003 feet) and the Sacramento Mountains (9,686 feet) on the east and in the Black Range (10,130 feet) on the west. The intrarift horsts are generally 1,000 to 3,000 feet lower. Elevations along the other rift systems are generally greatest on the raised rims.

The Jornada Del Muerto-Mesilla Basin

The Jornada del Muerto-Mesilla Basin is about 160 miles in length above the Mexican border; averages 20 miles in width and deepens to the south. The central part of the Jornada del Muerto Basin is apparently quite shallow compared to either end (King and others, 1971, p. 17) and is different in one aspect from other basins of the rift: it is a broad syncline formed by east-dipping Paleozoic and Mesozoic strata along the Caballo-Fra Cristobal uplift

and west-dipping Paleozoic strata in the San Andres Mountains. However, this structure is inherited from its location between two Laramide uplifts (Eardley, 1962, p. 399) and is not part of the Late Tertiary structural style. A gravity survey by Sanford (1968, p. 4, fig. 5) has revealed a deep depression in the northern end of the Jornada del Muerto which appears to be bounded by a sharp fault along its western margin and is estimated to contain about 3,000 feet of alluvial fill (op. cit., fig. 9). The south end of the Jornada del Muerto merges imperceptibly with the Mesilla Basin which is unquestionably a graben. An oil test in the north-central part of the Mesilla basin encountered 3,790 feet of alluvial fill (King and others, 1971, p. 22).

Uplift and erosion on the Caballo-Sierra de Las Uvas horst has exposed a thick section of lower and middle Santa Fe sediments in the Rincon-San Diego Mountain area at the southwest edge of the Jornada del Muerto. This area is similar to the Socorro-Lemitar uplift in providing an unusual opportunity to observe the basal Santa Fe sediments. Only by intrarift horsting or sharp tilting along the edge of a graben, as in the Espanola and upper Arkansas basins, is such an opportunity afforded. Hawley and others (1969, p. 68) and Seager and others (in press) measured 3,567 feet of Santa Fe Group alluvium in the Rincon-San Diego Mountain area. These sediments overlie mid-Tertiary volcanic rocks (Thurman Rhyolite Tuff, 33 m.y.; Uvas Basalt, 31 m.y.; Kottlowski, Weber, and Willard, 1969) and contain a basalt flow near the middle of the section which has been dated at 13 m.y. (Selden Basalt, op. cit.). Pleistocene deposits of Lake Cabeza de Vaca (Strain, 1966) and widespread alluvial deposits comprise the upper part of the Santa Fe Group in the Mesilla Basin. The Jornada del Muerto-Mesilla Basin is similar in age, alignment, and sedimentation to other basins of the Rio Grande rift in spite of having an inherited Laramide syncline in its central portion.

The San Marcial-Engle-Palomas-Eastern Mimbres Basin

The San Marcial, Engle, Palomas and eastern Mimbres basins form the narrowest of the three major parallel basins discussed in this section. Inclusion of the eastern Mimbres Basin is the main point to be considered here, since the other basins have already been included in the Rio Grande rift by Bryan and Kelley. Kottlowski (1958, p. 51) suggested that the Rio Grande rift terminates against the Sierra de Las Uvas at the south end of the Palomas Basin, while Bryan (1938) and Kelley (1954) considered it to extend southward to the Mexican border. Reeves (1969, p. 153), from a study of Pleistocene lake deposits and basin fill, has suggested that the Rio Grande depression might extend into the Los Muertos Basin of northern Chihuahua. As previously noted, there is an adequate thickness of Santa Fe sediments in the Mesilla Basin to justify extending the rift southward along the east side of the Sierra de Las Uvas and East Potrillo Mountains. Considering the general north-northeast trend of the rift, it seems inconsistent for the rift to abruptly jog eastward around the Sierra de Las Uvas in order to follow the Mesilla Basin. In the author's opinion, it is more likely that the Sierra de Las Uvas and Potrillo Mountains are an extension of the

Caballo-Fra Cristobal intrarift horst and that the west edge of the Rio Grande trough extends southward along the east side of the Cooks and Florida mountains. Evidence to support such an extension may be found in (1) the northerly trend of Cooks Range and the Florida Mountains, as opposed to the strong northwesterly trend of ranges to the south and west; (2) the great depth of alluvial fill between the Tres Hermanos and Potrillo Mountains; (3) the presence of fault scarps along both sides of the Potrillo Mountain block which suggests that it is a horst bounded on both sides by grabens (see Reeves, 1960, figs. 1 and 8); and (4) Late Tertiary structural doming of the Sierra de Las Uvas and uplift of basal Santa Fe sediments along the Sierra de Las Uvas-Caballo axis which again suggests an intrabasin horst. Data on depth of alluvial fill in the eastern Mimbres Basin is very sparse. The Skelley No. 1A oil test between the Tres Hermanos and West Potrillo mountains encountered 4,650 feet of Santa Fe-Gila Conglomerate alluvium (Kottlowski, Foster, and Wengerd, 1969, p. 194). A short distance to the east, on the Potrillo horst, the Sunray No. 1 test penetrated only 520 feet of fill (op. cit., p. 193). Between these two drill holes is a north-northeast trending fault scarp which may mark the boundary of the eastern Mimbres Basin and the Potrillo Mountains horst. The same fault scarp turns southeastward at the Mexican border and extends over 70 miles into northern Chihuahua along the east side of the Los Muertos Basin (see Reeves, 1969, figs. 1 and 9).

THE PLEISTOCENE SUMP AND PROBLEMS OF THE SOUTH END

The basins and uplifts of the Rio Grande rift are predominantly north-trending structures in contrast to the northwesterly trends of the adjoining Mexican Highlands section of the Basin and Range province. The Hueco, Franklin, and Florida mountains are the southernmost ranges along the rift which have northerly trends; south of these ranges, the structural fabric is dominated by northwest trends. Using this criteria, the Rio Grande rift might be terminated along a line passing through El Paso and trending northwesterly along the south end of the Hueco, Franklin, and Florida mountains. Thus defined, the rift would end approximately at the Mexican border.

Using the criteria of sedimentation related to the rift, a case can be made for extending the rift at least 70 miles into northwestern Chihuahua. After through drainage was established along the Rio Grande rift in Early to Middle Pleistocene time (Kottlowski, 1958) large lakes developed in southern New Mexico, in the Hueco Basin of Texas, and in northern Chihuahua. These lakes were the "sump" for the ancestral Rio Grande, which lacked a passage to the sea until its capture at El Paso in mid-Pleistocene time (Late Kansan-Early Illinoian; Kottlowski, 1958; Strain, 1959, p. 377; 1969, p. 122). The lake basins received enormous quantities of sediment and must have subsided rapidly to accommodate the filling. Lake Cabeza de Vaca (Strain, 1966) covered part of the Tularosa Basin, most of the Hueco and Mesilla basins, and extended southward for at least 100 miles into Chihuahua during Early to mid-

Pleistocene time. About 600 feet of lacustrine deposits are exposed along the Rio Grande Valley southeast of El Paso and these have been dated as early to mid-Pleistocene by vertebrate remains (Strain, 1966). The maximum thickness of Lake Cabeza de Vaca sediments is unknown; several thousand feet of alluvial fill underlies the area, but how much of this is Late Tertiary bolson deposits rather than Pleistocene lacustrine sediments is uncertain.

Following capture of the ancestral Rio Grande and entrenchment of its valley, about 3,000 square miles in the Los Muertos Basin of northwestern Chihuahua and the eastern Mimbres Basin of New Mexico was inundated by pluvial Lake Palomas (Reeves, 1969). The lake appears to have been controlled in part by uplift of the Potrillo Mountains-Los Medanos block, thus forming a barrier between the Mimbres and Rio Cases Grandes drainages to the west and the Rio Grande drainage to the east. The Camel Mountain escarpment which bounds the west side of the Potrillo Mountains in New Mexico bends to the southeast at the international border and extends for at least 70 miles into Chihuahua. The escarpment is in part due to Pleistocene faulting (Reeves, 1969, p. 150) and figures 1, 3, and 8 of Reeves (op. cit.) show that the eastern boundary of Lake Palomas approximately coincides with this scarp. Gravity surveys across the southern part of the Los Muertos Basin indicate 3,500 to 13,000 feet of alluvial fill which Reeves (1969, p. 153) suggested might be another indication of the extent of the Rio Grande depression.

Thus, the question of the southern extent of the rift seems largely one of the nature of its junction with the Basin and Range province and of whether or not to include the Pleistocene "sump." It can be argued that a rift is a structural feature and that the sump could have formed in low areas of the adjacent Basin and Range province. Also, if the Rio Grande rift is forming by the splitting away of the Colorado Plateau block from the continental interior, it may not be reasonable to extend the rift beyond the southern edge of the plateau, especially since its southern boundary is probably a major zone of strike slip movement (Eardley, 1962, p. 311). Also involved are questions as to whether an upwelling of mantle material is causing the rift, or whether the pulling away of the Colorado Plateau is causing an upwelling of mantle material; or, as Atwater (1970) and Stewart (1971) have recently suggested, the Late Tertiary structure of the Basin and Range province may be due to tensional crustal fragmentation subsidiary to right-lateral movement between the Pacific and North American plates. These questions cannot be answered here and the nature of the southern terminus of the Rio Grande rift is not critical to the derivation of a model.

BIFURCATION ALONG THE SAN AUGUSTIN LINEAMENT

A northeast-trending lineament transects the Datil-Mogollon volcanic field and intersects the Rio Grande rift near Magdalena, New Mexico. The lineament is marked by a series of *en echelon* northeast-trending fault zones and grabens, the largest of which forms the San Augustin Basin. Near the southwest end of this basin, 2,000 feet of

unconsolidated sediments were cored by a research group from Oberlin College (Foreman, Clisby, and Sears, 1959) without encountering volcanic rocks; two older wells are reported to have penetrated 1,000 feet of fill (Stearns, 1962, p. 31). The San Augustin Basin was the site of a Pleistocene lake which at its highest level in Wisconsinian time was 34 miles long, 11 miles wide, and 165 feet deep (op. cit., p. 29). While not conclusive evidence, a marked lithologic change at a depth of 950 feet in the Oberlin hole and the presence of a relict Tertiary flora below this depth suggests that the hole penetrated sediments as old as Pliocene (Foreman, Clisby, and Sears, 1959, p. 120). The Sun No. 1 San Augustin oil test, drilled in 1966 on a structural saddle between the southwestern and northeastern segments of the basin, penetrated only 230 feet of alluvial fill followed by 2,530 feet of the Hells Mesa Formation (31-32 m.y., Weber, 1971) and 1,860 feet of the Spears Formation (37 m.y., op. cit.) before encountering pre-Oligocene rocks (R. W. Foster, 1971, written communication). These thicknesses indicate that a nearly complete section of the Datil Group has been downfaulted and underlies the San Augustin graben. The Spears-Hells Mesa contact occurs at elevations of about 8,000 feet along the northwest side of the graben versus about 4,300 feet in the Sun No. 1 hole. The structural relief in this shallow part of the basin is about 3,700 feet; it may be twice as great in deeper portions of the basin.

Southwest of the San Augustin Basin, the town of Reserve is located in a narrow valley which follows a prominent zone of northeast-trending faults (Weber and Willard, 1959). The faults are progressively downthrown towards the valley axis to form a shallow graben which contains an unknown thickness of Gila Conglomerate. Ratté and others (1969, p. E21) have recently mapped a belt of northeast-trending faults which form a graben 15 to 30 miles wide in the Blue Range Primitive Area southwest of Reserve. This fault zone crosses the regional northwesterly structural trend and is an extension to the faulting at Reserve (op. cit., fig. 12). Faults of similar trend occur to the southwest near Morenci, Arizona. A rhyolitic ash-flow sheet dated at 25 m.y. (op. cit., p. E19) has been downfaulted 2,200 feet into the Blue River graben and is covered by at least 800 feet of Gila Conglomerate (op. cit., p. E17, E28).

Northeast of the San Augustin Basin, the lineament is marked by an alignment of low saddles between the San Mateo and Gallinas mountains and between the Magdalena and Bear mountains. Mapping in the southern Bear Mountains and Magdalena area by the author and D. M. Brown has revealed a number of northeast-trending faults which are probably related to the lineament. A major fault along U.S. Highway 60 appears to have offset the north end of the Anchor Canyon stock (28 m.y., Weber, 1971, p. 37) by left-lateral oblique slip motion; the block north of the fault has apparently been shifted 0.8 mile to the west and dropped about 2,000 feet in elevation. Along Bear Springs Draw in the southern Bear Mountains, another northeast-trending oblique-slip fault appears to have 1.0 to 1.5 miles of left-lateral movement and about 1,000

feet of uplift on the north side of the fault. Thus, the San Augustin lineament in the Magdalena area appears to be a 6-mile-wide belt of left-lateral movement which has created a zone of tension within which the crust is depressed by 1,000 to 2,000 feet relative to either side. The picture is complicated, however, by superimposed north-trending normal faults which have offset the northeast-trending faults. Such a zone of tension and left-lateral movement should be expected if the Colorado Plateau block in moving to the northwest were to partially break away from its southeastern corner (see fig. 3). Other faults along this lineament should be examined for possible left-lateral motion.

In summary, the San Augustine lineament transects rocks as young as Early Miocene and is marked by a series of *en echelon* grabens which have several hundred to several thousand feet of structural relief and which contain sediments of Late Tertiary to Pleistocene age. It is thus similar in style and age to the Rio Grande rift. As noted by Ratté and others (1969, p. E21), it crosses the northwesterly regional trend of Basin and Range structures and requires a different explanation. Elston (1970a; 1970b, fig. 2) has previously interpreted the San Augustin graben as a subsidiary structure to the Rio Grande trough. I believe that this zone represents a weakly developed southwest-trending limb of the Rio Grande rift which may have developed in an abortive attempt of the Colorado Plateau block to break away from its southeast corner. The apparent lack of fault scarplets along the San Augustin graben indicates that the zone has been quiescent in post-Wisconsin time (Stearns, 1962, p. 29). This is corroborated by a lack of recent seismicity (Sanford, 1971, oral communication).

SUMMARY

To the Rio Grande depression of Bryan (1938) and Kelley (1952), the author recommends the following modifications and additions:

- (1) Extend the north end to include the upper Arkansas graben.
- (2) Widen the rift south of the Albuquerque Basin to include a series of 3 major parallel basins separated by intrarift horsts. The basins are: (a) the Socorro-San Marcial-Engle-Palomas-eastern Mimbres Basin, (b) the Jornada del Muerto-Mesilla Basin, and (c) the Tularosa-Hueco Basin.
- (3) Include the San Augustin lineament as a southwest-trending bifurcation.
- (4) Include a number of subsidiary basins along the inflection line of the raised shoulders. Four such basins are the Antero, Pleasant Valley, Moreno, and Estancia basins; others probably exist.
- (5) Consider a possible extension of the rift into northern Chihuahua along the Los Muertos Basin. This decision must await further research on the nature of the junction of the Rio Grande rift with the Basin and Range province.

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