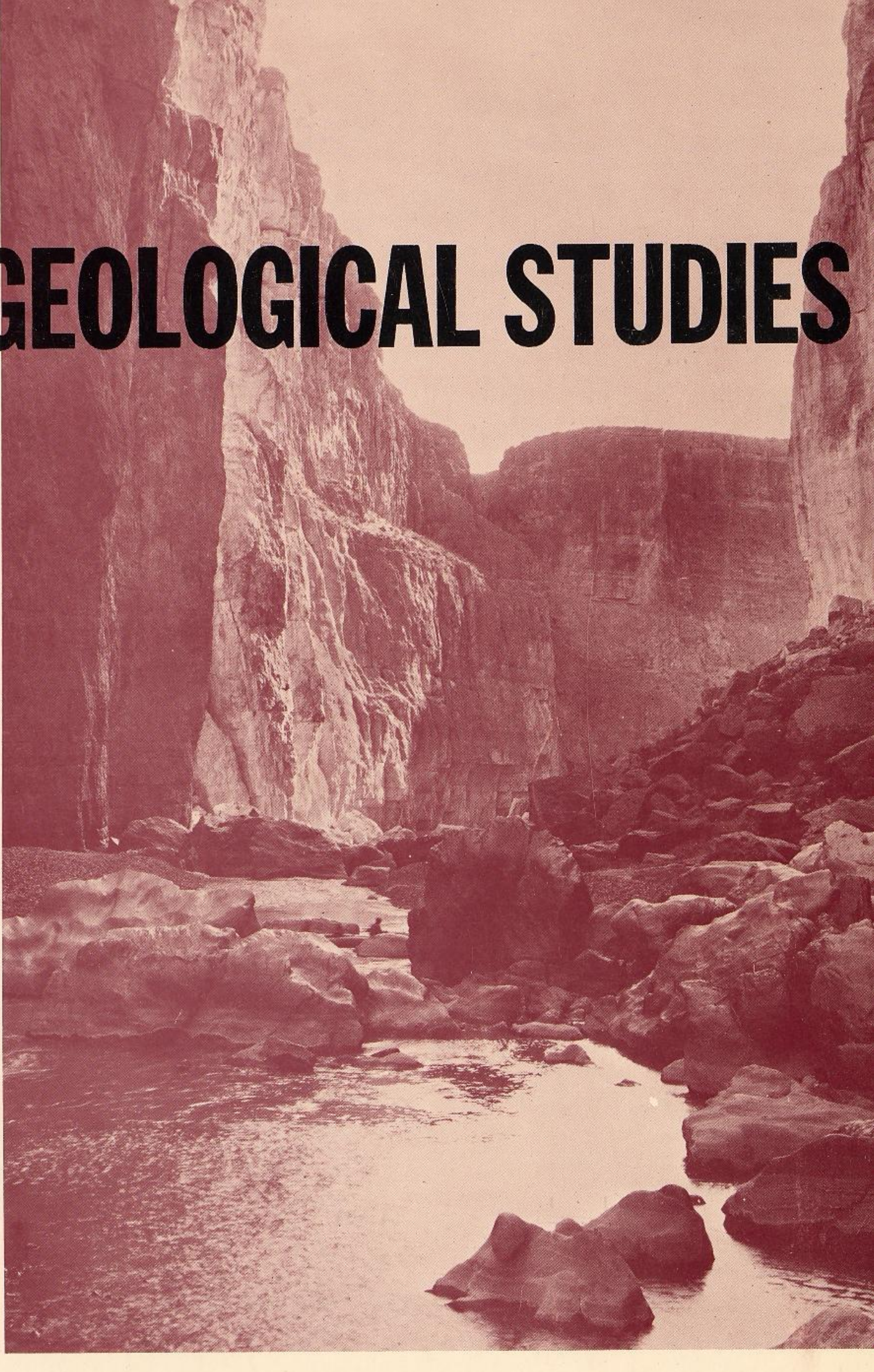
BAYLOR GEOLOGICAL STUDIES



FALL 1975

Bulletin No. 29

The Geomorphic Evolution of the Rio Grande

ROBERT C. BELCHER

"Creative thinking is more important than elaborate equipment--"

FRANK CARNEY, PH.D.
PROFESSOR OF GEOLOGY
BAYLOR UNIVERSITY
1929-1934

Objectives of Geological Training at Baylor

The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

The cover photograph is of Santa Elena Canyon in the Big Bend Region of Texas.

THE BAYLOR UNIVERSITY PRESS
WACO, TEXAS

BAYLOR GEOLOGICAL STUDIES

BULLETIN NO. 29

The Geomorphic Evolution of the Rio Grande

Robert C. Belcher

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Fall, 1975

Baylor Geological Studies

The Baylor Geological Studies Bulletin is published semi-annually, Spring and Fall, by the Department of Geology at Baylor University. The Bulletin is specifically dedicated to the dissemination of geologic knowledge for the benefit of the people of Texas. The publication is designed to present the results of both pure and applied research which will ultimately be important in the economic and cultural growth of the State.

ISSN 0005-7266

Additional copies of this bulletin can be obtained from the Department of Geology, Baylor University, Waco, Texas 76703. $1.05 postpaid.

CONTENTS

ILLUSTRATIONS

The Geomorphic Evolution of the Rio Grande

Robert C. Belcher

ABSTRACT

Laramide uplifts in New Mexico, Arizona, Colorado, and Mexico led to the development of through-flowing drainage systems. One system drained the south side of the San Juan Mountains and flowed southeastward across the San Juan basin. Another system headed in the ancestral Mogollon highlands of Arizona and flowed eastward across west-central New Mexico. These two systems joined in central New Mexico to form the ancestral Rio Grande-Pecos system which flowed southeastward across New Mexico and west Texas to join the ancestral Rio Conchos system. The ancestral Rio Conchos drained the volcanic highlands in northern Mexico and flowed generally east- and southeastward into the Rio Grande embayment of the Gulf of Mexico.

The middle Miocene uplift of the Sangre de Cristo Mountains diverted the original southeastward drainage to the southwest, to flow across north-central New Mexico through the area occupied by the present Jemez Mountains. The ancestral Rio Grande drainage was joined by the upper ancestral Arkansas River and exited the Rio Grande depression through the area of Glorieta Mesa during early Pliocene time.

In northern New Mexico during the extrusion of volcanics in the Taos Plateau, the Rio Grande experienced several periods of ponding and overflow in the vicinity of Tres Piedras. Early to middle Pleistocene uplift of the Picuris Range and tilting of basalt flows to the north caused the ancestral Rio Grande to entrench, forming the Rio Grande Gorge.

In southern New Mexico, the ancestral Rio Grande flowed through the Jornada del Muerto. Upon reaching south-central New Mexico during late Pliocene to early Pleistocene time, the ancestral Rio Grande flowed through Fillmore Pass into Hueco bolson and continued southeastward to join the Rio Conchos at Presidio. Next, the ancestral Rio Grande was diverted into northern Mexico across the La Mesa surface west of El Paso. Finally, in middle Pleistocene time, the ancestral Rio Grande was diverted into the Hueco bolson through El Paso Canyon, and again worked its way toward Presidio along a structural low, eventually joining the Rio Conchos to create the present integrated through-flowing Rio Grande system.

INTRODUCTION*

For over half of its length the Rio Grande flows through an area that has experienced periodic tectonism since the close of Cretaceous time. Since drainage ancestral to the Rio Grande may have originated with the first period of tectonic activity, it follows that each succeeding diastrophic event not only would force

---

*A thesis submitted in partial fulfillment of the requirements for the M.S. degree in Geology, Baylor University, 1975.

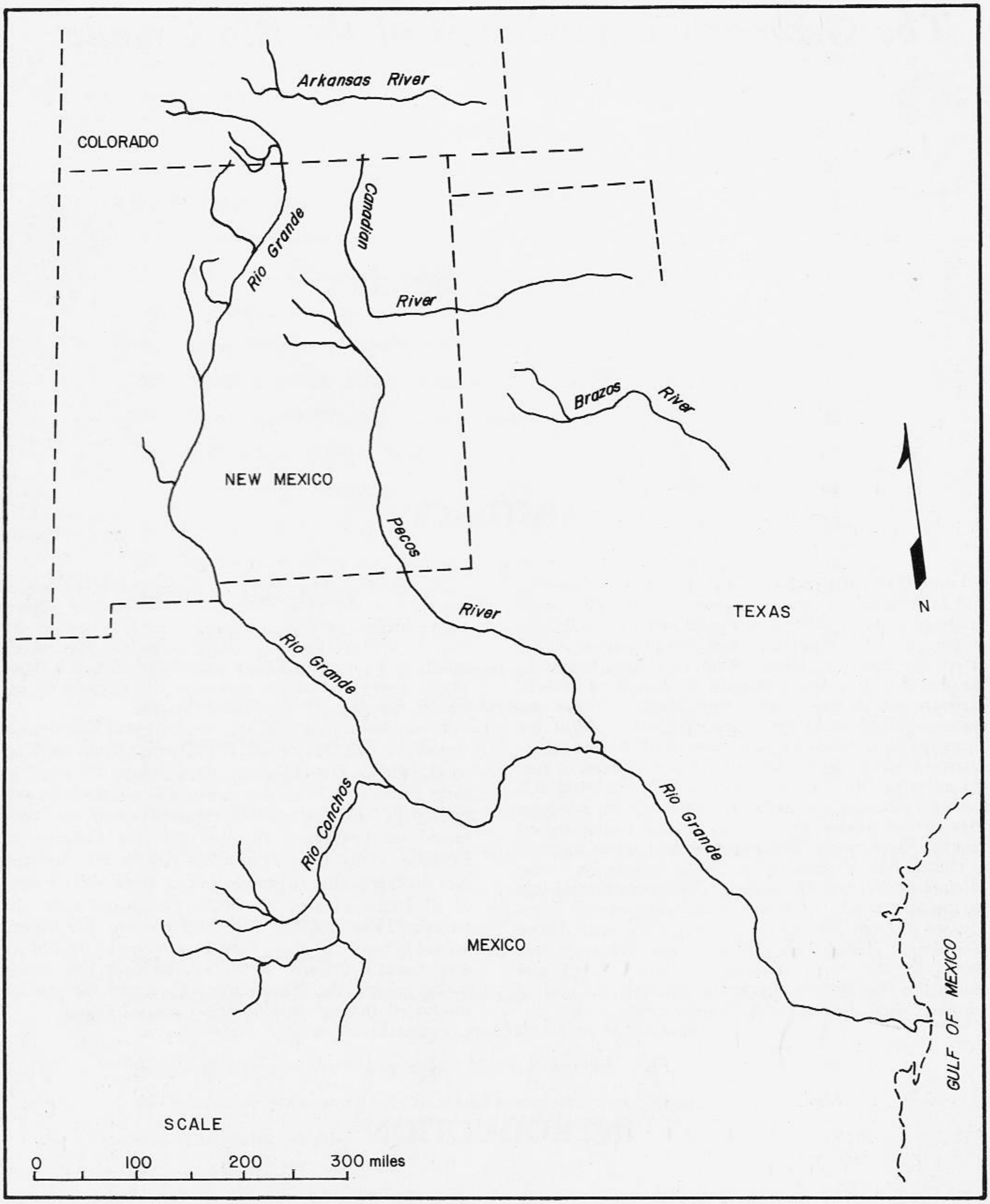


Fig. 1. Index map of the Rio Grande basin with major tributaries. The Arkansas, Canadian, and Brazos Rivers are shown to illustrate proximity and possible genetic relationships to the Rio Grande.

changes upon existing fluvial systems but also would obscure and occasionally destroy evidence pertaining to previous tectonism and related drainages. An abundance of data has enabled geologists to establish the Quaternary history of Rio Grande drainage with a reasonable degree of accuracy, but progressively older histories have not been established due to a corresponding scarcity of data.

As far as can be ascertained, this study is the first attempt to develop an evolutionary history for the Rio Grande as a system, starting with its seemingly logical beginning—the first stages of the Laramide disturbance. The reader should realize from the outset that this is a regional study based on a reconnaissance of the Rio Grande drainage basin. In this study several strong statements are made which are based on a minimum amount of data and which in a detailed sense may be in error, but are essentally correct when considered on a regional aspect.

This is a first attempt and, as is the case with all first attempts, it will undoubtedly undergo considerable modification as more evidence is discovered.

PURPOSE

The evolution of Rio Grande drainage has received the attention of most geologists who have worked in the southwestern United States. Generally, previous workers have separated into two schools of thought. One pictures the Rio Grande in existence during Pliocene time, flowing in a course west of its present position in northern New Mexico and continuing southward around the east side of the Jemez Mountains to the vicinity of Albuquerque. From there the river is thought to have flowed southward into a playa region in northern Mexico, at times flowing through the Jornada del Muerto. The other school of thought has the Rio Grande originating during early Pleistocene time as a result of drainage from the late Pliocene-early Pleistocene domal uplift of the San Juan Mountains region. From that point of origin, the river gradually worked its way southward by a process of basin spillover, first discharging into the playa region of northern Mexico, and later, during middle Pleistocene time, diverted into the Hueco bolson.

Because the evolution of the river was not a principal element in most earlier studies, both schools appear to have approached the problem of Rio Grande evolution from a static point of view, which considers the river only since middle Pliocene time when it had established most of its present course. However, when river evolution is the principal aspect of research a more realistic model can be obtained by considering the entire system from a dynamic point of view. This viewpoint adheres to the premise that water flows downhill and that the downhill direction may have changed several times in response to the various periods of tectonism during Tertiary time. Under this premise the search for drainage that may have evolved into the present Rio Grande system should begin with the first major uplift following the retreat of Late Cretaceous seas.

It is thought that the geomorphic processes which gradually brought about the integration of the present system of Rio Grande drainage were established with initial Laramide uplifts of the San Juan Mountains in southwestern Colorado and the ancestral Mongollon highlands in central Arizona, which started in Late Cretaceous time. Stratigraphic evidence in the San Juan basin, west and north-central New Mexico, Raton basin-Huerfano Park area, and the Texas Gulf Coast suggests that drainage has existed in these areas since Early Tertiary time. Wide-spread erosional surfaces overlain by Early to Middle Tertiary sediments, well-rounded gravels on elevated milled surfaces atop Middle Tertiary highlands, and wind gaps in Middle to Late Tertiary structures suggest that south- and southeastward drainage existed in New Mexico and western Texas during Early Tertiary time. Stratigraphic and physiographic evidence in the canyon lands of the Big Bend Region of Texas suggests that the river has occupied essentially the same position in this area since Early to Middle Tertiary time.

This reasoning suggests a far greater age for the Rio Grande drainage than is generally supposed. Therefore, the purpose of this study was to establish a model for the sequence of events through which Early Tertiary drainage of New Mexico and western Texas may have gradually evolved into the present Rio Grande system.

LOCATION

The Rio Grande flows 1,887 miles from southwestern Colorado to the Gulf of Mexico. It drains a basin of approximately 246,000 square miles, and while it may seem unimpressive when compared to eastern rivers, it is second in size only to the Colorado in the American Southwest.

The Rio Grande basin (Fig. 1) occupies parts of Colorado, New Mexico, Texas, Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas. In its course the Rio Grande traverses four geomorphic provinces of the United States and Mexico. From its headwaters in the Southern Rocky Mountain Province, it flows southward through the Mexican Highlands (Basin and Range Province), around the southwestern sides of the Stockton and Edwards Plateaus (Great Plains Province), and transects the West Gulf Coastal Plain (Coastal Plains Province) (Thornbury, 1965).

More specifically, the Rio Grande flows eastward from near Stony Pass (Fig. 2) east of Silverton, Colorado, through the San Juan Mountains towards Creede, and enters the San Luis Valley near Del Norte. From the San Luis Valley the river flows into the Taos Plateau near Taos, New Mexico, and then enters the Española Valley (Kelley, 1952) near Embudo, New Mexico. It continues southward through White Rock Canyon and the Santo Domingo basin to enter the Albuquerque-Belen basin (Kelley, 1952) near Albuquerque. From there the river flows southward through the Socorro constriction into the Hatch-Palomas basin and then through Selden Canyon into Mesilla Valley north of Las Cruces, New Mexico. It enters the Hueco bolson through El Paso Canyon and forms the southern boundary of the Trans-Pecos area of Texas (King, 1935). After the river passes through the Big Bend Region of Texas, it leaves the Trans-Pecos area and is entrenched in the Stockton and Edwards Plateaus northwest of Del Rio, Texas. South of Eagle Pass the Rio Grande enters the Gulf Coastal Plain, and con-

Fig. 2. (Locality 112) The beginning. This is a view of the snow bank in Stony Pass in the San Juan Mountains, southern Colorado, where the Rio Grande begins as a small trickle of snowmelt eventually to reach the Gulf of Mexico some 1,887 miles downstream.

tinues to its mouth, east of Brownsville, Texas, on the Gulf of Mexico.

Throughout its length the river's course is controlled by major structural forms, expressed as physiographic features. The Rio Grande originates within the domal uplift of the San Juan Mountains. In the San Luis Valley it enters the Rio Grande depression, a structurally complex system of linked *en echelon* grabens or basins which were first defined during late Oligocene time and accentuated during Miocene and Pliocene time. The Rio Grande depression is bordered on the east by the Sangre de Cristo, Sandia, Manzanita, Manzano, Los Piños, Fra Cristobal, Caballo, Doña Ana, San Andres, Organ, and Franklin Mountains. The depression is bordered on the west by the San Juan Mountains, San Luis Hills, Tusas Mountains, Jemez-Sierra Nacimiento Mountains, Sierra Ladron, Sierra Lucero, Lemitar-Socorro Mountains, Magadalena Mountains, San Mateo Mountains, Sierra de las Uvas, Robledo Mountains, and the East Potrillo Mountains.

Where the Rio Grande leaves the depression it enters the Hueco bolson, a basin partly filled with Tertiary sediments. Through the Trans-Pecos area of Texas it is bordered on the east by the structurally complex Quitman, Eagle, Sierra Vieja, Chinati, and Bofecillos Mountains. The river skirts the Big Bend Region of Texas through Santa Elena Canyon, is incised into the horst block of Mesa de Anguila, and continues through Mariscal Canyon, cut into the thrust faulted anticlinal Mariscal Mountain, to exit the region through Boquillas Canyon, cut through the tilted fault blocks of the Sierra del Carmen.

The river then enters deep canyons incised into the structurally horizontal Sockton and Edwards Plateaus, from which the Rio Grande emerges south of Del Rio to enter the Rio Grande embayment, a broad syncline plunging gently to the south.

Throughout its length the Rio Grande receives only eight sizable tributaries, listed from north to south: the Conejos River, Red River, Rio Chama, Jemez River, Rio Puerco, Rio Conchos, Pecos River, and the Rio de San Juan.

METHODS

This study encompassed such a large area that it was impossible to conduct detailed field investigations throughout the basin. For this reason it depended heavily on the works of others. However, this is not considered a major weakness, for rivers are systems and detailed studies of small parts of large systems will not define the framework of the entire system. For this reason it is considered essential to first conduct the regional survey here reported. From this it is hoped will come the general account of river history, and a closer indication of those areas most in need of more critical work.

Though there is considerable disagreement with this method of approach, it is thought that it provides a general model for river evolution which best identifies specific critical problem areas for detailed study. An example of the validity of this approach is the fact that the most obvious and concrete evidence for the early phase of river development lies entirely within Texas and would probably have been ignored by detailed studies in New Mexico and southwestern Colorado.

Dating is perhaps the most difficult aspect of this study, for it depends almost entirely on the work of others. The reasons for possible error are varied, but most relate to the need for time correlation of specific events over a very large area.

An extensive literature survey was conducted to review and evaluate works either directly or indirectly related to the Rio Grande basin. Special attention was paid to those articles related directly to the evolution of portions of Rio Grande drainage.

A composite of two degree topographic maps published by the U. S. Geological Survey (scale 1:250,000) covering the drainage basin of the Rio Grande and neighboring areas was studied in detail to identify topographic features suggestive of older drainage related to the Rio Grande.

A base was compiled from maps of 1:1,000,000 scale published by the U. S. Geological Survey (1955, 1966) and U. S. Air Force (1970). The resulting base map was reduced photographically (Fig. 3).

The long profile of the Rio Grande was plotted from topographic elevation data (Fig. 4) to be used as an aid in defining particular river features and evaluating the effect of tectonic features active subsequent to the development of through-flowing drainage.

These preliminaries furnished guidelines for field reconnaissance that occupied a total of four months and extended from the Arkansas and Colorado drainages in Colorado, throughout the length of the river in New Mexico and Texas, and in adjacent Gila, Pecos,

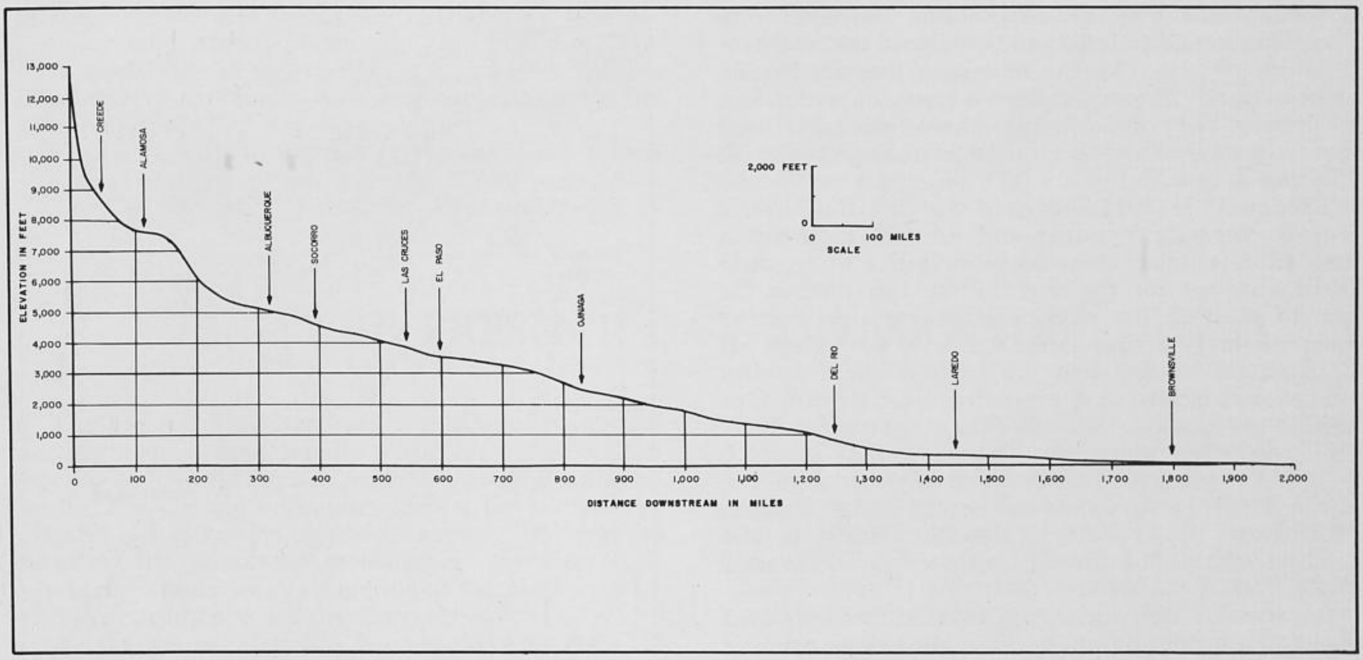


Fig. 4. Long profile of the Rio Grande.

and Rio Conchos drainages. During this work emphasis was given to geomorphic features and sedimentary deposits indicative of river origin. Also considered were adjacent areas thought to contain evidence of river history.

Deposits of fluvial origin are generally recognizable. Gravel suites typical of Rio Grande drainage are less certain but generally recognizable. However, it is never certain that the locality listed represents the earliest occurrence of that gravel in a given area. Gravel may have been moved and "stored" a number of times before formation of the deposit where it was observed in this study. Since high gravels are rarely preserved in undisturbed terraces, the presence of well rounded cobbles was considered evidence indicative of stream occupation of sampling sites at an earlier time.

Existing geologic maps and reconnaissance of possible provenance areas served to identify several distinctive suites of highly resistant rocks to be expected as gravel in streams draining those areas. The most resistant and distinctive gravels were of quartzite, and color combinations were found to be highly significant.

Finally, anomalous physiographic features, high surfaces, wind gaps, and abandoned valleys unrelated to present drainage were examined in some detail to determine their relationship to Rio Grande history. For any such feature to be considered related to the ancestral system, clearly distinctive "Rio Grande" gravel (purple, white and blue quartzites) had to be found associated with it.

Points of significant observations are shown in Figure 3 as numbered localities. These include localities where samples were collected, important physiographic relationships and data were encountered, and where other evidence was observed.

As an interesting parallel, a regional stratigraphic and petrologic study of Santa Fe sediments in the Rio Grande depression was completed to determine provenance of sediments and environments of deposition prior to the Pleistocene integration and entrenchment of the river.

In a region so large, and with a geologic history so long and complex, there are significant sources of potential error, caused by ignorance of details of local geology and difficulty in evaluating the work of others, but in general it is thought that these weaknesses affect interpretations of details of river history, rather than the major events and routes here described.

Thus, the sequence of events here described is presented as a reasonable approximation based upon knowledge available to the author. It is believed further that error is generally on the side of youth, and that events pictured as Pleistocene, for example, may well be older—in some cases, perhaps a great deal older. The overall impression is one of a long history and great age for the Rio Grande system as it is here defined.

PREVIOUS WORKS

The previous works section of this study contains a large number of articles and would be cumbersome to the reader. In order to facilitate the reading of this study a short summary of the previous works section is included here to show the progression of thought concerning the history of the Rio Grande.*

The first articles concerning the evolution of the Rio Grande appeared in the early 1900's. In these, river history was a peripheral interest, but they did suggest an old age for the Rio Grande. Bryan (1938) com-

---

*The complete previous works section is available for reproduction costs from the Department of Geology, Baylor University, Waco, Texas 76703.

pleted the first regional study of the Rio Grande in New Mexico and Colorado and concluded that the river originated during Pliocene time as a through flowing axial stream. Bryan's influence upon investigations concerning river history was considerable, and until the early 1950's the Rio Grande was considered to be Pliocene in age.

Kottlowski in 1953 suggested that the Rio Grande may be a youthful feature and in 1958 presented a detailed description of evidence indicative of an early Pleistocene age for the river. From this time to the present most of the works mentioning river history assumed that the river is early Pleistocene in age. It is important to note that the areas of these detailed studies were located in south-central New Mexico. One notable exception to this trend is a regional study of the Pecos River system by Thomas (1972) in which he postulated that the ancestral Pecos system originated during Early Tertiary time and headed in the San Juan Mountains. By implication, the Rio Grande is also considered to be old, since it had its origin in the same area.

In general, those working on regional problems tend to assign a greater age to the river than those working on more local areas.

ACKNOWLEDGEMENTS

I am indebted to a number of people and organizations who aided materially in the progress of this study. Through their generosity I was provided with financial support; access to areas normally closed; and information, advice, and constructive criticism.

Financial support was tendered by Mobil Oil Corporation; the New Mexico State Bureau of Mines and Mineral Resources; and the Bureau of Economic Geology, University of Texas. Particular thanks are extended to G. G. Tubb and Richard Church of Mobil Oil; Frank Kottlowski of the New Mexico State Bureau of Mines and Mineral Resources; and C. G. Groat of the Bureau of Economic Geology, University of Texas, both for securing the financial aid and for the technical help they contributed. Their efforts in my behalf made this work possible.

Appreciation is expressed to the United States Army, White Sands Missile Range, for permission to visit localities on the range. Particular thanks are offered to Felix Sedillo for aid in expediting the visit, and to Ishmael Rel for directing me to areas of particular interest, both in the range and in other areas far beyond the confines of the base.

Thanks are due the United States Army, Fort Bliss Military Reservation, for permission to visit sites on that post. Special thanks must go to John E. (Pete) Atkins who made my visit both possible and informative. Mr. Atkins also supplied information concerning gravels along the east side of the Franklin Mountains.

A special note of appreciation is extended to Charles B. Hunt, Kirtley F. Mather, Arthur A. Meyerhoff, Vincent C. Kelley, and Ronny Thomas who took time from their busy schedules to hear and criticize various aspects of the study.

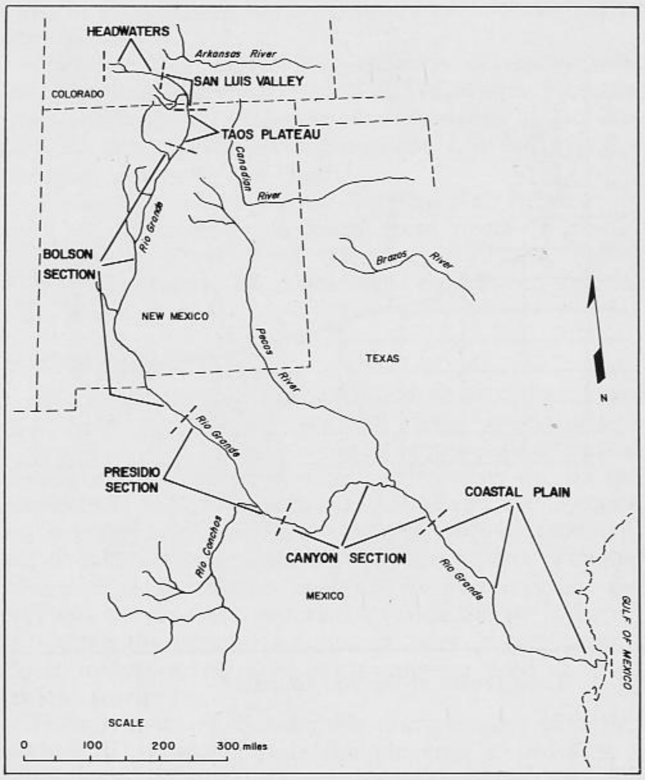


Fig. 5. Sketch map showing the locations of the seven natural sections of the Rio Grande.

Through the good offices of Lindrith Cordell and Frank Kottlowski, I was selected to attend the 1974 Penrose Conference on the tectonics of the Rio Grande graben. While at the conference I met a number of knowledgeable individuals exceptionally well informed about certain aspects of the Rio Grande region, and with them I was able to discuss at length the results and implications of this study. A sincere note of appreciation is extended to those people who discussed the problem with me, including Dan Axelrod, George Bachman, Roy Bailey, Elmer Baltz, Jon Callander, Chuck Chapin, Russ Clemmons, Lin Cordell, Bob Decker, Ted Galusha, John Greis, John Hawley, Dan Karig, Frank Kottlowski, Wayne Lambert, Pete Lipman, Kim Manley, Harold Malde, Tom McGetchen, Bill Seager, Clay Smith, Zane Spiegel and Tom Stevens.

I extend a special note of appreciation to John Hawley who accompanied me in the field for several days and who rarely agreed with either the method or the interpretation, but who was always courteous and helpful. His comments and observations caused me to make several modifications of this study.

Similar thanks are extended to Frank Kottlowski, Bob Weber, Charles Chapin, and Bill Stone of the New Mexico State Bureau of Mines and Mineral Resources who took time to hear my presentation. While disagreeing with many of my conclusions, particularly about the earliest history of the river, they too were extremely helpful.

I extend my sincere appreciation to O. T. Hayward, thesis advisor, who accompanied me in the field several times and who unselfishly spent numerous hours evaluating the study. Similar thanks are extended to J. N. Namy and Robert G. Font for their time spent evaluating, criticizing, and aiding the research as it progressed. Particular thanks are extended to Jean M. Spencer who edited the Bulletin for publication.

A special note of appreciation is extended to William Muehlberger for kindly reviewing the manuscript before publication.

Finally, I wish to express my most sincere thanks and appreciation to my parents, Clifton and Allie Belcher of Del Rio, Texas, for their never ending encouragement and financial support throughout the course of the study. Without their help the study would not have been possible.

While all of these aided in the study, the conclusions and errors are my own. I believe that the presentation is complete enough to show the development of most ideas, even those which later may be found in error.

THE PRESENT DAY RIO GRANDE

The present Rio Grande is a geologically youthful feature, dating from middle Pleistocene time (Kottlowski, 1958). There are, however, features adjacent to the Rio Grande indicative of older fluvial systems, possibly ancestral to present drainage. In order to establish the geomorphic evolution of the river it is essential to consider development of the older systems and their relation to the present river.

As the present day Rio Grande flows to the Gulf of Mexico, the river drops in elevation from approximately 12,500 feet at its headwaters in Stony Pass, Colorado, to sea level at Boca Chica on the Gulf of Mexico, a distance of 1,887 miles. In its course the Rio Grande may be divided into seven natural segments (Fig. 5): Headwaters, San Luis Valley, Taos Plateau, Bolson, Presidio, Canyon, and Coastal Plains sections.

THE HEADWATERS SECTION

The San Juan Mountains, in southwestern Colorado, are formed essentially by a broad domal uplift with a thick veneer of volcanic material. Higher peaks range from 12,000 to 13,000 feet in elevation. Topography is typically glacial with rugged peaks, U-shaped valleys, and numerous moraines, which show evidence of several periods of intense glaciation during Pleistocene time. The vegetation is well adapted to the cool temperate climate and consists principally of aspen, willow, and pine at the lower elevations, grading into pine, fir, and spruce at higher elevations, and abruptly changing to tundra grasses above the tree line.

In this section the Rio Grande begins as a small trickle of meltwater from a snowbank (Locality 9) at Stony Pass (Fig. 2) and is quickly joined by other tributaries to form a sizable mountain stream. Near its headwaters the Rio Grande flows in a single channel approximately 10 to 15 feet wide, occupying a moderately deep valley. Farther downstream the river enters steep-sided glacial valleys and assumes a braided pattern, choked with glacial debris (Fig. 6). Past Wagon Wheel Gap (Locality 10) it reforms a single channel and occupies a deep, steep-sided, relatively narrow valley. The stream gradient in the upper headwaters is approximately 150 feet per mile while in the vicinity of Creede, Colorado, the gradient decreases to approximately 25 feet per mile (Fig. 4). Bed-load deposits in the headwater reaches range from coarse sand to boulder-sized material, chiefly volcanic in origin.

For as long as the domal uplift of the San Juan Mountains has been present, there has been drainage ancestral to the Rio Grande, possibly heading in the Needle Mountains, west of Stony Pass, (Atwood and Mather, 1932) (Fig. 7). Subsequent stream piracy by the Animas River and its tributaries apparently has resulted in gradual eastward migration of the Continental Divide. Abundant quartzite in the Florida Gravels (Pleistocene) in the San Luis Valley suggests divide migration. Abundant quartzite in basal Tertiary formations of the San Juan and Raton basins suggests that drainage to the south, southeast, and east from the Needle Mountains area of the San Juan highlands has been in existence since Early Tertiary time.

THE SAN LUIS VALLEY SECTION

San Luis Valley is a large intermontane basin formed by a complex graben between the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west. The northern portion of the basin is characterized by a nearly featureless flat floor containing recent deposits of fluvial, lacustrine, and eolian origin. In the southern portion the topography changes as the flat floor is altered by the presence of the San Luis Hills. These volcanic hills and tilted basalt-capped mesas rise approximately two to three hundred feet above the basin floor. Upson (1939) described these hills as remnants carved from andesitic volcanics erupted after the development of the San Juan Peneplain.

As the Rio Grande emerges from the San Juan Mountains and enters the San Luis Valley its gradient decreases abruptly from 25 feet per mile to approximately one foot per mile (Fig. 4). This sudden decrease in gradient has resulted in the formation of a large alluvial fan extending radially outward from the vicintiy of Del Norte, Colorado. North of the San Luis Hills the river ranges in width from 100 to 400 feet with no perceptible valley; while south of the San Luis Hills the Rio Grande ranges from 70 to 100 feet in width and has begun to entrench into basalt flows and valley fill. Bed-load material ranges in size from fine sand to small cobbles, except in the vicinity of the volcanic centers where blocks of basalt are present in the stream bed.

THE TAOS PLATEAU SECTION

The Taos Plateau extends from the south end of the San Luis Hills just north of the Colorado-New Mexico state line, south to the Embudo constriction on the west flank of the Picuris Range in New Mexico. The plateau consists of a thick section of basalt flows lying between the Sangre de Cristo Mountains on the east

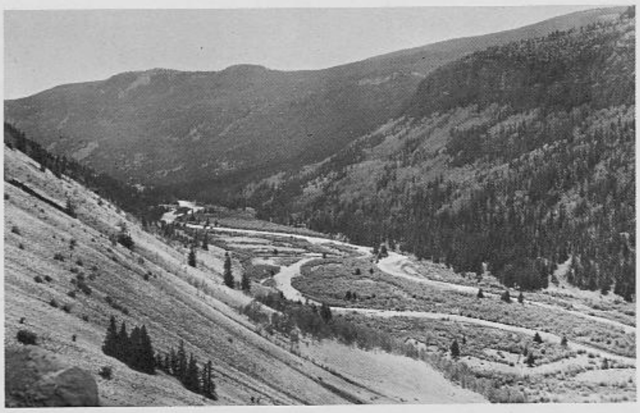


Fig. 6. (Locality 113) The Rio Grande as a mountain stream in the San Juan Mountains. Note the braided stream pattern caused by the heavy load of glacial debris.

Fig. 7. (Locality 114) View west toward the presumed headwaters of the ancestral Rio Grande in the Needles Mountains and Grenadier Range, the probable source for much of the quartzite in typical Rio Grande gravels. Headward erosion by the Animas River system has resulted in gradual eastward migration of the Continental Divide, and has recently removed these mountains from the drainage basin of the Rio Grande.

and the Tusas Mountains on the west, and contains an alluvial cover exhibiting a broadly undulating surface. The Rio Grande and several of its tributaries have deeply entrenched into the basalts forming the Rio Grande Gorge. This ranges in depth from a few feet at the north end to approximately 1,000 feet at the south end, and is appproximately 1,000 feet wide for most of the canyon except in the southern portion where it abruptly widens to approximately 3,000 feet.

The river itself, at low flow, is approximately 20 to 40 feet wide throughout the canyon with a gradient of approximately 25 feet per mile (Fig. 8). There is little if any gravel in the stream bed within the gorge except near confluences with tributaries, where gravels derived from the alluvial cover atop the plateau are deposited.

Gravels atop the Sangre de Cristo Mountains and in the Tertiary formations of Moreno Valley, and a deeply dissected high surface extending from the north end of Moreno Valley toward the San Luis Valley to the northwest, suggest that drainage from the San Juan Mountains flowed east- and southeastward across this area prior to the uplift of the ranges. Remnant erosional surfaces veneered with gravels in the Tusas Mountains to the west (Locality 18) and similar gravels on the east side of the Taos Plateau (Locality 20) suggest the existence of south- and southeastward drainage prior to the extrusions of the thick basalt sequence in the area.

THE BOLSON SECTION

The Bolson Section lies entirely within the Rio Grande depression, and extends from the north end of Española Valley (north of Santa Fe) at the Embudo constriction south to the Quitman Mountains in Trans-Pecos Texas. The section is bordered on the west by such geologic features as the Jemez volcanic center, Colorado Plateau, Datil volcanic province, and the extensive Florida-La Mesa plain; and on the east by the southern Sangre de Cristo Mountains, Sandia-Manzanita-Manzano-Los Piños mountain chain, Fra Cristobal-Caballo mountain chain, Jornada del Muerto, Doña Ana Mountains, and San Andres-Organ-Franklin mountain chain.

This section is an alternating sequence of connected bolsons and constrictions bordered by tilted fault blocks of Basin and Range type which extend from the Española basin in the north to the Hueco bolson in the south (Kelley, 1952). Arroyos and bad-land topography are well developed throughout most of the area. The arid climate characteristic of this section has resulted in the development of a scanty scrub brush and grass cover occasionally accompanied by dunes and blow sand.

The most prominent feature of this section is the extensive high level Ortiz surface in the northern portion of the section, and the correlative (?) Florida-La Mesa Plain in the southern part of the area. This surface, present throughout the section, extends for some distance into Mexico, and has the appearance of a sea of sand stretching to the horizon, above which project several island-like mountain masses. After integration of through-flowing drainage during middle Pleistocene time, the Rio Grande began a period of cyclic downcutting to produce several lower surfaces throughout the river valley in the Bolson section (Hawley, 1969).

In this section the Rio Grande ranges in width from 400 to 600 feet and is principally a sand-bed stream (Fig. 9). The river is within a wide valley with moderately steep and rounded valley walls except within the constrictions where the valley quickly narrows and the valley walls become vertical. The Rio Grande has no major tributaries within this section; drainage (arroyo) density is minimal, and mountain fronts are far from the river valley with large aprons of bolson fill in between.

An exhumed erosional surface in the San Pedro Mountains (near Locality 32) (Church and Hack, 1939) northwest of the Jemez mountain mass, and the high and intermediate level erosional remnants in the vicinity of Mount Taylor (near Locality 89) and to the south (Fitzsimmons, 1959), with occasional thin lags of quartzite gravel, suggest that drainage south from the San Juan Mountains may have been in existence prior to the period of intense volcanism which occurred in the Datil volcanic province of west-central New Mexico during Oligocene and early Miocene time.

THE PRESIDIO SECTION

The Presidio Section extends from the Quitman Mountains south to a point approximately 10 miles southeast of Redford, Texas (near Locality 63), where the Rio Grande enters the first sizable canyon in Texas. This region is one of sparse vegetation, rugged topography, with mountains and elevated basalt-capped mesas exhibiting bold and precipitous fronts. In contrast with upstream sections it (1) lacks a continuous high surface throughout most of the section; (2) lacks traceable correlative surfaces throughout the section, though numerous local noncorrelative surfaces are present; (3) has mountain fronts immediately adjacent to the river valley throughout the section except in the vicinity of Presidio; and (4) has a higher drainage (arroyo) density. The climate is hot and arid and typical desert vegetation abounds except in the river bottom where salt cedar and mesquite thrive. A small bolson is located in the vicinity of Presidio and Redford, Texas, at the confluence of the Rio Grande and Rio Conchos, the only major tributary of the Rio Grande in this section.

In the Presidio Section the river is approximately 125 feet wide and has a large floodplain covered with salt cedar and mesquite (Fig. 10). The bed load in the northern portion of the section is principally coarse gravel (particle size ranges from large pebble to small boulder) while in the Presidio-Redford area the bed load is principally sand and fine gravel. Numerous arroyos in the northern part of the section are responsible for the change in bed load, grade and stream size, and have formed prominent but noncorrelative surfaces (Groat, 1972).

The Rio Conchos may have been ancestral to the Rio Grande until middle Pleistocene time when the upper Rio Grande worked southeastward by basin spill-over to join the Rio Conchos, thus integrating into through-flowing drainage (Lee, 1907; Hill, 1934; Kottlowski, 1958; Reeves, 1965; Strain, 1970; Thomas 1972). The presence of high-level terrace remnants well below the top of the canyon of the Rio Conchos through Sierra Grande suggests that the river is antecedent to the Early Tertiary structure and that through-flowing drainage has been present in this area since the beginning of Tertiary time.

THE CANYON SECTION

The Canyon Section extends from approximately 10 miles southeast of Redford, Texas, where the Rio Grande enters the first sizable canyon, to south of Del Rio, where the river emerges from canyons in the Edwards Plateau.

This section is a land of contrasts between generally level bolson floors and elevated horst blocks (Fig. 11), island-like intrusive uplifts, and anticlinal mountains. The river has cut deep canyons through the elevated areas, and has extended canyons southeastward across the Stockton and Edwards Plateaus to the landward margin of the Rio Grande embayment. Throughout this region the climate is arid, with typical desert vegetation.

The river gradient is approximately 5 feet per mile and stream width ranges from 50 feet in portions of Santa Elena Canyon to one-fourth of a mile near Del Rio. Bed-load material is principally sand and gravel, ranging from fine sand to large cobbles.

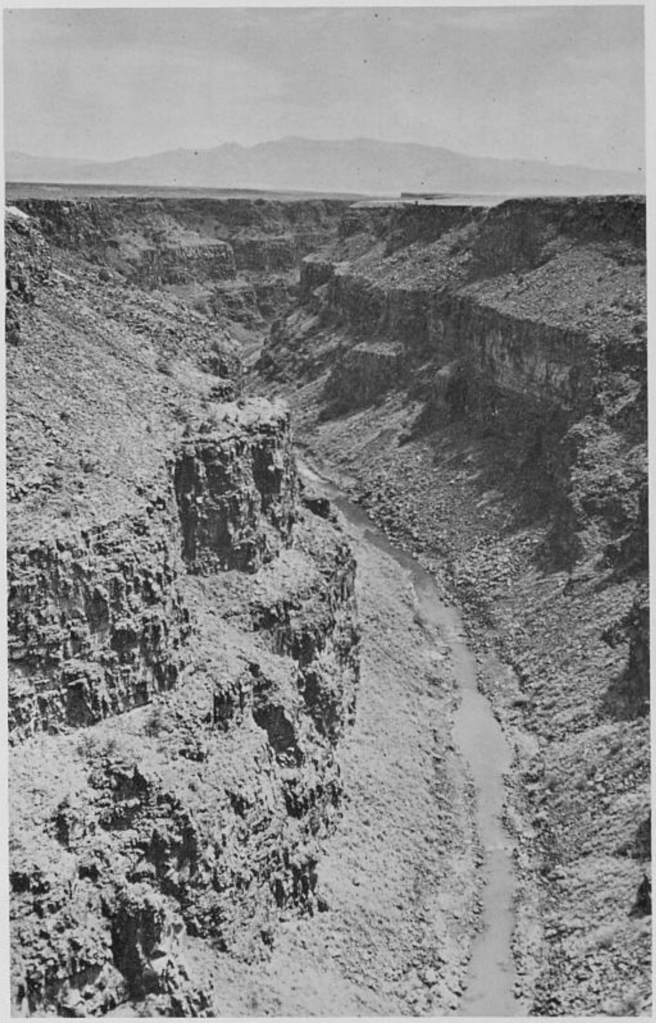


Fig. 8. (Locality 115) View south down the Rio Grande Gorge cut into basalt flows of the Taos Plateau. In this area the river is only 20 to 40 feet wide with a gradient of approximately 25 feet per mile (Fig. 4). The Picuris Range is in the background.

Canyons of the Big Bend Region transect structures which originated in Early and Middle Tertiary time. Maxwell and Dietrich (1972); Twiss (1970); Maxwell, Lonsdale, Hazzard and Wilson (1967); Zinn (1953); King and Adkins (1946); King (1935); and Baker (1927) proposed that during Pliocene time the area was buried beneath bolson fill to an elevation of at least 4,200 feet covering Mesa de Anguila, Mariscal Mountain, Sierra San Vicente, and all but the highest parts of Sierra del Carmen. The Rio Grande was integrated upon this fill and through erosion became superimposed upon the structures, forming the present day canyons. Hill (1934) and Udden, Baker and Böse (1916) believed the Rio Grande was antecedent to the structures, indicating an Early Tertiary age for the river. In the progress of this study a search for remnants of bolson fill atop Mesa de Anguila and Mariscal Mountain was conducted with negative results, while

Fig. 9. (Locality 116) The Rio Grande near Albuquerque, New Mexico, within the Bolson Section where it is a sand bed stream. Note the braided stream pattern and the shallow channel depth. The gradient here is approximately 4.5 feet per mile (Fig. 4).

quartzite gravels were found atop the Stockton Plateau suggesting that the Rio Grande may well be antecedent to the structures in this area. This implies that the Rio Grande (ancestral Rio Conchos) may have come into being during Early Tertiary time.

THE COASTAL PLAINS SECTION

The Coastal Plains Section extends from south of Del Rio to the Gulf of Mexico east of Brownsville. This section is a flat to gently undulating plain in which the local relief rarely exceeds 300 feet. Vegetation increases considerably to the south as the climate changes from semi-arid near Del Rio to sub-tropical near Brownsville.

The gradient of the Rio Grande decreases from approximately 4 feet per mile near Del Rio to approximately 1 foot per mile near Laredo and approaches sea level near Brownsville (Fig. 4). The bed-load material near Del Rio is principally sand and smaller gravel, grading to sand and then to sandy silt as the Gulf of Mexico is approached. Within the coastal plain, the river is entrenched as much as 50 feet into Tertiary formations of the Gulf Coast and has developed a wide floodplain.

Basal Tertiary formations in the Coastal Plains Section consist of marine rocks overlain by a fluvial sequence derived from the north and northwest, perhaps as far as the mountains of southwestern Colorado (Getzendaner, 1930; Trowbridge, 1932). Reynosa gravels of Pliocene age veneer most of the section, from Del Rio to Rio Grande City (Trowbridge, 1926 and 1932).

Gravels found in the Del Rio vicinity (Localities 67 and 68) are lithologically identical to gravels found by Thomas atop an erosional remnant above the projected Ogallala surface near Fort Stockton, Texas (Thomas, personal communication, 1974). Similar gravels have been traced from Del Rio to Rio Grande City, suggesting that a part of the lower Reynosa Gravel (Price, 1958) may be pre-Ogallala in age, possibly representing wide-spread erosion in southwestern Colorado and north-central New Mexico during Oligocene time, and indicative of an ancestral Rio Grande entering the Gulf of Mexico at least as early as Oligocene time.

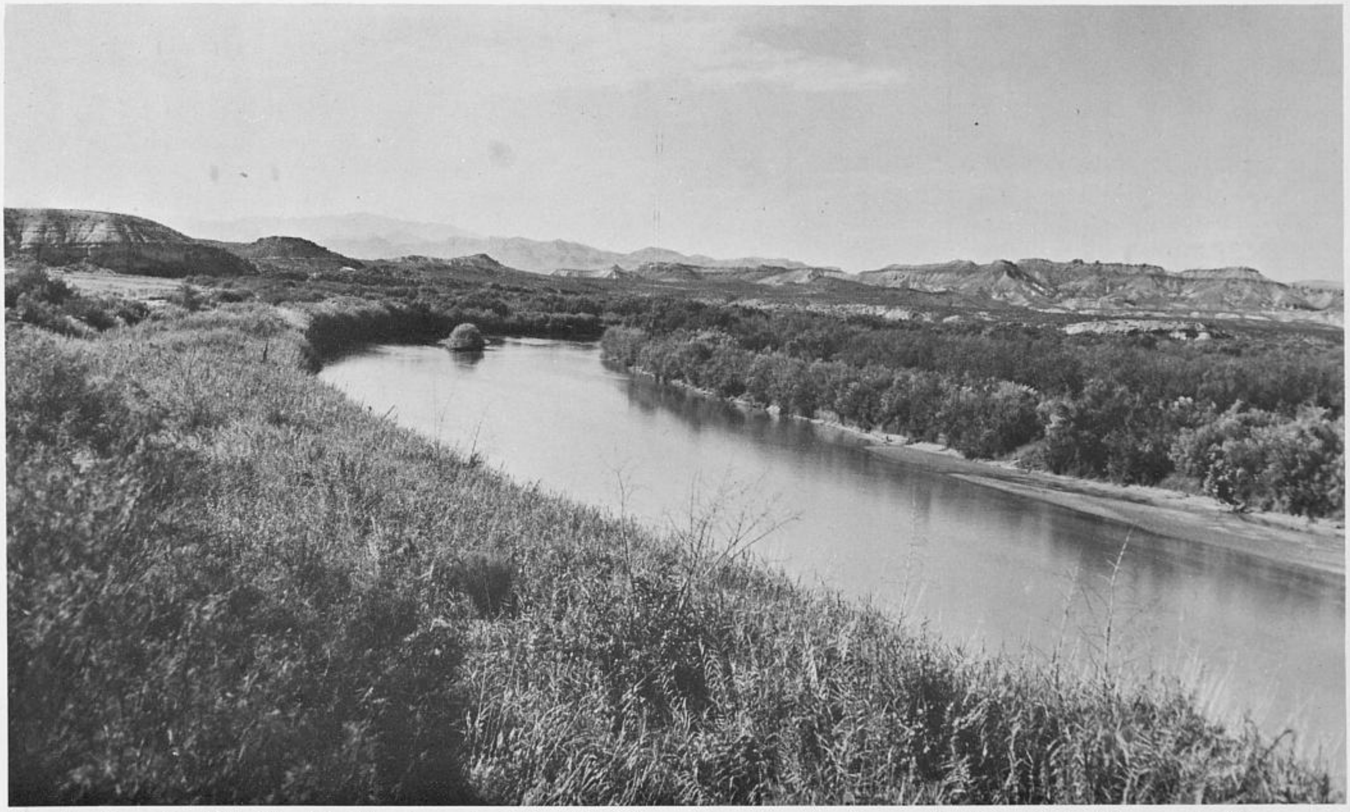


Fig. 10. (Locality 117) The Rio Grande south of Presidio, Texas, flows in a heavily vegetated floodplain. The gradient is approximately 4.5 feet per mile (Fig. 4). Shown in the background are the Bofecillos Mountains.

Fig. 11. (Locality 118) The mouth of Santa Elena Canyon cut by the Rio Grande into the horst block of Mesa de Anguila. The canyon here is approximately 1,600 feet deep and the Rio Grande is thought to have begun downcutting during Miocene time when the uplift of the horst block first occurred.

TECTONIC HISTORY

For over half its length the Rio Grande flows through a region that has been tectonically active since the end of Cretaceous time. The headwaters of the Rio Grande in the San Juan Mountains have experienced two episodes of domal uplift, and drainage from these highlands southeastward through New Mexico and Texas has probably been in existence since the first period of uplift in Late Cretaceous time. Throughout this vast period, stream courses have been dictated by tectonic events. Since water flows downhill and downhill has been determined by tectonism, the downhill direction may not have remained static since Late Cretaceous time. Thus, regional tectonics have been of primary importance in developing a dynamic model for drainage evolution.

LATE CRETACEOUS-EARLY TERTIARY TECTONISM

The first Laramide event, producing a noticeable effect upon the stable marine environment existing in the region of Colorado and New Mexico at the end of Cretaceous time, produced the initial broad domal uplift of the San Juan Mountain area. This uplift caused the seas to retreat, resulting in the deposition of continental sediments during the waning period of Cretaceous time and the beginning of Paleocene time (Atwood and Mather, 1932).

A Laramide geanticline, the San Luis uplift (Baltz, 1965), included the area occupied by the present day San Juan Mountains, the San Luis Valley, the Sangre de Cristo Mountains, and Brazos uplift. It continued in intermittent uplift throughout Eocene and into Oligocene time, marked on the east by intensive thrusting and folding, which can be seen in the present day Sangre de Cristo Mountains (Johnson, Dixon, and Wanek, 1956; Clark, 1966).

In New Mexico and Texas, Laramide tectonism produced broad folds that may contain intense local thrusting and folding (Spiegel, 1961; Kelley, 1952). Structural features thought to have been derived from Laramide tectonism exist in the Nacimiento and Lucero uplifts (Anonymous, 1961), Zuni Mountains (Kelley, 1955b), Manzano and Los Piños Mountains (Stark and Dapples, 1946), Joyita Hills (Kelley, 1952; Geddes, 1963), Socorro Mountain (Smith, 1963), Little San Pasqual Mountain (Geddes, 1963), Fra Cristobal Mountains (Kelley and McCleary, 1960), Caballo Mountains (Kelley and Silver, 1952), San Andres and Sacramento Mountains (Kelley, 1955a), Oscura Mountains (Bachman, 1968), Franklin Mountains (Harbour, 1972), Trans-Pecos area (Baker, 1927; King, 1935), Big Bend Region (Maxwell, Lonsdale, Hazzard, and Wilson, 1967; Maxwell and Dietrich, 1972), and Rio Grande embayment (Getzendaner, 1930).

MIDDLE TERTIARY TECTONISM

During Oligocene time the San Luis uplift was terminated and then foundered on the east side, producing the San Luis Valley (Baltz, 1965). Thrusting, folding, and normal faulting occurred in the northern Sangre de Cristo and Wet Mountains (Johnson, 1959). During this time the San Juan Mountains underwent intense episodic volcanic activity which gradually built up an extensive high volcanic plateau (Atwood and Mather, 1932; Larsen and Cross, 1956; Kelley, 1957).

Throughout New Mexico and Trans-Pecos Texas, this Oligocene to middle Miocene deformation was characterized by intense volcanic activity, large scale high-angle normal faulting, and basin formation. During this same period the Sangre de Cristo Mountains were worn away, to be rejuvenated in middle Miocene time (Clark and Read, 1972; Miller, Montgomery and Southerland, 1963; Clark, 1966); Moreno Valley, between Taos and Cimarron Ranges of the Sangre de Cristo Mountains was outlined by high-angle normal faulting (Ray and Smith 1941); the Brazos uplift was tilted eastweard (Muehlberger, 1960b); the Picuris Range was uplifted (Montgomery, 1956); the Datil region of west-central New Mexico underwent intensive volcanism which started during early Oligocene and ended during Miocene time (Wright, 1946). The Fra Cristobal Mountains (Thompson, 1955) and Caballo Mountains (Kelley and Silver, 1952) underwent general uplift accompanied by intense faulting. The Sacramento Mountains entered a period of volcanism and porphyry intrusion, followed by uplift of tilted fault blocks (Kelley and Thompson, 1964). The Franklin Mountains were uplifted along reverse faults (Harbour, 1972), while the Guadalupe Mountains underwent broad arching accompanied by minor faulting (King, 1948). In the Trans-Pecos area an early period of intense volcanism was followed by a period of complex high-angle faulting and tilting (Baker, 1927; King, 1935; Twiss, 1970). In the Big Bend Region, Mesa de Anguila was uplifted as a great horst block (Wilson, 1970), and the Sierra del Carmen was broken into a number of eastward-tilted fault blocks by high angle faulting (Maxwell, Lonsdale, Hazzard, and Wilson, 1967).

Produced during this period of deformation was the Rio Grande depression, a series of internally complex linked *en echelon* basins extending from Leadville, Colorado, in the north (Van Alstine, 1968) to south of Las Cruces, New Mexico (Kelley, 1952). This depression, originating in late Oligocene time (Stearns, 1943), was clearly outlined throughout its length by early Miocene time and received Santa Fe sediments during middle Miocene time. Recurrent movement along this depression exerted significant control upon Middle to Late Tertiary drainage systems in the area.

LATE TERTIARY-QUATERNARY TECTONISM

The transition from Tertiary to Quaternary time is thought to have been marked by the second doming of the San Juan Mountains during late Pliocene time. This uplift became stable during the Hinsdale volcanic epoch, and then was reactivated to continue activity into Pleistocene time.

In New Mexico and Trans-Pecos Texas this period

Fig. 12. (Locality 14) The Rio Grande is the southern portion of San Luis Valley. Here the valley cut by the Rio Grande is in alluvium approximately 300 feet thick overlying basalts, through which the Rio Grande has cut a deep canyon to the south. Shown in the background are the San Luis Hills.

Fig. 13 (Locality 13) The start of the Rio Grande Gorge in the southern San Luis Valley. The gorge begins with a depth of only a few feet. Overlying the basalts is approximately 300 feet of alluvial material.

of tectonism caused renewed movement along trends established during Middle Tertiary deformation, and was accompanied by arching and gentle tilting. The Sangre de Cristo Mountains were rejuvenated during early Pleistocene time (Cabot, 1938); the Jemez volcanic center came into existence during late Pliocene time (Ross, Smith, and Bailey, 1961); the Sandia-Manzano-Los Piños mountain chain was rejuvenated during late Pliocene time (Stark and Dapples, 1946; Reiche, 1949); the Fra Cristobal Mountains (Thompson, 1955) and the Caballo Mountains (Kelley and Silver, 1952) continued to experience uplift; the San Andres-Organ mountain chain was tilted to the west during late Pliocene time (Dunham, 1935), a movement which may yet be occurring (Bachman, 1968); the Guadalupe Mountains experienced intensive arching and block faulting resulting in the present configuration of the mountain mass (King, 1948); and the Trans-Pecos area underwent minor tilting and normal faulting (Twiss, 1970).

The Rio Grande depression appears to have been tectonically inactive during deposition of the Santa Fe sediments north of Santa Fe, New Mexico (Galusha, personal communication, 1974), but reactivation apparently occurred during this period of tectonism. This is suggested by faulting in the middle Miocene-Pliocene Santa Fe sediments throughout the depression. Recent seismic activity in the vicinity of Socorro and Albuquerque, New Mexico, suggests that movement is still occurring (Sanford, 1963).

The complexity of the Rio Grande depression is suggested by the fact that in the vicinity of Socorro and Albuquerque (New Mexico) both Mesozoic and Paleozoic rocks underlie Tertiary sediments in the trough, while in the vicinity of Santa Fe, only Paleozoic material is believed to underlie the Tertiary sediments within the depression (Anonymous, 1961). The presence of Precambrian rock within and bordering the Rio Grande depression north of Santa Fe suggests that Precambrian strata underlie Tertiary sediments in this area. Though the nature of the transition and structure is unknown, evidence for a postulated solution may be found in the vicinity of the Picuris Range and Taos Plateau to the north (Fig. 3). The salient factors are these. (1) Immediately south of the San Luis Hills, near the New Mexico-Colorado border, the Rio Grande has cut through approximately 200 feet of alluvial sediment (Fig. 12) overlying basalt flows into which the river is further entrenched 20 or 30 feet. The alluvium thins southward to a point approximately 2.5 miles south of the Rio Grande Gorge bridge (4 miles north of Locality 31) where the thickness is approximately 15 feet. (2) The Rio Grande Gorge increases in depth from a few feet near the San Luis Hills (Fig. 13) to approximately 1,000 feet near the Embudo constriction (Locality 31). (3) From the vicinity of the San Luis Hills to a point approximately 2.5 miles south of the Rio Grande Gorge bridge the basalt flows dip gently northward. South from this point several reversals of dip produce numerous gentle anticline-syncline sequences in the basalt layers. (4) Along the small gorge cut by the Arroyo Hondo from its confluence with the Rio Grande east to the town of Arroyo Hondo the basalts also exhibit an eastward component of dip which increases in magnitude to a point just west of the town of Arroyo Hondo where they disappear beneath alluvial cover. (5) From its beginning near the San Luis Hills to a point approximately 2.5 miles south of the Rio Grande Gorge bridge, the Rio Grande Gorge maintains a width of about one quarter of a mile, but south of this point the canyon abruptly widens to approximately one mile (Fig. 14). (6) The Rio Grande Gorge contains numerous slump blocks in the southern portion (Fig. 15), though they are absent north of the point shown in Figure 13. (7) On the north and northwest sides of the Picuris Range, sediments of upper Santa Fe or younger age have been highly deformed; in some places the deposits stand on end. (8) The Rio Grande has cut a small gorge known as the Embudo constriction into the west flank of the Picuris Range (Fig. 16).

Though there are several possibilities, a sequence of events which might explain the uplift of the Picuris Range, the formation of the various listed phenomena, and the entrenchment of the Rio Grande into the basalts of the Taos Plateau is here postulated.

Subsequent to the outlining of the Rio Grande depression during late Oligocene time, the portion of the trough in the vicinity of Taos, New Mexico, and the Picuris Range (henceforth designated the Taos Block) underwent uplift as a tilted horst block bounded by faults along the west front of the Sangre de Cristo Mountains, south of the present day Picuris Range, and west of the present Rio Grande. This uplift resulted in stripping of overlying Paleozoic and Mesozoic rocks from the Precambrian basement, prior to deposition of Santa Fe sediments which began during middle Miocene time, following uplift of the Sangre de Cristo Mountains.

After deposition of Santa Fe sediments, the situation was similar to that depicted in Figure 17A. Either immediately prior to or during the Hinsdale volcanic epoch the Taos Block was broken by faulting along which recurrent movement occurred, allowing accumulation of the thick sequence of basalt flows of the Taos Plateau as shown in Figure 17B. Following extrusion of the upper basalt flows the Rio Grande entered the area and gradually deposited a layer of alluvial sediment atop the basalt as shown in Figure 17C.

Some time later recurrent uplift took place along the bounding faults of the old Taos Block as well as along cross-cutting faults. As shown in Figure 17D, this uplift resulted in (1) gentle northward tilting of the basalts in the northern portion of the block, (2) a zone of deformation within the southern portion of the block, (3) exposure of the Precambrian Picuris "Hills," and (4) initial down-cutting of the Rio Grande into the basalts at the south end of the Taos Plateau.

As movement continued (Fig. 17E) (1) the Picuris "Hills" were elevated into the Picuris Range; (2) basalts north of the deformation zone were caused to dip northward, while at the same time assuming an eastward component of dip resulting from drag effects along faults at the front of the Sangre de Cristo Mountains; (3) the degree of deformation increased in the southern portion of the block; (4) the sequence of alluvial sediment overlying the basalts thickened to the north due to alluviation produced by modification of the local base level caused by the elevation of the basalts and entrenchment of the Rio Grande into the west flank

Fig. 14. (Locality 119) The abrupt widening of the Rio Grande Gorge where the width changes from approximately one-quarter of a mile to nearly three-quarters of a mile. Note the large slump blocks in the wider portion of the canyon.

Fig. 15. (Locality 120) Slump blocks in the Rio Grande Gorge have widened the canyon. Note that the alluvial cover atop the slump blocks is similar to that atop the canyon walls.

of the Picuris Range; and (5) the Rio Grande gradually extended the gorge northward, cutting through both the overlying alluvial deposits and the basalts as it became entrenched into the southern portion of the block.

Concurrent with development of the Rio Grande Gorge the canyon walls within the zone of deformation retreated by slump failure, thought to have resulted from the deepening of the canyon and the more highly fractured nature of the deformed basalts.

This sequence of events may account not only for the observed phenomena but also may explain the anomalous east-west trend of the Picuris Range, the presence of upper Santa Fe and later sediments immediately adjacent to both the northern and southern flanks of the Picuris Range, the abrupt change in gradient of the Rio Grande in the vicinity of the San Luis Valley and the Taos Plateau (Fig. 4), and the existence of the Rio Grande Gorge.

If this sequence of events is truly representative, it is suggested that the transition from Paleozoic to Precambrian material underlying the sediments within the Rio Grande depression is abrupt, and that the uplift of the east-west trending Picuris Range is the related cross structure.

LATE CRETACEOUS–EARLY MIOCENE DRAINAGE

During its first stage of evolution, ancestral Rio Grande drainage consisted of two general systems: (1) Rio Grande-Pecos and (2) Rio Conchos. These systems undoubtedly underwent modification by episodic Laramide tectonism and sporadic volcanism but were completely reorganized by Middle Tertiary deformation, which brought the first phase to a close.

Rio Grande drainage began with the uplift of the headwaters region [(1) ancestral Mogollon highlands in central Arizona and (2) San Juan Mountains of Atwood and Mather, 1932; Larsen and Cross, 1956; and Kelley, 1957; or San Luis uplift of Baltz, 1965] during Late Cretaceous and Early Tertiary time, but through-flowing drainage was probably not established until Early Tertiary, as is indicated by marine and coastal plain strata of Late Cretaceous age in the San Juan basin.

The emphasis here on these highlands as the headwaters for the river is based upon tectonic history and lithology. Other areas were elevated during Early Tertiary time and collected runoff, but none of these is known to be of both adequate size and specific lithology to serve as the source of both water and distinctive sediments for the ancestral Rio Grande.

Udden, Baker, and Böse (1916) suggested that the Rio Grande came into existence during Eocene time, as evidenced by Early Tertiary fluvial sediments in the Rio Grande embayment of Texas. Hill (1934) suggested that during Early Miocene time the Rio Grande was composed of two parts: a northern river which flowed into large playa lakes in northern Mexico, and a southern river which consisted of the Pecos River and its continuation to the Gulf of Mexico. Thomas (1972) suggested that the Rio Grande drainage originated with the uplift of the San Juan Mountains and originally flowed down the ancestral Pecos River to join an ancestral Rio Conchos.

Numerous authors have presented evidence suggesting the presence of Early Tertiary drainage in southern Colorado, New Mexico, and Trans-Pecos Texas. Baltz (1967) described Early Tertiary strata of fluvial origin in the San Juan Basin and postulated sources to the northeast and northwest. Renick (1931) described an unconformity at the base of the Wasatch Formation (San Jose in later works) within the San Juan basin, suggesting subaerial erosion. Burbank and Goddard (1937); Johnson, Dixon, and Waneck (1956); and Johnson (1959) described Early Tertiary strata of Huerfano Park, Colorado, and Raton basin, New Mexico, composed of fluvial material derived from highlands to the west and northwest. Mather (1957) suggested extensive Early Tertiary erosion, culminating in Oligocene time, which reduced once lofty highlands of southern Colorado to a region of low rounded hills projecting above a broadly undulating plain. Smith (1938) described the El Rito Formation (Eocene) of north-central New Mexico, as derived from highlands to the north, and stated that this material was deposited by streams upon pre-Tertiary rocks that had been tilted and beveled by widespread erosion. Church and Hack (1939) stated that an erosional remnant atop the San Pedro Mountains north of Sierra Nacimiento, north-central New Mexico, was indicative of prolonged erosion in Early Tertiary time. Budding, Pitrat, and Smith (1960) described the El Rito Formation as a torrential stream deposit draining highlands to the north. Ray and Smith (1941) described basal Tertiary strata in Moreno Valley in the Sangre de Cristo Mountains containing quartzite conglomerates derived from north and northwest sources, and suggested that during Early Tertiary time this area was occupied by monadnocks rising above a widespread erosional surface across which flowed numerous streams. Stearns (1943) described the Galisteo Formation of central New Mexico as deposited by slow moving streams draining highlands to the north and northwest and suggested that widespread erosion occurred before and after the deposition of the Galisteo. Givens (1957) and Tonking (1957) described portions of the Baca Formation containing quartzite conglomerate, and Willard (1959) described alternating coarsening and fining of the Baca Formation west of Socorro, New Mexico.

Well-rounded gravels within the El Rito Formation, overlying Jurassic sediments west of Abiquiu, New Mexico (Locality 27), and overlying Cretaceous deposits at Cerro Pedernal (Locality 30) (Fig. 18) suggest the presence of a drainage system flowing possibly south- or southeastward during Eocene time. Gravels containing quartzite cobbles were found at Localities 39 and 40 on portions of Cebolleta Mesa (Fig. 19) at elevations of 7,600 and 7,300 feet respectively. Reconnaissance investigations in west-central

Fig. 16. (Locality 121) The Embudo constriction, the gorge cut by the Rio Grande into the western flank of the Picuris Range. Uplift of the range during Pleistocene time may have initiated downcutting by the Rio Grande into the basalts of the Taos Plateau.

New Mexico revealed the presence of similar gravels in the Baca Formation (Eocene) as far west as the Arizona-New Mexico state line. The occurrence of these gravels suggests the presence of major eastward through-flowing drainage that may have headed in the ancestral Mogollon highlands of Arizona.

A highly dissected erosional remnant at an elevation of approximately 11,500 feet in the Costilla Creek area within the Sangre de Cristo Mountains north of Moreno Valley (Fig. 22), which can be projected over the San Luis Valley and the anamolous north-south trend of Moreno Valley (Fig. 23), suggests that drainage from the San Juan Mountains may have extended across this area just prior to the uplift of the Sangre de Cristo range in Miocene time. This interpretation may be further supported by the presence of well-rounded quartzose gravels of local provenance atop high terraces near Eagle Nest, New Mexico, which were traced south to the vicinity of Las Vegas, New Mexico (Localities 25, 26, 35 and 43). Although these gravels have been credited to a Pleistocene river originating just north of Moreno Valley (Clark and Read, 1972), their distribution suggests earlier drainage. As middle Miocene uplift of the Sangre de Cristo range began, river entrenchment into an existing erosional surface occurred, apparently creating several local drainage basins. After uplift diverted through-flowing drainage to the west, smaller streams of local origin continued to maintain drainage flowing in the same direction as earlier through-flowing streams.

Baker (1927), King (1935), and Maxwell and others (1967) suggested that in the Big Bend Region of Texas the Rio Grande originated during late Pliocene or early Pleistocene time at the close of an extended period of basin filling, which produced a river bed elevation of at least 4,200 feet. After through-flowing drainage had been established on this alluvial surface, the river entrenched in the basin fill and in the process encountered buried features, such as Mesa de Anguila (elevation 3,850 feet), Mariscal Mountain (elevation 3,900 feet), the north flank of Sierra San Vicente (elevation 2,250 feet) and portions of the Sierra del Carmen, producing the impressive canyons of the Big Bend.

However, had the Big Bend Region been filled so recently to an elevation of 4,200 feet as was suggested, some remnant of this fill should yet be present on top of each of the formerly buried features. Field investigations failed to encounter such material atop Mesa de Anguila (Locality 104) (Fig. 24) or Mariscal Mountain (Locality 105) (Fig. 25).

If the Rio Grande canyon through the north flank of the anticlinal Sierra San Vicente (Fig. 26) is superposed, then it is thought that the sequence of events depicted in the left portion of Figure 27 would have occurred. First, the Sierra would have been buried by

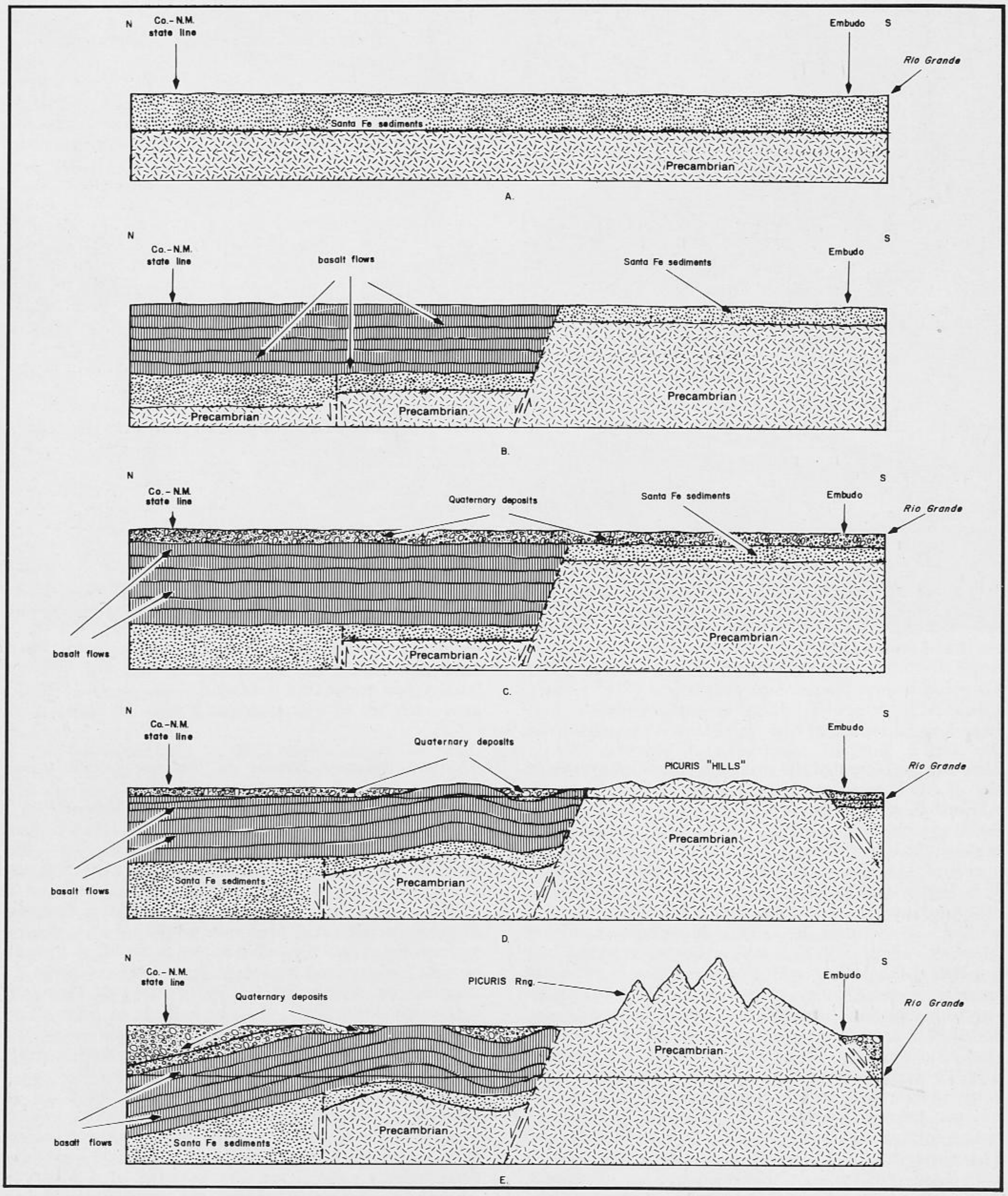


Fig. 17. Origin of the Rio Grande Gorge. The sequence of events which is thought to have occurred, resulting in formation of the Rio Grande Gorge include: (A) Santa Fe sediments were deposited directly upon Precambrian basement from which Paleozoic and Mesozoic material had been removed by an earlier period of erosion. (B) Recurrent faulting allowed thick accumulation of basalts in the Taos Plateau, extruded during the Hinsdale volcanic epoch. (C) After volcanism ceased the Rio Grande was diverted onto the Taos Plateau and deposited a cover of alluvial material atop the basalts. (D) The uplift of the Picuris Range began, deforming basalt flows near the southern portion of the plateau and tilting the flows gently to the north (dips are exaggerated). This caused the first entrenchment by the Rio Grande. (E) Uplift of the Picuris Range progressed, further tilting and deforming the basalt flows (dips are exaggerated). This resulted in the present entrenchment of the Rio Grande into basalt flows.

Fig. 18. (Locality 30) The El Rito Formation on Cerro Pedernal was deposited by streams draining highlands to the north (Smith, 1938). The streams which deposited these gravels are thought to have been part of Early Tertiary Rio Grande drainage.

basin fill as shown in Figure 27A. Once through-flowing drainage was established the river would entrench into the basin fill (Fig. 27B) until reaching the massive limestones of the Sierra San Vicente, when the river should migrate down dip tending to remain within softer basin fill sediments (Fig. 27C). Eventually the Rio Grande would reach the buried Early Tertiary sediments and establish a course north of the Sierra San Vicente (Fig. 27D).

If the Rio Grande were antecedent to the structure then it is thought that the sequence of events depicted in the right portion of Figure 27 would occur. First, the Rio Grande would flow across undisturbed Cretaceous sediments (Fig. 27A). As uplift of the Sierra San Vicente began (Fig. 27B), the river would gradually entrench and continue to deepen its canyon as uplift progressed (Fig. 27C). When the uplift ceased, the Rio Grande would have cut a deep canyon (Fig. 27D). This last sequence of events should have produced the present canyon through the north flank of Sierra San Vicente, suggesting that the Rio Grande may be antecedent in the Big Bend Region of Texas.

As shown in Figure 26 some Late Cretaceous sediments form low cuestas along the north flank of the Sierra San Vicente. These cuestas probably owe their presence to the down-cutting action of the Rio Grande. If the river were superposed across this structure and down-cutting started so recently (middle Pleistocene), some remnant of the cuesta-forming sediments should be present atop the anticline. The absence of such a remnant suggests that as the Early Tertiary deformation began the ancestral Rio Grande (Rio Conchos), then possibly flowing across the area presently occupied by the crest, may have "slid off" of the anticline, stripping the cuesta-forming sediments as down-dip migration progressed. This possibility suggests antecedence and implies a much greater age for this section of the river than is generally supposed.

King (1935) and King and Adkins (1946) suggest that the Rio Conchos is a subsequent stream in the Trans-Pecos area (Texas and Chihuahua), thus implying a post Laramide age (Miocene ?) for the river. West of Ojinaga, Chihuahua, the Rio Conchos has

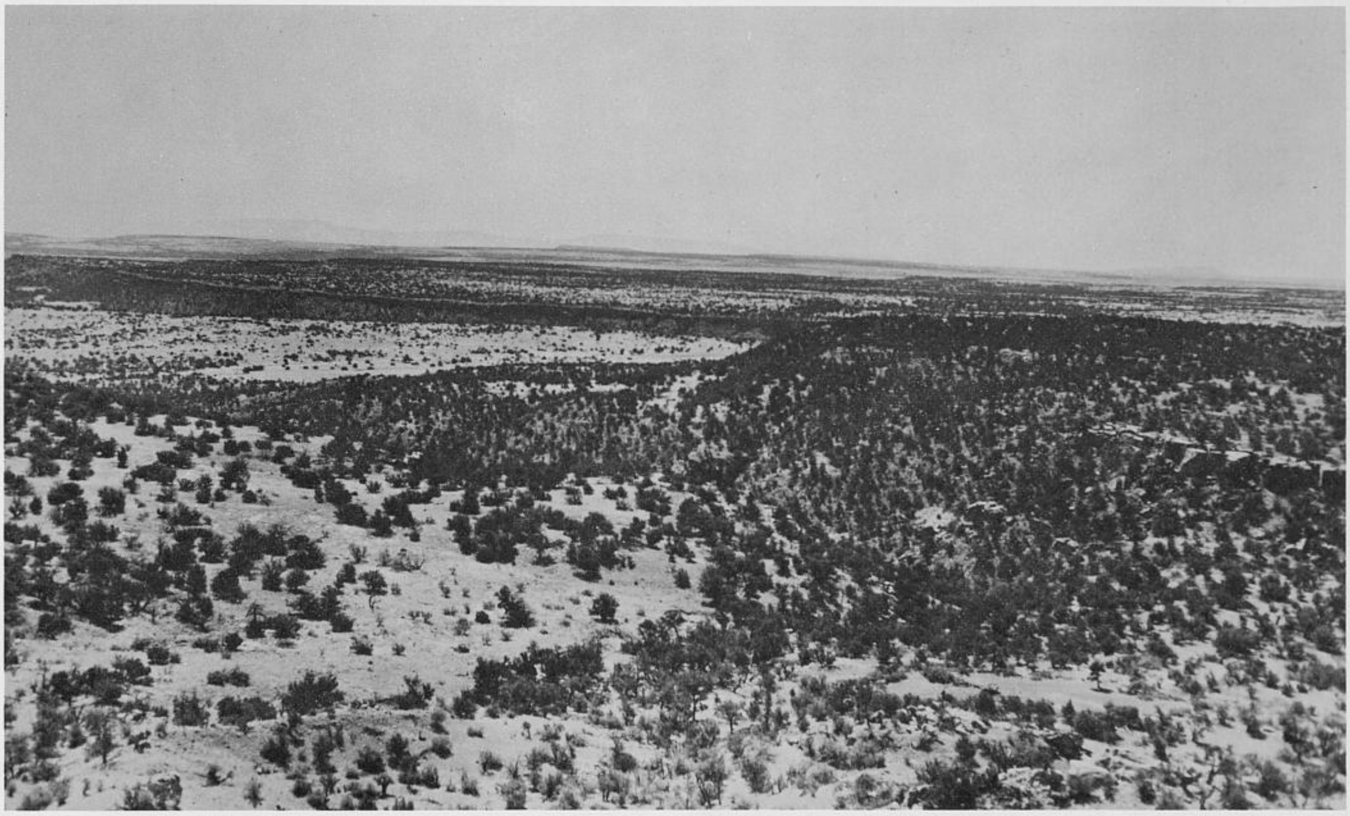


Fig. 19. (Locality 40) View southeast across the eastern portion of Cebolleta Mesa where rounded quartzite gravels were found at elevations of 7,300 and 7,600 feet. In the distant background is Sierra Ladron.

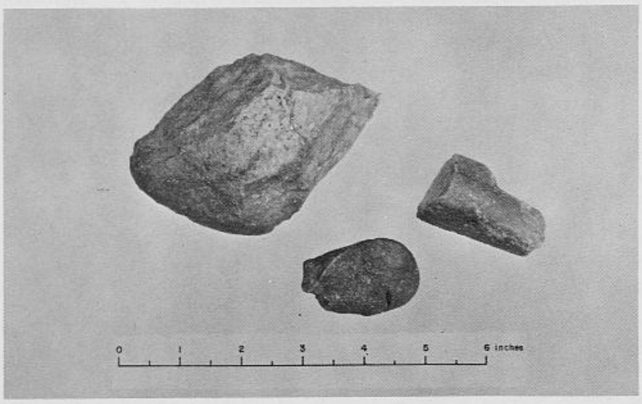


Fig. 20. (Locality 39) Rounded quartzite gravels from Cebolleta Mesa found at an elevation of approximately 7,600 feet, beneath the basalt cap. These gravels suggest ancestral drainage from the San Juan Mountains to the north.

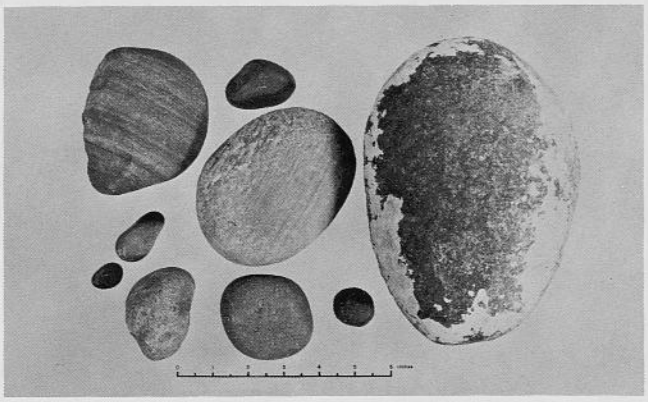


Fig. 21. (Locality 40) Rounded quartzite gravels from Cebolleta Mesa found at an elevation of approximately 7,300 feet, thinly veneering the southeastern portion of Cebolleta Mesa in the vicinity of Bluewater Creek. The largest cobble is approximately 10 inches in diameter.

Fig. 22. (Locality 86) View north across high surface in the Sangre de Cristo Mountains, seen from Goose Lake south of Red River, New Mexico. This highly dissected surface extends northward from Moreno Valley (to right of picture) to project over San Luis Valley (surface extends between the two peaks on the skyline on the left side of the picture). This suggests drainage from the San Juan Mountains prior to the middle Miocene uplift of the Sangre de Cristo Range.

Fig. 23. (Locality 25) View south down Moreno Valley, east of Taos, New Mexico, in the Sangre de Cristo Mountains. The broad flat floor of the valley was occupied during Pleistocene time by a large stream heading in the north and flowing southward toward Las Vegas, New Mexico. The stream may have originated from ancestral drainage of the San Juan Mountains prior to the middle Miocene uplift of the Sangre de Cristo Range.

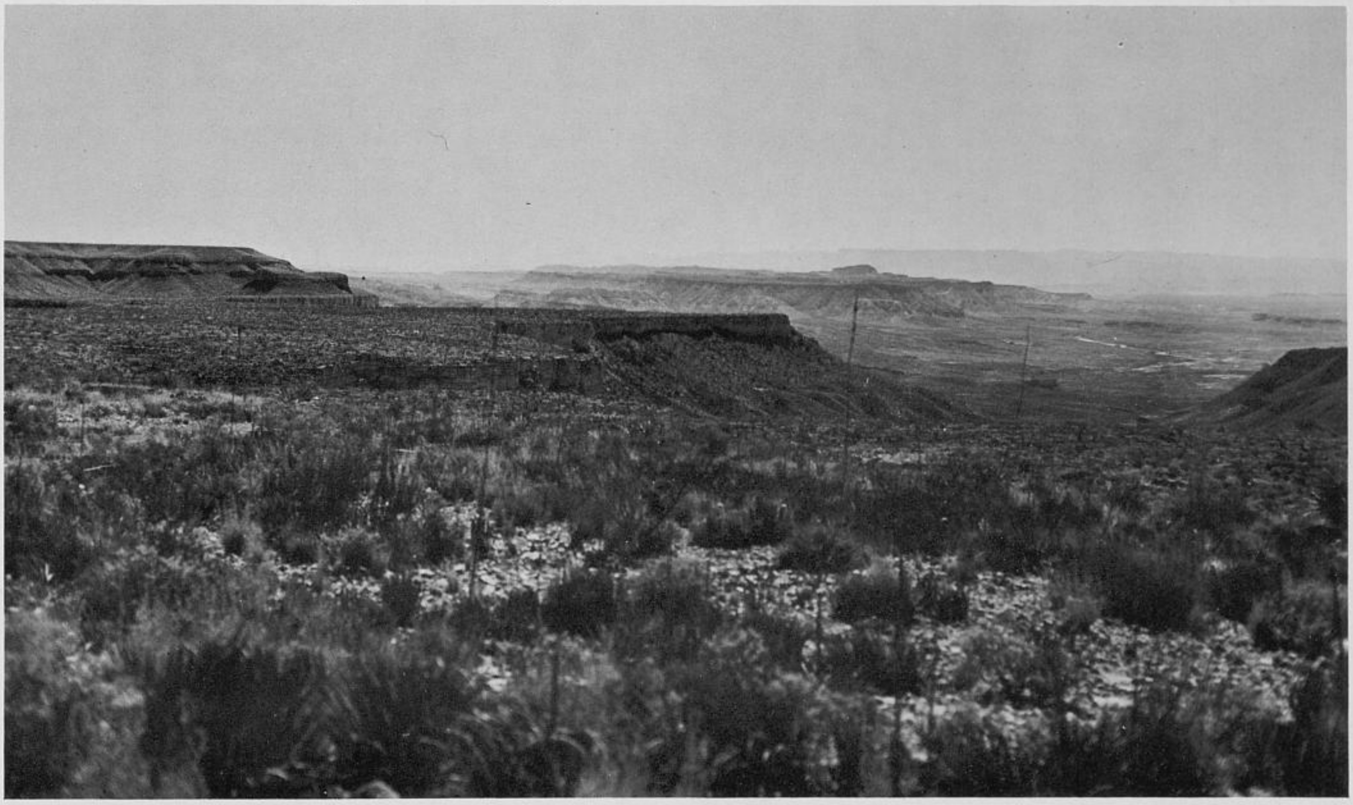


Fig. 24. (Locality 104) The summit of Mesa de Anguila in the Big Bend Region of Texas. Had this area been buried by basin fill to an elevation of 4,200 feet then this surface would have been overlain by more than 400 feet of fluvial deposits. The absence of remnant deposits or gravel lag of any kind on this surface suggests that such fill never existed.

Fig. 25. (Locality 105) View north along the summit of Mariscal Mountain. Had the Big Bend Region been filled by fluvial deposits to an elevation of approximately 4,200 feet, then this surface would have been overlain by more than 300 feet of such material. The absence of remnant basin fill deposits or lag gravel on this surface suggests that such fill was never deposited. Shown in the background are the Chisos Mountains.

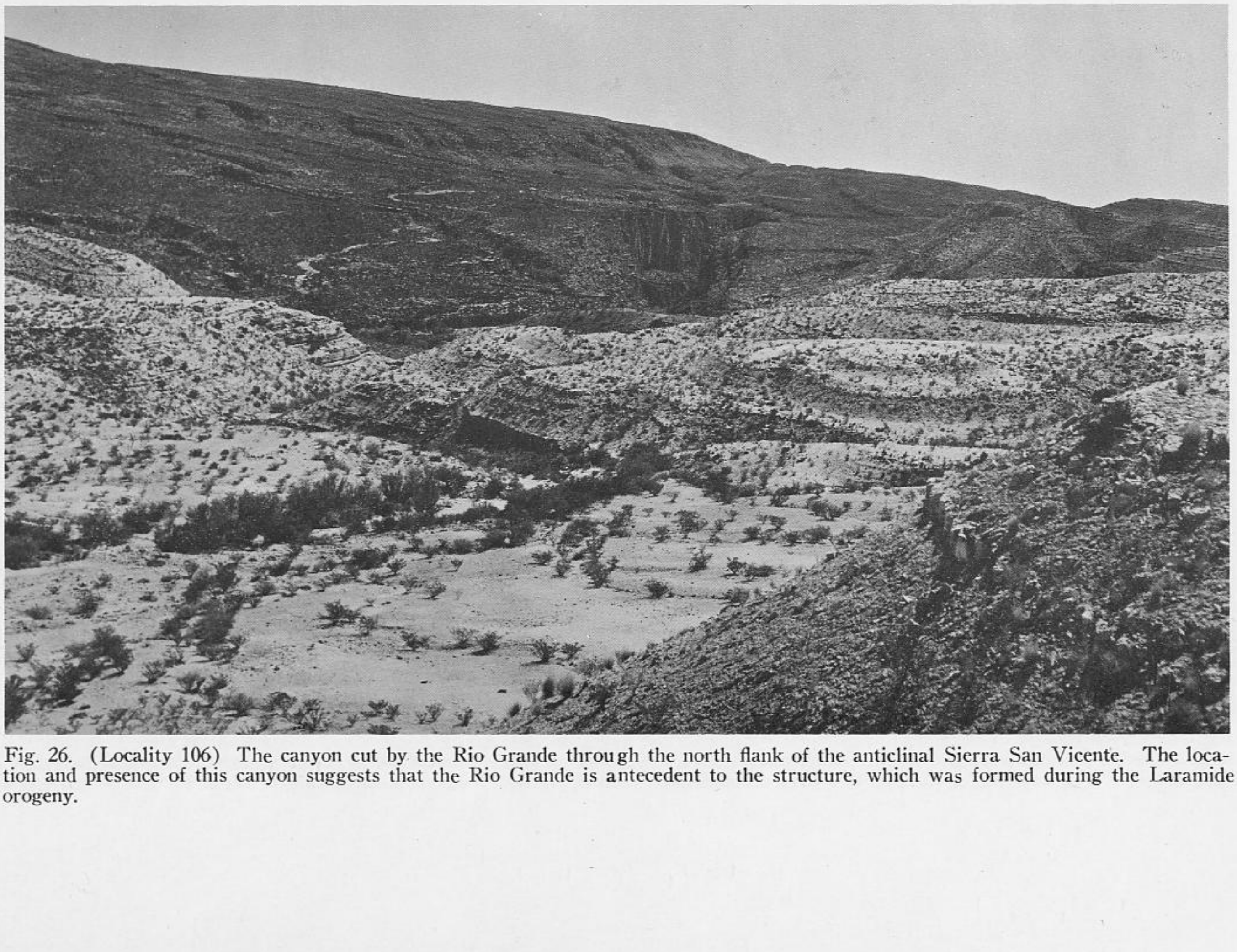


Fig. 26. (Locality 106) The canyon cut by the Rio Grande through the north flank of the anticlinal Sierra San Vicente. The location and presence of this canyon suggests that the Rio Grande is antecedent to the structure, which was formed during the Laramide orogeny.

incised deep canyons through large anticlinal folds of Laramide age (Twiss, 1970) as shown in Figure 28. Along the east flank of the anticlinal fold individual terrace remnants occur representing separate periods of alluviation (highest being the oldest) (Fig. 29). Since the highest record of alluviation is far below the crest of the mountain mass it seems unlikely that the Rio Conchos was "let down" on the structure by drainage integration after basin-filling (Miocence- Pliocene). Instead, this suggests an ancestral Rio Conchos in existence prior to Laramide deformation (Late Cretaceous-Early Tertiary) which was entrenched into the fold as uplift progressed.

It has been suggested that structures in the Trans-Pecos area of Texas and Chihuahua were buried during a period of basin filling (Miocene-Pliocene time) which eventually established a continuous surface from El Paso southeast to the Big Bend Region (King, 1935; King and Adkins, 1946; Zinn, 1953; Sayre and Livingstone, 1945; Maxwell and others, 1967). This reasoning and the presence of abundant lacustrine deposits in the Ojinaga-Presidio area (Groat, 1972; Groat, personal communication, 1974) suggest the recency of the Rio Conchos.

Assuming that this continuous surface did exist, the discrepancy in an age for the Rio Conchos is indicated by canyons cut through Early Tertiary structures (antecedent) versus that suggested by the abundant lacustrine deposits in the Ojinaga-Presidio area (superposed) may be resolved through a process of anteposition (Hunt, 1956; Hunt, personal communication, 1974).

With the Rio Conchos the process may have been as follows: the river originated in Late Cretaceous or Early Tertiary time as indicated by (1) the highest alluvial surfaces well below the top of canyon walls cut through Early Tertiary structures (Sierra Grande, Chihuahua); (2) the absence of remnant basin fill and lag deposits atop Mesa de Aguila and Mariscal Mountain; and (3) the canyon through the north flank of the anticlinal Sierra San Vicente. As the Early, Middle, and Late Tertiary periods of tectonism began and progressed, the Rio Conchos experienced repeated cycles of entrenchment, ponding, and spillover.

Entrenchment occurred until the rate of uplift exceeded the down-cutting ability of the river, at which point ponding began. Lacustrine deposition took place until the basin floor exceeded the height of the drainage divide in the uplifted river canyon, whereupon spillover occurred reinitiating entrenchment.

The continuity of this process depended upon the Rio Conchos repeatedly reoccupying its former channel after each spillover occurred. This was the case since during initial stages of uplift the river integrated drainage in each of the newly formed basins and became the base level to which local tributaries flowed. During ponded intervals the closed basins maintained the original channel, since the tributaries continued to flow towards the former river position. Thus, when spillover occurred, through-flowing drainage always reoccupied its past channel.

This process appears to reconcile the paradox of an old river flowing through old canyons separated by basins containing younger widespread lacustrine deposits.

Weathered, well-rounded gravels containing brown quartzite in a caliche matrix (Fig. 30) were found on the Stockton Plateau at Locality 66. Similar gravels containing typical Rio Grande quartzites (purple, white, gray, blue-gray, and black) were found in the Del Rio vicinity (Localities 68 and 69) (Fig. 31) and traced to a point south of Rio Grande City, Texas (Fig. 32), at Locality 73 where they are known as the Reynosa Gravels (Pliocene).

The gravels at Localities 68 and 69 are similar in composition and texture to gravels found by R. G. Thomas atop an erosional remnant near Fort Stockton, Texas (Thomas, personal communication, 1974), substantially above the projected elevation of the High Plains surface upon which the Miocene-Pliocene Ogallala gravels occur. This suggests that these gravels are pre-Ogallala in age and that their deposition corresponded to a widespread period of erosion in northern New Mexico and southwestern Colorado which occurred during late Oligocene time. These gravels were transported by southeastward drainage from southwestern Colorado prior to the early Miocene uplift of the Sangre de Cristo Mountains which have since effectively blocked the movement of such sediments.

Evidence related to the early Rio Grande may suggest a sequence of transgressions and regressions by the Gulf of Mexico into the Rio Grande embayment during Cenozoic time. Surficial Paleocene deposits are absent in the Rio Grande embayment, and the Midway Group (Eocene) immediately overlies Upper Cretaceous strata. This suggests that during most of Paleocene time the shoreline was south and east of the Midway outcrop, perhaps in the general vicinity of the present shoreline (Fig. 33A), and that during late Paleocene and early Eocene time a transgression occurred which resulted in a shoreline position as shown in Figure 33B. The presence of the Oligocene Reynosa Gravels south of Rio Grande City, Texas (Locality 73), implies a major regression which produced a shoreline considerably more seaward than the present one (Fig. 33C). Just east of Falcon Dam (Locality 122) the Reynosa Gravels are overlain by a small remnant of marine shale containing abundant oyster shells, suggesting a Miocene (?) transgression (Fig. 33D) followed by a gradual Pliocene regression (Fig. 33E). During Pleistocene time the shoreline position fluctuated considerably due to eustatic changes in sea level, resulting from alternate glaciation and deglaciation, but is thought to have been in the general vicinity of the zone indicated in Figure 33F.

From the evidence presented the following generalized reconstruction of Late Cretaceous to early Miocene drainage in New Mexico and Trans-Pecos Texas is postulated (Fig. 34).

Through-flowing drainage in New Mexico and Trans-Pecos Texas did not begin until the Late Cretaceous seas had retreated due to the regional uplifts accompanying early stages of Laramide tectonism.

In New Mexico the ancestral Rio Grande consisted of two general drainage systems. One system drained the south side of the San Juan uplift and flowed southeastward across the San Juan basin. The other system headed in the ancestral Mogollon highlands of Arizona and flowed eastward across west-central New Mexico. These two systems may have joined in central New

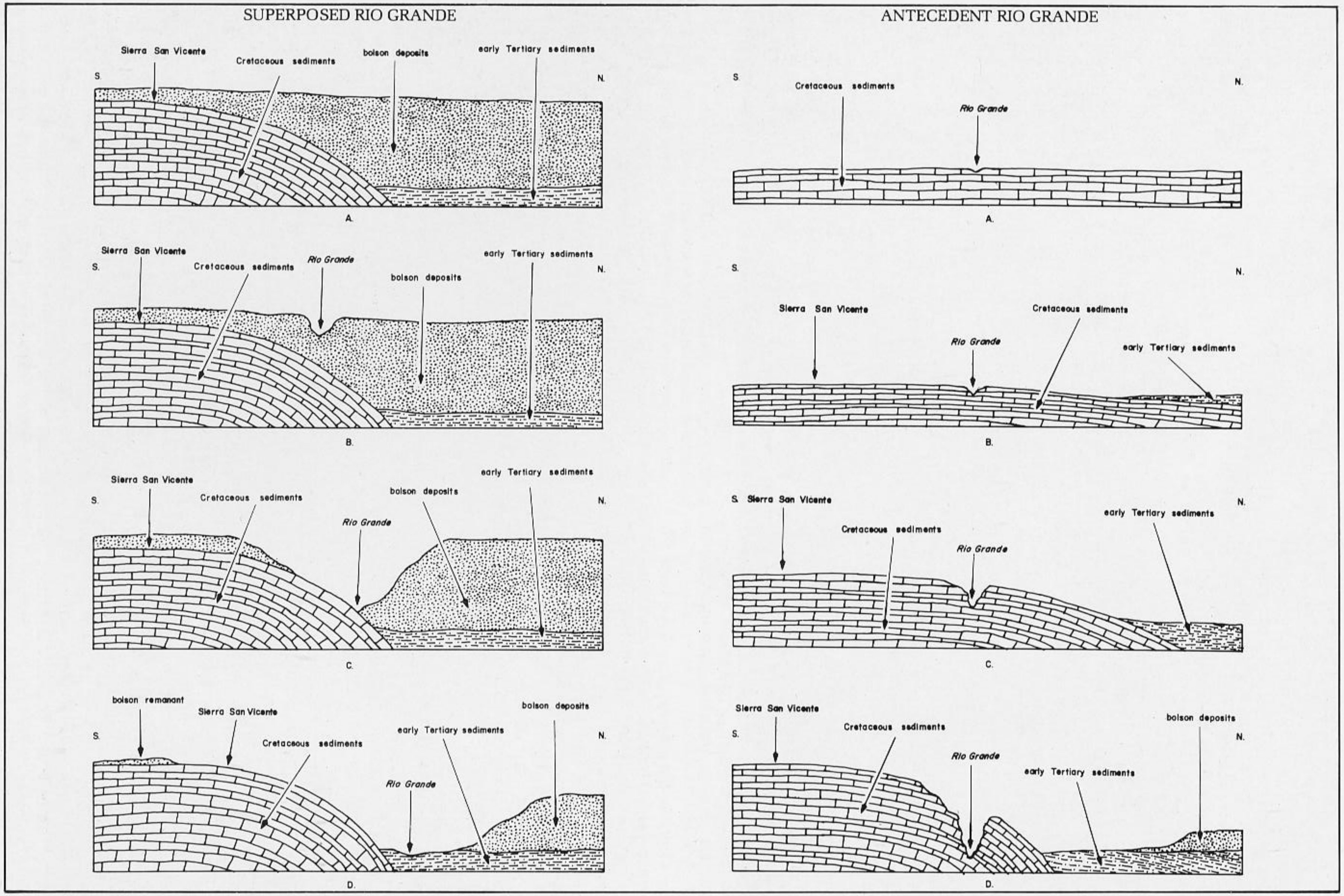


Fig. 27. This chart shows the events postulated to have occurred if the Rio Grande were superposed or antecedent. LEFT SIDE: SUPERPOSED RIO GRANDE (A) The situation existing prior to integration of through-flowing Rio Grande drainage. At this time Sierra San Vicente has been buried by basin-fill sediments. (B) Integration of through-flowing drainage has occurred and the ancestral Rio Grande (Rio Conchos) is beginning to entrench in the basin fill. (C) The down-cutting river has encountered massive Cretaceous limestones of Sierra San Vicente. The river begins to migrate downdip to remain within the softer basin-fill sediments. (D) The Rio Grande has migrated onto Early Tertiary sediments where it has established a course north of Sierra San Vicente. RIGHT SIDE: ANTECEDENT RIO GRANDE (A) The Rio Grande is shown flowing over Cretaceous limestones prior to Laramide deformation. (B) Initial folding of Sierra San Vicente started, resulting in slight entrenchment by the Rio Grande. (C) The folding of Sierra San Vicente has continued as has entrenchment by the river. (D) The folding of Sierra San Vicente has ceased and downcutting by the river has resulted in the canyon present today.

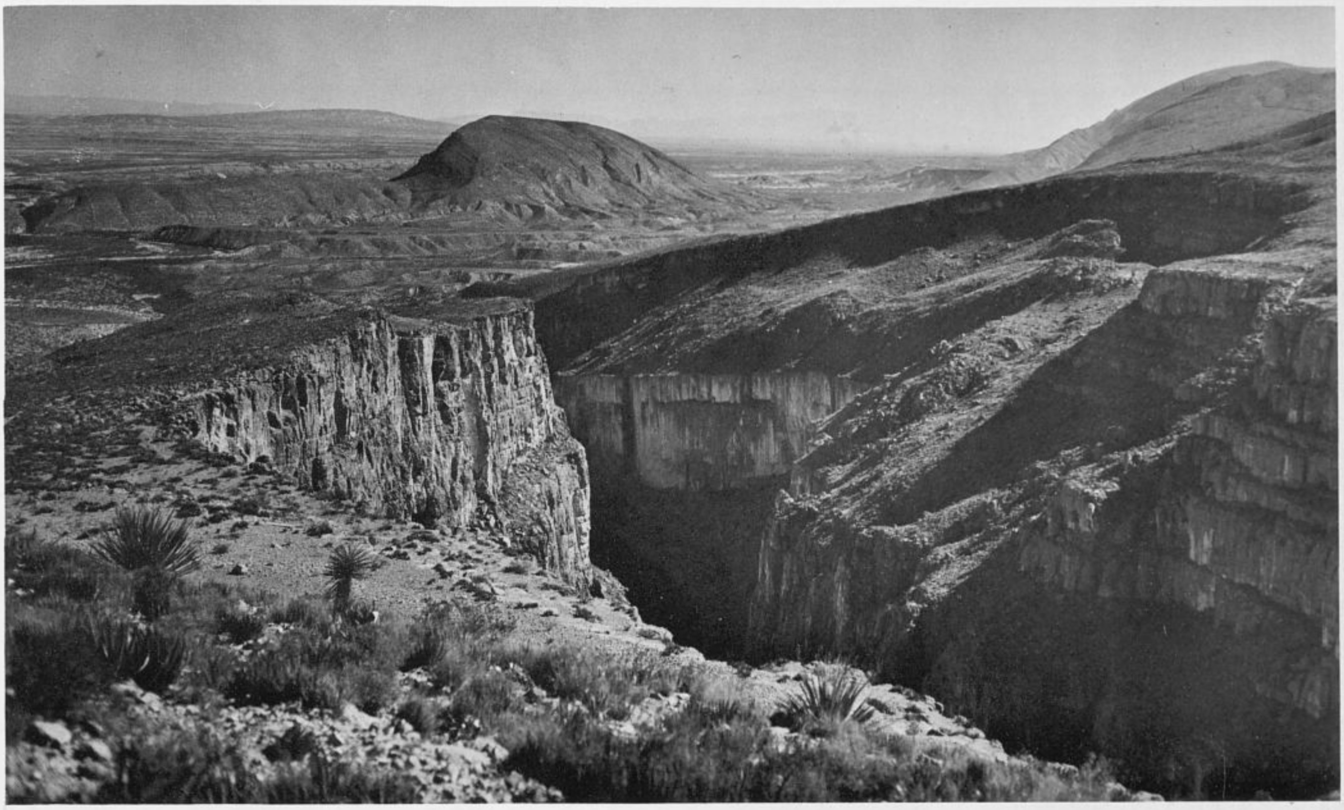


Fig. 28. (Locality 108) View east from Sierra Grande (Chihuahua) toward the valley of the Rio Grande. Note the deep canyon cut by the Rio Conchos into the anticlinal mountain mass.

Fig. 29. (Locality 108) View southeast along east flank of Sierra Grande (Chihuahua). Note the different terrace remnants, each representing a separate period of alluviation. Also note that the highest remnant (oldest) is far below the crest of the mountain. This suggests the antecedence of the Rio Conchos to the Early Tertiary structure.

Fig. 3. Physiographic map of the Rio Grande drainage basin.

Fig. 30. (Locality 66) Middle to late Oligocene (?) gravels of ancestral Rio Grande drainage atop the Stockton Plateau northwest of Del Rio, Texas. These gravels contain quartzite but no volcanic material. They are thought to have been deposited during late Oligocene by tributaries to the ancestral Rio Grande-Pecos system draining southwestern Colorado.

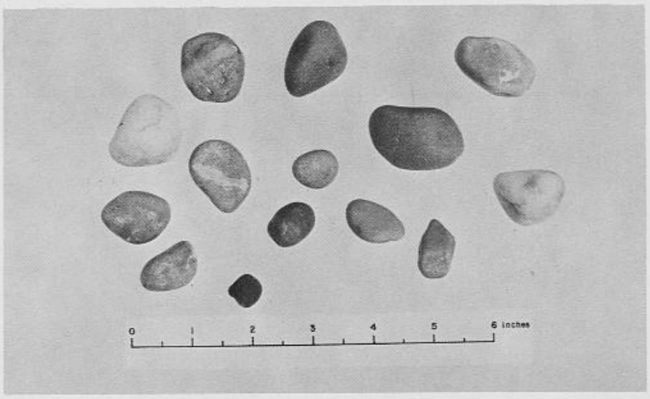


Fig. 31. (Locality 69) Small well-rounded quartzite gravels of San Juan provenance which cap hills near Del Rio, Texas. The fact that these gravels are well above the projected High Plains surface suggests a pre-Ogallala age, possibly middle to late Oligocene.

Fig. 32. (Locality 73) Middle to late Oligocene (?) gravels of ancestral Rio Grande drainage south of Rio Grande City, Texas. These gravels contain quartzites and volcanics which are embedded within a caliche matrix.

Mexico, forming the ancestral Rio Grande-Pecos system which flowed southeastward across New Mexico and west Texas to the Rio Grande embayment in south Texas.

The Rio Conchos system, originating in highlands of the Sierra Madre Occidental in northern Mexico, flowed generally east- and southeastward to eventually join the Rio Grande-Pecos system in the general vicinity of their present confluence east of the Big Bend Region.

As episodic Laramide tectonism continued, each system underwent modification, ranging from relocation, to entrenchment, to complete cessation The Rio Grande-Pecos system may have been responsible for deposition and erosion of Early Tertiary fluvial sediments, while forming portions of extensive erosional surfaces in Early Tertiary rocks of northern New Mexico. As the Tularosa basin subsided in the San Andres-Sacramento upwarp, a portion of the Rio Grande system may have extended through the basin, contributing to basin fill, and then flowed either eastward to join the ancestral Pecos system or southward to join the ancestral Rio Conchos. As regional uplift in Trans-Pecos Texas progressed, the Pecos River began entrenchment into the Stockton-Edwards Plateau and the Rio Conchos started downcutting into the structural blocks of the Big Bend Region.

As Oligocene time drew to a close, northern New Mexico underwent a period of extensive peneplanation or pedimentation; volcanism in the Datil province approached its climax; the Rio Grande depression was in its beginning stages, and the Middle Tertiary fault blocks of the Big Bend Region were just beginning to take form. Thus began Middle Tertiary tectonism which would produce profound changes in the drainage patterns of the separate fluvial systems.

MIDDLE MIOCENE TO MIDDLE PLIOCENE DRAINAGE

Middle Tertiary tectonism completely rearranged Early Tertiary drainage in New Mexico and Trans-Pecos Texas. In New Mexico the ancestral Rio Grande-Pecos system was diverted eastward across the present High Plains area into an ancestral Canadian or Brazos River, and the upper Arkansas River flowed into the San Luis Valley.

This stage of drainage evolution may have begun during late Oligocene time while the Rio Grande depression was first forming, but the most obvious beginning was with the early Miocene uplift of the Sangre de Cristo Mountains, which caused westward diversion of former east- and southeastward drainage.

Bryan (1938) believed that the Rio Grande originated during late Miocene or Pliocene time and in its headwaters section flowed west of Española, New Mexico, to the vicinity of Cerro Pedernal. From this point the river continued along the east side of the

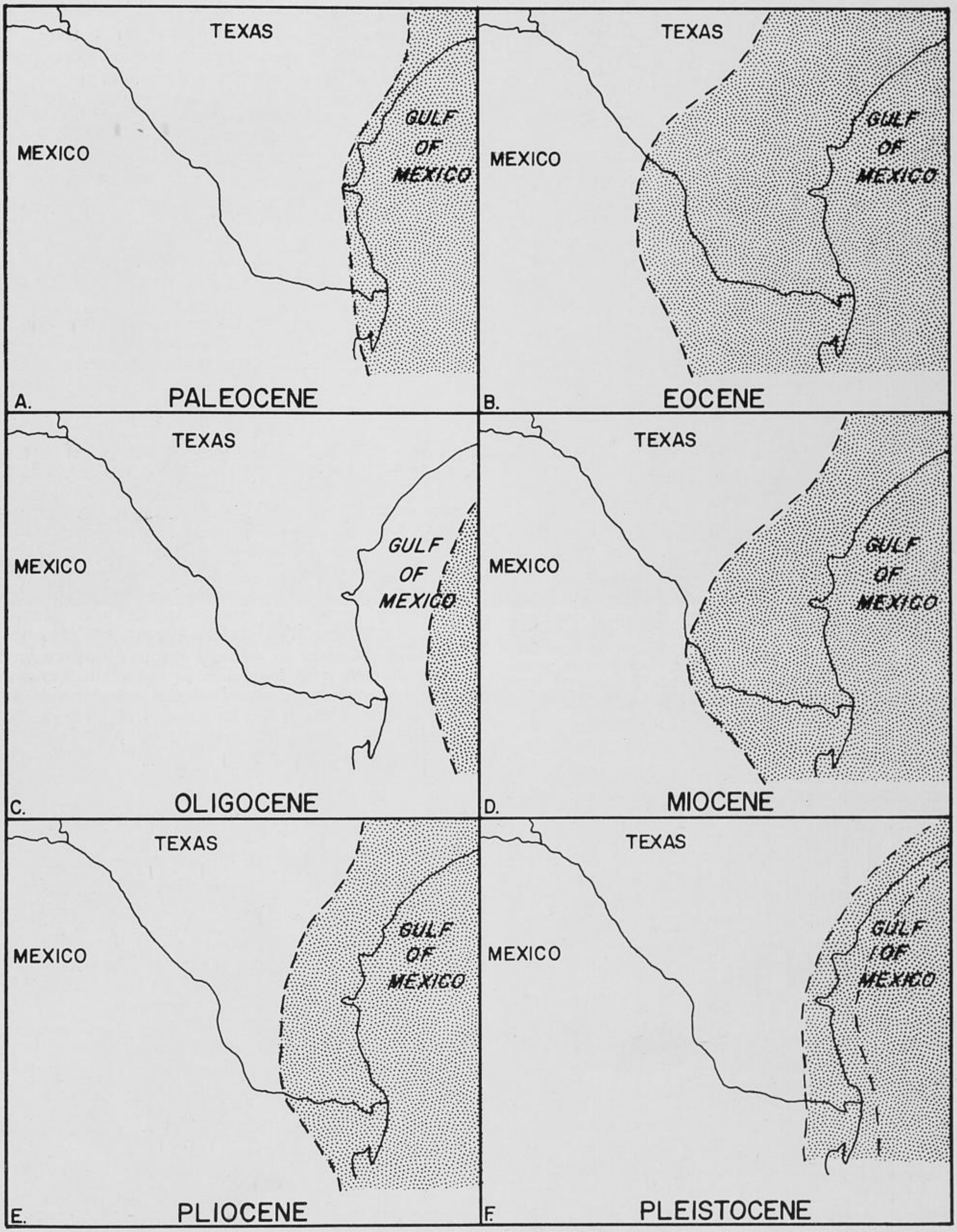


Fig. 33. A possible sequence of transgressions and regressions by the Gulf of Mexico into the Rio Grande embayment during Cenozoic time. (A) The Paleocene shoreline may have been near the vicinity of the present shoreline. (B) A transgression occurred during Eocene time producing a shoreline at some point between Eagle Pass and Laredo, Texas. (C) During Oligocene time a major regression occured placing the shoreline far seaward of the present one. (D) During Miocene time another transgression occurred in which the ocean advanced to the vicinity of Laredo, Texas. (E) A regression began resulting in a gradual retreat of the shoreline in Pliocene time. (F) During Pleistocene time the shoreline fluctuated a great deal due to glacial eustatic changes but is thought to have remained within a zone near the present shoreline.

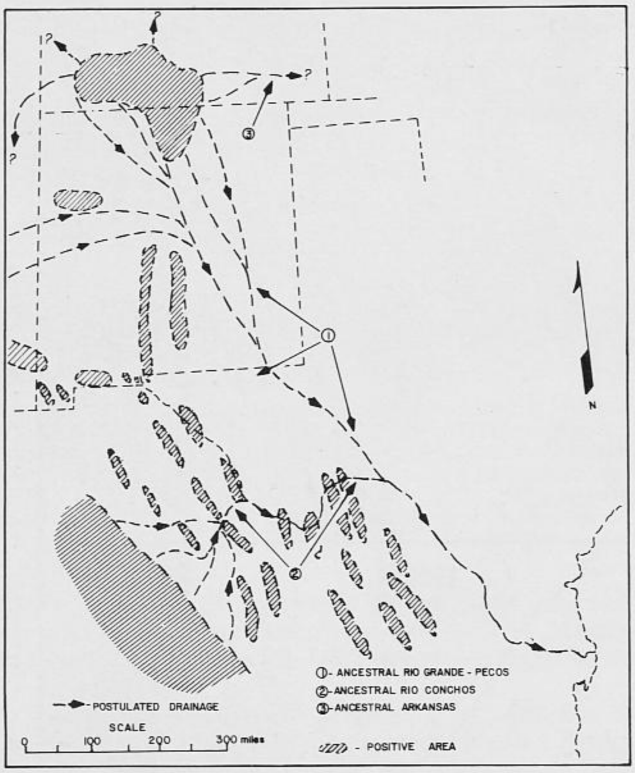


Fig. 34. Late Cretaceous to early Miocene drainage of the ancestral Rio Grande system in New Mexico, Trans-Pecos Texas and northern Mexico. Shown here is a schematic representation of general drainage systems thought to have been created by the uplift of the San Juan Mountains in southwestern Colorado. The pattern represents the general locations of positive elements thought to have been capable of exerting influence upon drainage routes.

present day Jemez Mountains and southward to the vicinity of Las Lunas (south of Albuquerque). From there the river flowed across the southern end of the Los Piños Mountains and into the Jornada del Muerto.

Other authors suggested Middle Tertiary drainage in New Mexico and south Texas. Smith (1938) believed that portions of the Abiquiu Tuff (Abiquiu Quadrangle) were deposited by streams draining highlands to the north and east, and that the streams responsible for the deposition of the Santa Fe Formation were graded to an ancestral Rio Grande situated west and southwest of Cerro Pedernal. Denny (1940b) described river deposits in the Santa Fe Formation indicative of a large through-flowing stream (called the ancestral Rio Grande) which served as the base level for Santa Fe deposition in the Española Valley. Denny (1940a) described river deposits in the Rio Grande depression from White Rock Canyon to south of San Acacia which suggest an ancestral Rio Grande during Pliocene time, east of its present position, and which continued across the southern end of the Los Piños Mountains. Wright (1946) traced the river gravels of Bryan (1938) southward along the eastern side of the Albuquerque-Belen basin and across the Los Piños Mountains, eventually returning to the main depression south of Socorro. Stearns (1953) described the Santa Fe Formation in the Abiquiu area of New Mexico as a deposit of streams flowing west from the Sangre de Cristo Mountains to a master drainage west of any known exposure of Rio Grande deposits. Meinzer (1911) reported beds of well washed, rounded gravels in the central portion of Estancia Valley beneath a thick sequence of lacustrine deposits. Lee (1907) described geographic and physiographic evidence in southern New Mexico which suggested to him that the Rio Grande flowed through the Jornada del Muerto and into the playa region of northern Mexico during Pliocene time. Dunham (1935) described a mature topography in the summit portion of the San Andres Mountains representative of prolonged erosion, during Pliocene time.

Terrace remnants found in Poncha Pass (Fig. 35) just south of Salida, Colorado, and in San Luis Valley approximately 10 miles south of the pass (Fig. 36), as well as an equivalent surface north of Poncha Pass at the base of Mount Shavano (Fig. 37), suggest that at some time drainage from the upper Arkansas River flowed into the San Luis Valley possibly to join an ancestral Rio Grande. Cobbles of epidote granite, dark green phyllite, and light-colored granite were common at Localities 1, 2, 3, 4, and 37 (Appendix; Fig. 3). When the upper Arkansas River may have flowed into the San Luis Valley is not known, but based on the preservation of the remnants, degree of weathering of material atop the surfaces, and geologic history of the area, a Miocene-Pliocene age is suggested.

Rounded quartzite gravels of local provenance at Localities 18 and 19 (Fig. 38) on an erosional surface extending across the Brazos uplift-Tusas Mountain area of northern New Mexico suggest the presence of drainage tributary to through-flowing drainage in this area, derived from highlands to the north and northwest. Rounded gravels of similar composition (Fig. 39) beneath a basalt flow at Locality 20 adjacent to the Sangre de Cristo Mountains north of Taos, New Mexico, suggest that drainage from the Brazos uplift-Tusas Mountain area and the San Juan Mountains to the west and northwest once flowed into this area. These gravels and the overlying basalt are thought to have been emplaced prior to the eruption of the basalts of the Rio Grande Gorge and are thought to be unrelated to present Sangre de Cristo drainage. This is suggested because the gravels and basalt flow are 100 to 200 feet above the uppermost flow of the Taos Plateau, isolated, and are not part of alluvial fans now present along the front of the Sangre de Cristo Mountains (Fig. 40) where streams draining the mountain front are deflected around the remnant.

Well-rounded quartzite gravels of San Juan provenance along the west side of the Brazos uplift and Magote Peak area of northern New Mexico (Localities 17 and 22) suggest that north-south through-flowing drainage existed west of the Brazos uplift, and continued southward through the region presently occupied by the Jemez volcanic pile.

Clean, washed sand and well-rounded gravel beneath the basalt cap of Cerro Pedernal (Fig. 42) (Localities 28 and 29) (Figs. 43 and 44) suggest that drainage to the west and southwest may have been present within this area between early Miocene and middle Pliocene time. The material at Locality 29, described as the Abiquiu Tuff by Smith (1938), contains abundant granitic material thought to be derived from the Sangre de Cristo Mountains and deposited by streams flowing

Fig. 35. (Locality 3) Terrace remnants in Poncha Pass, Colorado, thought to be deposits of the upper ancestral Arkansas River as it flowed into San Luis Valley to join the ancestral Rio Grande system.

Fig. 36. (Locality 4) Terrace remnants (San Luis Valley) of a surface thought to be correlative with the surfaces in Poncha Pass (Locality 3).

Fig. 37. (Locality 2) View south (toward Poncha Pass) of a high surface at the base of Mount Shavano in Arkansas River drainage. This surface is approximately correlative with surfaces in Poncha Pass and to the south, formed by the ancestral upper Arkansas River as it flowed into the ancestral Rio Grande system.

westward. Locality 28, mapped by Dane and Bachman (1965) as lower Santa Fe Formation, consists principally of quartzite gravels of San Juan provenance and contains only minor amounts of material typical of the Sangre de Cristo Mountains.

Well-rounded quartzite cobbles within gravels which appear to be upper Santa Fe sediment at Localities 31, 33, 34 and 38 suggest that during the later stages of Santa Fe deposition drainage from the northwest, ancestral to the Rio Grande, flowed across this area.

Well-rounded quartzite gravels atop small hills south of Cuba, New Mexico, at Locality 32 (Fig. 41) appear to be of San Juan provenance and suggest the presence of southward through-flowing drainage (ancestral Rio Grande?) in this area. The presence of similar gravel in the east wall of the valley of the Rio Puerco (Locality 43) west of Albuquerque, New Mexico, suggests that this fluvial system continued southward into the Albuquerque area.

Well-rounded quartzite cobbles of Brazos uplift provenance (Fig. 45) within the Totavi Member (Fig. 46) of the Puye Conglomerate (Griggs, 1964) suggest that a separate fluvial system draining the Brazos uplift flowed southward through this area prior to the late Pliocene volcanism in the Jemez Mountains.

Well-rounded gravels (Fig. 47) containing quartzite similar to that at Localities 17 and 22 occur on the low hills of Glorieta Mesa (Locality 42) (Fig. 48), suggesting that through-flowing drainage flowed east- and southeastward through this area.

Rounded to well-rounded quartzite gravels of San Juan and Brazos uplift provenance found on Conejos Mesa (Fig. 49) west of Fort Sumner, New Mexico, at Locality 47 suggest that drainage from the west or northwest once flowed through this area.

The presence of well-rounded pieces of vein quartz in gravels at Locality 74 (Fig. 50) within Oscura Gap between the San Andres and Oscura Mountains (Fig. 51) suggests that through-flowing drainage into the Tularosa basin from highlands to the north or northwest occupied this windgap prior to the late Pliocene uplift of the San Andres Mountains. The gravels are not typical of the Rio Grande suite, and no admixture of granite from the adjacent Oscura Mountains is present. This suggests that the headwaters may have been distant, perhaps within the Zuni Mountains to the northwest where quartz is common.

High surfaces in the San Francisco Creek valley (Fig. 52) near Alma, New Mexico, along the New Mexico-Arizona state line, and a general fining of the Gila Conglomerate to the southeast (Thomas, personal communication, 1974) suggest that, during Pliocene and early Pleistocene time, the eastern portion of the Gila River may have flowed southeastward into the playa region of northern Mexico, where it possibly was joined by the ancestral Rio Grande in late Pliocene time.

In northern Mexico numerous elongated, flat-floored

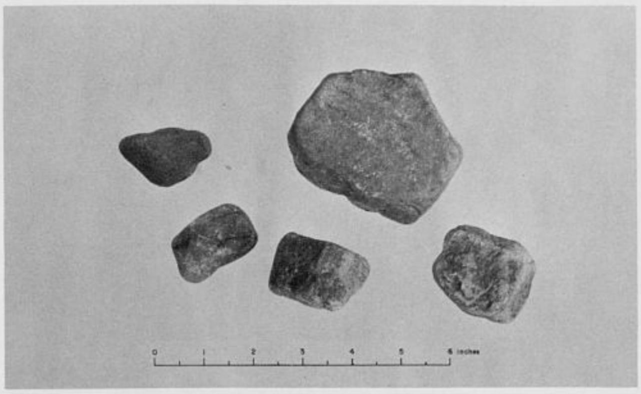


Fig. 38. (Locality 19) Rounded quartzite gravels from an erosional surface across the Brazos uplift-Tusas Mountain area. These gravels appear to have been derived from drainage originating to the north and northwest.

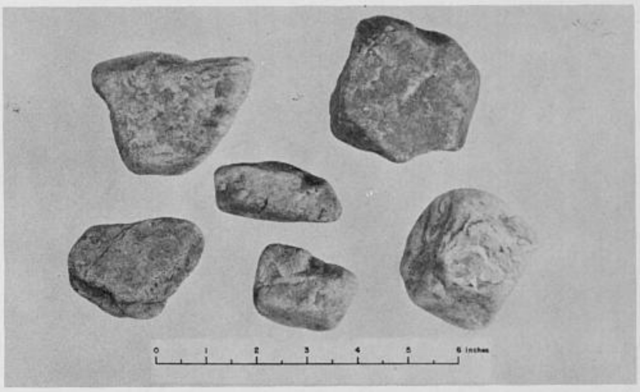


Fig. 39. (Locality 20) Rounded quartzite gravels from north of Taos, New Mexico, are similar to those capping the erosional surface in the Brazos uplift-Tusas Mountain area. These gravels were collected from a basalt-defended remnant north of Taos, New Mexico.

enclosed basins with low drainage divides (Fig. 53) and abundant well-rounded gravels composed of Datil (?) volacinc material (Fig. 3, Localities 75 through 82) in these basins suggest that during basin-filling (Miocene-Pliocene time) drainage from volcanic highlands to the north joined the Rio Conchos. The highlands were produced by Oligocene volcanism in the Datil province of western New Mexico.

From the evidence presented the following general reconstruction of middle Miocene to middle Pliocene drainage in New Mexico and Trans-Pecos Texas is postulated (Fig. 54).

During Miocene-Pliocene time the San Juan Mountains experienced episodes of intense volcanic activity that gradually built a large plateau. This eventually supplied runoff to be joined by the ancestral upper Arkansas River then flowing through the recently-formed San Luis Valley. During middle Miocene time the uplift of the Sangre de Cristo Mountains gradually diverted southeastward drainage through the Moreno Valley area to the west. This drainage was eventually pushed west of Cerro Pedernal by active alluvial fan development prograding from the youthful Sangre de Cristo Mountains (Fig. 55). The drainage remained in this position throughout early and middle Santa Fe time.

That ancestral drainage continued southward through the area now occupied by the Jemez volcanic pile is indicated by gravels at Localities 17 and 22. At times it may have flowed west of the San Pedro-Sierra Nacimiento mountain chain as suggested by gravels at Locality 32. From this point drainage departed from the present Rio Grande depression and continued east- or southeastward, as is suggested by gravels atop Glorieta Mesa (Locality 47).

From Glorieta Mesa there are several possible routes for the ancestral Rio Grande. (1) The river may have flowed southward through Estancia Valley and across Chupadera Mesa into the Tularosa basin, and then either into the Hueco bolson or across the area now occupied by Otero Mesa and the Guadalupe Mountains and thus into the ancestral Pecos River. (2) The river may have flowed southeastward directly into Pecos drainage. (3) The River may have flowed eastward into either the Canadian or Brazos River, diverting southern Colorado and northern New Mexico drainage from the Gulf Coastal region of south Texas during this time.

Well-rounded quartzite gravels of San Juan and Brazos uplift provenance occur atop Conejos Mesa (Locality 47) west of Fort Sumner, and a hiatus exists between the pre-Ogallala (Oligocene?) Reynosa Gravels and the Pleistocene Lissie Gravels of south Texas. These together suggest that ancestral Rio Grande drainage was diverted from the south Texas area during middle Miocene to middle Pliocene time.

In late Pliocene time southern Colorado and northern New Mexico underwent extensive erosion which produced the San Juan peneplain. The period of block faulting and canyon cutting within the Big Bend Region was drawing to a close. Thus began Late Tertiary tectonism in which the ancestral Rio Grande underwent modification to achieve some of the pattern the present river yet retains.

LATE PLIOCENE TO EARLY PLEISTOCENE DRAINAGE

Late Tertiary tectonism diverted southern Colorado and northern New Mexico drainage back to the south where it gradually integrated into the present north-south through-flowing system. This stage of drainage evolution began with the second domal uplift of the San Juan Mountains, which started during late Pliocene time.

Kottlowski (1958) believed that the Rio Grande resulted from runoff originating with the Pleistocene doming of the San Juan Mountains in southwestern

Fig. 40. (Locality 20) Isolated basalt-capped remnant north of Taos, New Mexico, from which quartzite gravels similar to deposits to the west were collected. These gravels are thought to have been deposited by drainage from the northwest. The elevation and isolated nature of this remnant suggest that the basalt cap may be older than flows of the Rio Grande Gorge. Notice that tributaries draining the Sangre de Cristo Mountains are deflected around the remnant.

Colorado. The river gradually extended southward, first flowing into the playas of northern Mexico and then diverting through El Paso canyon eventually to create present drainage. He noted the conformance of the Rio Grande to structural features originating in late Pliocene time and stated that this behavior strongly suggests the youthfulness of the Rio Grande.

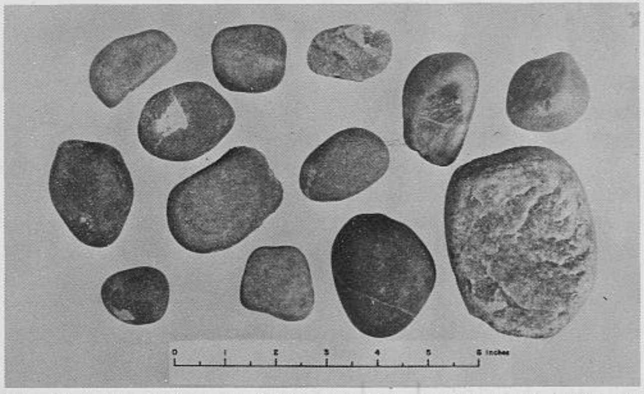


Fig. 41. (Locality 32) Well-rounded gravels from south of Cuba, New Mexico, similar to gravels to the northwest at Localities 17 and 22, suggest that at one time the ancestral Rio Grande flowed to the west of the San Pedro-Sierra Nacimiento mountain chain.

Numerous authors have presented evidence suggesting a late Pliocene-Pleistocene Rio Grande. Galusha and Blick (1971) concluded from their study of the Santa Fe Group in the type area north of Santa Fe, New Mexico, that the Rio Grande formed after the close of Santa Fe deposition, since no deposits of perennial streams were found within the Santa Fe Group. Baldwin (1956) studied the Santa Fe Group in the lower Jemez River area and concluded that the Rio Grande originated during the time that the post-Santa Fe Puye Gravels were deposited. Ross, Smith, and Bailey (1961) suggested that the Rio Grande was present during volcanism in the Jemez area and that it has suffered periodic damming by ejected material. Debrine, Spiegel, and Williams (1963) cite evidence of the ancestral Rio Grande on the east side of Socorro Valley during late Pliocene and early Pleistocene time. Kelley and Silver (1952) studied the Caballo Mountains and because of the peneplanation of the headwaters region discounted the possibility that the Rio Grande was a through-flowing stream during Pliocene time. In a study of the Rincon Quadrangle in southern New Mexico, Seager and Hawley (1973) concluded that the Rio Grande did not come into being in this area until early Pleistocene time. Strain (1965) studied the Mesilla Valley of southern New Mexico and believed that there was a through-flowing stream during early Pleistocene time, and that it flowed into northern Mexico, and was later diverted into the Hueco bolson. Hawley (1965) reported the presence of wide spread gravels beneath the La Mesa surface and suggested

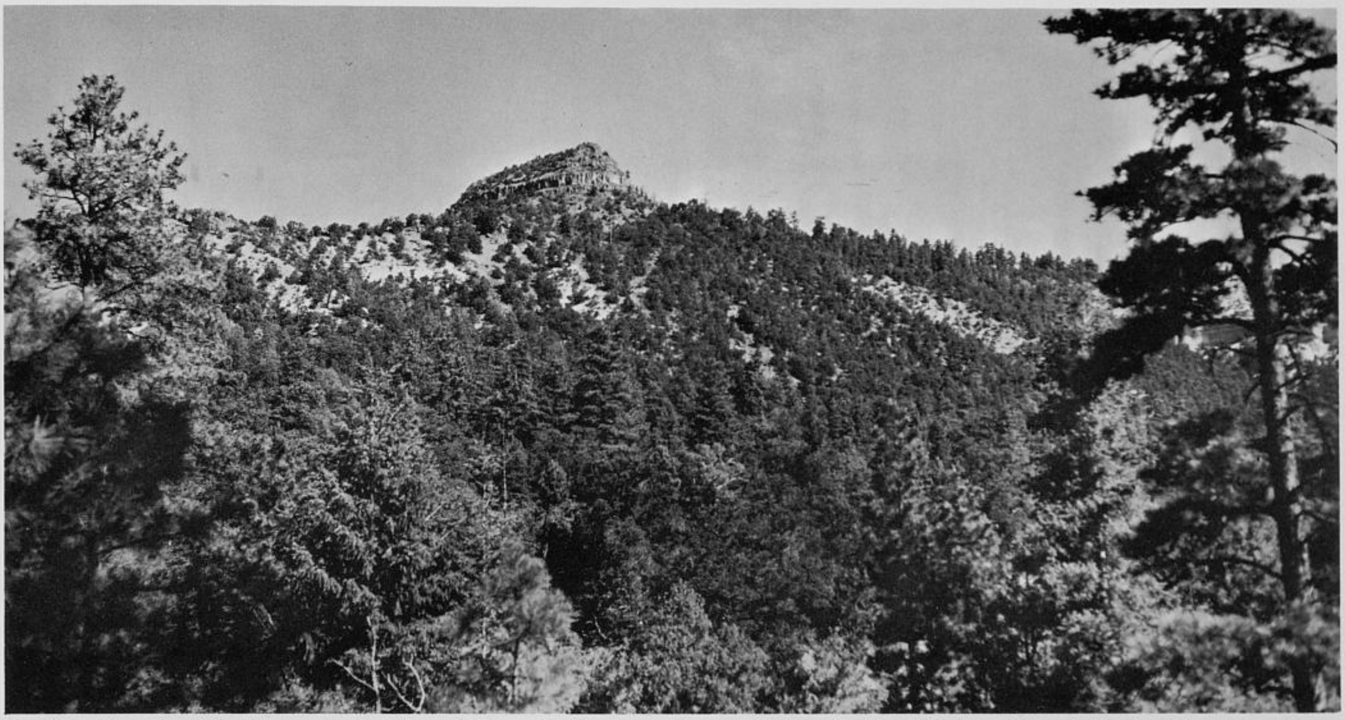


Fig. 42. (Locality 28) The summit region of Cerro Pedernal southwest of Abiquiu, New Mexico. Beneath the basalt cap is approximately 1,000 feet of fluvial material apparently deposited by drainage from the north, northwest, and east.

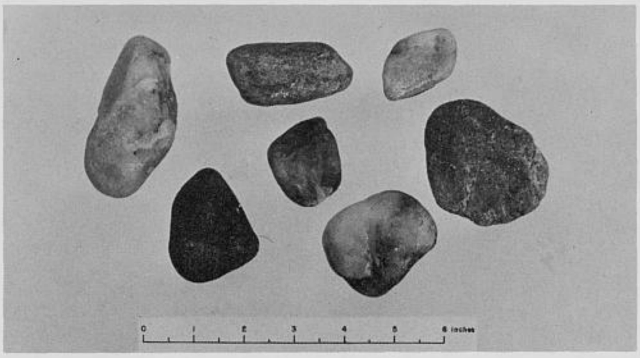


Fig. 43. (Locality 28) Well-rounded quartzite gravels (collected from beneath the basalt cap) from Cerro Pedernal. They were apparently deposited by streams flowing to the south and southwest.

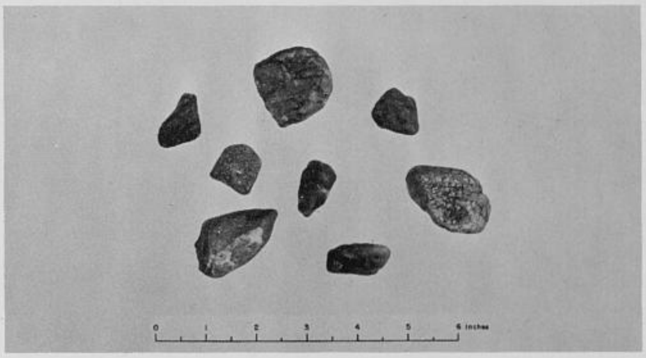


Fig. 44. (Locality 29) Gravels collected from the Abiquiu Tuff on Cerro Pedernal (Smith, 1938) approximately 200 feet beneath the basalt cap. The substantial granitic component was apparently derived from the Sangre de Cristo Mountains to the east and deposited by streams flowing westward toward a master stream to the southwest.

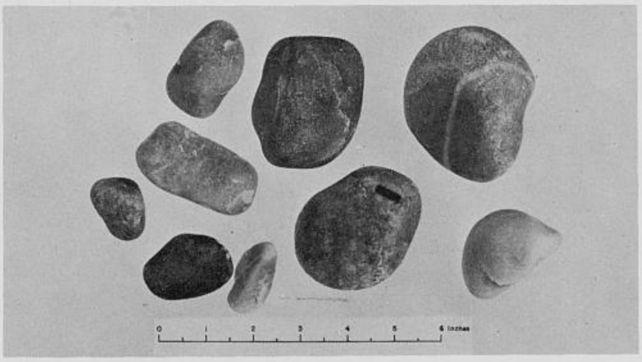


Fig. 45. (Locality 37) Well-rounded quartzite gravels from the east side of the Jemez Mountains from the Totavi Member of the Puye Conglomerate. These gravels are overlain by local volcanic detritus, suggesting that the Rio Grande was present prior to volcanic activity in the Jemez Mountains.

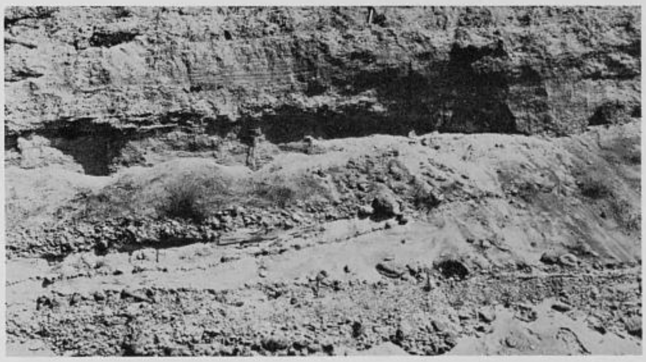


Fig. 46. (Locality 37) The Totavi Member of the Puye Conglomerate. Notice the channel forms, sand drapes, and cross-bedding. The lower part of the section contains the quartzose conglomerates.

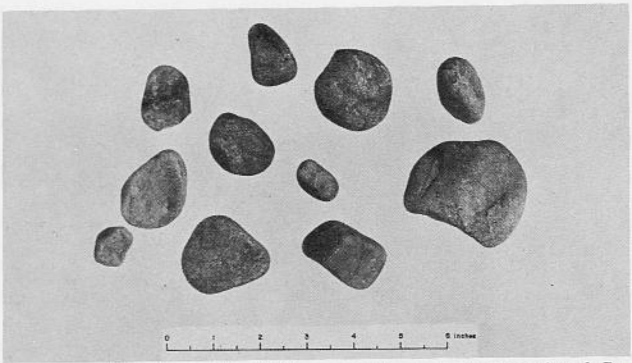


Fig. 47. (Locality 42) Well-rounded quartzite gravels of San Juan and Brazos uplift provenance that were found capping low hills atop Glorieta Mesa.

that these stream deposits resulted from a braided distributary system. Hawley and others (1968) studied the Santa Fe Group in southern New Mexico and concluded that the Mesilla and Hueco bolsons were connected during later stages through Fillmore Pass and El Paso Canyon. The Rio Grande was considered a time-transgressive distributary system, having different loci of deposition throughout its existence. Hawley and Kottlowski (1968) studied the Quaternary geology of south-central New Mexico and concluded that the ancestral Rio Grande first flowed through Fillmore Pass into Hueco bolson before being diverted to the west. Reeves (1965) discussed the features of northwestern Chihuahua and suggested the presence of a large lake into which the Rio Grande may have flowed during early Pleistocene time. Reeves (1969) later

Fig. 48. (Locality 42) Low gravel-capped hills atop Glorieta Mesa. Gravels contain quartzites similar to the Brazos uplift area to the northwest, suggesting that at one time the ancestral Rio Grande may have flowed eastward across this area.

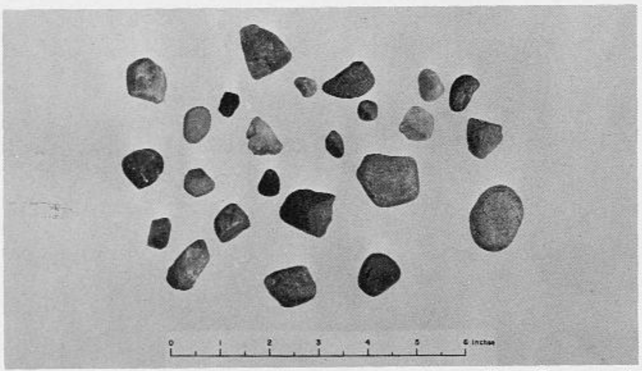


Fig. 49. (Locality 47) Rounded gravels of San Juan and Brazos uplift provenance from Conejos Mesa west of Fort Sumner, New Mexico. These gravels suggest that the ancestral Rio Grande flowed eastward through this area and into the drainage system of the ancestral Brazos River.

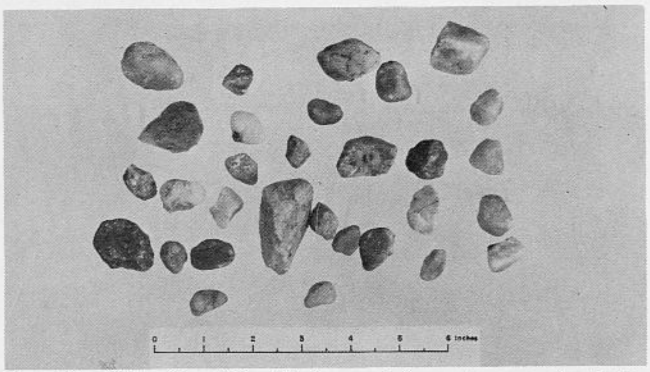


Fig. 50. (Locality 74) Well-rounded quartz gravels from Oscura Gap between the San Andres and Oscura Mountains from the south side of the northwest end of Oscura Gap approximately 500 feet above the gap floor. These gravels suggest that at one time a stream flowed through the gap, possibly from the Zuni Mountains to the northwest where abundant vein quartz crops out.

Fig. 51. (Locality 74) Oscura Gap (view from the southeast) located between the Mockingbird Gap Hills (left) and the Oscura Mountains (right). Physiography and the presence of well-rounded gravels at the northeast end suggest that this gap was formed in part by fluvial processes, though there is no concrete evidence that the drainage was ancestral to the Rio Grande.

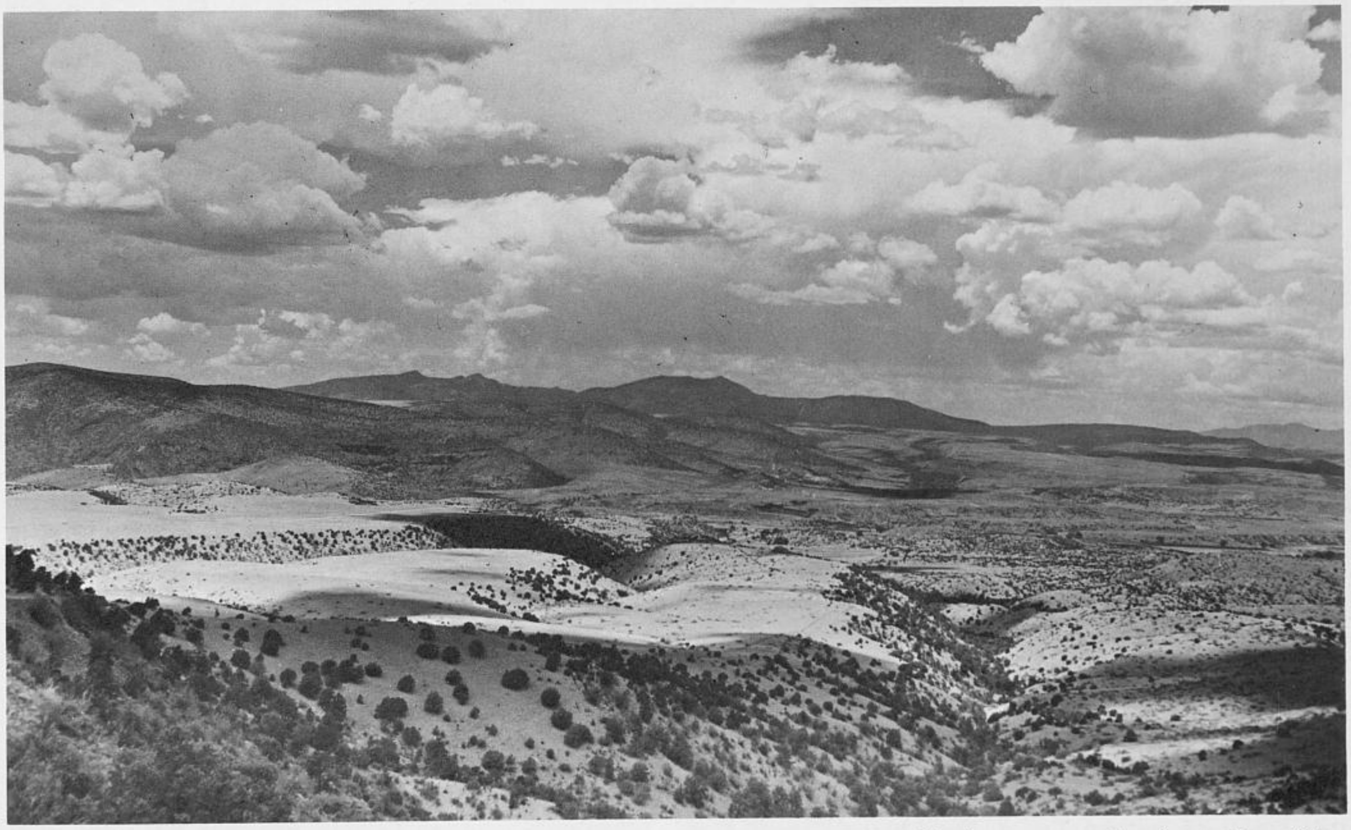


Fig. 52. (Locality 107) High surfaces above San Francisco Creek valley, western New Mexico, were traced as far south as Silver City. These surfaces suggest that at one time an ancestral Gila (?) River may have flowed to the southeast into northern Mexico.

Fig. 53. (Locality 109) View east across the valley of the Rio del Carmen from an unnamed range just east of Ricardo Flores Magon, Chihuahua. The broad flat floor containing well-rounded gravels of volcanic rock and a low drainage divide (far right) suggest that this basin was once occupied by through-flowing drainage.

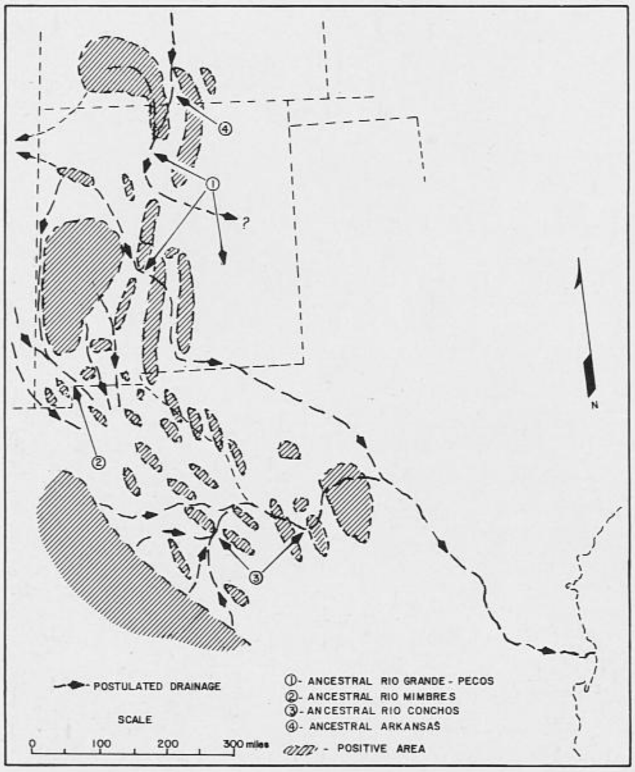


Fig. 54. Reconstruction of middle Miocene to middle Pliocene drainage of the ancestral Rio Grande in New Mexico, Trans-Pecos Texas, and northern Mexico. Notice that the ancestral drainage of the Rio Grande is thought to have been diverted from south Texas during this time.

presented a detailed description of early Pleistocene Lake Palomas and indicated that the ancestral Rio Grande flowed into this area during late Pliocene and early Pleistocene time. Strain (1969) suggested that a large lake once occupied the Hueco bolson and surrounding areas, and that it drained to the south, possibly cutting the channel of the ancestral Rio Grande below El Paso. Strain (1959) earlier recognized a Blancan age fauna in the Hueco bolson, indicating that the Rio Grande was not diverted through El Paso Canyon until middle Pleistocene time. Albritton and Smith (1965), in Hudspeth County, Texas, recognized a locally derived fanglomerate, thought to be late Pliocene in age, truncated by fluviatile deposits containing exotic gravels, thought to be early Pleistocene in age. Sayre and Livingstone (1945) noted the absence of basalt cobbles in the basin fill of the Hueco bolson, and their abundance in the Mesilla bólson, suggesting that during Pliocene time the ancestral Rio Grande did not flow into the area southeast of El Paso. In a study of the Trans-Pecos area, Baker (1927) concluded that after Middle to Late Tertiary basin-filling, the Rio Grande established its course through the area. King (1935) postulated that the Rio Grande did not come into being until long after Middle-to-Late Tertiary block faulting and basin filling had terminated. Zinn (1953), commenting on the fine-grained playa deposits in the Presidio area, suggested that the Rio Grande did not come into existence until Pleistocene time. In a review of the Cenozoic history of the Rimrock Country of the Trans-Pecos area, Twiss (1970) indicated that the Rio Grande did not come into being until Pleistocene time. Strain (1970) described the Rio Conchos as a product

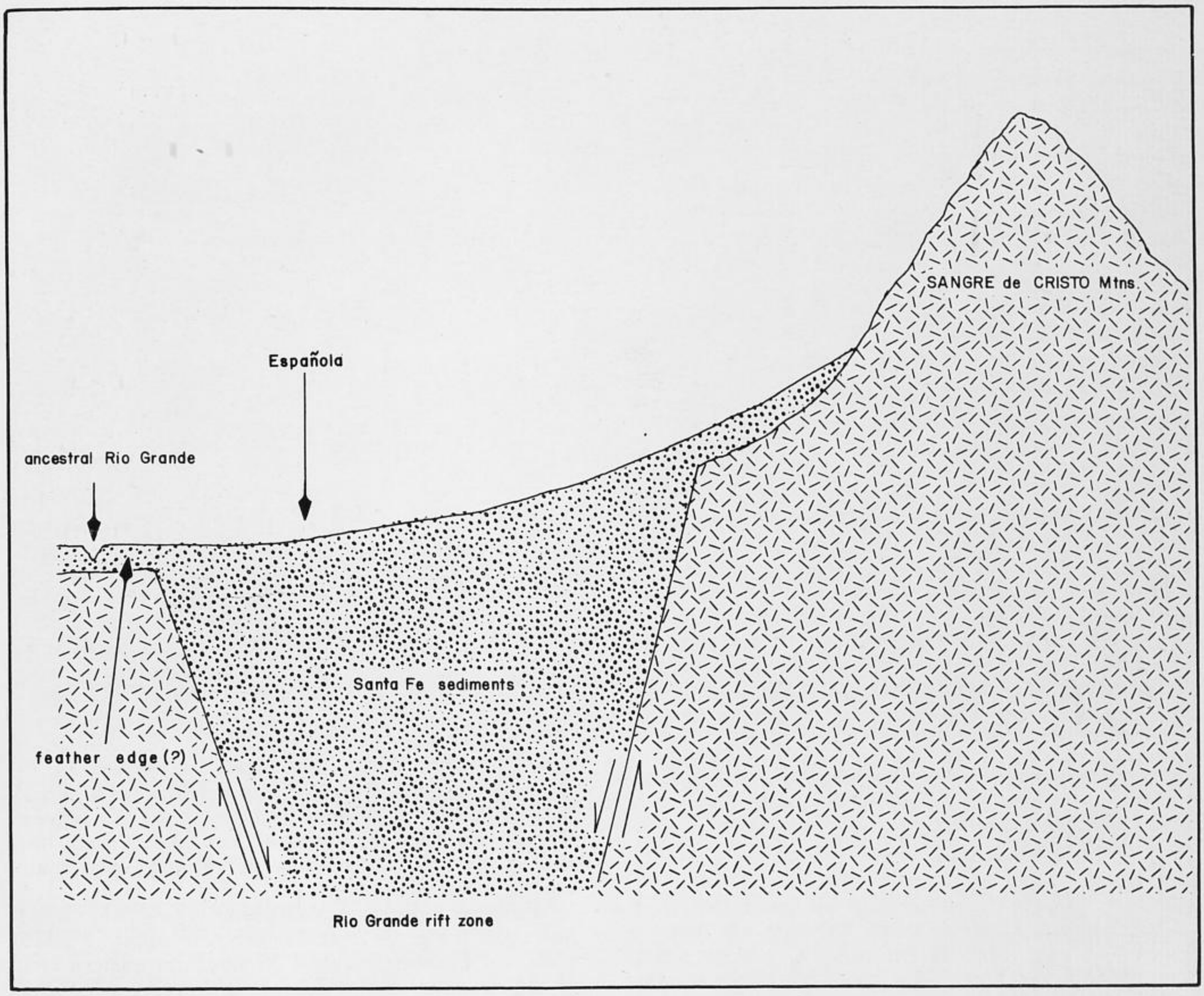


Fig. 55. The Santa Fe sediments and the ancestral Rio Grande. It is thought that during Santa Fe deposition the ancestral Rio Grande flowed to the west of its present position and was held there by active alluvial fan development from the youthful Sangre de Cristo Mountains, as shown here. It was not until late to post-Santa Fe time that fan development was greatly reduced allowing the Rio Grande to migrate to the east.

of basin spillover, and believed that a tributary worked headward from Presidio to capture the Rio Grande in the vicinity of El Paso. In discussing the geologic history of the Big Bend Region, Maxwell and others (1967) suggested that the Rio Grande did not originate until after basin filling had terminated in late Pliocene to early Pleistocene time. Kelley (1956) in a study of the Rio Grande depression, doubted that the Rio Grande existed prior to Pliocene time, since its principal headwaters region had been reduced to a peneplain. Mather (1957) summarized the history of the San Juan Mountain region, and described the peneplain which came into existence toward the end of Pliocene time as an undulating plain across which flowed several old rivers. Ruhe (1962) did not believe the Rio Grande once flowed through the Jornada del Muerto, and concluded that the river did not originate until early Pleistocene time. Kottlowski, Cooley, and Ruhe (1965) stated that the Rio Grande was probably Pleistocene

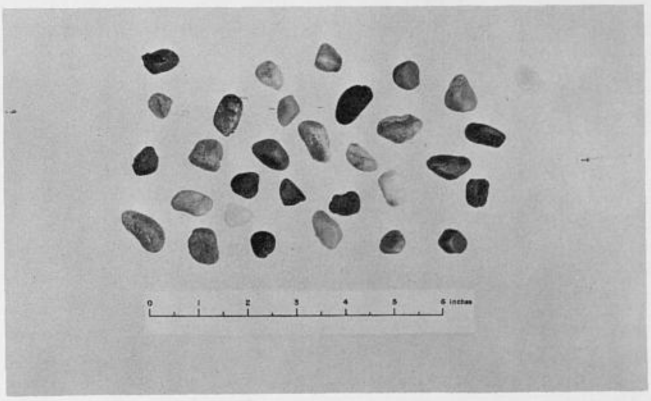


Fig. 56. (Locality 48) Small, well-rounded quartzite gravels having a San Juan provenance from the northern portion of the Jornada del Muerto. These gravels suggest that at one time the ancestral Rio Grande flowed into the Jornada into south-central New Mexico.

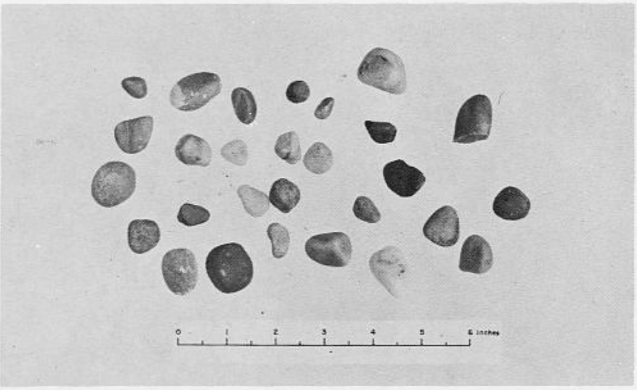


Fig. 57. (Locality 56) Gravels from Fillmore Pass between the Organ and Franklin Mountains exhibit a typical Rio Grande quartzite component, which suggests that the ancestral Rio Grande at one time flowed into the Hueco bolson through this gap.

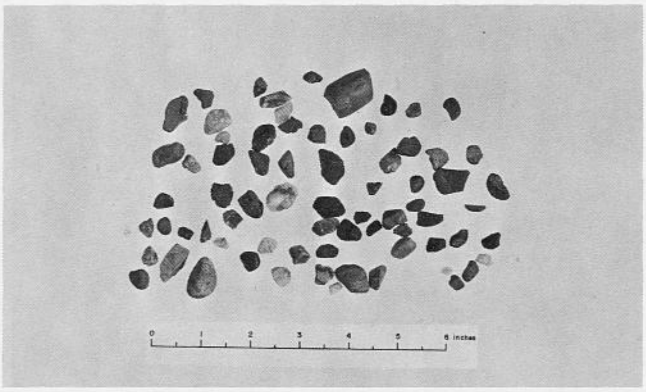


Fig. 58. (Locality 59) Gravels collected from the La Mesa surface west of El Paso, Texas, in small deflation basins near the East Potrillo Mountains. The presence of these typical Rio Grande gravels suggests that the ancestral Rio Grande once flowed in this vicinity toward northern Mexico.

in age, and that during this same time the eastern Gila and Salt Rivers may have flowed southeastward into northern Mexico.

Small well-rounded quartzose gravels, sand, and mud in the vicinity of the San Luis Hills at Localities 13, 14, and 15 suggest that alluviation and ponding of the ancestral Rio Grande occurred prior to and during entrenchment of the river into the underlying basalts in this area.

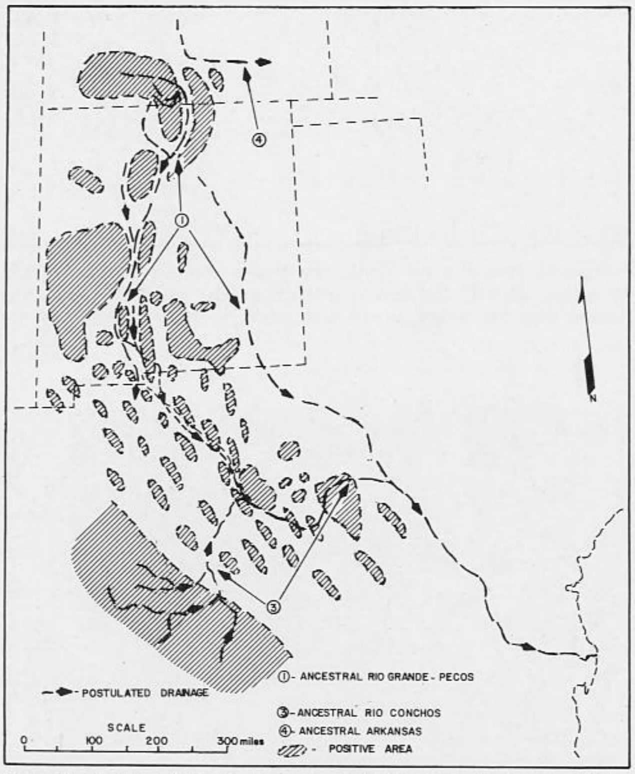


Fig. 59. Late Pliocene to early Pleistocene drainage of the ancestral Rio Grande in New Mexico, Trans-Pecos Texas, and northern Mexico. Note that during this stage the ancestral Rio Grande is thought to have flowed into northern Mexico, except for the route through Fillmore Pass, by which the Rio Grande reached Presidio for a considerable period of time.

Well-rounded siliceous gravels within the walls of the Rio Grande Gorge at Localities 23 and 24 suggest that at times a perennial stream existed in this area, between extrusions of the volcanic material of the Taos Plateau. The absence of typical Rio Grande gravel (purple and dark gray quartzites) suggests that during these periods of alluviation the Rio Grande was further west, possibly in the vicinity of Tres Piedras (west of Taos).

Small, well-rounded gravels (Fig. 56) containing quartzite were found atop drainage divides in the northern portion of the Jornada del Muerto at Localities 48 and 49. The presence of these gravels suggests that at one time the ancestral Rio Grande may have flowed through the Jornada del Muerto into south-central New Mexico.

Well-rounded gravels containing typical Rio Grande quartzites (Fig. 57), at Locality 56 within Fillmore Pass and Localities 57 and 58 along the eastern front of the Franklin Mountains and at Locality 60 west of the Quitman Mountains, suggest that at one time the Rio Grande flowed through Fillmore Pass into the Hueco bolson and southward past the Quitman Mountains toward Presidio.

Well-rounded gravels containing quartzite (Fig. 58) in small deflation basins on the La Mesa surface west of El Paso (Locality 59) suggest that at one time an ancestral Rio Grande flowed across this surface into the northern Mexico playa region.

From the evidence presented the following reconstruction of late Pliocene to early Pleistocene drainage of the ancestral Rio Grande within New Mexico is postulated (Fig. 59).

As the second episode of domal uplift in the San Juan Mountains Region began, accompanied by the Hinsdale volcanic epoch and the climaxing stages of the Jemez volcanism to the south, the ancestral Rio Grande undoubtedly underwent several episodes of ponding with interludes of overflow, as suggested by lacustrine deposits within the San Luis Valley and in the Jemez Mountains area. The point of overflow and route of drainage during the episodic extrusion of the basalts in the Taos Plateau is thought to have been west of Taos, New Mexico, possibly in the vicinity of Tres Piedras,

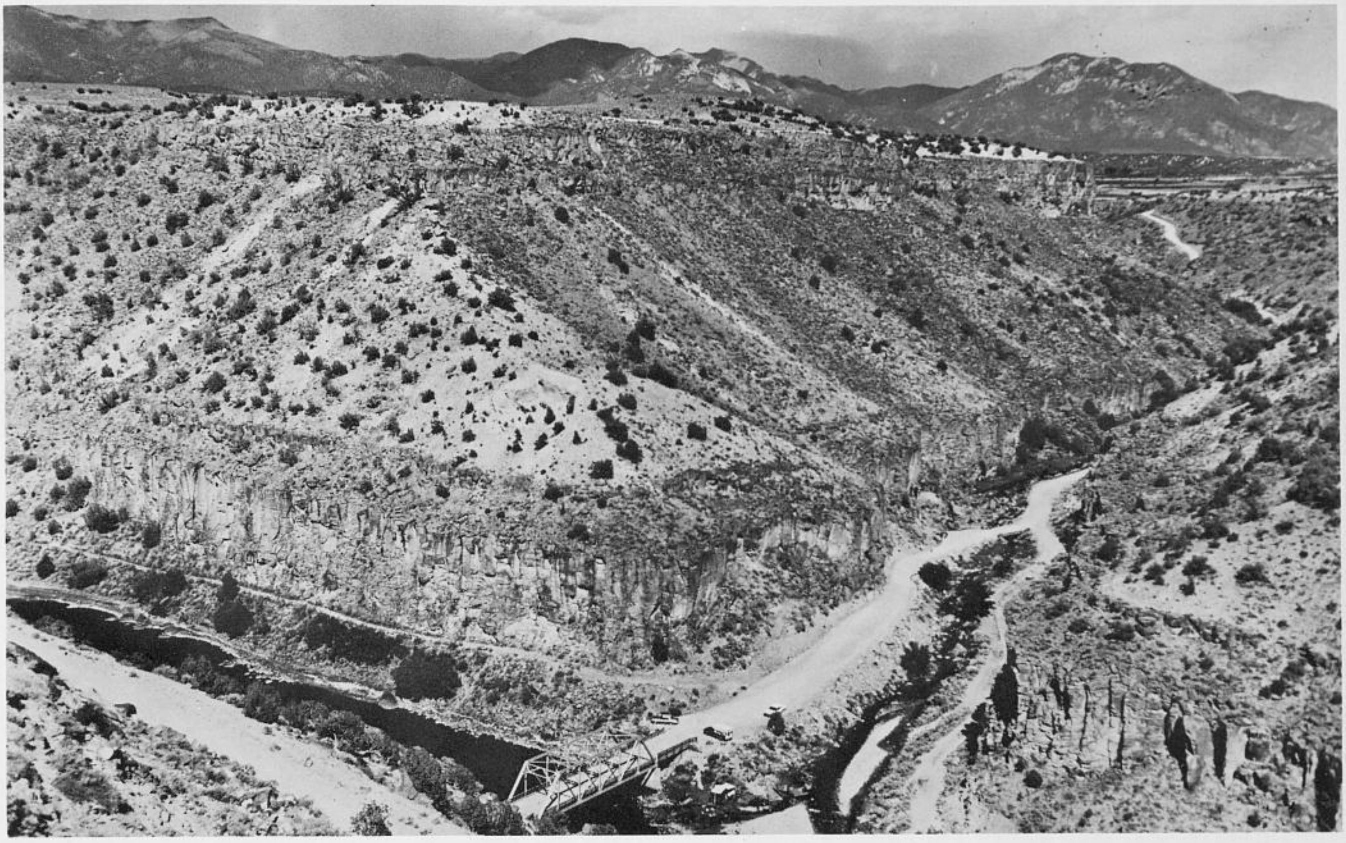


Fig. 60. (Locality 23) Large gravel section in the Rio Grande Gorge north to Taos, New Mexico. The absence of typical Rio Grande material suggests that this section was deposited by a stream which drained a portion of the Sangre de Cristo Mountains and flowed to an ancestral Rio Grande thought to have been farther west, near Tres Piedras, New Mexico.

as is suggested by the absence of typical Rio Grande material within the gravel sequence in the walls of the Rio Grande Gorge at the confluence of the Arroyo Hondo and the Rio Grande (Fig. 60).

During the last stages of Hinsdale volcanism, the Rio Grande, Conejos River, and Rio de los Piños were diverted north of the San Luis Hills and into the vicinity of the present river by basalt flows. As the uplift of the Taos Block and the Picuris Range started, so did entrenchment into the volcanics of the Taos Plateau. This caused the Rio Grande to alluviate and possibly pond north of the point of initial entrenchment, resulting in the gradual deposition of thick fluvial sediments south of the San Luis Hills.

During this time the ancestral Rio Grande remained in the general vicinity of its present channel within the Española and Albuquerque-Belen basins.

As the southward diversion from Glorieta Mesa was completed in middle to late Pliocene time, the ancestral Rio Grande may have initially flowed along the east side of the Socorro Valley, as suggested by Debrine, Spiegel, and Williams (1963). It continued into the northern Jornada del Muerto and flowed southward through the Jornada del Muerto into south-central New Mexico, as is suggested by typical Pleistocene Rio Grande gravels at Localities 48 and 49.

At some time during early Pleistocene, recurrent movement along the Rio Grande depression probably diverted the ancestral Rio Grande westward from its course in the Jornada del Muerto into its present position within the Palomas bolson. Typical Rio Grande gravels beneath playa deposits both north and south of the Doña Ana Mountains (Hawley, personal communication, 1974) suggest that the ancestral Rio Grande was in the general vicinity of the Doña Ana Mountains as it flowed from the Sierra de las Uvas through Fillmore Pass (Fig. 61) into the Hueco bolson. The ancestral Rio Grande is thought to have flowed through Fillmore Pass for a considerable length of time since the gravel deposits at Locality 58 are reported to be over 800 feet thick (Atkins, personal communication, 1974).

From Fillmore Pass the river may have continued southward near the Quitman Mountains, as suggested by gravel at Locality 60, and continued southeast toward Presidio through a structural low, that apparently existed in this area as a result of Middle and Late Tertiary deformation.

Recurrent movement along the Rio Grande depression apparently diverted the ancestral Rio Grande from its course through Fillmore Pass, toward the La Mesa surface east of the East Potrillo Mountains (Fig. 62) and southward into northern Mexico: a course the river retained until diverted into the Hueco bolson through El Paso Canyon.

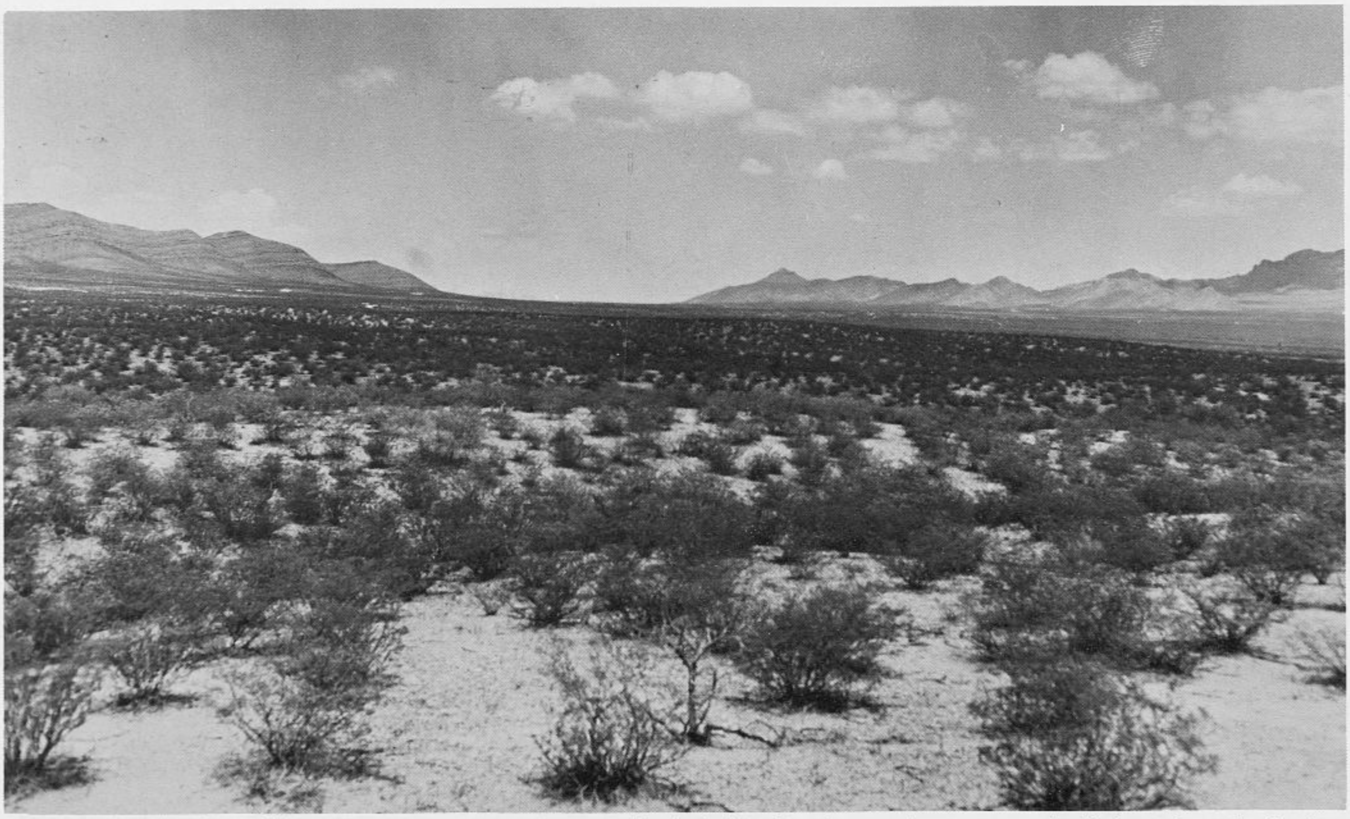


Fig. 61. (Locality 56) Fillmore Pass as seen from the east. Typical Rio Grande gravels occur on the high surfaces in the foreground. Their presence here suggests that the ancestral Rio Grande once flowed into the Hueco bolson through this gap.

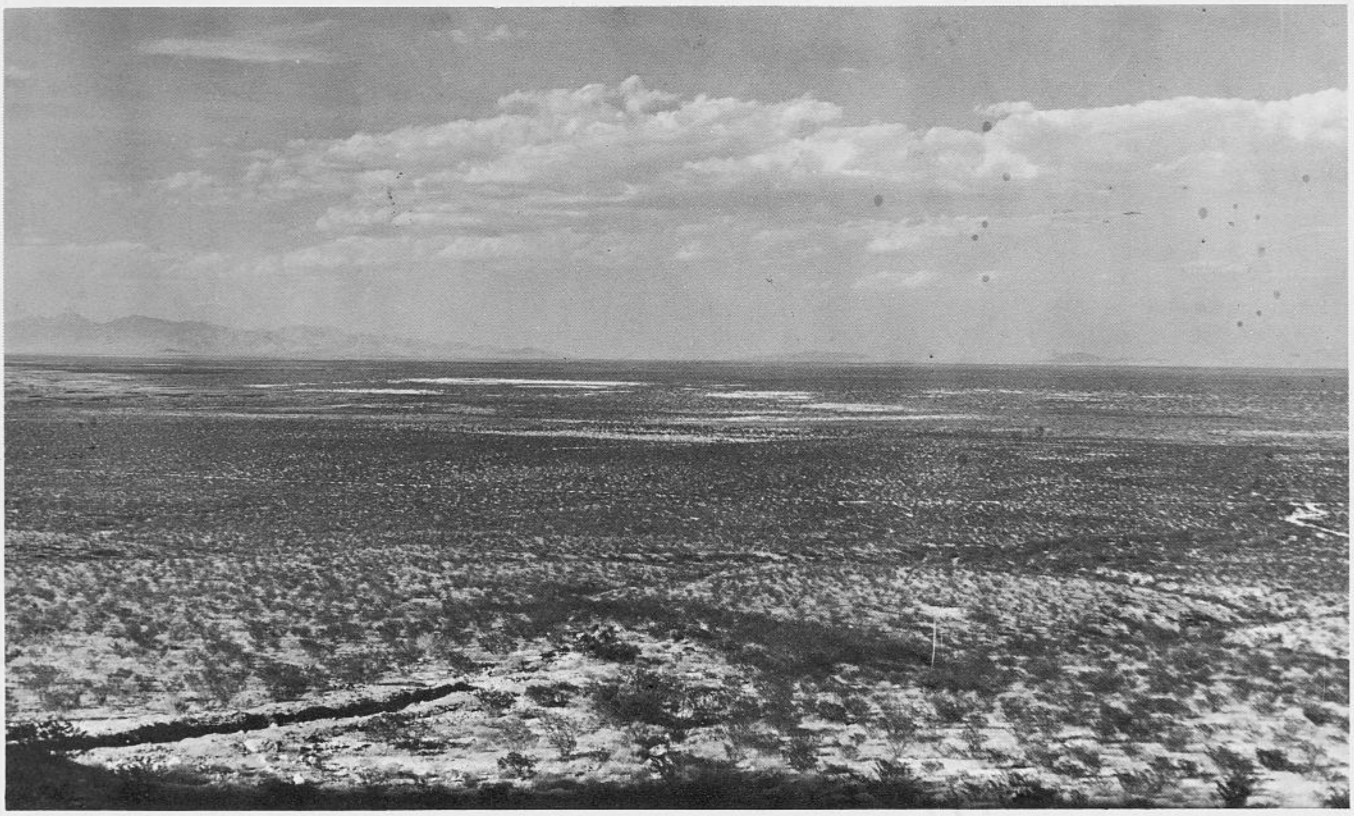


Fig. 62. (Locality 59) Extensive La Mesa surface as seen from the East Potrillo Mountains. Typical Rio Grande gravels in deflation basins on this surface suggest that at one time the Rio Grande flowed through this area into northern Mexico.

Fig. 63. (Locality 110) El Paso Canyon as seen from the west side of the Franklin Mountains. It was through this area that the Rio Grande was diverted into the Hueco bolson to eventually integrate into the present system of drainage.

MIDDLE PLEISTOCENE TO HOLOCENE DRAINAGE

Toward the end of early Pleistocene time the Rio Grande had been diverted from its course into the Hueco bolson through Fillmore Pass to a route across the La Mesa surface and into playas in northern Mexico. During middle Pleistocene time, the Rio Grande was diverted from its course to northern Mexico into the Hueco bolson via El Paso Canyon (Fig. 63) either through capture by a headward-eroding tributary in the Hueco bolson as concluded by Kottlowski (1958) and Strain (1969), or by basin spillover as suggested by Reeves (1969). As diversion into the Hueco bolson was completed, the Rio Grande gradually extended toward Presidio, following the same structural low suggested as the route of the early Pleistocene Rio Grande, and integrated into the present north-south drainage (Fig. 64).

SUMMARY

The geomorphic processes which gradually brought about the integration of the present system of Rio Grande drainage were established with the initial Late Cretaceous Laramide uplifts in New Mexico, Arizona, Colorado, and Mexico. As uplift progressed the Late Cretaceous seas retreated leaving behind the developing fluvial systems.

The Late Cretaceous and Early Tertiary stratigraphy of the San Juan basin, Raton basin, west-central New Mexico, and the Texas Gulf Coast suggests that there were two general fluvial systems which gradually evolved into the present Rio Grande system: the ancestral Rio Grande-Pecos and the ancestral Rio Conchos.

In New Mexico the ancestral Rio Grande-Pecos system was actually composed of two separate through-flowing systems that joined in central New Mexico. One system drained the south side of the San Juan uplift and flowed southeastward across the San Juan basin; the other system headed in the ancestral Mogollon highlands of Arizona and flowed eastward across west-central New Mexico. The combined systems formed the ancestral Rio Grande-Pecos system which flowed southeastward across central New Mexico, along the east side of the Sacramento upwarp, and across the Stockton-Edwards Plateau to join the ancestral Rio Conchos system near the mouth of the present Pecos River. The Rio Grande-Pecos system entrenched into the Pecos River canyon as regional uplift occurred in the Trans-Pecos area during Early Tertiary time.

The ancestral Rio Conchos system flowed east- and southeastward from volcanic highlands in northern Mexico, entrenching itself across rising Laramide structures in the Big Bend Region, and flowed northeastward and then southeastward to the Rio Grande embayment of the Gulf of Mexico.

As this initial stage of drainage progressed the separate systems undoubtedly underwent numerous modifications, which in some cases may have led to complete cessation of drainage. As Oligocene time drew to a close wide spread erosion began, resulting in distribution of gravels throughout southeastern New Mexico and Texas.

The next phase of drainage evolution had been foreshadowed by the first volcanism in the Datil Province of west-central New Mexico and the San Juan Mountains of southwestern Colorado, as well as by the initial development of the Rio Grande depression, both of which took place during late Oligocene time. This phase actually began with the uplift of the Sangre de Cristo Mountains during middle Miocene time, which diverted the original southeastward drainage southwestward.

Volcanism continued in the San Juan Mountain region into Miocene time and built up a plateau, supplying runoff which was joined by flow from the upper portion of the ancestral Arkansas River. This Middle Tertiary system originally flowed southward through the area presently occupied by the Jemez volcanic pile, then eastward across the Glorieta Mesa area.

The course of the ancestral Rio Grande eastward from Glorieta Mesa during middle Miocene to middle Pliocene time is conjectural, but the hiatus existing in the Texas Gulf Coast between the pre-Ogallala (Oligocene ?) Reynosa Gravels and the Pleistocene Lissie Gravels suggests that Rio Grande drainage did not reach south Texas during this time. It could have flowed eastward into either ancestral Canadian or Brazos drainage.

As middle Pliocene time drew to a close a period of wide-spread erosion began, which gradually reduced the highlands in southern Colorado to the San Juan Peneplain.

During late Pliocene time the San Juan Mountain region began a second domal uplift, accompanied by the Hinsdale volcanic epoch. This resulted in extrusion of large quantities of basalt, especially in the Taos Plateau. During this time the damming effect of the volcanic flows in the Taos Plateau area, as well as in the Jemez volcanic area, undoubtedly caused the ancestral Rio Grande to experience several periods of ponding accompanied by overflow, thought to have occurred near Tres Piedras, west of Taos, New Mexico. Eventually the Rio Grande was diverted to its present course across the Taos Plateau, and began gradual entrenchment as the uplift of the Picuris Range began.

After diversion from Glorieta Mesa was complete the Rio Grande flowed along the east side of Socorro Valley through the Jornada del Muerto into south-central New Mexico. The river flowed toward the Doña Ana Mountains and through Fillmore Pass into the Hueco bolson and on to the Rio Conchos at Presidio. Later, recurrent movement diverted the ancestral Rio Grande south from its route through Fillmore Pass, and the river then continued across the La Mesa surface west of El Paso into northern Mexico. During middle Pleistocene time the ancestral Rio Grande was diverted east from its course into northern Mexico to a route through El Paso Canyon into the Hueco bolson. From the Hueco bolson the ancestral Rio Grande again gradually worked southward to Presidio by a process of basin spillover along a structural low.

Once the ancestral Rio Grande joined the ancestral Rio Conchos at Presidio, Texas, integration into the present day system of drainage was complete.

SPECULATIONS

During the course of almost any regional study speculations arise as by-products of the investigation. Some of these have become aspects of the study, others, because of their peripheral nature, remain as speculations. For these latter, answers are not forthcoming from the investigation, but for the investigator they remain interesting and perplexing questions.

Below is a list of the more interesting questions and speculations which resulted from the current study.

(1) In a study of the geomorphology of the Canadian River basin Roberson (1973) suggested that the western Ogallala outcrop area was uplifted during Pliocene time and served as a source area for the eastern Ogallala sediments, which implies that the western Ogallala is older than the eastern Ogallala. Thomas (1972), in an investigation of the geomorphic evolution of the Pecos River system, stated that such positive features as the Sangre de Cristo Mountains, Pedernal uplift, and the Manzano Mountains were unlikely source areas for the conglomerates in the basal Ogallala. He suggested that the siliceous constituents were derived from the San Juan Mountain region of Colorado and New Mexico prior to the Pleistocene uplift of the ranges on the east side of the Rio Grande depression. Several authors have described a prolonged period of erosion which occurred in northern New Mexico and southern Colorado during Oligocene time (Mather, 1957; Church and Hack, 1939; Ray and Smith, 1941; and Stearns, 1943) prior to the Miocene uplift of the Sangre de Cristo Mountains (Galusha and Blick, 1971; Clark, 1966; and Clark and Read, 1972).

Is it possible that the siliceous sands and gravels of

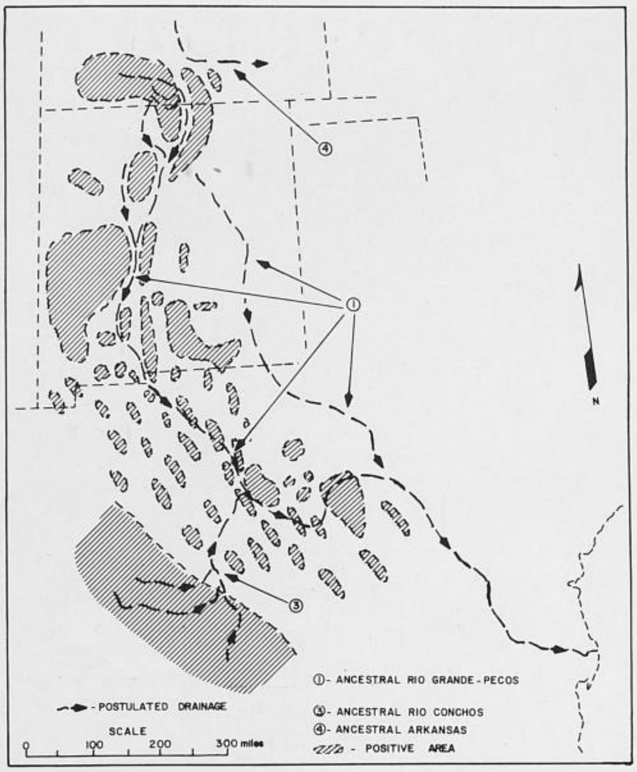


Fig. 64. Evolution of middle Pleistocene to Holocene Rio Grande drainage of New Mexico, Trans-Pecos Texas, and northern Mexico. Shown here is the end result achieved by the Rio Grande after it was diverted into the Hueco bolson during middle Pleistocene time.

the basal Ogallala were derived from the San Juan Mountains and that they were deposited during late Oligocene time prior to the early Miocene uplift of the Sangre de Cristo Mountains? If so, this would suggest a much greater age for the basal Ogallala in its western outcrop than previously has been supposed. If these gravels are of Oligocene age, then they may be correlative with the pre-Ogallala (Oligocene ?) Reynosa Gravels of south Texas which are of similar composition.

(2) Several authors, in describing the Tertiary history of the headwaters region of the Little Colorado River in eastern Arizona, comment on a period of wide-spread erosion during Early to Middle Tertiary time which resulted in the formation of the Tsaile surface. It was upon this surface that the Deza Formation and Chuska Sandstone were deposited. Following this deposition, erosion and stream entrenchment occurred, producing the Hopi Buttes surface upon which the lower member of the Bidahochi Formation was deposited. Later, another period of erosion and entrenchment occurred, forming the Zuni surface upon which the volcanic and upper members of the Bidahochi Formation were deposited. Following deposition of the Bidahochi Formation the ancestral Little Colorado River came into existence, generally in its present form, and cut the Black Point and Wupatki surfaces (Cooley, 1958; Wright, 1956; Cooley and Akers, 1961; and Hack, 1942).

The period of erosion which shaped the Hopi Buttes surface began during Miocene time. It may equate with the Miocene uplift of the Sangre de Cristo Mountains. If these events are time correlative, then during Miocene time drainage from the Sangre de Cristo Mountains may have flowed westward across the San Juan basin and into ancestral Little Colorado drainage.

The Abiquiu Tuff in north-central New Mexico has been described as containing fluvial sediments transported from the San Juan Mountains by southeasterly flowing streams (Atwood and Mather, 1932; and Smith, 1938). Work by Galusha and Blick (1971) in the type area of the Santa Fe Group indicates that the Chama-El Rito Formation was derived from the San Juan Mountains, as was the Los Piños Formation which intertongues with the Santa Fe Group (Bingler, 1968). These studies suggest that during Miocene and Pliocene time drainage from the San Juan Mountains flowed to the southeast into the type area of the Santa Fe Group north of Santa Fe, New Mexico, and may negate the possibility of drainage from the Sangre de Cristo Mountains reaching eastern Arizona during this time.

Another factor discounting the presence of Sangre de Cristo drainage across the San Juan basin is a conclusion reached by Galusha and Blick (1971) concerning the deposition of the Santa Fe Group in the type area. The absence of growth faults and faults terminating within the Santa Fe sediments suggests that at the beginning of Santa Fe deposition a large basin or depression developed adjacent to the west front of the Sangre de Cristo Mountains; it was into this depression that the streams responsible for the deposition of the Santa Fe Group flowed (Galusha, personal communication, 1974). If the large depression did exist, it seems unlikely that drainage from the Sangre de Cristo Mountains reached eastern Arizona.

In spite of the evidence against it, the possibility of drainage from the Sangre de Cristo Mountains flowing across the San Juan basin into ancestral Little Colorado drainage during Miocene time should be considered by future workers since the origin of eastern Arizona drainage responsible for the Miocene and Pliocene periods of erosion is still an open question. Possible sources at this time may have been volcanic highlands in the San Juan Mountains and/or volcanic highlands in the Datil province in west-central New Mexico.

(3) The origin of Otero Mesa in south-central New Mexico has remained a perplexing question throughout the course of this study. Otero Mesa has the appearance of a milled surface but numerous investigations atop the surface have failed to encounter stream gravels, except at Locality 99 where a few rounded limestone cobbles, apparently of local origin, were found.

The east-west trend of the serpentine bends in the Guadalupe Mountains block at Locality 100 suggests east-west drainage across this area of New Mexico prior to the Pliocene uplift of the Guadalupe Mountains. Investigations within these serpentine bends also failed to reveal diagnostic gravels, again leaving open to question the origin of the drainage responsible for Otero Mesa and the serpentine bends.

(4) Oscura Gap, between the Mockingbird Gap Hills and Oscura Mountains, has been described as a graben by Bachman (1968). Investigations within the gap (Locality 74) revealed the presence of well-rounded vein quartz gravels at the northwest end approximately 500 feet above the gap floor. Even though abundant

Fig. 65. (Locality 45) The large windgap separating the Manzano (left) and Los Piños (right) Mountains. These two ranges are one structural unit which suggests that the windgap was eroded by a stream flowing to the east or west through this area.

vein quartz is found within the Precambrian granite section of the Oscura Mountains, no granitic components were associated with the well-rounded gravels in the gap. This, and the roundness (0.9) and sphericity (0.7 to 0.9) of the gravels suggest a distant source.

It is thought that the stream in Oscura Gap was not directly related to ancestral Rio Grande drainage and that it flowed across this area into the Tularosa basin prior to and during the Pliocene rejuvenation of the San Andres Mountains described by Dunham (1935). The Zuni Mountains are suggested as a possible source region since they lie in the right direction, have the right age, and are known to provide the right rock type (Locality 88).

If a stream did head in the Zuni Mountains and flow southeastward through Oscura Gap prior to the Pliocene rejuvenation of the San Andres Mountains, additional support is lent to the suggested eastward course of the ancestral Rio Grande during Miocene to middle Pliocene time. Had the Rio Grande flowed southward along its present course, Zuni drainage would have crossed the Rio Grande—an unlikely event, even for speculations like these.

(5) From its course through Fillmore Pass into the Hueco bolson the ancestral Rio Grande is thought to have flowed southeastward through a structural depression to join the ancestral Rio Conchos. The existence of this depression was suggested by (1) mapping by Amsbury (1958), McKnight (1970), Underwood (1963), and Jones and Reaser (1970) which indicated

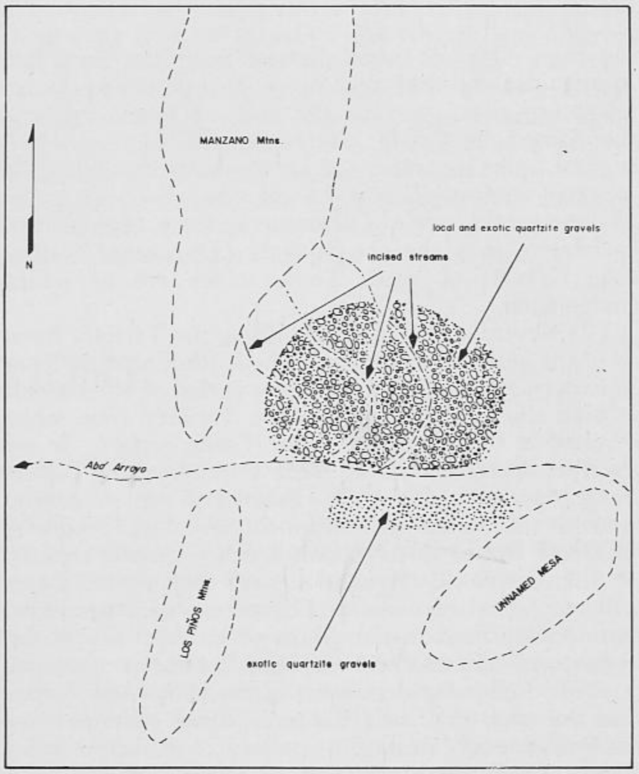


Fig. 66. Schematic representation of the Manzano-Los Piños Mountains vicinity. The presence of exotic gravels and the anomalous bends in the incised arroyos suggest that the windgap may have been occupied at one time by a larger stream that flowed to the east.

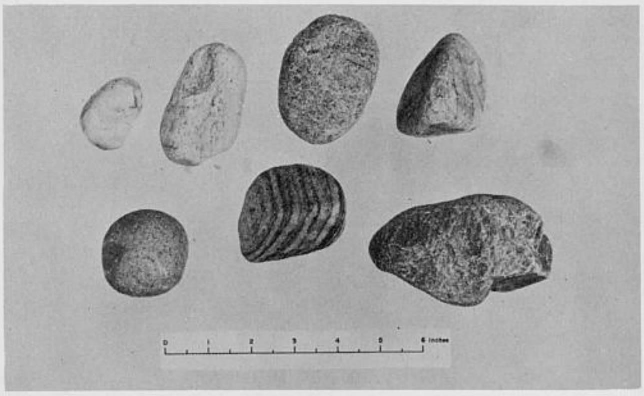


Fig. 67. (Locality 46) Well-rounded exotic and local gravels from the windgap between the Manzano and Los Piños Mountains found capping small hills. While the greater proportion of gravels are of local origin, some of the quartzite is similar to quartzites found to the north in the San Juan, Brazos, and Sangre de Cristo Mountains. These gravels and other features suggest that the windgap was formed by a competent stream flowing to the east.

that the Rio Grande may be located within a graben extending from the Quitman Mountains southeastward to the vicinity of the Bofecillos Mountains, and (2) the fact that from near the Quitman Mountains (Locality 102) southeastward to the Bofecillos Mountains (Locality 65) the course of the Rio Grande cuts across the grain of the Eastern Chihuahuan tectonic belt.

The alignment of this supposed graben with the Rio Grande depression near Las Cruces suggests a possible genetic relationship. If so, the Rio Grande depression extends to the Bofecillos Mountains. Caution should be exercised when extending the Rio Grande depression to the Bofecillos Mountains since this southeastward extension lies within the region of complex Laramide thrusting in the Eastern Chihuahuan tectonic belt. The initial structures of this graben possibly originated with the release of compression rather than extension as supposed for the Rio Grande rift zone, which would negate any genetic relation. But still, the alignment is interesting.

(6) The Manzano and Los Piños Mountains of central New Mexico comprise one structural unit, separated topographically by a prominent windgap (Fig. 65) that is difficult to explain by present drainage. The gap, presently occupied by the ephemeral entrenched, westward-flowing Abo Arroyo (Fig. 66) contains evidence suggesting that it may have been formed or occupied by eastward-flowing drainage. Several incised ephemeral arroyos, which in their upper portions trend southeastward, turn abruptly to the southwest and appear to be barbed tributaries of Abo Arroyo. This suggests that these arroyos were originally tributary to drainage flowing eastward through the gap and have since adjusted to westward flow of Abo Arroyo. Entrenchment of tributaries and portions of Abo Arroyo may have occurred in response to the middle Pleistocene entrenchment of the Rio Grande. Well-rounded quartzite gravels, both locally derived and exotic, (Fig. 67) scattered atop small hills within the windgap area north of Abo Arroyo suggest through-flowing eastward drainage which may have originated

Fig. 68. (Locality 46) The valley of Abo Arroyo as seen from the Manzano Mountains to the north (view is to the south). Notice the east-west trend of the valley and the benches on the south side. It appears unlikely that the small ephemeral Abo Arroyo could have eroded a valley of this magnitude.

in highlands to the north. Exotic gravels on the south side of the windgap also suggest through-flowing drainage.

When viewed from a distance, the dimensions and form of the windgap (Fig. 68) are suggestive of former occupance by a larger drainage system than that now present.

Evidence suggesting through-flowing drainage also exists in a comparison between degree of roundness of local gravels and exotics in the windgap and locally derived gravels in arroyos isolated from the windgap area. Isolated gravels of local origin were sampled at points equally distant from the mountain front (Locality 44) as were sampling points within the windgap. The gravels in the windgap constantly exhibited greater roundness than did the isolated gravels of local origin. This difference may stem from the fact that the isolated gravels were within arroyos and have undergone hydraulic erosion only during occasional periods of runoff, while the gravels in the windgap appear to be those of a permanent stream which were constantly subjected to hydraulic abrasion.

It is not known if the drainage responsible for this windgap is related to the ancestral Rio Grande. This windgap has been suggested as an Eocene feature formed by drainage flowing either east- or westward through the gap (Hawley, personal communication, 1975). When this windgap originated and what drainage was responsible for it is a perplexing question, the answer to which must fit into the final picture of Rio Grande evolution.

(7) The high gravels capping hills from Del Rio, Texas, to south of Rio Grande City (Localities 67 to 73) contain quartzites of San Juan provenance. These gravels are thought to have been deposited by the ancestral Rio Grande during middle to late Oligocene time.

In the San Juan Mountains region during late Eocene time, a wide-spread period of erosion was followed by a period of volcanism during Oligocene and Miocene time. Were the San Juan Quartzite sources blanketed by these volcanics?

Fig. 69. (Locality 111) The end. Shown here is a view of the Gulf of Mexico near Boca Chica, the mouth of the Rio Grande, some 1,887 miles downstream from its headwaters.

If they were not, quartzite detritus possibly could have been supplied to an ancestral Rio Grande system flowing southeastward. If the sources were covered, the gravels at Del Rio would have been deposited prior to Oligocene time—possibly during late Eocene time.

If these gravels were deposited during late Eocene time, their implacement may have corresponded to the depositional epochs of the Baca, Galisteo, and El Rito Formations of New Mexico. Even though these formations are thought to have been deposited by local streams in closed basins (Chapin, Weber, and Kottlowski, personal communication, 1975), this possible time equivalence suggests that the above formations may have been deposited by through-flowing drainage —possibly the ancestral Rio Grande system.

APPENDIX

LOCALITIES

Locality 1. (38°50′N, 106°02′W, Montrose Sheet)
Gravels collected atop highest surface approximately 400 yards north of State Highway 24, approximately 2 miles east of junction with U. S. Highway 285 south of Buena Vista, Colorado.
Quartzite Content: light gray.
Other Contents: light-colored granite, pink granite, epidote (?) granite, vein quartz, and volcanics.
Condition: subangular to moderately well-rounded, weathered.
Size: 1″ to 6″; Roundness: 0.5 to 0.9; Sphericity: 0.3 to 0.7.

Locality 2. (38°35′N, 106°08′W, Montrose Sheet)
Gravels collected on high surface at base of Mounts Shavano and Aetna west of Salida, Colorado.
Quartzite Content: light gray.
Other Contents: light-colored granite, epidote (?) granite, vein quartz, volcanics.
Condition: subangular to moderately well-rounded, weathered.
Size: 1″ to 6″; Roundness: 0.5 to 0.7; Sphericity: 0.3 to 0.7.

Locality 3. (38°25′N, 106°09′W, Montrose Sheet)
Gravels collected in south end of Poncha Pass on second terrace (?) approximately 1 mile east of U. S. Highway 285 south of Salida, Colorado.
Quartzite Content: light gray.
Other Contents: light-colored granite, red granite, dark green phyllite, volcanics, vein quartz.
Condition: weathered, subangular to subrounded.
Size: 1″ to 6″; Roundness: 0.5 to 0.7; Sphericity: 0.5 to 0.7.

Locality 4. (38°05′N, 106°01′W, Montrose Sheet)
Gravels collected atop high surface 1 mile west of U. S. Highway 285 on road to Whale Hill and Round Mountain, approximately 10 miles south of Poncha Pass, Colorado.
Quartzite Content: light gray, light tan.
Other Contents: light-colored granite, red granite, dark green phyllite, volcanics.
Condition: highly weathered, subangular to rounded.
Size: 1″ to 5″; Roundness: 0.5 to 0.7; Sphericity: 0.5 to 0.7.

Locality 5. (37°56′N, 107°50′W, Durango Sheet)
Gravels collected from north wall of the head of the San Miguel River valley, approximately 2 miles east of Telluride, Colorado.
Quartzite Content: purple, white, green, gray.
Other Contents: vein quartz, other metamorphics.
Condition: well rounded.
Size: 0.25″ to 1″; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 6. (37°26′N, 107°50′W, Durango Sheet)
Gravels collected from bed of Animas River east of U. S. Highway 550, approximately 10 miles north of Durango. Colorado.
Quartzite Content: light gray, light blue, light purple, white.
Other Contents: light-colored gneiss, other metamorphics.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 7. (37°11′N, 107°50′W, Durango Sheet)
Gravels collected atop Florida Mesa, Colorado, approximately 3.5 miles south-southeast of the intersection between State Highways 172 and 160.
Quartzite Content: purple, banded, white, gray.
Other Contents: gneiss.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 8. (37°05′N, 107°48′W, Durango Sheet)
Gravels collected atop Mesa Mountains, approximately 8 miles due south of Oxford, Colorado.
Quartzite Content: purple, gray, banded, white.
Other Contents: white gneiss.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.7 to 0.9; Sphericity 0.7 to 0.9.

Locality 9. (37°47′N, 107°31′ W, Durango Sheet)
Gravels collected from bed of Rio Grande, approximately 3 miles southeast of its headwaters at Stony Pass, Colorado.
Quartzite Content: white.
Other Contents: volcanics, light metamorphics.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.5 to 0.7; Sphericity: 0.5 to 0.7.

Locality 10. (37°49′N, 106°54′W, Durango Sheet)
Gravels collected from first terrace of the Rio Grande at intersection of State Highway 149 and Deep Creek Road, approximately 7 miles southeast of Creede, Colorado.
Quartzite Content: banded, light purple, white.
Other Contents: none.
Condition: well rounded.
Size: 0.5″ to 5″; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 11. (36°55′N, 106°33′W, Aztec Sheet)
Gravels collected from bed of Chama River at bridge approximately 1.5 miles northeast of Chama, New Mexico, alongside State Highway 17.
Quartzite Content: gray, white, banded white and purple, dark gray.
Other Contents: volcanics and vein quartz.
Condition: well rounded.
Size: 1″ to 6″; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.7.

Locality 12. (37°08′N, 106°18′W, Durango Sheet)
Gravels collected from bed of Conejos River just upstream of bridge at intersection of State Highway 17 and road to Platoro, Colorado.
Quartzite Content: light gray, dark gray.
Other Contents: volcanic material.
Condition: well rounded.
Size: 1″ to 6″; Roundness: 0.5 to 0.7; Sphericity: 0.5 to 0.7.

Locality 13. (37°04′N, 105°49′W, Trinidad Sheet)
Gravels collected 0.5 miles downstream from bridge where State Highway 248 crosses the Rio Grande between Antonito and Mesita, Colorado.
Quartzite Content: white, purple, banded gray and purple.
Other Contents: granite, epidote (?) granite, gneiss.
Condition: well rounded.
Size: 0.5″ to 2″; Roundness: 0.9; Sphericity 0.5 to 0.9.

Locality 14. (37°05′N, 105°47′W, Trinidad Sheet)
Gravels collected atop Rio Grande valley approximately 2 miles east of the bridge where State Highway 248 crosses the Rio Grande between Antonito and Mesita, Colorado.
Quartzite Content: white.
Other Contents: granite, volcanics.
Condition: well rounded.
Size: 0.25″ to 1″; Roundness: 0.7 to 0.9; Sphericity 0.7.

Locality 15. (37°06′N, 105°39′W, Trinidad Sheet)
Gravels collected approximately 2.5 miles west of intersection of State Highways 248 and 159 south of San Luis, Colorado.
Quartzite Content: white, purple, gray, brown.
Other Contents: light-colored granite, epidote granite.
Condition: well rounded.
Size: 1″; Roundness: 0.7; Sphericity: 0.7.

Locality 16. (37°11′N, 105°37′W, Trinidad Sheet)
Gravels collected along north side of San Pedro Mesa in road cut adjacent to State Highway 159 just west of bridge crossing Venturo Creek west of San Luis, Colorado.
Quartzite Content: white, micaceous.
Other Contents: light-colored granite, pink granite, volcanics.
Condition: well rounded.
Size: 0.5″ to 2″; Roundness: 0.5 to 0.7; Sphericity: 0.5 to 0.7.

Locality 17. (36°45′N, 106°27′W, Aztec Sheet)
Gravels collected from bed of Rio de Los Brazos at point where U. S. Highway 84 crosses the river immediately south of Brazos, New Mexico.
Quartzite Content: light purple, light gray, light green.
Other Contents: none.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 18. (36°46′N, 106°15′W, Aztec Sheet)
Gravels collected on north side of U. S. Highway 64, approximately 0.2 mile east of the Brazos overlook near Tierra Amarilla, New Mexico.
Quartzite Content: light gray, dark gray, light purple, white, banded.
Other Contents: none.
Condition: subangular to moderately well rounded.
Size: 1″ to 4″; Roundness: 0.5 to 0.7; Sphericity: 0.5 to 0.7.

Locality 19. (36°44′N, 106°08′W, Aztec Sheet)
Gravels collected on both sides of Forest Road 133, approximately 5 miles north of U.S. Highway 64 east of Tierra Amarilla, New Mexico.
Quartzite Content: banded dark and light gray, light purple, light gray.
Other Contents: light-colored granite.
Condition: subangular to moderately well rounded.
Size: 1″ to 4″; Roundness: 0.5 to 0.7; Sphericity 0.3 to 0.5.

Locality 20. (36°35′N, 105°42′W, Raton Sheet)
Gravels collected in road cut on east side of State Highway 3, immediately north of D. H. Lawrence-San Cristobal turn-off north of Taos, New Mexico.
Quartzite Content: dark gray, light gray, light purple, white.
Other Contents: white gneiss.
Condition: Subangular to moderately well rounded.
Size: 1″ to 4″; Roundness: 0.5 to 0.7; Sphericity: 0.5.

Locality 21. (36°35′N, 105°47′ W, Raton Sheet)
Gravels collected from gravel pit south of State Highway 111 on top of the Rio Grande Gorge, approximately 1.5 miles west of the Rio Grande north of Taos, New Mexico.
Quartzite Content: white, light gray, light purple.
Other Contents: light-colored granite, pink granite.
Condition: well rounded.
Size: 1″ to 5″; Roundness: 0.5 to 0.9; Sphericity: 0.5 to 0.9.

Locality 22. (36°36′N, 106°22′W, Aztec Sheet)
Gravels collected on east-northeast side of U. S. Highway 84 approximately 2.2 miles south of intersection with State Highway 115 to Canjilon, New Mexico.
Quartzite Content: light purple, light gray, white.
Other Contents: none.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.7.

Locality 23. (36°43′N, 105°47′W, Aztec Sheet)
Gravels collected from west side of the Rio Grande Gorge, approximately 50 feet below upper basalt flow, in road cut adjacent to State Highway 111 north of Taos, New Mexico.
Quartzite Content: white.
Other Contents: light-colored granite, pink granite, volcanics.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 24. (36°43′N, 105°47′W, Aztec Sheet)
Gravels collected from west side of Rio Grande Gorge approximately mid-way down the wall in a road cut adjacent to State

Highway 111 north of Taos, New Mexico.
Quartzite Content: white, light purple.
Other Contents: light-colored granite.
Condition: well rounded.
Size: 1″ to 5″; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.7.

Locality 25. (36°44′N, 105°14′W, Raton Sheet)
Gravels collected on north side of road to Idlewilde, New Mexico, approximately 1.3 miles west of intersection with U. S. Highway 64 in Moreno Valley, north of Eagle Nest, New Mexico.
Quartzite Content: white, micaceous.
Other Contents: granite.
Condition: weathered, well rounded.
Size: 1″ to 3″; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 26. (36°44′N, 105°13′W, Raton Sheet)
Gravels collected on north side of road to Idlewilde, New Mexico, approximately 0.5 mile west of intersection with U.S. Highway 64 in Moreno Valley, north of Eagle Nest, New Mexico.
Quartzite Content: light purple, white, micaceous.
Other Contents: granite.
Condition: weathered, well rounded.
Size: 0.5″ to 3″; Roundness: 0.7; Sphericity: 0.7.

Locality 27. (36°14′N, 106°18′W, Aztec Sheet)
Gravels collected from road cut on northeast side of U. S. Highway 84 approximately 3.3 miles west of Abiquiu, New Mexico.
Quartzite Content: dark gray, dark purple, banded gray and purple.
Other Contents: none.
Condition: well rounded.
Size: 1″ to 5″; Roundness: 0.9; Sphericity: 0.5 to 0.9.

Locality 28. (36°09′N, 106°17′W, Aztec Sheet)
Gravels collected at base of basalt cap atop Cerro Pedernal southeast of Youngsville, New Mexico.
Quartzite Content: white, light purple, light gray, dark gray.
Other Contents: none.
Condition: well rounded.
Size: 0.25″ to 1″; Roundness: 0.9; Sphericity: 0.7.

Locality 29. (36°09′N, 106°17′W, Aztec Sheet)
Gravels collected approximately 200 feet below the base of the basalt cap atop Cerro Pedernal southeast of Youngsville, New Mexico.
Quartzite Content: light gray, dark gray, banded light and dark gray, light purple.
Other Contents: light-colored granite, pink granite, gneiss, vein quartz.
Condition: well rounded.
Size: 0.5″ to 4″; Roundness: 0.5 to 0.7; Sphericity: 0.3 to 0.7.

Locality 30. (36°09′N, 106°17′W, Aztec Sheet)
Gravels collected at base of Cerro Pedernal on north side of Forest Road 160 approximately 0.3 miles east of intersection with Forest Road 100 to Encino look out southeast of Youngsville, New Mexico.
Quartzite Content: light purple, dark purple, light gray, dark gray, white.
Other Contents: none.
Condition: well rounded.
Size: 1″ to 4″; Roundness: 0.7; Sphericity: 0.5 to 0.7.

Locality 31. (36°17′N, 105°49′W, Raton Sheet)
Gravels collected in east wall of Rio Grande Gorge, approximately 1.5 miles north of Pilar, New Mexico, along State Highway 96, Pilar branch.
Quartzite Content: dark purple, dark gray, light gray, white, light purple.
Other Contents: other metamorphics.
Condition: well rounded.
Size: 1″ to 3″; Roundness: 0.5 to 0.9; Sphericity: 0.5 to 0.7.

Locality 32. (35°54′N, 106°57′W, Albuquerque Sheet)
Gravels collected at an elevation of appproximately 7,000 feet atop small hills on both sides of old State Highway 44, approximately 5.3 miles south of Cuba, New Mexico.
Quartzite Content: dark purple, dark gray, light gray, white, orange.
Other Contents: none.
Condition: well rounded.
Size: 0.5″ to 4″; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 33. (36°12′N, 105°56′W, Raton Sheet)
Gravels collected in roadcut on south side of State Highway 75, approximately 1 mile east of junction with State Highway 68, north of Embudo, New Mexico.
Quartzite Content: white, light purple, light gray, dark gray.
Other Contents: gneiss, granite.
Condition: well rounded.
Size: 0.25″ to 1″; Roundness: 0.9; Sphericity: 0.7.

Locality 34. (36°16′N, 105°49′W, Raton Sheet)
Gravels collected on west side of State Highway 68, approximately 0.5 miles north of Pilar, New Mexico .
Quartzite Content: light gray, light purple, banded light and dark gray, dark gray, white.
Other Contents: other metamorphics and granite.
Condition: subangular to well rounded.
Size: 1″ to 3″; Roundness: 0.5 to 0.9; Sphericity: 0.5 to 0.7.

Locality 35. (36°14′N, 105°15′W, Raton Sheet)
Gravels collected on both sides of State Highway 38 approximately 3 miles south of Black Lake near the headwaters of Coyote Creek draining Moreno Valley, New Mexico.
Quartzite Content: white, gray, banded dark and light gray.
Other Contents: light-colored granite.
Condition: moderately well rounded.
Size: 1″ to 4″; Roundness: 0.7; Sphericity: 0.5 to 0.7.

Locality 36. (35°53′N, 105°09′W, Albuquerque Sheet)
Gravels collected in road cut on west side of State Highway 4, approximately 1 mile east of the White Rock-Los Alamos intersection east of Los Alamos, New Mexico.
Quartzite Content: white, light purple, light gray, dark gray.
Other Contents: assorted volcanics.
Condition: well rounded.
Size: 0.5″ to 3″; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 37. (35°53′N, 105°07′W, Albuquerque Sheet)
Gravels collected in road cut on north side of State Highway 4, approximately 2 miles west of the Española-Pojoaque junction, east of Los Alamos, New Mexico.
Quartzite Content: white, pink, light gray, light purple, banded white and purple, dark gray.
Other Contents: granite, epidote (?) granite, assorted volcanics.
Condition: well rounded.
Size: 0.5″ to 4″; Roundness: 0.9; Sphericity: 0.5 to 0.9.

Locality 38. (36°07′N, 105°48′W, Raton Sheet)
Gravels collected in road cut on west side of State Highway 76, approximately 0.5 mile south of Trampas, New Mexico, east of Española, New Mexico.
Quartzite Content: dark gray, dark purple, light gray, light purple, white.
Other Contents: none.
Condition: well rounded.
Size: 0.5″ to 4″; Roundness: 0.9; Sphericity: 0.5 to 0.7.

Locality 39. (34°51′N, 107°54′W, Socorro Sheet)
Gravels collected from northwest side of Cebollita Mesa, approximately 3 miles east of State Highway 117, approximately 16.2 miles south of intersection with Interstate Highway 40, east of Grants, New Mexico.
Quartzite Content: banded dark purple, light purple.
Other Contents: granite.
Condition: fractured, weathered, rounded.
Size: 1″ to 3″; Roundness: 0.9; Sphericity: 0.3 to 0.5.

Locality 40. (34°′43′N, 108°40′W, Socorro Sheet)
Gravels collected from vicinity of Blue Water Creek and Victorino Mesa approximately 15 to 20 miles south of Acoma Pueblo, Acoma Indian Reservation, New Mexico.
Quartzite Content: dark purple, brown, light tan, dark gray, light gray.
Other Contents: light- and dark-colored gneiss, light-colored granite.
Condition: weathered, well rounded.
Size: 1″ to 10″; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 41. (35°02′N, 106°56′W, Albuquerque Sheet)
Gravels collected in east side of the Rio Puerco valley, approxi-

mately 1 mile east of a Stuckey's Restaurant, approximately 15 miles west of Albuquerque, New Mexico.
Quartzite Content: light purple, light gray, white.
Other Contents: assorted volcanics.
Condition: well rounded.
Size: 0.25" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.3 to 0.7.

Locality 42. (35°20'N, 105°44'W, Santa Fe Sheet)
Gravels collected atop flat hills on Glorieta Mesa, approximately 12 miles south of Interstate Highway 25 on State Highway 34 southeast of Rowe, New Mexico.
Quartzite Content: light purple, dark purple, light gray, dark gray, brown.
Other Contents: gneiss, light-colored granite, pink granite.
Condition: well rounded.
Size: 0.5" to 3"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.7.

Locality 43. (35°54'N, 105°15'W, Santa Fe Sheet)
Gravels collected atop road cut on west side of State Highway 3, approximately 3 miles south of La Cueva, New Mexico.
Quartzite Content: white, light gray.
Other Contents: light-colored granite, pink granite.
Condition: weathered, rounded.
Size: 1" to 4"; Roundness: 0.3 to 0.7; Sphericity: 0.5 to 0.7.

Locality 44. (34°43'N, 106°46'W, Socorro Sheet)
Gravels collected from bed of Arroyo del Cuervo, approximately 4 miles south of Torreon, New Mexico, beside State Highway 14.
Quartzite Content: light purple, dark gray.
Other Contents: metamorphics.
Condition: angular to subangular.
Size: 1" to 3"; Roundness: 0.3; Sphericity: 0.3.

Locality 45. (34°26'N, 106°13'W, Socorro Sheet)
Gravels collected alongside a county road approximately 0.5 mile south of U. S. Highway 60 and approximately 8 miles southwest of Mountainair, New Mexico.
Quartzite Content: light purple, dark purple, light gray.
Other Contents: vein quartz, light-colored granite, pink granite.
Condition: weathered, rounded.
Size: 0.25" to 2"; Roundness: 0.3 to 0.5; Sphericity: 0.1 to 0.5.

Locality 46. (34°28'N, 106°15'W, Socorro Sheet)
Gravels collected on small hills approximately 1 mile north of U. S. Highway 60, approximately 8.2 miles southwest of Mountainair, New Mexico.
Quartzite Content: light purple, light gray, white, brownish gray.
Other Contents: gneiss, granite.
Condition: subangular to well rounded.
Size: 0.25" to 4"; Roundness: 0.3 to 0.9; Sphericity: 0.3 to 0.5.

Locality 47. (34°16'N, 104°29'W, Fort Sumner Sheet)
Gravels collected on Conejos Mesa along a county road approximately 13 miles due south of Yeso, New Mexico, on U. S. Highway 60 west of Fort Sumner, New Mexico.
Quartzite Content: banded dark purple, light purple, banded purple and gray, white, light gray, orange.
Other Contents: chert, granite, vein quartz.
Condition: angular to well rounded.
Size: 0.25" to 1"; Roundness: 0.3 to 0.9; Sphericity: 0.3 to 0.7.

Locality 48. (33°28'N, 106°59'W, Tularosa Sheet)
Gravels collected on top of drainage divide along side of road to U. S. Naval surveillance station, approximately 17 miles north of Engle, New Mexico.
Quartzite Content: light purple, light gray, white, orange.
Other Contents: chert, volcanics, granite, vein quartz.
Condition: subangular to well rounded.
Size: 0.25" to 1"; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 49. (35°15'N, 107°01'W, Tularosa Sheet)
Gravels collected atop drainage divide east of road to U. S. Naval surveillance station, approximately 7 miles north of Engle, New Mexico, east of Truth or Consequences, New Mexico.
Quartzite Content: light purple, white, banded white and purple, light gray.
Other Contents: chert, volcanics, granite.
Condition: subangular to well rounded.
Size: 0.25" to 1"; Roundness: 0.3 to 0.9; Sphericity: 0.7.

Locality 50. (33°07'N, 107°05'W, Tularosa Sheet)
Gravels collected atop small hills south of State Highway 52, approximately 4.5 miles east of Elephant Butte dam, New Mexico.
Quartzite Content: white, brown, light gray.
Other Contents: chert, volcanics.
Condition: well rounded.
Size: 0.25" to 0.75"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 51. (32°28'N, 107°32'W, Las Cruces Sheet)
Gravels collected from a gravel pit northwest of State Highway 26, approximately 8.4 miles southwest of Nutt, New Mexico.
Quartzite Content: light gray, brown, light green, light purple.
Other Contents: chert, volcanics.
Condition: subangular to rounded.
Size: 0.5" to 3"; Roundness: 0.3 to 0.7; Sphericity: 0.1 to 0.5.

Locality 52. (32°33'N, 107°29'W, Las Cruces Sheet)
Gravels collected approximately 1 mile south of State Highway 26 on a flat-topped hill between the Sierra de Las Uvas and the Goodsight Hills.
Quartzite Content: white, light purple.
Other Contents: granite, volcanics, chert.
Condition: angular to subrounded.
Size: 0.1" to 2"; Roundness: 0.1 to 0.7; Sphericity: 0.3 to 0.5.

Locality 53. (32°14'N, 107°38'W, Las Cruces Sheet)
Gravels collected in a gravel pit on north side of State Highway 549, approximately 15 miles east of Deming, New Mexico.
Quartzite Content: light gray, white, light purple, banded dark and light gray.
Other Contents: volcanics, chert.
Condition: subangular to rounded.
Size: 0.25" to 2"; Roundness: 0.3 to 0.7; Sphericity: 0.3 to 0.5.

Locality 54. (31°50'N, 107°40'W, El Paso Sheet)
Gravels collected south of county road between Columbus, New Mexico, and La Union, Texas, approximately 3 miles east of Columbus, New Mexico.
Quartzite Content: light purple, light gray, white, banded dark and light gray.
Other Contents: volcanics, granite, chert.
Condition: subangular to well rounded.
Size: 0.25" to 1"; Roundness: 0.3 to 0.9; Sphericity: 0.3 to 0.9.

Locality 55. (31°50'N, 107°36'W, El Paso Sheet)
Gravels collected south of county road between Columbus, New Mexico, and La Union, Texas, approximately 8 miles east of Columbus, New Mexico.
Quartzite Content: light gray, light purple, white.
Other Contents: volcanics, granite.
Condition: subangular to rounded, coated by desert varnish.
Size: 0.25" to 1"; Roundness: 0.3 to 0.7; Sphericity: 0.3 to 0.5.

Locality 56. (32°08'N, 106°32'W, Las Cruces Sheet)
Gravels collected in Fillmore Pass, approximately 5 miles west of the Doña Ana Range Camp on the Fort Bliss Military Reservation.
Quartzite Content: white, light purple, dark purple, light gray.
Other Contents: chert, volcanics, granite.
Condition: well rounded.
Size: 0.25" to 1"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 57. (32°05'N, 106°32'W, Las Cruces Sheet)
Gravels collected approximately 2.5 miles south of Fillmore Pass immediately east of the northernmost extension of the Franklin Mountains into New Mexico.
Quartzite Content: purple, white, blue, gray, black.
Other Contents: chert, volcanics, granite.
Condition: well rounded.
Size: 0.2" to 1"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 58. (32°00'N, 106°26'W, El Paso Sheet)
Gravels collected in a gravel pit on the west side of McCombs Road, approximately 100 yards south of the New Mexico-Texas state line and approximately 1.5 miles northeast of the Newman power plant.
Quartzite Content: white, light purple, dark purple, light gray.
Other Contents: chert, volcanics, granite.
Condition: well rounded.
Size: 0.1" to 0.75"; Roundness: 0.3 to 0.9; Sphericity: 0.3 to 0.7.

Locality 59. (31°51'N, 106°58'W, El Paso Sheet)
Gravels collected approximately 0.5 mile east of the south end of the East Potrillo Mountains along the Bureau of Land Management road to Kilborn's Hole.
Quartzite Content: light purple, light gray, white.
Other Contents: volcanics, chert, granite.
Condition: subangular to well rounded.
Size: 0.1" to 0.75"; Roundness: 0.3 to 0.9; Sphericity: 0.3 to 0.7.

Locality 60. (31°19'N, 105°51'W, Van Horn Sheet)
Gravels collected in Camp Rice Arroyo, approximately 0.5 miles downstream from the Camp Rice flood prevention dam, approximately 3 miles north of Fort Hancock, Texas.
Quartzite Content: white, light purple, dark purple, light gray.
Other Contents: granite, chert, volcanics.
Condition: well rounded.
Size: 0.2" to 1"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 61. (29°43'N, 104°18'W, Presidio Sheet)
Gravels collected along U. S. Highway 67, approximately 7 miles north of Presidio, Texas.
Quartzite Content: none.
Other Contents: chert, volcanics.
Condition: subangular to rounded.
Size: 0.1" to 1"; Roundness: 0.5 to 0.7; Sphericity: 0.3 to 0.5.

Locality 62. (29°33'N, 104°18'W, Presidio Sheet)
Sample collected in road cut along west side of U. S. Highway 67, approximately 300 yards north of Cibolo Creek, approximately 2 miles north of Presidio, Texas.
Quartzite Content: white, light gray, light purple, dark purple.
Other Contents: volcanics, chert.
Condition: well rounded.
Size: fine to coarse sand; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 63. (29°22'N, 104°10'W, Presidio Sheet)
Sample collected in road cut along State Highway 170, approximately 5 miles southeast of Redford, Texas.
Quartzite Content: white, light purple, light gray, dark purple.
Other Contents: volcanics, chert.
Condition: well rounded.
Size: fine sand to 0.3"; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 64. (29°19'N, 104°06'W, Presidio Sheet)
Sample collected in road cut approximately 10 miles southeast of Redford, Texas, along side of State Highway 170.
Quartzite Content: white, light gray, light purple, dark purple, orange.
Other Contents: volcanics, chert.
Condition: well rounded.
Size: fine to coarse sand; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 65. (29°17'N, 103°48'W, Emory Peak Sheet)
Sample collected in road cut approximately 2.5 miles west of Lajitas, Texas along State Highway 170.
Quartzite Content: light purple, white, light gray.
Other Contents: volcanics, chert.
Condition: well rounded.
Size: fine to coarse sand; Roundness: 0.7 to 0.9; Sphericity: 0.7 to 0.9.

Locality 66. (29°52'N, 101°50'W, Del Rio Sheet)
Gravels collected on top of the Stockton Plateau approximately 3 miles west of Lozier Canyon along U. S. Highway 90, approximately 45 miles east of Sanderson, Texas.
Quartzite Content: white.
Other Contents: chert.
Condition: weathered, well rounded.
Size: 0.5" to 3"; Roundness 0.7 to 0.9; Sphericity: 0.3 to 0.7.

Locality 67. (29°20'N, 100°56'W, Del Rio Sheet)
Gravels collected on top of Cienegas Hills approximately 1.5 miles west of Del Rio International Airport, Del Rio, Texas.
Quartzite Content: white, light gray.
Other Contents: volcanics, chert.
Condition: weathered, well rounded, embedded in caliche.
Size: 0.5" to 3"; Roundness: 0.5 to 0.9; Sphericity: 0.5 to 0.7.

Locality 68. (29°18'N, 100°50'W, Del Rio Sheet)
Gravels collected atop Eagle Pass Hill, approximately 1.7 miles south of bridge where U. S. Highway 277 crosses San Felipe Creek southeast of Del Rio, Texas.
Quartzite Content: white, light purple, dark purple, light gray.
Other Contents: volcanics, chert, limestone.
Condition: weathered, well rounded, embedded in caliche.
Size: 0.5" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 69. (29°10'N, 100°45'W, Del Rio Sheet)
Gravels collected in road cut along U. S. Highway 277, approximately 24 miles south of Del Rio, Texas.
Quartzite Content: white, light purple, light gray, dark purple, banded dark and light gray.
Other Contents: chert, volcanics, limestone.
Condition: well rounded, weathered, embedded in caliche.
Size: 0.25" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 70. (28°37'N, 100°28'W, Eagle Pass Sheet)
Gravels collected along a county road approximately 0.9 mile west of its intersection with County Road 1021 to El Indio from Eagle Pass, Texas; intersection is 0.6 mile south of intersection between County Roads 1021 and 2030.
Quartzite Content: light purple, light gray, white.
Other Contents: chert, volcanics.
Condition: well rounded, weathered, embedded in caliche.
Size: 0.25" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 71. (28°18'N, 100°14'W, Eagle Pass Sheet)
Gravels collected on west side of County Road 1021, approximately 20 miles south of El Indio, Texas.
Quartzite Content: light purple, light gray, white.
Other Contents: volcanics, chert.
Condition: well rounded, weathered, embedded in caliche.
Size: 0.25" to 1.5"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.9.

Locality 72. (27°18'N, 99°22'W, Laredo Sheet)
Gravels collected along west side of U. S Highway 83, approximately 25 miles south of Laredo, Texas, and 0.25 mile south of the Webb-Zapata County line.
Quartzite Content: light purple, light gray, white.
Other Contents: volcanics, chert.
Condition: well rounded, embedded in caliche.
Size: 0.25" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.3 to 0.9.

Locality 73. (26°17'N, 98°45'W, McAllen Sheet)
Gravels collected in road cut on south side of U. S. Highway 83, approximately 5 miles southeast of Rio Grande City, Texas, and 1 mile southeast of the Garciaville turn-off.
Quartzite Content: light purple, light gray, white.
Other Contents: volcanics, chert.
Condition: well rounded, embedded in caliche.
Size: 0.5" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.3 to 0.9.

Locality 74. (33°38'N, 106°20'W, Tularosa Sheet)
Gravels collected on southwest side of the northwest end of Oscura gap between the Mockingbird Gap Hills and the Oscura Mountains. The gravels were found approximately 500 feet above the gap floor.
Quartzite Content: none.
Other Contents: vein quartz.
Condition: well rounded, weathered.
Size: 0.5" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.7.

Locality 75. (31°12'N, 107°54'W)
Gravels collected approximately 2 miles west of junction between Mexico Highways 16 and 2 in a gravel pit on the northwest side of Highway 2, approximately 23 miles south of Palomas, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material.
Condition: well rounded, weathered.
Size: 0.5" to 1.5"; Roundness: 0.9; Sphericity: 0.7.

Locality 76. (31°03'N, 108°06'W)
Gravels collected in a gravel pit on west side of Mexico Highway 2, approximately 5 miles south of La Ascension, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material.
Condition: well rounded, weathered.
Size: 0.5" to 2"; Roundness: 0.7 to 0.9; Sphericity: 0.5 to 0.7.

Locality 77. (29°28'N, 107°34'W)
Gravels collected in a gravel pit on north side of Rio Santa

Maria, approximately 25 miles north of Buenaventura, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material.
Condition: well rounded, weathered.
Size: 0.25" to 2"; Roundness: 0.9; Sphericity: 0.5 to 0.7.

Locality 78. (29°55'N, 106°30'W)
Gravels collected on north side of Mexico Highway 10, approximately 10 miles west of intersection with Mexico Highway 45.
Quartzite Content: none.
Other Contents: assorted volcanic material.
Condition: well rounded, weathered.
Size: 0.5" to 2"; Roundness: 0.9; Sphericity: 0.5 to 0.7.

Locality 79. (29°50'N, 106°23'W)
Gravels collected in a small gravel pit west of Mexico Highway 45, approximately 1 mile south of El Sueco, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material.
Condition: weathered, well rounded.
Size: 0.5" to 3"; Roundness: 0.5 to 0.9; Sphericity: 0.7 to 0.9.

Locality 80. (28°56'N, 105°58'W)
Gravels collected in gravel pit on alluvial plain north of Mexico Highway 16, approximately 8 miles east of Aldama, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material.
Condition: well rounded, weathered, fractured.
Size: 0.5" to 4"; Roundness: 0.9; Sphericity: 0.5 to 0.9.

Locality 81. (29°28'N, 105°06'W)
Gravels collected from the first terrace of the Rio Coyame along Mexico Highway 16 east of Coyame, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material and limestone.
Condition: well rounded, weathered.
Size: 0.5" to 3"; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 82. (29°29'N, 104°54'W)
Gravels collected from highest terrace of the Rio Conchos along Mexico Highway 16, approximately 8 miles east of Coyame, Chihuahua.
Quartzite Content: purple (local).
Other Contents: assorted volcanic material and limestone.
Condition: rounded to well rounded, weathered.
Size: 0.5" to 4"; Roundness: 0.5 to 0.9; Sphericity: 0.5 to 0.9.

Locality 83. (29°29'N, 104°52'W)
Gravels collected from first terrace of the Rio Conchos in a road cut beside Mexico Highway 16, approximately 12 miles east of Coyame, Chihuahua.
Quartzite Content: none.
Other Contents: assorted volcanic material and limestone.
Condition: well rounded, weathered.
Size: 0.5" to 3"; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 84. (29°34'N, 104°38'W)
Gravels collected from the second terrace of the Rio Grande approximately 10 miles west of Ojinaga, Chihuahua.
Quartzite Content: purple, white, blue.
Other Contents: assorted volcanic material and limestone.
Condition: well rounded.
Size: 0.5" to 4"; Roundness: 0.9; Sphericity: 0.7 to 0.9.

Locality 85. (37°54'N, 106°57'W, Durango Sheet)
High surface (elevation 11,800 feet) approximately 5 miles northwest of Creede, Colorado. No gravels of any type were found.

Locality 86. (36°38'N, 105°27'W, Raton Sheet)
View northeast from top of cirque wall at Goose Lake approximately 5 miles south of Red River, New Mexico, reveals presence of an extremely dissected high surface trending north-south within the Sangre de Cristo Mountains.

Locality 87. (36°30'N, 105°41'W, Raton Sheet)
Flat surface extending west from Sangre de Cristo Mountains approximately 11 miles northwest of Taos, New Mexico. View north reveals the presence of an isolated basalt-capped remnant thought to be older than the basalts of the Taos Plateau.

Locality 88. (35°15'N, 108°15'W, Gallup Sheet)
Vicinity in the Zuni Mountains approximately 21 miles southeast of McGaffey, New Mexico, where an abundant amount of vein quartz crops out.

Locality 89 (34°49'N, 107°52'W, Socorro Sheet)
Northwest side of Cebollita Mesa approximately 17 miles due south of intersection of State Highway 117 and Interstate Highway 40. View to the northwest reveals that the Zuni Mountains are low and rounded even though they exhibit a structural displacement of approximately 14,000 feet.

Locality 90. (33°58'N, 105°55'W, Roswell Sheet)
North end of Tularosa basin approximately 24 miles due northwest of Carrizozo, New Mexico, along State Highway 10. No diagnostic gravels were found.

Locality 91. (34°01'N, 106°11'W, Socorro Sheet)
Vicinity of Chupadera Mesa approximately 20 miles southwest of Gran Quivera, New Mexico, along State Highway 41. No diagnostic gravels were found.

Locality 92. (33°51'N, 105°52'W, Roswell Sheet)
Flat surface on east side of Tularosa basin approximately 13 miles north of Carrizozo, New Mexico, just west of U. S. Highway 54. No diagnostic gravels were found.

Locality 93. (33°51'N, 105°22'W, Tularosa Sheet)
East side of the Jornada del Muerto along U. S. Highway 380, approximately 30 miles east of San Antonio, New Mexico. A wide north-south valley is present but no diagnostic gravels were found.

Locality 94. (33°51'N, 106°43'W, Tularosa Sheet)
West side of Jornada del Muerto along U. S. Highway 380, approximately 10 miles east of San Antonio, New Mexico. A wide north-south valley is present but no diagnostic gravels were found.

Locality 95. (32°23'N, 107°26'W, Las Cruces Sheet)
Low divide at the south end of the Sierra de Las Uvas-Goodsight Hills syncline approximately 15 miles due southeast of Nutt, New Mexico. No diagnostic gravels were found.

Locality 96. (31°52'N, 107°30'W, El Paso Sheet)
Low rounded escarpment approximately 9 miles east of Columbus, New Mexico. Investigations along the scarp failed to reveal the presence of a fault.

Locality 97. (31°52'N, 107°00'W, El Paso Sheet)
Low rounded escarpment along the east side of the East Potrillo Mountains approximately 26 miles due west of Canutillo, Texas. Investigations along the scarp failed to reveal the presence of a fault.

Locality 98. (31°52'N, 105°45'W, Carlsbad Sheet)
Southwest portion of Otero Mesa approximately 13 miles due southwest of Cox Ranch beside Shiloh Draw. Investigations atop high surfaces failed to reveal the presence of diagnostic gravels.

Locality 99. (32°23'N, 105°37'W, Carlsbad Sheet)
Northern portion of Otero Mesa approximately 5 miles due south of the Prather Ranch. Investigations atop high surfaces failed to reveal the presence of diagnostic gravels.

Locality 100. (32°06'N, 104°46'W, Carlsbad Sheet)
Summit region of Guadalupe Mountains approximately 3 miles due east of El Paso Gap, New Mexico. No diagnostic gravels were found.

Locality 101. (32°06'N, 104°32'W, Carlsbad Sheet)
Serpentine bends in Guadalupe Mountains approximately 24 miles due southwest of Carlsbad, New Mexico. No diagnostic gravels were found.

Locality 102. (30°47'N, 105°12'W, Marfa Sheet)
Small bolson present between the Quitman and Eagle Mountains approximately 8 miles due east of Indian Hot Springs Resort.

Locality 103. (29°51'N, 104°34'W, Presidio Sheet)
Numerous surfaces composed of locally derived material along the west side of the Chinati Mountains approximately 10 miles due southeast of Ruidosa, Texas.

Locality 104. (29°14′N, 103°42′W, Emory Peak Sheet)
Summit region of Mesa de Anguila approximately 6 miles due southeast of Lajitas, Texas. No remnant bolson fill or lag deposits were found.

Locality 105. (29°03′N, 103°09′W, Emory Peak Sheet)
Summit region of Mariscal Mountain approximately 20 miles due south of Panther Junction, Texas. No remnant bolson fill or lag deposits were found.

Locality 106. (29°07′N, 103°05′W, Emory Peak Sheet)
North flank of Sierra San Vicente approximately 6 miles northeast of Mariscal Mountain (Locality 105). View south reveals the presence of a canyon cut by the Rio Grande through the north flank of a large anticline.

Locality 107. (33°23′N, 108°55′W, Clifton Sheet)
High surfaces above San Francisco Creek valley approximately 3 miles east of Alma, New Mexico. These surfaces were traced south to the vicinity of Silver City, New Mexico, across present day Gila drainage.

Locality 108. (29°31′N, 104°47′W)
Canyon cut through Sierra Grande by the Rio Conchos and the alluvial surfaces along the east side of the mountain approximately 20 miles west of Ojinaga, Chihuahua.

Locality 109. (29°56′N, 106°50′W)
Valley of the Rio del Carmen approximately 10 miles east of Magon, Chihuahua.

Locality 110. (31°47′N, 106°31′W, El Paso Sheet)
El Paso Canyon on the northwest side of El Paso, Texas.

Locality 111. (26°00′N, 97°11′W, Brownsville Sheet)
Boca Chica, Texas, near the mouth of the Rio Grande approximately 25 miles east of Brownsville, Texas.

Locality 112. (37°47′N, 107°32′W, Durango Sheet)
Stony Pass in the San Juan Mountains approximately 8 miles east of Silverton, Colorado.

Locality 113. (37°44′N, 107°37′W, Durango Sheet)
The Rio Grande as a braided stream in the San Juan Mountains approximately 6 miles northeast of the Rio Grande Reservoir.

Locality 114. (37°43′N, 107°13′W, Durango Sheet)
The Needles Mountains approximately 10 miles due south of Silverton, Colorado.

Locality 115. (37°30′N, 105°44′W, Raton Sheet)
The Rio Grande Gorge due east of Taos, New Mexico.

Locality 116. (35°00′N, 106°43′W, Albuquerque Sheet)
The Rio Grande as a sand bed stream approximately 3 miles south of Albuquerque, New Mexico.

Locality 117. (29°23′N, 104°12′W, Presidio Sheet)
The Rio Grande in a heavily vegetated floodplain approximately 16 miles due southeast of Presidio, Texas.

Locality 118. (29°11′N, 103°38′W, Emory Peak Sheet)
The mouth of Santa Elena Canyon approximately 12 miles due southeast of Lajitas, Texas.

Locality 119. (36°24′N, 105°44′W, Raton Sheet)
Point approximately 2.5 miles south of the Rio Grande Gorge bridge where the Rio Grande Gorge abruptly widens west of Taos, New Mexico.

Locality 120. (36°24′N, 105°44′W, Raton Sheet)
Slump blocks within the Rio Grande Gorge, approximately 3 miles south of the Rio Grande Gorge bridge west of Taos, New Mexico.

Locality 121. (36°15′N, 105°47′W, Raton Sheet)
The Embudo constriction where the Rio Grande has cut a small gorge through the west end of the Picuris Range.

Locality 122. (26°30′N, 99°05′W, McAllen Sheet)
Small remnant where the Oligocene Reynosa Gravels are capped by a marine shale containing abundant oyster shells. The remnant is located east of Falcon Dam at the junction of U. S. Highway 83 and the road northwest to Falcon Heights, Texas.

REFERENCES

Albritton, C. C., Jr. and Smith, J. F., Jr. (1965) Geology of the Sierra Blanca area, Hudspeth County, Texas: U. S. Geological Survey Prof. Paper 479, 131 p.

Amsbury, David L. (1958) Geology of the Pinto Canyon area, Presidio County, Texas: Texas Bureau of Economic Geology, Geologic Quadrangle Map 22.

Anonymous (1961) Structural problems of the Rio Grande Trough in the Albuquerque country: New Mexico Geological Society, Guidebook for 12th Field Conference, Albuquerque country, p. 144-147.

Atwood, Wallace W. and Mather, Kirtley F. (1932) Physiography and Quaternary geology of the San Juan Mountains, Colorado: U. S. Geological Survey Prof. Paper 166, 176 p.

Bachman, George O. (1968) Geology of the Mockingbird Gap Quadrangle, Lincoln and Socorro Counties, New Mexico: U. S. Geological Survey Prof. Paper 594-J, 43 p.

Baker, Charles L. (1927) Exploratory geology of a part of southwestern Trans-Pecos Texas: Univ. of Texas Bull. 2745, 70 p.

Baldwin, Brewster (1956) The Santa Fe Group of north-central New Mexico: New Mexico Geological Society, Guidebook for 7th Field Conference, southeastern Sangre de Cristo Mountains, p. 115-121.

Baltz, Elmer H. (1965) Stratigraphy and history of Raton Basin and notes on San Luis Basin, Colorado-New Mexico: American Association of Petroleum Geologists Bull., v. 49, p. 2041-2075.

__________ (1967) Stratigraphy and regional tectonic implication of part of Upper Cretaceous and Tertiary rocks east-central San Juan Basin, New Mexico: U. S. Geological Survey Prof. Paper 552, 101 p.

Baltz, Elmer H. and Bachman, G. O. (1956) Notes on the geology of the southeastern Sangre de Cristo Mountains: New Mexico Geological Society, Guidebook for 7th Field Conference, southeastern Sangre de Cristo Mountains, p. 96-105.

Barker, Fred (1958) Precambrian and Tertiary geology of Las Tablas Quadrangle, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Bull. 45, p. 10-36.

Bingler, Edward C. (1968) Geology and mineral resources of Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull., v. 91, 158 p.

Bretz, J. H. (1949) Carlsbad Caverns and other caves of the Guadalupe Block, New Mexico: Jour. Geol., v. 57, p. 447-463.

Bryan, Kirk (1938) Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico *in* Rio Grande joint investigation in the upper Rio Grande Basin in Colorado, New Mexico, and Texas: National Resources Committee Washington, Regional Planning, pt. 6, p. 196-225.

Bryan, Kirk and McCann, Franklin T. (1936) Successive pediments and terraces of the upper Rio Puerco in New Mexico: Jour. Geol., v. 44, p. 145-172.

__________ (1938) The Ceja del Rio Puerco: A border feature of the Basin and Range Province in New Mexico: Jour. Geol., v. 46, p. 1-16.

Budding, A. J.; Pitrat, C. W.; and Smith, C. T. (1960) Geology of the southeastern part of the Chama Basin: New Mexico Geological Society, Guidebook for 11th Field Conference, Chama country, p. 78-92.

Burbank, W. S. and Goddard, E. N. (1937) Thrusting in Huerfano Park, Colorado, and related problems of orogeny in the Sangre de Cristo Mountains: Geol. Soc. Amer. Bull., v. 48, p. 931-976.

Cabot, Edward C. (1938) Fault border of the Sangre de Cristo Mountains north of Santa Fe, New Mexico: Jour. Geol., v. 46, p. 88-105.

Callaghan, Eugene (1953) Basin and Range structure in southwestern New Mexico: New Mexico Geological Society, Guidebook for 4th Field Conference, southwestern New Mexico, p. 116-117.

Church, Fermer S. and Hack, John T. (1939) An exhumed erosion surface in the Jemez Mountains, New Mexico: Jour. Geol., v. 47, p. 613-629.

Clark, Kenneth F. (1966) Geology of the Sangre de Cristo Mountains and adjacent areas, between Taos and Raton, New Mexico: New Mexico Geological Society, Guidebook for 17th Field Conference, Taos-Raton-Spanish Peaks country, p. 57-65.

Clark, Kenneth F. and Read, C. B. (1972) Geology and ore deposits of Eagle Nest area, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Bull. 94, 152 p.

Cooley, Maurice E. (1958) Physiography of the Black Mesa Basin area, Arizona: New Mexico Geological Society, Guidebook for 9th Field Conference, Black Mesa Basin, p. 146-149.

Cooley, Maurice E. and Akers, J. P. (1961) Late Cenozoic geohydrology in the central and southern parts of Navajo and Apache Counties, Arizona: Arizona Geological Society Digest, v. 4, p. 69-77.

Dane, C. H. and Bachman, G. O. (1965) Geologic map of New Mexico: U. S. Geological Survey.

Darton, N. H. (1916) Geology and underground water of Luna County, New Mexico: U. S. Geological Survey Bull. 618, 188 p.

DeBrine, D.; Spiegel, Z.; and Williams, D. (1963) Cenozoic sedimentary rocks of the Socorro Valley, New Mexico: New Mexico Geological Society, Guidebook for 14th Field Conference, Socorro region, p. 123-131.

Denny, Charles S. (1940) Tertiary geology of the San Acacia area, New Mexico: Jour. Geol., v. 48, p. 73-106.

——— (1940) Santa Fe Formation in the Española Valley, New Mexico: Geol. Soc. Amer. Bull., v. 51, p. 677-694.

——— (1941) Quaternary geology of the San Acacia area, New Mexico: Jour. Geol., v. 49, p. 225-260.

Dunham, Kingsley C. (1935) The geology of the Organ Mountains: New Mexico State Bureau of Mines and Mineral Resources Bull. 11, 272 p.

Evans, George C. (1963) Geology and sedimentation along the lower Rio Salado in New Mexico: New Mexico Geological Society, Guidebook for 14th Field Conference, Socorro region, p. 209-216.

Fitzsimmons, J. Paul (1955) Geomorphology of south-central New Mexico: New Mexico Geological Society, Guidebook for 6th Field Conference, south-central New Mexico, p. 105-107.

——— (1959) The structure and geomorphology of west-central New Mexico—A regional setting: New Mexico Geological Society, Guidebook for 10th Field Conference, west-central New Mexico, p. 112-116.

Galusha, Ted and Blick, J. C. (1971) Stratigraphy of the Santa Fe Group, New Mexico: Bull. of the American Museum of Natural History, v. 144, Article 1, 127 p.

Geddes, R. W. (1963) Geology of Little San Pasqual Mountain: New Mexico Geological Society, Guidebook for 14th Field Conference, Socorro region, p. 197-203.

Getzendaner, F. M. (1930) Geologic section of Rio Grande Embayment, Texas, and implied history: American Association of Petroleum Geologists, v. 14, part 2, p. 1425-1437.

Givens, David B. (1957) Geology of Dog Springs Quadrangle, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Bull. 58, 40 p.

Griggs, R. L. (1964) Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey Water-Supply Paper 1753, 107 p.

Groat, C. G. (1972) Presidio Bolson, Trans-Pecos Texas and adjacent Mexico: Geology of a desert basin aquifer system: Texas Bureau of Economic Geology, Report of Investigations 76, 46 p.

Hack, John T. (1942) Sedimentation and volcanism in the Hopi Buttes, Arizona: Geol. Soc. of Amer. Bull., v. 53, p. 335-372.

Harbour, R. L. (1972) Geology of the northern Franklin Mountains, Texas and New Mexico: U. S. Geological Survey Bull. 1298, 129 p.

Hawley, John W. (1965) Geomorphic surfaces along the Rio Grande Valley from El Paso, Texas to Caballo Reservoir, New Mexico: New Mexico Geological Society, Guidebook for 16th Field Conference, southwestern New Mexico II, p. 188-197.

——— (1969) Notes on the geomorphology and Late Cenozoic geology of northwestern Chihuahua: New Mexico Geological Society, Guidebook for 20th Field Conference, border region, p. 121, 142.

Hawley, John W.; Kottlowski, F. E.; Strain, W. S.; Seager, W. R.; King, W. E.; and LeMone, D. V. (1968) The Santa Fe Group in the south-central New Mexico border region *in* Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 52-76.

Hawley, John W. and Kottlowski, F. E. (1968) Quaternary geology of the south-central New Mexico border region *in* Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 89-115.

Hill, R. T. (1934) Running the canyons of the Rio Grande: Dallas Morning News, Dallas, Texas.

Hunt, Charles B. (1956) Cenozoic geology of the Colorado Plateau: U. S. Geological Survey Prof. Paper 279, 99 p.

Joesting, H. R.; Case, J. E.; and Cordell, L. E. (1961) The Rio Grande trough near Albuquerque, New Mexico: U. S. Geological Survey Prof. Paper 424-D, p. 282-286.

Johnson, R. B.; Dixon, G. H.; and Wanek, A. A. (1956) Late Cretaceous and Tertiary stratigraphy of the Raton Basin of New Mexico and Colorado: New Mexico Geological Society, Guidebook for 7th Field Conference, southeastern Sangre de Cristo Mountains, p. 122-135.

Johnson, R. B. (1959) Geology of the Huerfano Park area, and Custer Counties Colorado: U. S. Geological Survey Bull. 1071-D, p. 87-119.

Jones, Bill R. and Reaser, Donald F. (1970) Geology of southern Quitman Mountains, Hudspeth County, Texas: Texas Bureau of Economic Geology, Geologic Quadrangle Map 39.

Kelley, V. C. (1952) Tectonics of the Rio Grande depression of central New Mexico: New Mexico Geological Society, Guidebook for 3rd Conference, Rio Grande country, p. 93-103.

——— (1955a) Regional tectonics of south-central New Mexico: New Mexico Geological Society, Guidebook for 6th Field Conference, south-central New Mexico, p. 96-104.

__________ (1955b) Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. of New Mexico Publications in Geology 5, 87 p.

__________ (1956) The Rio Grande depression from Taos to Santa Fe: New Mexico Geological Society, Guidebook for 7th Field Conference, Sangre de Cristo Mountains, p. 109-114.

__________ (1957) General geology and tectonics of the western San Juan Mountains, Colorado: New Mexico Geological Society, Guidebook for 8th Field Conference, southwestern San Juan Mountains, p. 154-162.

Kelley, V. C. and Silver, Caswell (1952) Geology of the Caballo Mountains: Univ. of New Mexico Publications in Geology 4, 286 p.

Kelley, V. C. and McCleary, J. T. (1960) Laramide orogeny in south-central New Mexico. American Association of Petroleum Geologists Bull., v. 44, p. 1419-1420.

Kelley, V. C. and Thompson, Tommy B. (1964) Tectonics and general geology of the Ruidoso-Carrizozo region, central New Mexico: New Mexico Geological Society, Guidebook for 15th Field Conference, Ruidoso country, p. 110-121.

King, Phillip B. (1935) Outline of structural development of Trans-Pecos Texas: American Association of Petroleum Geologists Bull., v. 19, p. 221-261.

__________ (1948) Geology of the southern Guadalupe Mountains, Texas: U. S. Geological Survey Prof. Paper 215, 183 p.

King, Robert E. and Adkins, W. S. (1946) Geology of a part of the lower Conchos Valley, Chihuahua, Mexico: Geol. Soc. Amer. Bull., v. 57, p. 275-294.

Knowles, Doyle B. and Kennedy, R. A. (1956) Groundwater resources of the Hueco bolson, northwest of El Paso, Texas: U. S. Geological Survey Water-Supply Paper 1426, 186 p.

Kottlowski, Frank E. (1953) Tertiary-Quaternary sediments of the Rio Grande Valley in southern New Mexico: New Mexico Geological Society, Guidebook for 4th Field Conference, southwestern New Mexico, p. 144-148.

__________ (1958) Geologic history of the Rio Grande near El Paso: West Texas Geol. Soc. Guidebook, 1958 Field Trip, Franklin and Hueco Mountains, Texas, p. 46-54.

Kottlowski, F. E.; Cooley, M. E.; and Ruhe, R. V. (1965) Quaternary geology of the Southwest *in* The Quaternary of the United States: Princeton Univ. Press, Princeton, New Jersey, p. 287-298.

Larsen, E. S. and Cross, Whitman (1956) Geology and petrology of the San Juan region, southwestern Colorado; U. S. Geological Survey Prof. Paper 258, 303 p.

Lee, W. T. (1907) Water resources of the Rio Grande Valley in New Mexico: U. S. Geological Survey Water-Supply Paper 188, 59 p.

Leggat, E. R.; Lowry, M. E.; and Hood, J. W. (1963) Ground-water resources of the lower Mesilla Valley, Texas and New Mexico: U. S. Geological Survey Water-Supply Paper 1669-AA, 49 p.

Mather, Kirtley F. (1957) Geomorphology of the San Juan Mountains: New Mexico Geological Society, Guidebook for 8th Field Conference, southwestern San Juan Mountains, p. 102-108.

Maxwell, Ross A.; Lonsdale, John T.; Hazzard, Roy T.; and Wilson, John A. (1967) Geology of the Big Bend National Park, Brewster County, Texas: Univ. of Texas Publication 6711, 320 p.

Maxwell, Ross A. and Dietrich, J. W. (1972) Geologic summary of the Big Bend region *in* Geology of the Big Bend area, Texas: West Texas Geological Society, Publication 72-59, p. 11-33.

McKnight, John F. (1970) Geology of Bofecillos Mountains area, Trans-Pecos Texas: Texas Bureau of Economic Geology, Geologic Quadrangle Map 37.

Meinzer, O. E. (1911) Geology and water resources of Estancia Valley, New Mexico: U. S. Geological Survey Water-Supply Paper 275, 89 p.

Miller, John P.; Montgomery, Arthur; and Sutherland, Patrick K. (1963) Geology of part of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Mem. 11, 106 p.

Montgomery, Arthur (1956) Precambrian geology of the Picuris Range, north-central New Mexico: New Mexico Geological Society, Guidebook for 7th Field Conference, southeastern Sangre de Cristo Mountains, p. 145-146.

Muehlberger, William R. (1960a) Precambrian rocks of the Tusas Mountains, Rio Arriba County, New Mexico: New Mexico Geological Society, Guidebook for 11th Field Conference, Rio Chama country, p. 45-47.

__________ (1960b) Structure of the central Chama platform, northern Rio Arriba County, New Mexico: New Mexico Geological Society, Guidebook for 11th Field Conference, Rio Chama country, p. 103-109.

Powers, William E. (1935) Physiographic history of the upper Arkansas River valley and the Royal Gorge, Colorado: Jour. Geol., v. 43, p. 184-199.

Price, W. A. (1958) Sedimentology and Quaternary geomorphology of south Texas: Gulf Coast Association of Geological Societies Transactions, v. 8, p. 41-75.

Ray, Louis L. and Smith, J. Fred, Jr. (1941) Geology of the Moreno Valley, New Mexico: Geol. Soc. Amer. Bull., v. 52, p. 177-210.

Reeves, C. C., Jr. (1965) Fluvial Lake Palomas, northwestern Chihuahua and Pleistocene geologic history of south-central New Mexico: New Mexico Geological Society, Guidebook for 16th Field Conference, southwestern New Mexico II, p. 199-203.

__________ (1969) Fluvial Lake Palomas northwestern Chihuahua, Mexico: New Mexico Geological Society, Guidebook for 20th Field Conference, border region, p. 143-154.

Reiche, Parry (1949) Geology of the Manzanita and north Manzano Mountains, New Mexico: Geol. Soc. Amer. Bull., v. 60, p. 1183-1212.

Renick, B. C. (1931) Geology and ground-water resources of western Sandoval County, New Mexico: U. S. Geological Survey Water-Supply Paper 620, 115 p.

Roberson, G. D. (1973) The geomorphology of the Canadian River basin: Unpublished Master's Thesis, Baylor University, 156 p.

Ross, C. S.; Smith, R. L.; and Bailey, R. A. (1961) Outline of the geology of the Jemez Mountains, New Mexico: New Mexico Geological Society, Guidebook for 12th Field Conference, Albuquerque country, p. 139-143.

Ruhe, R. V. (1962) Age of the Rio Grande Valley in southern New Mexico: Jour. Geol., v. 70, p. 151-167.

Sanford, Allen R. (1963) Seismic activity near Socorro: New Mexico Geological Society, Guidebook for 14th Field Conference, Socorro region, p. 146-151.

Sayre, A. N. and Livingston, P. (1945) Ground-water resources of the El Paso area, Texas: U. S. Geological Survey Water-Supply Paper 919, 190 p.

Seager, William R.; Hawley, John W.; and Clemmons, Russell E. (1971) Geology of San Diego Mountain area, Doña Ana County, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Bull. 97, 38 p.

SEAGER, WILLIAM R. and HAWLEY, JOHN W. (1973) Geology of Rincon Quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 101, 42 p.

SIEBENTHAL, C. T. (1910) Geology and water resources of the San Luis Valley, Colorado: U. S. Geological Survey Water-Supply Paper 240, 28 p.

SMITH, CLAY T. (1963) Preliminary notes on the geology of part of the Socorro Mountains, Socorro County, New Mexico: New Mexico Geological Society, Guidebook for 14th Field Conference, Socorro region, p. 185-196.

SMITH, HAROLD T. U. (1938) Tertiary geology of the Abiquiu Quadrangle, New Mexico: Jour. Geol., v. 46, p. 933-965.

SPIEGEL, ZANE (1961) Late Cenozoic sediments of the lower Jemez River region: New Mexico Geological Society, Guidebook for 12th Field Conference, Albuquerque country, p. 132-138.

STARK, J. T. and DAPPLES, E. C. (1946) Geology of the Los Piños Mountains, New Mexico: Geol. Soc. Amer. Bull., v. 57, p. 1121-1172.

STEARNS, CHARLES E. (1943) The Galisteo Formation of north-central New Mexico: Jour. Geol., v. 51, p. 301-319.

__________ (1953) Tertiary geology of the Galisteo-Tonque area, New Mexico: Geol. Soc. Amer. Bull., v. 64, p. 459-508.

STRAIN, W. S. (1959) Blancan mammalian fauna from Rio Grande Valley, Hudspeth County, Texas: Geol. Soc. Amer. Bull., v. 70, p. 375-378.

__________ (1965) Early Pleistocene history of southern part of Mesilla bolson: New Mexico Geological Society, Guidebook for 16th Field Conference, southwestern New Mexico II, p. 243.

__________ 1969) Late Cenozoic strata of the El Paso-Juarez area: New Mexico Geological Society, Guidebook for 20th Field Conference, border region, p. 155-157.

__________ (1970) Late Cenozoic bolson integration in the Chihuahua tectonic belt *in* The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society and the Univ. of Texas at Austin, 76 p.

THOMAS, R. G. (1972) The geomorphic evolution of the Pecos River system: Baylor Geological Studies Bull. 22, 40 p.

THOMPSON, SAM (1955) Geology of the Fra Cristobal Range: New Mexico Geological Society, Guidebook for 6th Field Conference, south-central New Mexico, p. 155-157.

THORNBURY, W. D. (1965) Regional geomorphology of the United States: John Wiley, 609 p.

TIGHT, W. G. (1905) Bolson plains of the Southwest: American Geologist, v. 36, p. 271-284.

TONKING, W. H. (1957) Geology of the Puertecito Quadrangle, Socorro County, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Bull. 41, 67 p.

TROWBRIDGE, A. C. (1926) Reynosa Formation in lower Rio Grande region, Texas: Geol. Soc. Amer. Bull., v. 37, p. 455-462.

__________ (1932) Tertiary and Quaternary geology of the lower Rio Grande region, Texas: U. S. Geological Survey Bull. 837, 260 p.

TWISS, P. C. (1970) Cenozoic history of Rim Rock country, Trans-Pecos Texas *in* The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society and the Univ. of Texas at Austin, p. 50-52.

UDDEN, J. A.; BAKER, C. L.; and BÖSE, EMIL (1916) Review of the geology of Texas: Texas Bureau of Economic Geology, Publication 44, p. 21-22.

UNDERWOOD, JAMES R., JR. (1963) Geology of Eagle Mountains and vicinity, Hudspeth County, Texas: Texas Bureau of Economic Geology, Geologic Quadrangle Map 26.

U. S. AIR FORCE AERONAUTICAL CHART AND INFORMATION CENTER (1970) Operational Navigational Chart ONCH-23: U. S. Air Force.

U. S. GEOLOGICAL SURVEY (1955) Santa Fe: U. S. Geological Survey Topographic Map NI-13.

__________ (1966) Pikes Peak: U. S. Geological Survey Topographic Map NJ-13.

UPSON, J. E. (1939) Physiographic subdivisions of the San Luis Valley, southern Colorado: Jour. Geol., v. 47, p. 721-736.

VAN ALSTINE, RALPH E. (1968) Tertiary trough between the Arkansas and San Luis Valleys, Colorado: U. S. Geological Survey Prof. Paper 600-C, p. 158-160.

WILSON, JOHN A. (1970) Vertebrate biostratigraphy of Trans-Pecos Texas and northern Mexico *in* The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society and the Univ. of Texas at Austin, p. 54-55.

WILLARD, M. E. (1959) Tertiary stratigraphy of northern Catron County, New Mexico: New Mexico Geological Society, Guidebook for 10th Field Conference, west-central New Mexico, p. 92-111.

WRIGHT, H. E., JR. (1946) Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geol. Soc. Amer. Bull., v. 57, p. 383-456.

__________ (1956) Origin of the Chuska Sandstone, Arizona-New Mexico: A structural and petrographic study of a Tertiary aeolian sediment: Geol. Soc. of Amer. Bull., v. 67, p. 413-434.

ZINN, R. L. (1953) Basin deposits of the Presidio area: West Texas Geological Society, Guidebook for Spring Field Trip, Chinati Mountains, p. 52-54.

INDEX

BAYLOR GEOLOGICAL PUBLICATIONS*

Baylor Geological Studies

1. Holloway, Harold D. (1961) The Lower Cretaceous Trinity aquifers, McLennan County, Texas: Baylor Geological Studies Bull. No. 1 (Fall). Out of print.
2. Atlee, William A. (1962) The Lower Cretaceous Paluxy Sand in central Texas: Baylor Geological Studies Bull. No. 2 (Spring). $1.00 per copy. Out of print.
3. Henningsen, E. Robert (1962) Water diagenesis in Lower Cretaceous Trinity aquifers of central Texas: Baylor Geological Studies Bull. No. 3 (Fall). $1.00 per copy. Out of print.
4. Silver, Burr A. (1963) The Bluebonnet Member, Lake Waco Formation (Upper Cretaceous), central Texas—A lagoonal deposit: Baylor Geological Studies Bull. No. 4 (Spring). $1.00 per copy.
5. Brown, Johnnie B. (1963) The role of geology in a unified conservation program, Flat Top Ranch, Bosque County, Texas: Baylor Geological Studies Bull. No. 5 (Fall). $1.00 per copy. Out of print.
6. Beall, Arthur O., Jr. (1964) Stratigraphy of the Taylor Formation (Upper Cretaceous), east-central Texas: Baylor Geological Studies Bull. No. 6 (Spring). $1.00 per copy.
7. Spencer, Jean M. (1964) Geologic factors controlling mutation and evolution—A review: Baylor Geological Studies Bull. No. 7 (Fall). $1.00 per copy. Out of print.

Urban geology of Greater Waco. A series on urban geology in cooperation with Cooper Foundation of Waco.

8. Part I: Geology (1965) Geology and urban development by Peter T. Flawn; Geology of Waco by J. M. Burket: Baylor Geological Studies Bull. No. 8 (Spring). $1.00 per copy.
9. Part II: Soils (1965) Soils and urban development of Waco by W. R. Elder: Baylor Geological Studies Bull. No. 9 (Fall). $1.00 per copy.
10. Part III: Water (1966) Surface waters of Waco by Jean M. Spencer: Baylor Geological Studies Bull. No. 10 (Spring). $1.00 per copy.
11. Part III: Water (1966) Subsurface waters of Waco by H. D. Holloway: Baylor Geological Studies Bull. No. 11 (Fall). $1.00 per copy.
12. Part IV: Engineering (1967) Geologic factors affecting construction in Waco by R. G. Font and E. F. Williamson: Baylor Geological Studies Bull. No. 12 (Spring). $1.00 per copy.
13. Part V: Socio-Economic Geology (1967) Economic geology of Waco and vicinity by W. T. Huang; Geology and community socio-economics—A symposium coordinated by R. L. Bronaugh: Baylor Geological Studies Bull. No. 13 (Fall). $1.00 per copy.
14. Part VI: Conclusions (1968) Urban geology of greater Waco—Summary and recommendations by Editorial Staff: Baylor Geological Studies Bull. No. 14 (Spring). $1.00 per copy.

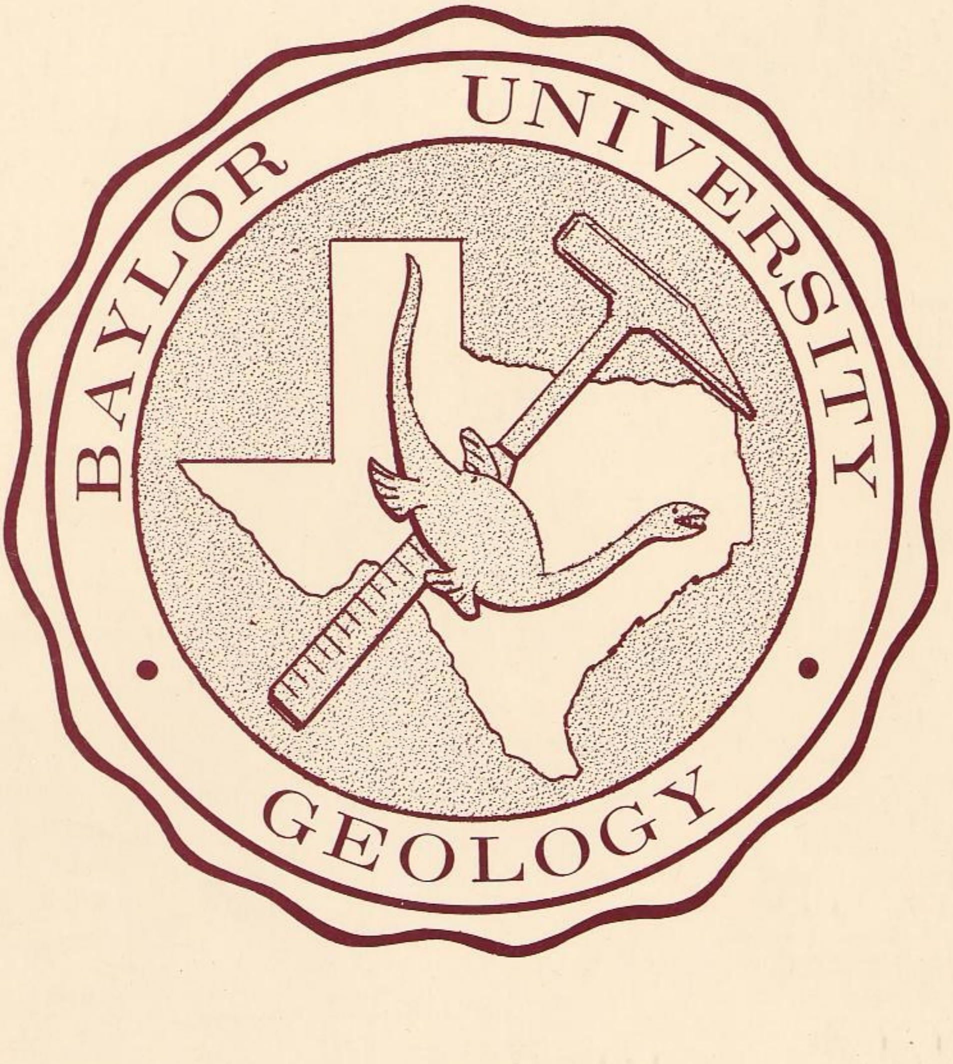
15. Boone, Peter A. (1968) Stratigraphy of the basal Trinity (Lower Cretaceous) sands, central Texas: Baylor Geological Studies Bull. No. 15 (Fall). $1.00 per copy.
16. Proctor, Cleo V. (1969) The North Bosque watershed, Inventory of a drainage basin: Baylor Geological Studies Bull. No. 16 (Spring). $1.00 per copy.
17. LeWand, Raymond L., Jr. (1969) The geomorphic evolution of the Leon River system: Baylor Geological Studies Bull. No. 17 (Fall). $1.00 per copy.
18. Moore, Thomas H. (1970) Water geochemistry, Hog Creek basin, central Texas: Baylor Geological Studies Bull. No. 18 (Spring). $1.00 per copy.
19. Mosteller, Moice A. (1970) Subsurface stratigraphy of the Comanchean Series in east central Texas: Baylor Geological Studies Bull. No. 19 (Fall). $1.00 per copy.
20. Byrd, Cilfford Leon (1971) Origin and history of the Uvalde Gravel of central Texas: Baylor Geological Studies Bull. No. 20 (Spring). $1.00 per copy. Out of print.
21. Brown, Thomas E. (1971) Stratigraphy of the Washita Group in central Texas: Baylor Geological Studies Bull. No. 21 (Fall). $1.00 per copy.
22. Thomas, Ronny G. (1972) The geomorphic evolution of the Pecos River system: Baylor Geological Studies Bull. No. 22 (Spring). $1.00 per copy.
23. Roberson, Dana Shumard (1972) The paleoecology, distribution and significance of circular bioherms in the Edwards Limestone of central Texas: Baylor Geological Studies Bull. No. 23 (Fall). $1.00 per copy.
24. Epps, Lawrence Ward (1973) The geologic history of the Brazos River: Baylor Geological Studies Bull. No. 24 (Spring). $1.00 per copy.
25. Bain, James S. (1973) The nature of the Cretaceous-pre Cretaceous contact in north-central Texas: Baylor Geological Studies Bull. No. 25 (Fall). $1.00 per copy.
26. Davis, Keith W. (1974) Stratigraphy and depositional environments of the Glen Rose formation, north central Texas: Baylor Geological Studies Bull. No. 26 (Spring). $1.00 per copy.
27. Baldwin, Ellwood E. (1974) Urban geology of the Interstate Highway 35 growth corridor between Belton and Hillsboro, Texas: Baylor Geological Studies Bull. 27 (Fall). $1.00 per copy.
28. Allen, Peter M. (1975) Urban geology of the Interstate Highway 35 growth corridor from Hillsboro to Dallas County, Texas: Baylor Geological Studies Bull. No. 28 (Spring). $1.00 per copy.
29. Belcher, Robert C. (1975) The geomorphic evolution of the Rio Grande: Baylor Geological Studies Bull. No. 29 (Fall). $1.00 per copy.

Baylor Geological Society

101. Type electric log of McLennan County. 1"-100'; 1"-50'-$2.00.
102. Reptile charts—Comparison of flying and swimming reptiles. $0.10 each. Comparison of the dinosaurs. $0.10 each.
103-114. Out of print. For titles see earlier Baylor Geological Studies Bulletins.
115. Why teach geology? A discussion of the importance and cost of teaching geology in high schools, junior colleges and smaller 4-year institutions. Free upon request. 27 pp. (1961).
116. Popular geology of central Texas: The hill country—McLennan, Coryell and Bosque counties, 1963. $1.00 per copy. Revised. Out of print.
117. Shale environments of the mid-Cretaceous section, central Texas—A field guide. Leaders—Beall, A. O.; Johnson, C.F.; and Silver, B. A.; 1964. $2.00 per copy.
118. Geology and the city of Waco—A guide to urban problems, 1964. $2.00 per copy. Out of print.
119. The Bosque watershed. Geology of the Bosque River basin, 1966. Out of print.
120. Valley of the giants. Lower Comanchean section of the Paluxy River basin, 1967. Out of print.
121. The Hog Creek watershed. Environmental study of a watershed, 1968. $1.00 per copy. Out of print.
122. The Waco region. Geologic section of the area around Lake Waco, McLennan County, Texas, 1968. $1.00 per copy. Out of print.
123. Mound Valley. A physiographic study of central Texas, 1969. Out of print.
124. The Bosque watershed (revised). Geology of the Bosque River basin, 1969. Out of print.
125. Lampasas Cut Plain. Geomorphic evolution of the Lampasas Cut Plain, southwest of Gatesville, 1970. $1.00 per copy. Out of print.
126. Middle Bosque Basin. Geology of the Middle Bosque drainage basin, 1970. $1.00 per copy. Out of print.
127. Thee Guidebook. Geology of the Trinity Group in the type area. A professional level guide, 1970. $4.00 per copy.
129. Urban Geology, 1972. $6.00 per copy.
132. Valley of the giants (revised). Lower Comanchean section of the Paluxy River basin, 1973. $1.50 per copy.
133. Whitney Reservoir. Geology of the Whitney Reservoir Area, 1974. $1.50 per copy.
134. The Black and Grand Prairies. A physiographic study of two central Texas Prairies, 1974. $1.50 per copy.
137. Structural geology of central Texas. A professional level guidebook. $6.00 per copy.

---

*Publications available from Baylor Geological Studies or Baylor Geological Society, Baylor University, Waco, Texas 76703.
Texas residents add five cents per dollar for state tax.


BAYLOR UNIVERSITY
GEOLOGY