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EVOLUTION OF THE RIO GRANDE RIFT IN THE SOCORRO AND LAS CRUCES AREAS

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INTRODUCTION

Much controversy in recent years surrounding the Rio Grande rift has been caused by failure to look beyond its present geomorphic expression at its past history. Specifically, when did rifting begin? ... What were the early basins and uplifts like? ... Where were they? ... How big? ... How much volcanism and of what kind? ... What were the main source areas for the basin-fill sediments? ... Under what conditions were the sediments transported and deposited? ... Was there a culmination of uplift and faulting? ... If so, when? ... Has the type or rates of sedimentation and volcanism changed with time? ... When did integrated drainage begin and how has it evolved? ... If the rift was different in the past, what might it be like in the future? The answers to these questions, and to others unperceived, are recorded in the basin-fill deposits. To read this record requires knowledge of the sequence and distribution of rock types on the uplifts in order to work out the sequence and facies of deposits in the basins which, in turn, is necessary to unravel the structural history of the uplifts. In other words, a circuitous and often repetitious path of investigation, from basin margin to basin fill and back again, is necessary to understand the whole.

The purpose of this paper is to document the sequential development of the Rio Grande rift in two areas where the basin-fill deposits are well-exposed and where extensive field studies have provided the necessary stratigraphic detail. The similar geologic histories of these two areas (interpreted independently until our collaboration on this paper) gives us confidence that the data may be of wider applicability. We have used time subdivisions for the Cenozoic as given by Harland and others (1964); they are plotted on Figure 9.

We wish to acknowledge the work of our colleagues without whom this paper could not have been written. Russell E. Clemons, John W. Hawley, and Frank E. Kottlowski have provided major contributions to our understanding of the Las Cruces area. Thesis investigations by R. B. Blakestad, D. M. Brown, J. E. Bruning, C. Burton, R. M. Chamberlin, E. G. Deal, D. A. Krewedl, D. B. Simon, E. J. Spradlin, W. H. Wilkinson, and T. M. Woodward aided greatly in unraveling the late Cenozoic history of the Socorro-Magdalena area. G. 0. Bachman and J. W. Hawley provided stimulating discussions of the late Cenozoic sedimentary and geomorphic features and improved the manuscript. W. E. Elston read parts of the manuscript and provided data and helpful advice on the Datil-Mogollon volcanic field. P. E. Damon was a catalyst for the section on Transitional Volcanism from a discussion at the 1974 Geological Society of America Meeting in Flagstaff and through recent discussions of unpublished data. We are especially indebted to J. W. Stinnett, Jr., for permission to use unpublished chemical and isotopic data. To all of these people we express our gratitude; any errors in interpretation, however, are solely the responsibility of the authors.

THE PIONEERING WORK OF KIRK BRYAN

Any discussion of the Rio Grande rift should begin with the work of Kirk Bryan, his students, and the masterful paper published by Bryan in 1938. This paper, buried in an obscure hydrologic report, has not received the attention it merits. Bryan coined the term "Rio Grande depression" for the series of structural basins through which the Rio Grande flows from the San Luis Valley of Colorado to El Paso, Texas (Fig. 1). Recognizing the similarities in age and origin of the basin-fill deposits, Bryan assigned them to the Santa Fe Formation (since raised to group status by Baldwin, 1963).

Bryan recognized that the Rio Grande rift had evolved over a considerable period of geologic time as is evident from the following excerpts from his 1938 paper:

> 1) "The end of the great volcanic period ... [middle Tertiary] ... merged into the beginning of the series of movements by which the Rio Grande depression was formed, ..." (p. 205)
>
> 2) "It appears, however, that initial basins were formed, into which streams carried gravel and sand derived from the erosion of the previously extruded lavas and into which tuffs from the still lingering volcanoes were blown or washed by the streams, and that these deposits were deeply eroded and in places faulted before the succeeding Santa Fe formation was deposited." (p. 205)
>
> 3) "... deformation is evident and has become one of the principal criteria for distinguishing the formation ... [lower Santa Fe Group] ... from the Quaternary sand and gravel." (p. 209)
>
> 4) "Most of the existing mountains and highland areas were also mountainous in Santa Fe time. They were reduced in Pliocene time ... [now known to be Miocene] ... and were rejuvenated to form the present ranges. Other mountains appear to have been new-born ... [very late Cenozoic, but pre-Pleistocene] ... as, for example, the Socorro-Lemitar uplift. So far as present information goes, all the ranges, with the exception of the Magdalena Mountains and the part of the Sangre de Cristo Range north of Sierra Blanca, owe their present position to the post ... [lower] ... Santa Fe uplift." (p. 209)
>
> 5) "The Rio Grande depression is a structural depression consisting of minor basins and reentrants and having a border of diverse types that merges to the south into a number of similar basins. The structural depression is only in part coincident with the present course of the river." (p. 215).

Some of Bryan's statements need to be modified in light of

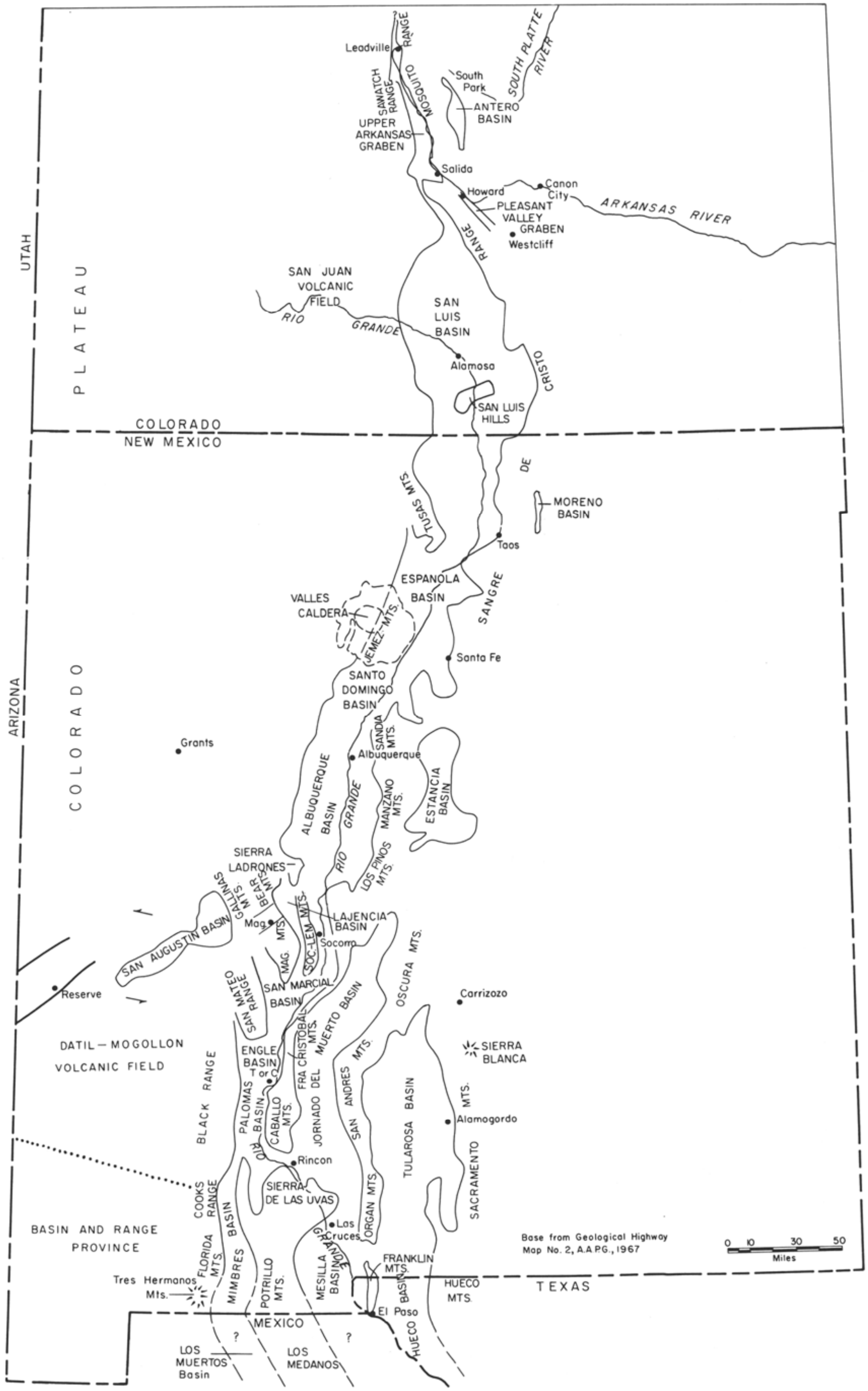

Figure 1. Generalized map of the Rio Grande rift (after Chapin, 1971a).

recent data (as we have done in brackets), but they clearly demonstrate that 37 years ago his perception of the Rio Grande rift was that of a dynamic structure, changing with time.

PRERIFT GEOLOGIC SETTING

The "Rio Grande depression" is an intracratonic continental rift superimposed during the late Cenozoic upon a north-trending tectonic belt that was intensely deformed during the late Paleozoic (Ancestral Rocky Mountains) and again during the Laramide. Figure 2 shows how well these three periods of deformation are superimposed and how previous deformations influenced later ones. For example, the change in trend from north-northeast to north-northwest in southern Colorado for all three deformations is impressive. The Rio Grande rift is essentially a "pull-apart" structure caused by tensional fragmentation of western North America. Obviously, a plate subjected to strong tensional forces will begin to fragment along major pre-existing zones of weakness and the developing "rifts" will reflect the geometry of the earlier structures.

The Laramide (Late Cretaceous to middle Eocene) uplifts were worn down by erosion nearly as fast as they rose and the detritus filled adjacent synclinal downwarps coincident with subsidence. Then, in middle Eocene (beginning about 45-50 m.y. ago), relaxation of compressional stresses to an essentially neutral stress field (Chapin, 1974a) brought an end to tectonic rejuvenation of topographic relief; erosion rapidly planed the topography forming an erosion surface of low relief and regional extent (Epis and Chapin, 1973, 1975). It was upon this surface that voluminous eruptions of calc-alkalic magmas (beginning at about the Eocene-Oligocene boundary, 37 m.y. ago) constructed the Datil-Mogollon, San Juan, and other volcanic fields which flank the Rio Grande rift. Widespread eruption of latite-andesite magmas formed breccia complexes and alluvial aprons, such as the Conejos, Spears, and Rubio Peak Formations, which were capped 5 to 7 m.y. later by extensive ash-flow sheets. The resultant ignimbrite shields (Macdonald, 1972, p. 268) remained essentially undeformed, except in the immediate vicinity of cauldrons, until the onset of regional extension in late Oligocene time.

BEGINNING OF REGIONAL EXTENSION

The timing and nature of the transition from middle Cenozoic epeirogeny to late Cenozoic extension is controversial; each writer's viewpoint is strongly colored by events in the area or areas in which he has worked. The similarity of this transition in the Socorro and Las Cruces areas encouraged us to write this paper in the belief that we could provide a well-documented case history with which other areas could be compared.

Socorro Area

Early rift structures in the Socorro area are best known in and around the Magdalena mining district where the western margin of the rift is relatively well-exposed and where several hundred square miles of detailed mapping have been conducted by C. E. Chapin and the graduate students acknowledged in the introduction. Here, the first evidence of regional extension consists of numerous normal faults of average trend N10° W distributed across a belt as much as 17 mi in width (Figs. 3, 4, 5). This extensional fault zone apparently broke the roof of an Oligocene batholith and allowed the intrusion of numerous stocks and dikes (Chapin and others, 1974). Radiometric dating of plutons and intruded ash-flow sheets has bracketed the extensional faulting as occurring after 30 to 31 m.y. but prior to 28 m.y. The critical dates are:

Potato Canyon Tuff 30.3 ± 1.6 m.y.
The youngest major ash-flow unit involved in intrusion-alteration-mineralization events in the Magdalena district and dated by E. I. Smith (in press) by the fission-track method. This date is in good agreement with a 31.8 ± 1.7 m.y. fission-track date on the underlying A-L Peak Tuff (Smith, op. cit.) and a 31.7 m.y. average of three K-Ar dates (Burke and others, 1963; Weber and Bassett, 1963; Weber, 1971) on the Hells Mesa Tuff (restricted sense, Chapin, 1974b) whose eruption preceded the A-L Peak.

Nitt stock Weber and Bassett (1963); Weber (1971)	(K-Ar, biotite)	28.0 ± 1.4 m.y.
Anchor Canyon stock Weber and Bassett (1963); Weber (1971)	(K-Ar, biotite)	28.3 ± 1.4 m.y.
Water Canyon stock Chapin (new date)	(K-Ar, biotite)	30.5 ± 1.2 m.y.
Monzonite dike N.E. of Riley Chapin (new date)	(K-Ar, biotite)	28.1 ± 1.2 m.y.

The extensional fault zone and its associated intrusions are conspicuous on geologic maps of the Kelly mining district (Loughlin and Koschmann, 1942; Blakestad, 1974), Lucero uplift (Kelley and Wood, 1946), Puertecito Quadrangle (Tonking, 1957), New Mexico (Dane and Bachman, 1965), southern Bear Mountains (Brown, 1972), Council Rock district (Chamberlin, 1974), Cat Mountain-Tres Montosas area (Wilkinson, 1974) central Magdalena Mountains (Krewedl, 1974), Granite Mountain area (Chapin, unpub. map), and on the Tectonic Map of the Rio Grande Region (in pocket). Closely spaced, north-trending faults and dikes of the extensional fault zone are also visible on the Skylab photo (Fig. 4) where the Rio Salado has exposed pre-Oligocene rocks between the Ladron and Bear Mountains.

After the initial period of extensional faulting and intrusion, the Magdalena area was subjected to erosion for 3 or 4 million years before the earliest known bolson-type sediments were deposited. During this interval, erosion removed several hundred feet of ash-flow tuffs and andesite flows and breached the Hale Well stock and the Magdalena composite pluton (Fig. 3), both of which had intruded the A-L Peak Tuff (Deal and Rhodes, in press), probably within 1,500 ft of the earth's surface. The outflow facies of the Potato Canyon Tuff (Deal and Rhodes, op. cit.) was largely stripped from the area north of U.S. Highway 60, although several hundred feet of these tuffs were preserved in the Lemitar Mountains (Woodward, 1973), the Joyita Hills (Spradlin, 1975), the Chupadera Mountains, and in the central Magdalena Mountains. Volcanic rocks tilted by intrusion and/or normal faulting were eroded to hogbacks. The detritus, however, was apparently removed from the area by through-flowing streams as no record of sedimentation has been found.

Fanglomerates and interbedded lava flows of intermediate composition along the east side of the Milligan Gulch graben, 4 mi west of Magdalena, yield the first record of bolson sedimentation. Simon (1973) informally designated these deposits the unit of Arroyo Montosa (Fig. 3) and subdivided them into a volcanic facies, consisting of two or more flows aggregating at least 100 ft in thickness, and a conglomerate facies, consisting

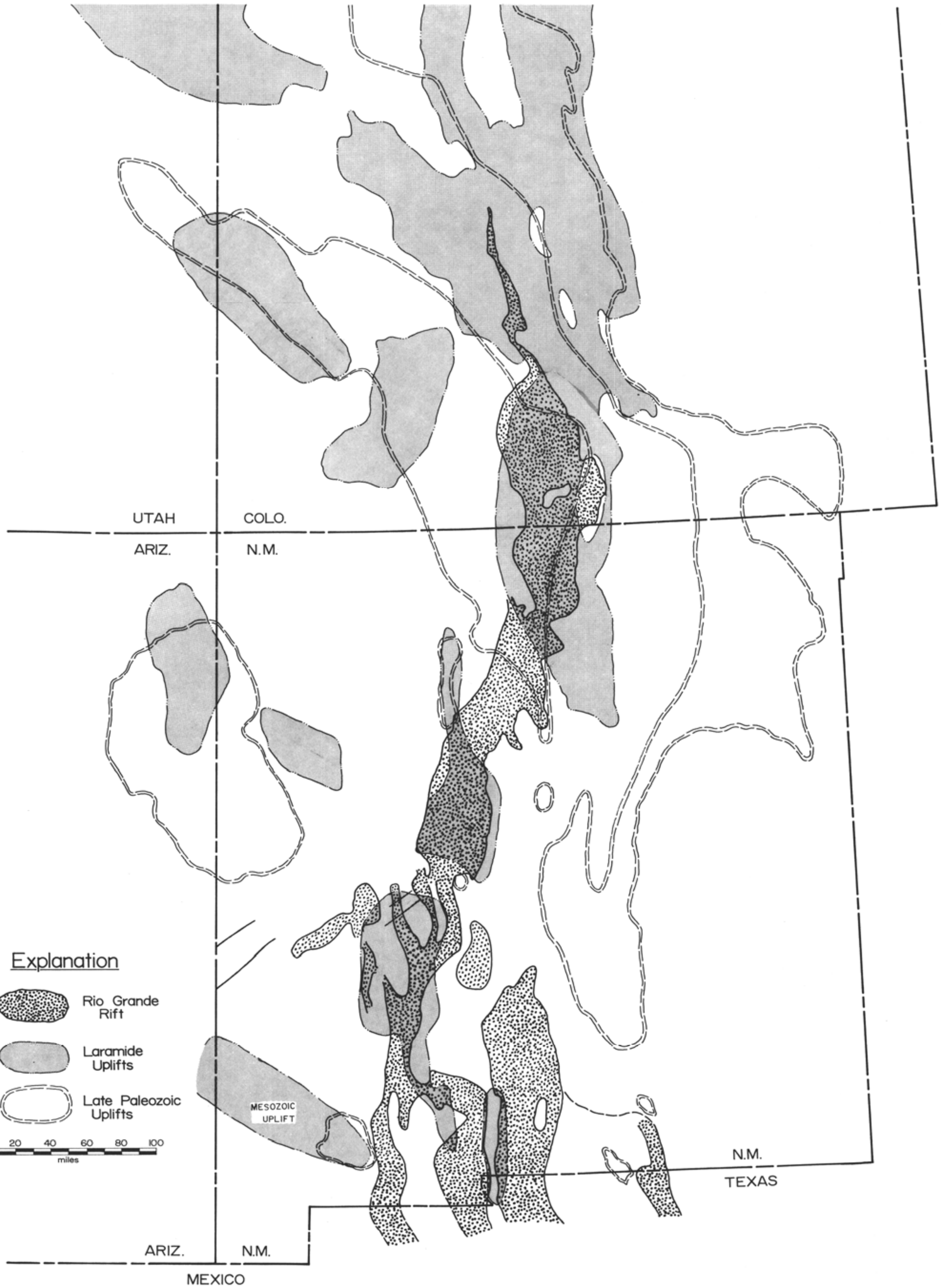

Figure 2. Map showing overprinting of the Rio Grande rift on structures of Laramide and late Paleozoic age. Data compiled from Mallory (1960), Eardley (1962), Kottlowski (1960), Elston (1958), Chapin and Seager (unpub.).

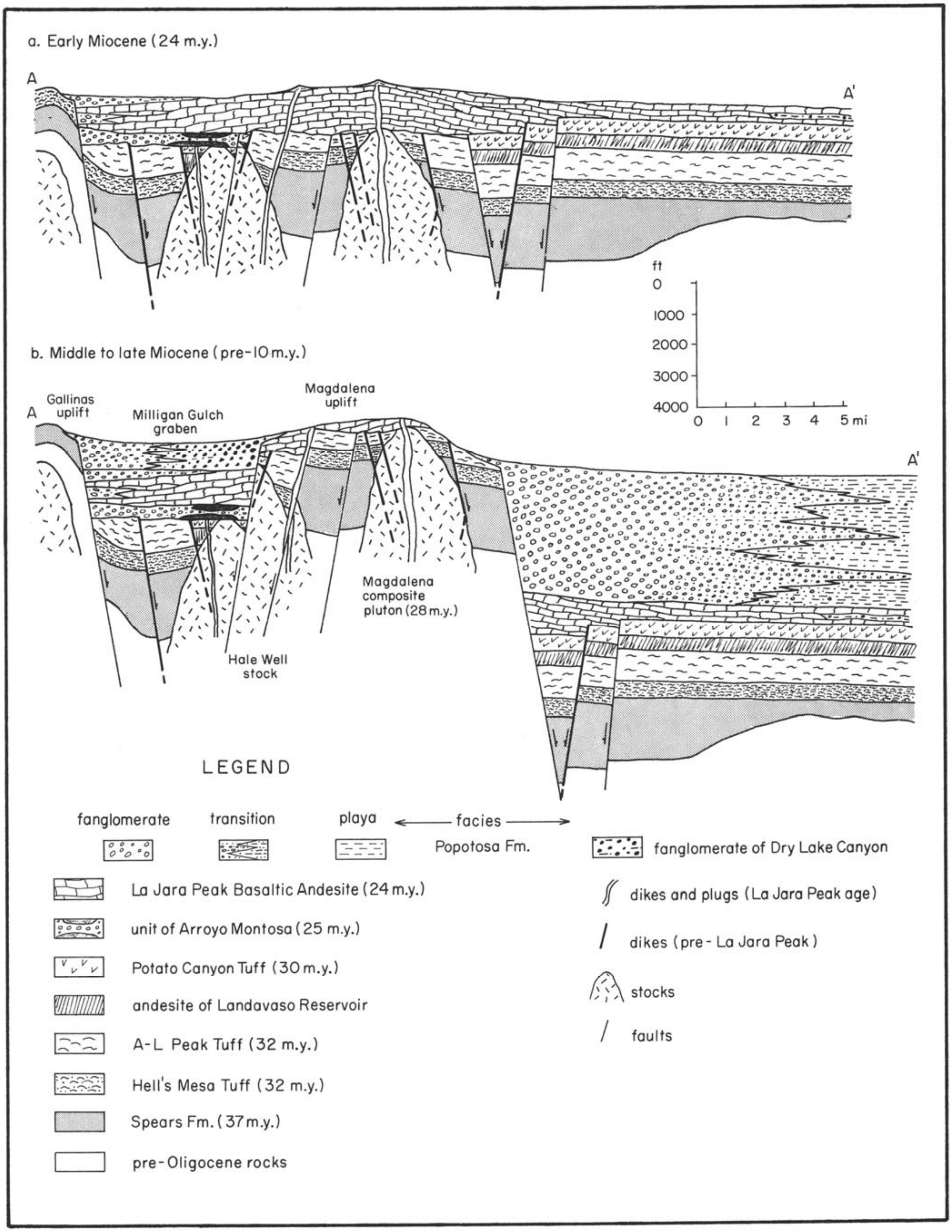

Figure 3. Schematic cross-sections of the Popotosa basin from the Gallinas Range to the present Lemitar Range (not shown). The approximate line of section (A-A') is shown on Figure 5.

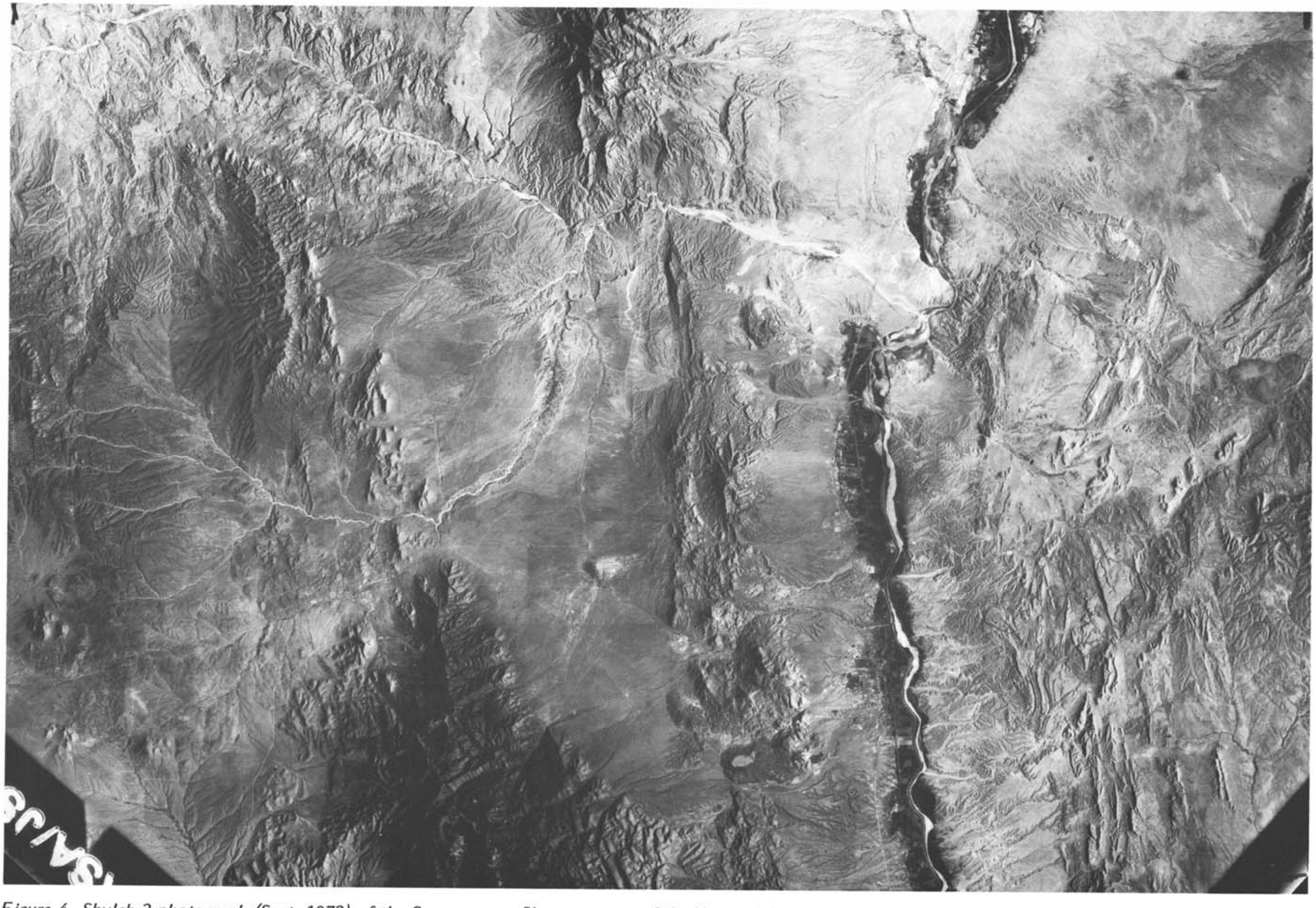

Figure 4. Skylab 3 photograph (Sept. 1973) of the Socorro area. Photo courtesy of the National Aeronautics and Space Administration and the Technology Application Center, Albuquerque, New Mexico.

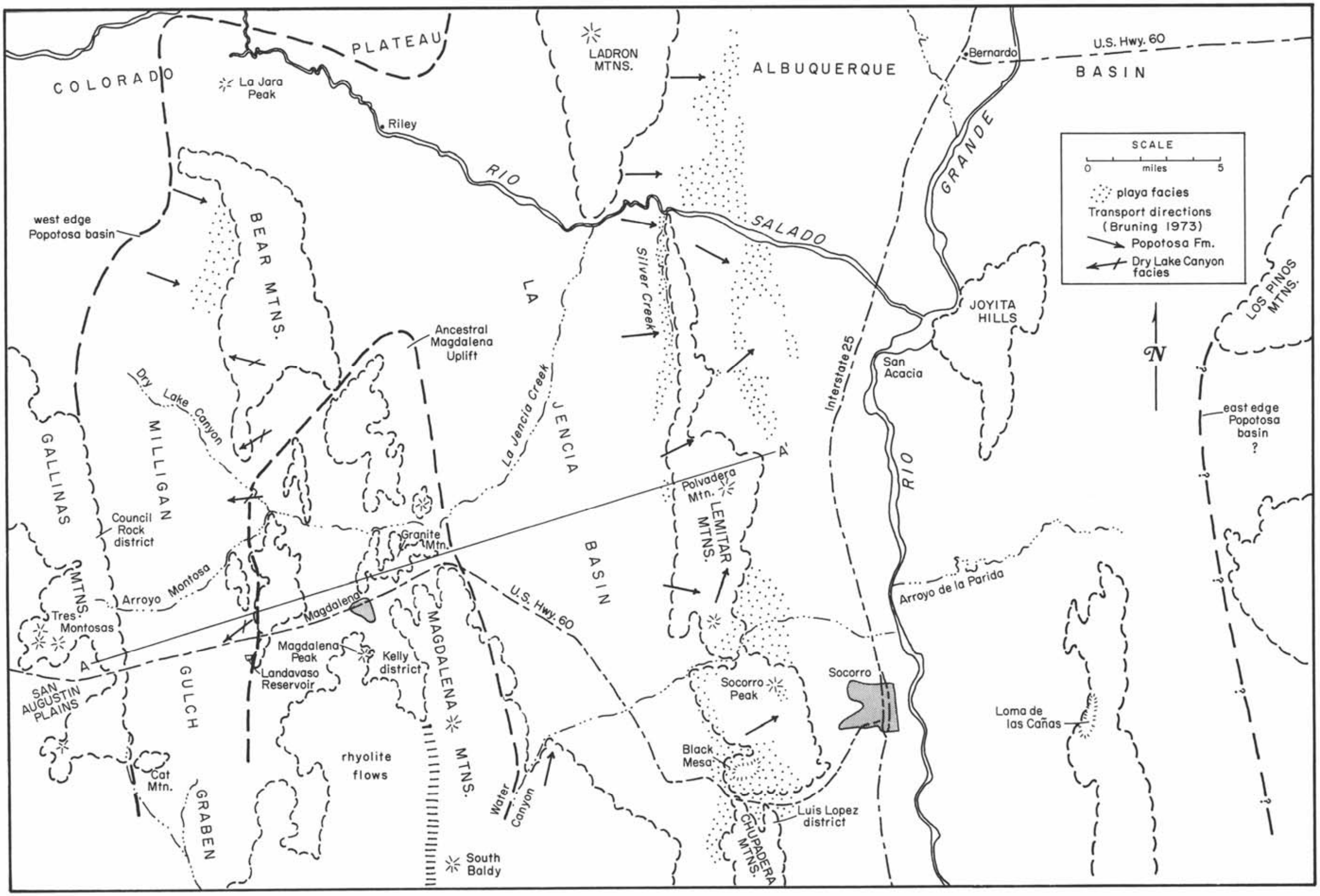

Figure 5. Sketch map of the Socorro area (from the Skylab photograph, Fig. 4) showing the Miocene Popotosa basin and its segmentation by modern intrabasin horsts.

of 500 to 700 ft of reddish, well-indurated pebble conglomerates with thin, interbedded sandstone lenses. The flows are interbedded with the conglomerates which contain clasts derived from the flows. The unit of Arroyo Montosa rests on an unconformity which truncates the Hale Well pluton (undated, but assumed to be similar in age to the other Magdalena plutons as it intrudes the A-L Peak Tuff). A K-Ar date of 25.2 ± 1.2 m.y. on one of the flows and the stratigraphic position of the unit of Arroyo Montosa beneath the La Jara Peak Basaltic Andesite, dated at 23.8 ± 1.2 m.y. (Chapin, 1971b), provide good control on the onset of fanglomerate sedimentation.

Las Cruces Area

In the Las Cruces area documentation of the beginning of regional extension is complicated by the existence of a north-trending volcano-tectonic depression, termed the Goodsight-Cedar Hills depression (Seager, 1973; this guidebook), which persisted from early Oligocene into early Miocene time. This asymmetric, elliptical basin of approximate dimensions 50 x 25 miles is elongated parallel to the Rio Grande rift and lies within it. This basin may be viewed either as a precursor of regional extension or as a very large volcano-tectonic depression upon which later, and totally unrelated, rifting has been superimposed. Most volcanic activity related to the Goodsight-Cedar Hills depression has been dated at 33 to 39 m.y. ago (Seager, op. cit.), but major basaltic andesite volcanism at about 26 m.y. ago (Seager, op. cit.) formed the Uvas Basaltic Andesite. The Uvas flows filled the depression and were subsequently bowed upward in the center to form the resurgent dome of the Sierra de las Uvas (Fig. 6).

The Uvas Basaltic Andesite (Fig. 7) will be discussed in more detail in the next section but the critical data as to the beginning of regional extension will be presented here. The Uvas was erupted from two main clusters of vents, one in the Cedar Hills vent zone (Seager and Clemons, 1975) and one in the Sierra de las Uvas area (Clemons and Seager, 1973). Dating of initial rifting can be demonstrated in the Cedar Hills area (Fig. 6). One Uvas vent, a cinder cone about one mile in diameter, formed on the Cedar Hills fault, one of the major rift faults in the region. Flows, whose apparent source was the cone, interfinger southward with thick fanglomerate deposits derived from the upthrown side of the fault. These relations indicate that rift faulting was in progress at least 26 m.y. ago and that faulting and basaltic andesite volcanism were contemporaneous. Alternatively, one could argue that the fanglomerates simply reflect the existence of a cauldron wall and that the basaltic andesite volcanism is related to the cauldron. However, similar patterns of faulting, fanglomerate deposition, and basaltic andesite volcanism elsewhere along the rift (discussed in the next section) indicate more than a coincidental relationship.

The critical dates are:

Bell Top Formation ash-flow tuffs 34.7 m.y.
(This date is an average of five K-Ar dates, ranging from 39 to 33 m.y., on ash-flow tuffs underlying the Uvas Basaltic Andesite within the Goodsight-Cedar Hills depression.)

Uvas Basaltic Andesite (K-Ar, whole rock) 25.9 ± 1.5 m.y.
(K-Ar, whole rock) 26.1 ± 1.4 m.y.

In the Cedar Hills area, described above, the Uvas Basaltic Andesite was structurally high during the early and middle Miocene and is overlapped disconformably by middle to late Miocene fanglomerates of the Santa Fe Group. However, a few miles to the north, near Rincon, thick Santa Fe bolson fill of early Miocene age grades downward into rhyolitic tuffaceous sedimentary rocks which, in turn, interfinger with the Uvas (Figs. 6, 7). These deposits represent an early rift basin within which a nearly complete sequence of deposits of Miocene age record the post-Uvas evolution of the rift. These, and similar deposits in the Socorro area are the subject of a later section.

Other Areas

The beginning of regional extension along the western margin of the San Luis basin in Colorado has been well-documented and is described in the following quote from Christiansen and Lipman (1972, p. 261):

> "In the San Juan Mountains of southwestern Colorado the beginning of basaltic and high-silica rhyolite eruptions can be shown to have occurred simultaneously with the first appearance of a deepening graben in the San Luis Valley to the east and of normal faulting and block tilting along the eastern margin of the San Juan Mountains (Lipman and Mehnert 1969). The youngest calc-alkalic ash-flow tuffs of the mid-Tertiary San Juan volcanic field, about 27 Ma old (Steven, Mehnert & Obradovich 1967), were deposited uniformly across the positions of later normal faults and thin eastward across the margin toward what was to become a major depositional basin in the San Luis Valley. Miocene basaltic and rhyolitic rocks as old as about 23 Ma (Lipman et al. 1970) lie unconformably on the tilted older ash flows and are interlayered with basin-fill gravels at the edge of the San Luis Valley."

More recently, Lipman and Mehnert (1973) state that:

> "Along the west margin of the San Luis Valley, silicic alkalic basalts as old as 26 m.y. rest unconformably on a pediment cut on middle Tertiary andesitic and related rocks (35-27 m.y. old) and similar basalts 20-0.24 m.y. old interfinger with and overlie volcaniclastic alluvial-fan deposits (equivalent to Santa Fe Group) that accumulated in the subsiding depression."

This evidence suggests that regional extension began nearly simultaneously along the length of the Rio Grande rift.

In the Datil-Mogollon volcanic field, Elston and others (1973, p. 2263) suggest that the beginning of Basin and Range faulting occurred about 20-21 m.y. ago. This estimate is based on K-Ar dates on two basaltic andesite flows interbedded with basal beds of the Gila Conglomerate at the localities sampled. However, older Gila may be present near basin centers in the region. The youngest major ash-flow tuff whose eruption appears to have preceded block faulting, and which is unequivocally dated, is the Bloodgood Canyon Tuff dated by both Damon (Elston and others, 1973) and Bikerman (1972, sample UP-M675, p. 11) at 26.3 m.y. Basaltic andesite volcanism was voluminous and widespread between 26 and 20 m.y. ago as discussed in the following section. The beginning of regional extension has not yet been established in the central and western portions of the Datil-Mogollon field; several radiometric dates and stratigraphic correlations are currently being re-evaluated (W. E. Elston and J. C. Ratté, oral commun., 1975).

Discussion

The nature of the transition from the middle Tertiary period of neutral stress field, calc-alkalic magmatism, and through drainage to the late Tertiary period of regional extension, bimodal volcanism, and largely closed drainage is difficult to decipher due to scarcity of data. How did the stable fore-

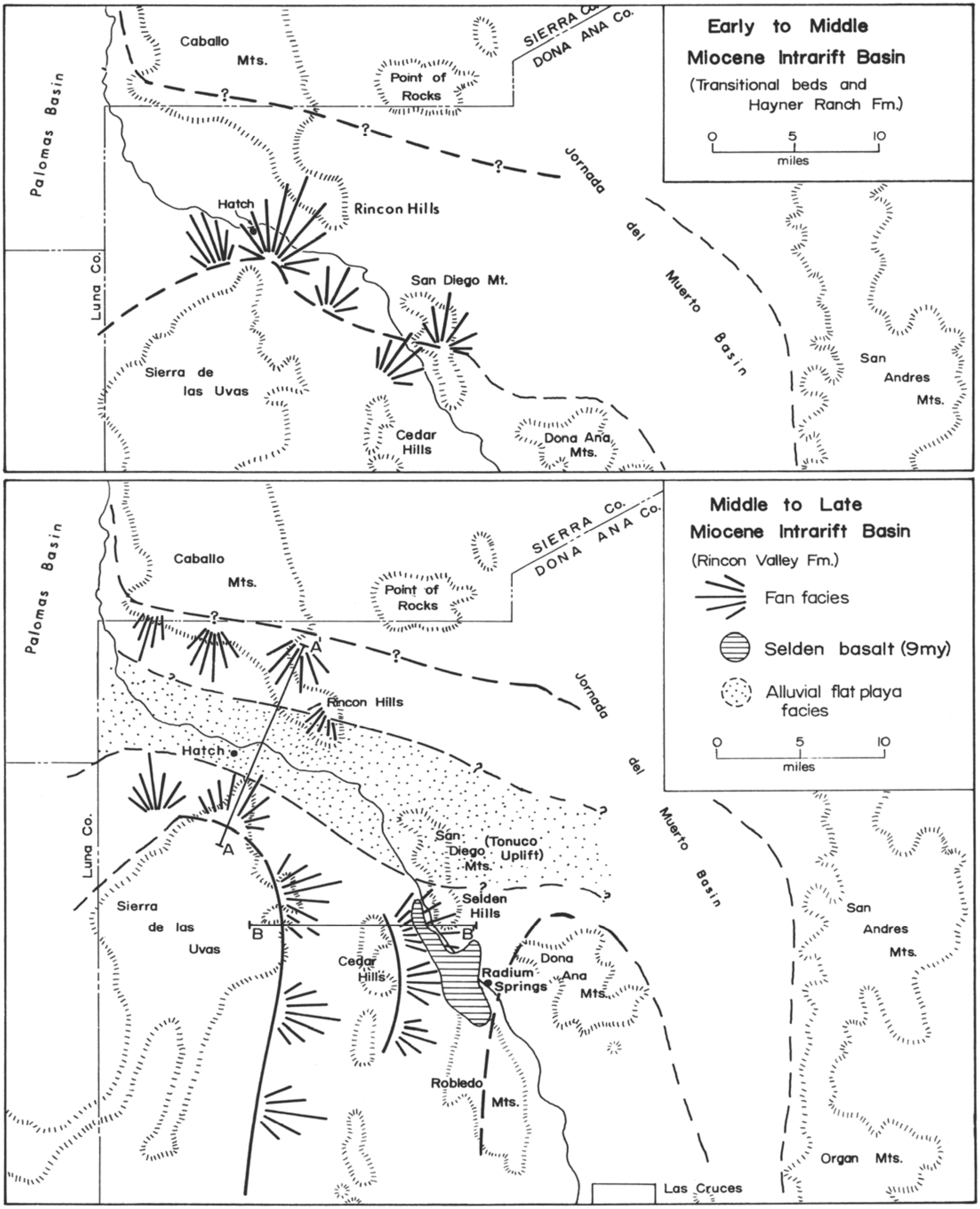

Figure 6. Sketch maps of northern Dona Ana County showing Miocene rift basins and modern intrabasin horsts, such as the Rincon Hills, Tonuco uplift (San Diego Mountain), Cedar Hills, Selden Hills and Robledo Mountains.

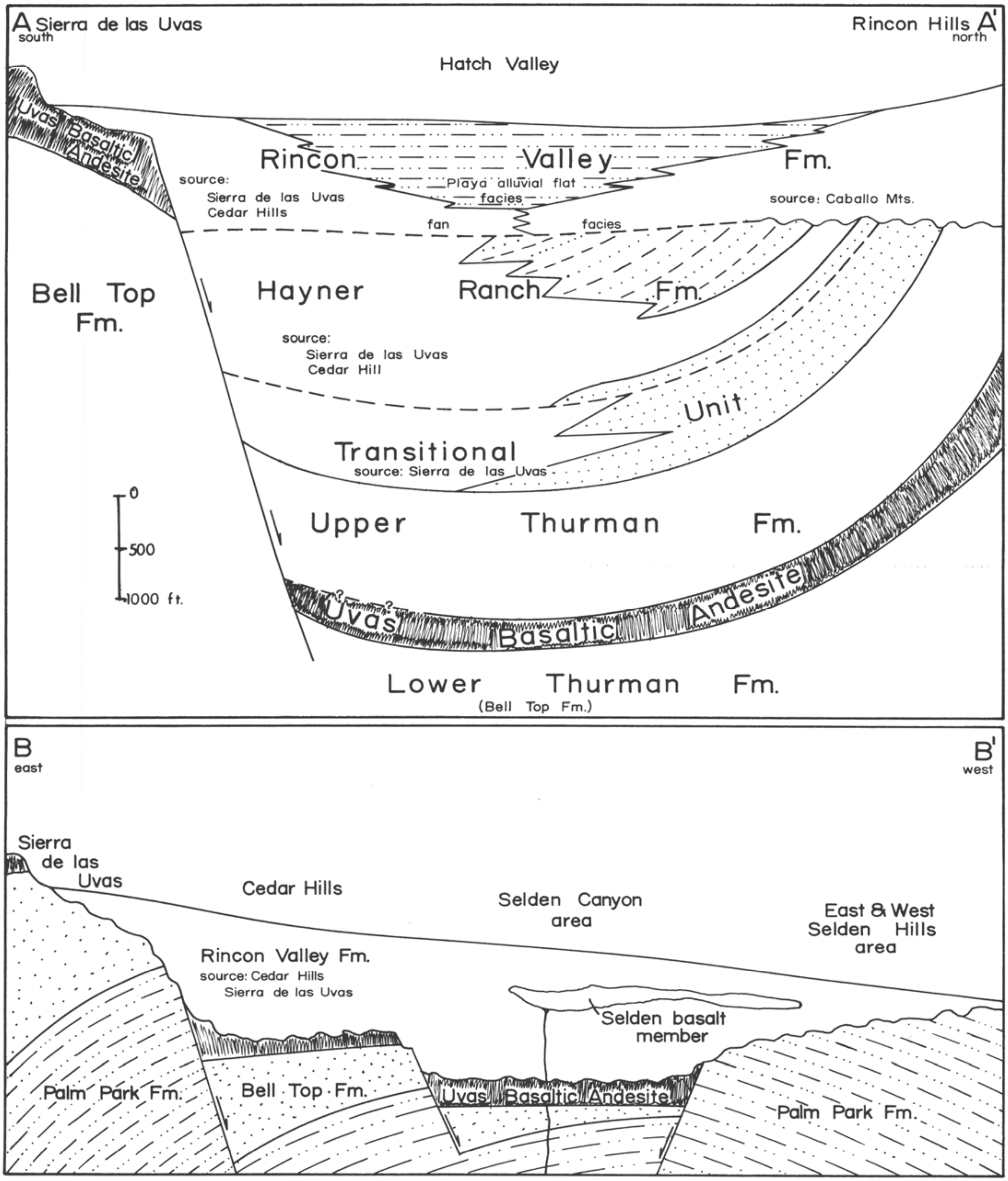

Figure 7. Schematic cross-sections of Miocene basins shown in Figure 6.

land area of New Mexico and Colorado react to the first stirrings of regional extension? How much time elapsed from the earliest "feeling" of regional extension to the deposition and preservation of igneous and sedimentary rocks which could later be interpreted as products of that extension? What kinds of evidence should we look for? These are difficult questions, seldom asked.

Some insight as to the possible nature of the middle Tertiary-late Tertiary tectonic transition is available from recent mapping in the Socorro-Magdalena area. Major northeast-trending paleovalleys are preserved in the rock record from deposition of the earliest Oligocene Spears Formation (37 m.y., Burke and others, 1963) through deposition of the youngest major ash-flow sheet, the Potato Canyon Tuff (30 m.y., E. I. Smith, in press). These paleovalleys, structurally controlled by the Morenci-Magdalena lineament (Chapin and others, 1974), facilitated transport of volcanic materials from source areas in the Magdalena and San Mateo Mountains northeastward through the area of the Lemitar Mountains (Woodward, 1973), to the Joyita Hills (Spradlin, 1975), where unusually thick and complete sections are preserved. The beginning of north-trending block faulting at about 29 m.y. ago apparently diverted this drainage northward, causing the upper part of the volcanic pile to be stripped to the level of the A-L Peak Tuff in the area north of U.S. Highway 60 and between the La Jencia basin and the San Augustin Plains. No record of the postulated north-trending drainage is known and it can only be inferred from the anomalous amount of post-Potato Canyon, pre-La Jara Peak erosion in this area. Blockage of the inferred north-trending drainage by the rising Colorado Plateau on the north and by the east margin of the Rio Grande rift (Los Pinos Mountains and mesas to the south) may have formed the closed basin in which the basaltic andesite flows of the La Jara Peak Formation (24 m.y.) and the bolson sediments of the Popotosa Formation accumulated. No sedimentary or volcanic record is known for the interval between the beginning of regional extension at about 29 m.y. ago and the first fanglomerates and lava flows in the Milligan Gulch graben (the unit of Arroyo Montosa dated at 25 m.y.). We can only speculate that through drainage, perhaps accelerated by regional uplift, swept detritus from the area in a degradational fluvial regime. If these inferences are valid, 3 to 4 million years elapsed before through drainage was sufficiently disrupted by block faulting and by a drier climate for bolson sedimentation to begin. This story is a tenuous thread. But it takes into account the best data we have and it suggests that one should be cautious in assuming that the first bolson sediments are the earliest record of regional extension. Through drainage may be easily diverted by tectonic movements, volcanism, or capture, but the formation of a closed basin requires a combination of tectonic and climatic changes that require an unknown, but appreciable, interval of time.

TRANSITIONAL VOLCANISM

Thick sequences of basaltic andesite flows are a conspicuous part of the early record of the Rio Grande rift where it transects or borders the Datil-Mogollon volcanic field. These flows are often regarded as prerift deposits but in the Socorro and Las Cruces areas they are interbedded with fanglomerates that formed in closed basins. If the beginning of rifting is defined by the earliest evidence of extensional faulting and bolson sedimentation, then these basaltic andesites are synrift deposits. Other basaltic andesites along the elevated margins of the rift, not interbedded with fanglomerates but of comparable age, should also be considered synrift.

To the north, where the Rio Grande rift transects the San Juan volcanic field, the structural and magmatic transition has been described by Lipman and others (1970, p. 2333) as:

> "Near the end of the period of major ash-flow and related eruptions, both tectonic environment and nature of volcanic activity changed notably. The eastern part of the volcanic field was broadly warped, regionally faulted, and tilted to the east in response to initial development of the Rio Grande rift depression (Lipman and Mehnert, 1969), and widespread basalt and local silicic alkali rhyolite flows were emplaced. The oldest of these rocks constitute the Hinsdale Formation, which consists mainly of alkalic olivine basalt and basaltic andesite with small scattered rhyolite plug domes and one small rhyolite ash-flow sheet."

According to Lipman and others (op. cit.), these basaltic and minor rhyolitic rocks were emplaced intermittently through the Miocene and Pliocene and formed a widespread thin veneer over the older volcanic terrain. It is evident from the Geologic Map of New Mexico (Dane and Bachman, 1965) that a similar veneer of mafic flows spread across the Datil-Mogollon field during the late Cenozoic. However, in New Mexico the basaltic cover is less eroded, may have been thicker and more extensive originally, is largely early Miocene in age, and in the Socorro and Las Cruces areas is interbedded with fanglomerate deposits of the Santa Fe Group.

La Jara Peak Basaltic Andesite

The La Jara Peak Basaltic Andesite forms the high part of the Bear Mountains north of Magdalena where Tonking (1957) measured a type section of 1,175 ft of mafic flows and 25 ft of intercalated conglomerate and sandstone. He described the lavas as dark gray basalt at the base grading upward into medium-gray porphyritic basaltic andesite and named the unit the La Jara Peak Member of the Datil Formation. Chemical analyses of the basal and uppermost flows were included in Tonking's report (op. cit., p. 50); they yielded 50.50% SiO_2 and 1.90% K_2O for the basal flow, 55.25% SiO_2 and 3.44% K_2O for the upper flow. Tonking recognized that the intercalated conglomerates and sandstones were lithologically similar to the overlying Santa Fe Group and suggested that they "... support the conclusion that intermittent extrusion and sedimentation characterize the close of the Datil period of volcanism." (op. cit., p. 31).

To Tonking's excellent work we can now add that the La Jara Peak Basaltic Andesite is early Miocene (24 m.y.) in age (Chapin, 1971 b); that it postdates the beginning of block faulting by 4 to 5 million years, as described in the preceding section; that it rests on a major unconformity, during the carving of which several hundred feet of ash-flow tuffs and interbedded andesite flows were removed and 28-m.y.-old stocks were breached; that it overlies 25-m.y.-old fanglomerates and interbedded lava flows in the Milligan Gulch graben west of Magdalena (Simon, 1973); that it is extensively interbedded with the overlying Popotosa Formation (Santa Fe Group) through a stratigraphic interval of several hundred feet; that pebble imbrications in the interbedded La Jara Peak-Popotosa interval reveal the initial uplift of the Colorado Plateau (Bruning, 1973; Bruning and Chapin, 1974); and that the La Jara Peak was erupted mainly from fissures within a structural basin bounded by the Colorado Plateau on the north and the Gallinas Range on the west.

Lithologically, the La Jara Peak flows consist predominantly of medium-gray, dense, basaltic andesite with abundant small, reddish, oxidized ferromagnesium phenocrysts (mostly pyroxene). Plagioclase is not a phenocrystic mineral. Individual flows are generally thin (10 to 30 ft) with autobrecciated tops and bottoms, typical of andesitic lavas. Similar appearing basaltic andesites comprise much of the mafic veneer over the Datil-Mogollon volcanic field. Chemical analyses by Tonking (1957), Deal (1973), and J. W. Stinnett, Jr. (unpub. data) show that the La Jara Peak is an alkalic basalt near the base but grades abruptly upward into a thick pile of basaltic andesites averaging about 56% SiO_2 and 4.3% K_2O. An unpublished Sr^{87}/Sr^{86} analysis by J. W. Stinnett, Jr. yielded a ratio of 0.7078. These chemical and isotopic compositions are typical of most of the mafic veneer over the Datil-Mogollon field (Chemical analyses from: W. E. Elston, 1957; Ericksen and others, 1970; E. G. Deal, 1973; R. V. Fodor, 1975; H. L. Jicha, Jr., 1954; J. C. Ratte' and others, 1969; R. C. Rhodes, 1970 and unpub. data; W. R. Seager and R. E. Clemons, unpub. data; J. W. Stinnett, Jr., unpub. data; and W. H. Tonking, 1957. Isotopic analyses from J. W. Stinnett, Jr. unpub. data.)

Uvas Basaltic Andesite

The Uvas Basaltic Andesite is the youngest volcanic fill in the Goodsight-Cedar Hills depression (Seager, 1973; this volume) and the oldest stratigraphic unit in the Las Cruces area demonstrably related to initial block faulting in the Rio Grande rift (see previous section). The Uvas was named by Kottlowski (1953) for as much as 145 ft of basalt/basaltic andesite with interbedded scoria and basaltic tuffs cropping out along the Rio Grande Valley near Las Cruces. Clemons and Seager (1973) recently designated a type locality in the Sierra de las Uvas and measured 785 ft of basaltic andesite flows at the type section. The geometry of the volcanic pile in this area suggests a shield-like accumulation of flows whose summit vents coincide with the center of the Goodsight-Cedar Hills depression as well as with the summit of the somewhat younger Sierra de las Uvas structural dome. These Uvas vents appear to be related to volcano-tectonic features rather than to obvious rift faults, although the northerly elongated Goodsight-Cedar Hills depression may be a precursor of rift structure (see article by Seager, this guidebook).

A second cluster of Uvas vents is located in the Cedar Hills vent zone bounding the east side of the Goodsight-Cedar Hills depression. Stratigraphic relationships of Uvas flows erupted from these vents were described in the previous section because they can be used to date initial rifting. Several attempts have been made to date the Uvas with ages ranging from 12.9 to 31.0 m.y. ago; the two best samples, however, from flows in the Sierra de las Uvas and Cedar Hills, respectively, yielded ages of 25.9 ± 1.5 m.y. (Clemons and Seager, 1973) and 26.1 ± 1.4 m.y. (Clemons, in press). Near Rincon, thick Santa Fe bolson fill of early Miocene age grades downward into rhyolitic tuffaceous sedimentary rocks which, in turn, interfinger with the Uvas. Thus, an early Miocene age is indicated both stratigraphically and radiometrically.

Lithologically, the Uvas flows consist predominantly of grayish-black to medium-gray, dense, basaltic andesite with small oxyhornblende phenocrysts enclosed in an intergranular felted matrix of andesine laths, pyroxene, and iron oxide grains (Clemons and Seager, 1973). Olivine phenocrysts occur in a few of the darker flows, but plagioclase composition (An45-50) in these flows differs little from flows without olivine. As in the La Jara Peak Basaltic Andesite, plagioclase is generally not a phenocrystic mineral. Chemical analyses (Clemons, in press, unpub. data of J. M. Hoffer) indicate that the Uvas Basaltic Andesite is somewhat more mafic and lower in alkalies than the La Jara Peak. Silica ranges (6 analyses) from 49.8 to 57.5% and potash from 1.5 to 2.4%.

Discussion

Confusion exists in the literature as to whether mafic rocks of the late Cenozoic transition are basalts, basaltic andesites, andesites, or latites. Usage varies among authors according to personal preference. However, when these rocks are plotted on a total alkalis versus silica diagram (Fig. 8), it is apparent that a continuum of compositions exists between alkalic basalts, silicic alkalic basalts, basaltic andesites, andesites, and latites. In spite of differences in nomenclature, a nearly complete compositional overlap exists between late Cenozoic mafic rocks of the San Juan volcanic field and corresponding rocks of the Datil-Mogollon field. The problem is readily explained by Figure 8; it was recognized long ago by Larsen and Cross (1956, p. 195) who referred to the rocks of the Hinsdale Formation as latite-basalts. Because most mafic rocks of the late Cenozoic transition are higher in silica and potash than true basalts and have field and petrographic characteristics intermediate between basalts and andesites, we prefer the term basaltic andesite.

The composition and tectonic significance of igneous rocks emplaced during the transition to late Cenozoic regional extension is a subject of much controversy. Lipman (1970) and Christiansen and Lipman (1972) have postulated that volcanism changed from calc-alkalic andesites and related ash-flow tuffs to a bimodal basalt-rhyolite suite (termed "fundamentally basaltic") concurrent with the transition to crustal extension in the western United States. However, P. E. Damon (1971, oral commun., 1974) has pointed out that basaltic andesites have chemical and isotopic affinities with the calc-alkalic suite and that the transition to basaltic volcanism occurred much later than that proposed by Christiansen and Lipman. Figures 8 and 9 substantiate Damon's argument.

W. E. Elston presented a convincing case at the 1974 Penrose Conference on the Rio Grande rift that the transition from middle Cenozoic calc-alkalic volcanism to the volcanism termed "late Cenozoic bimodal" by Christiansen and Lipman (1972) occurred over an interval of 10 to 15 million years and in a complicated manner. According to Elston, basaltic andesite volcanism began in early Oligocene time (-35 m.y. ago), increased after 30 m.y. ago, and was replaced by basaltic volcanism after 20 m.y. ago (Fig. 9). Elston (Penrose Conference and Elston and others, abstract, this guidebook) also pointed out that high-silica, high-alkali rhyolites (the rhyolites of Christiansen and Lipman's bimodal suite) were erupted as early as 31 m.y. ago. T. A. Steven, at the same Penrose Conference, documented the importance of alkali rhyolites to mineralization and indicated that their emplacement began as early as 30 m.y. ago in Colorado. Thus, the model of Lipman (1970) and Christiansen and Lipman (1972), which has done much to direct attention to the late Cenozoic structural and

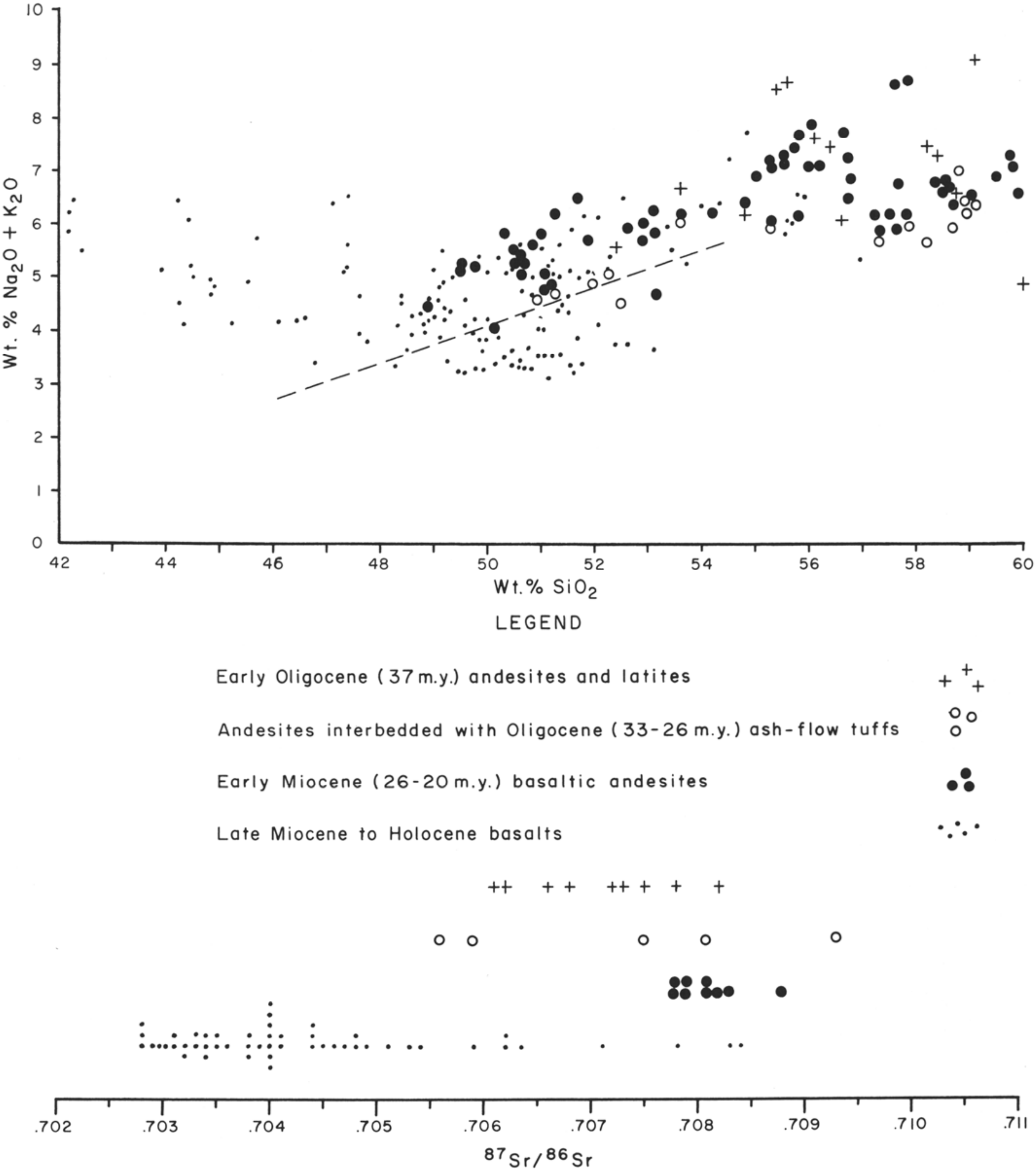

Figure 8. Total alkalis vs silica diagram and $^{87}Sr/^{86}Sr$ ratios comparing late Cenozoic basalts and basaltic andesites with middle Cenozoic andesites and latites. Dashed line separates fields of Hawaiian tholeiitic and alkalic basalts (Macdonald and Katsura, 1964) and is included only for comparison. Data includes rocks of the San Juan and Datil-Mogollon volcanic fields and basalts of southern Colorado and New Mexico along the Rio Grande rift and the Springerville-Raton lineament. Data from Lipman (1969), Lipman and Moench (1972), Lipman, Bunker, and Bush (1973), Stormer (1972a, b), Aoki (1967a, b), Larsen and Cross (1956), Renault (1970), Laughlin and others (1971, 1972a, b), Baldwin and Muehlberger (1959), Ratté and others (1969), Fodor (1975), Rhodes (1970, unpub.), J. W. Stinnett, Jr. (unpub.), Kudo and others (1971, 1972), Aoki and Kudo (in press), Baker and Ridley (1970), Leeman (1970), Doe and others (1969), Hedge and Walthall (1963), Elston (1957), Deal (1973), Ericksen and others (1970), Jicha (1954), Clemons (in press), Tonking (1957), Hoffer (unpub.), Jones and others (1974).

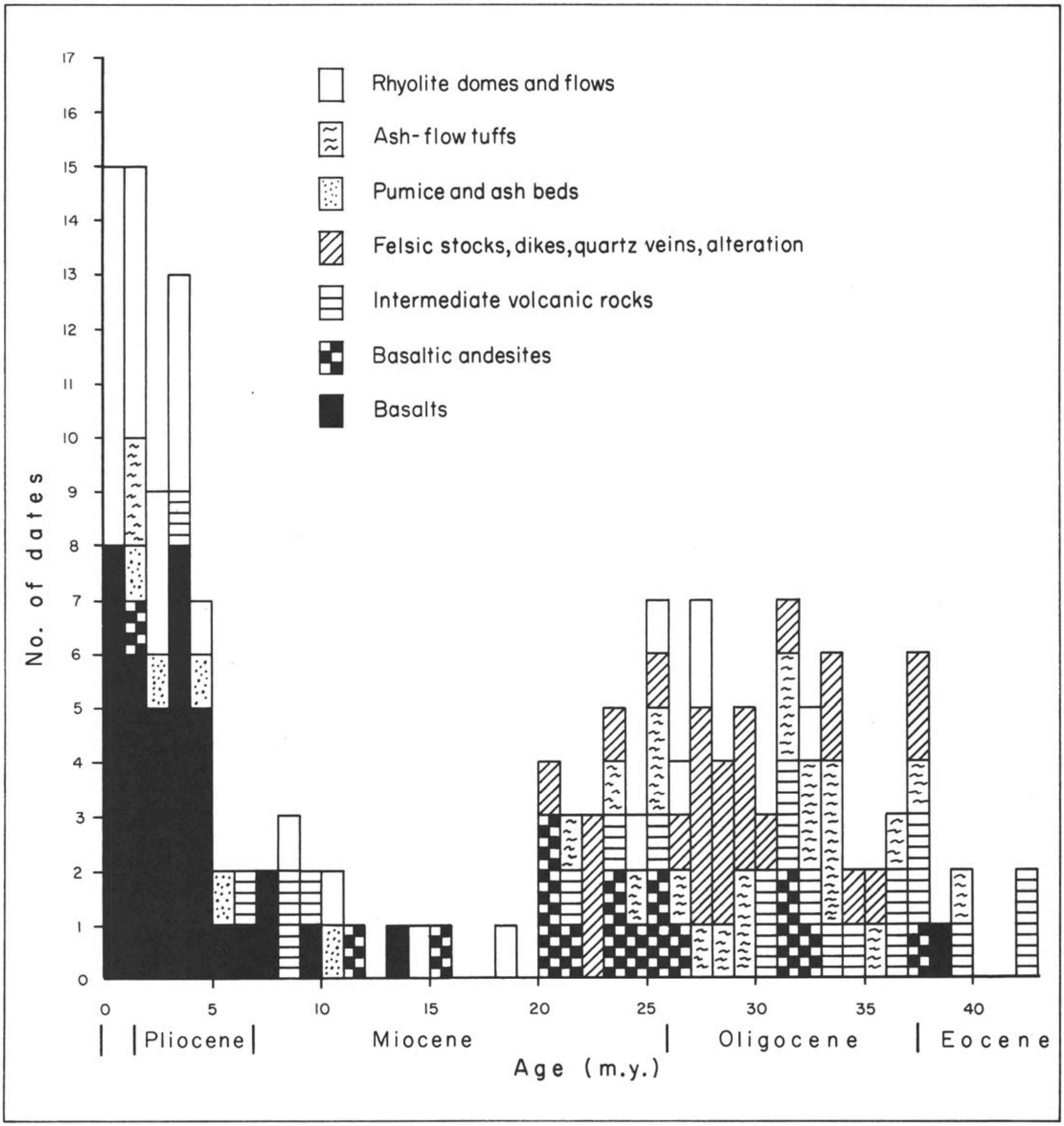

Figure 9. Histogram of 161 K/Ar and fission-track dates on igneous rocks of late Eocene to Holocene age in New Mexico. Data from a compilation by Chapin and others (1975). Dates known, or suspected, to be invalid on geological grounds have been eliminated. Some ages represent an average of two or more dates on the same rock unit. The Plio-Pleistocene basalt/rhyolite ratio is biased in favor of rhyolites because of the scarcity of dates on basalt flows and the abundance of dates on rhyolitic domes and flows of the Valles caldera. Oligocene and early Miocene mafic and intermediate rocks are under-represented relative to their volume.

magmatic transition, is too simple when the transition is examined in detail.

Our estimate that regional extension began along the Rio Grande rift 25 to 29 m.y. ago (based on structure, sedimentation, and major basaltic andesite volcanism) falls near the middle of the complicated magmatic transition which Elston considers to have occurred mainly between about 31 and 20 m.y. ago. The most voluminous outpourings of basaltic andesite flows occurred between about 26 and 20 m.y. ago (Fig. 9) which suggests that crustal extension greatly accelerated a type of magmatism which had begun earlier in the Oligocene. Note, also, the abundance of stocks and dikes between 27 and 30 m.y. (Fig. 9). In central New Mexico, many of these fill extensional fault zones of regional extent.

In considering the Rio Grande rift as a whole, there are differences in the distribution of basaltic andesites and true basalts, both in time and space. Basaltic andesites were most abundant during the earliest stages of rifting (26-20 m.y. ago) where the Rio Grande rift transected major Oligocene volcanic fields. In contrast, true basalts were most abundant from late Miocene to Holocene time, especially from about 5 m.y. ago to the present, and were widely distributed from near Alamosa, Colorado to the Mexican border. Volcanism was relatively quiescent along the Rio Grande rift during the interval 20-14 m.y. ago (Fig. 9). This suggests a model involving two different thermal regimes separated by an interval of low heat flow. (A similar, middle Miocene lull in volcanism has been reported by McKee and others (1970) for the Great Basin, Damon (1971) for the Basin and Range province, and by Marvin and others (1974) for Colorado.) When regional extension began during the waning stages of middle Tertiary calc-alkalic volcanism, both the Datil-Mogollon and San Juan fields were obviously areas of high heat flow. Extension allowed the eruption of large volumes of mafic magma, either by providing conduits for magmas already present or by releasing pressure on materials in the basal crust and/or lithospheric mantle which were near their melting point and could then undergo partial melting. The basaltic andesites thus generated have chemical and isotopic compositions related to the calc-alkalic suite and are indistinguishable in the Datil-Mogollon field from basaltic andesites interbedded with Oligocene ash-flow tuffs (Fig. 8). They also show significant chemical and isotopic similarities to the early andesitic-latitic rocks of the Rubio Peak and Spears Formations (Fig. 8).

The thermal engines driving these middle-Tertiary fields cooled with time and magma generation decreased. Then, beginning about 12 to 14 m.y. ago, the Rio Grande rift had sufficiently necked the crust to allow upward movement of mantle material and development of a new thermal regime related geometrically to the rift and driven by mantle processes. Large volcanic centers began to develop (Jemez Mountains and Socorro Peak and Magdalena Peak) where major crustal lineaments (Springerville-Raton and Morenci-Magdalena lineaments, respectively) intersected the Rio Grande rift. With further passage of time, generation of basaltic magma within the mantle became more widespread and basaltic flows and fields began to dot the rift from southern Colorado to Mexico and became abundant along the Springerville-Raton lineament. Tholeiitic flood basalts of the Rio Grande Gorge began about 4.5 m.y. ago (Ozima and others, 1967) and most of the basalt flows so conspicuous today are late Pliocene to Holocene in age. Thus, the prominent heat flow anomaly along the west edge of the Rio Grande rift, recently outlined by Reiter and others (1975), is a young feature, probably still growing, and almost certainly different in distribution and intensity from earlier patterns. To lump the products of both periods of volcanism as "fundamentally basaltic" is misleading and tends to disguise their different origins.

Note: The paper by Lipman and Mehnert in Geological Society of America Memoir 144, 1975, was not available to us until after this volume went to press.

UPLIFT OF THE COLORADO PLATEAU

The evolution of the Rio Grande rift is fundamentally related to the evolution of the Colorado Plateau. The rift is a "pull-apart" structure formed by the separation of the Colorado Plateau from the craton along a major pre-existing flaw in the earth's crust (Fig. 2). Tectonic movements affecting one are bound to affect the other.

In the Socorro area, the earliest evidence for differential uplift of the Colorado Plateau, following middle Cenozoic volcanism, comes from fanglomerates interbedded with the upper part of the La Jara Peak Basaltic Andesite (24 m.y., Chapin, 1971b) at the northwest end of the Bear Mountains (Fig. 5). Pebble imbrications in the fanglomerates indicate that the detritus was shed southeastward away from the Colorado Plateau and into the basin in which the La Jara Peak flows were accumulating. The clasts are composed mainly of ash-flow tuffs and andesites from the upper part of the Datil volcanic sequence. In the Oligocene, the distal edge of the Datil-Mogollon volcanic field undoubtedly extended northward at least 10 to 20 mi farther than it does today. As the Colorado Plateau began to rise, the first rocks stripped were the Datil volcanic rocks and this detritus was transported southeastward into a downwarp we refer to as the Popotosa basin. Today, one can stand near Magdalena at an elevation of about 6,500 ft and on a volcanic section about 3,500 to 4,000 ft thick and look northward to where rocks of Paleozoic and Mesozoic age crop out at about the same elevation along the southern edge of the Colorado Plateau. The Cenozoic volcanic rocks and older formations dip southwestward at angles of 6 to 20 degrees beneath the Datil-Mogollon field. The amount of uplift of the Colorado Plateau to produce these relationships is difficult to estimate precisely because of complications of Laramide structure and northward thinning of the volcanic section, but it is at least several thousand feet. The northward slope of Oligocene constructional topography formed by the broad shield-like Datil volcanic pile has been reversed and the north edge of the field upturned and beveled by erosion. A very considerable volume of rock was eroded during this uplift and dumped into the subsiding Popotosa basin just south of the Plateau margin.

Initial uplift of the Colorado Plateau in early Miocene time, concurrent with formation of the early rift basins, is at variance with estimates published by Luchitta (1972) and McKee and McKee (1972) for uplift of the Plateau relative to the Basin and Range province. Space limitations prevent a review of this problem here.

EARLY BASINS OF THE RIO GRANDE RIFT

As the continental crust began to neck along the southern Rocky Mountains deformed belt in latest Oligocene or earliest Miocene time, the first basins were probably broad downwarps controlled largely by pre-existing structures. Since regional extension seems to have begun first in Trans-Pecos Texas, southern New Mexico-Arizona, and along the Rio Grande rift (Christiansen and Lipman, 1972, Figs. 5, 7, 9), the rift must have appeared as an en echelon series of shallow basins transecting the gentle, constructional topography of broad ignimbrite shields and other terrain of relative stability and low relief. In the Socorro and Las Cruces areas, studies of the basin fill have permitted partial reconstruction of these early basins.

Popotosa Basin

In the Socorro-Magdalena area, the basal and thickest unit of the Santa Fe Group is the Popotosa Formation. The term "Santa Fe" is used as a group term according to the recommendations of Baldwin (1963) and follows current usage by most geologists. Bryan stated the case succinctly in 1938 (p. 199), when he wrote: "The Santa Fe formation ... [Group] ... is the principal body of sedimentary deposits in the structural basins which in this paper are collectively called the Rio Grande depression." For a more detailed discussion of the Santa Fe Group and its nomenclature, the reader is referred to Hawley and others (1969), Galusha and Blick (1971), and Seager and Hawley (1973).

Both Bryan (1938) and Kelley (1952) thought that the Rio Grande rift narrowed 12 miles north of Socorro at San Acacia (Figs. 5, 6). Kelley (op. cit., p. 97) stated that:

> The Socorro constriction as defined here extends about 40 miles from the San Acacia channel on the north to the San Marcial basin on the south. South of the Albuquerque basin there is, in addition to a pronounced narrowing of the Rio Grande depression, a marked change in the structural alinement of the bordering uplifts.... The Rio Grande depression along this channel is only 5 to 10 miles wide."

Chapin (1971a) has shown, however, that the "Socorro constriction" is an illusion and that the Rio Grande rift actually widens in the Socorro area into a series of parallel basins separated by intrarift horsts (Fig. 1).

Bryan (1938) recognized that the Socorro basin was complex and that the Socorro-Lemitar uplift was "new born," but he failed to follow these observations to the logical conclusion that the basin, and therefore the rift, was much wider during Santa Fe deposition. However, C. S. Denny, one of Bryan's students, pieced much of the story together from detailed studies in the San Acacia area and wrote:

> 1) "Toward the close of the Miocene(?) ... [Oligocene] ... time volcanism subsided and the volcanic rocks were considerably deformed and eroded. Later deformation produced the enclosed basin in which from 3,000 to 5,000 feet of Popotosa beds were laid down. At the center of the basin there was a *playa* wherein fine-grained alluvium and salts were deposited.... Continued deformation produced new structural basins in which the Santa Fe formation ... [upper Santa Fe Group] ... began to accumulate." (Denny, 1940, p. 105)
>
> 2) "In post-Santa Fe time, the Socorro Mountains have risen athwart the *playa* of the Socorro basin." (op. cit., p. 76, see also fig. 10, p. 97)
>
> 3) "Deformation in post-Santa Fe (post-Pliocene?) time uplifted Los Pinos and Socorro mountains and re-elevated the Sierra Ladron. This deformation produced the present basins, which are somewhat narrower than the basins of Santa Fe (Pliocene?) time.... The Socorro Mountains were uplifted in the middle of the wide Socorro Basin of Santa Fe time." (Denny, 1941, p. 231)

Statement 1) is excellent but statements 2) and 3) pose some problems. Rifting culminated in latest Miocene and/or Pliocene time with uplift and rotation of fault blocks in the thin-skinned style described by Anderson (1971) for southeastern Nevada (see following section). Most beds of the upper Santa Fe Group have low dips and rest with angular unconformity upon strongly tilted Popotosa. Axial river deposits of the ancestral Rio Grande dated as late Pliocene by Needham (1936) and Bachman (oral commun., 1975) are related geometrically to the modern Rio Grande Valley and are little deformed. Hence, the deformation which produced the present basins preceded deposition of most of the upper Santa Fe Group. The playa Denny refers to in statement 2) is the Miocene playa of the Popotosa basin which is the "wide Socorro basin" of statement 3).

Recent work by J. E. Bruning (1973) and the senior author has extended the Popotosa basin westward through the very youthful Bear Mountains to the east flank of the Gallinas Range (Fig. 5). The basin had a width in middle Miocene time of about 40 miles and is now segmented into three parallel and relatively narrow basins by uplift in latest Miocene and/or Pliocene time of the Socorro-Lemitar and Magdalena-Bear Mountain axes. Thus, if the term "Socorro basin" is used, it is necessary to specify which basin: the broad Miocene basin or the narrow latest Miocene to Holocene basin along the so-called "Socorro constriction." To avoid confusion we use Popotosa basin for the Miocene structure.

Figure 3 consists of two diagrammatic cross-sections across the western half of the Popotosa basin as it appeared in early Miocene and middle to late Miocene time, respectively. The approximate line of cross-section is labeled A-A' on Figure 5. The oldest basin deposits are the fanglomerates and interbedded lava flows informally termed the unit of Arroyo Montosa by Simon (1973) and dated at 25 m.y. (see section on Beginning of Regional Extension). Overlying the unit of Arroyo Montosa are 1,200 ft, or more, of basaltic andesite flows of the La Jara Peak Formation dated at 24 m.y. (see section on Transitional Volcanism).

The reader is referred to Denny (1940) and Bruning (1973) for detailed documentation of the Popotosa basin and its deposits. In addition to fan, playa, and transitional facies (plus interbedded volcanic rocks), the Popotosa Formation contains strikingly different compositional facies. The great bulk of the unit consists of reddish, well-indurated volcanic conglomerates composed mainly of clasts of basaltic andesites and ash-flow tuffs derived from the upper part of the Datil volcanic section and from the La Jara Peak Basaltic Andesite. (Bruning, 1973, pls. 2, 3, 5). The ratio of basaltic andesite to ash-flow tuff clasts generally varies from 3:1 to 1:3. However, in a facies derived from a dip slope of La Jara Peak Basaltic Andesite on the north end of the ancestral Magdalena Range, andesites comprise more than 90 percent of the clasts (Bruning, 1973, pl. 4). Brown (1972) called this facies the fanglomerate of Dry Lake Canyon. In contrast, a facies derived from uplift of the Ladron Mountains contains 25 to 75 percent clasts of Precambrian and Paleozoic rocks (Bruning, 1973, pl. 2B). Bruning called this facies the fanglomerate of Ladron Peak. Fanglomerates in the upper part of the Santa Fe Group tend to be lighter in color, poorly indurated, and rich in clasts of Precambrian and Paleozoic rocks. They generally dip less than 10 degrees, whereas, Popotosa strata are more strongly deformed with dips usually ranging from 10 to 60 degrees. In other words, the Popotosa Formation records the erosion of emerging uplifts whose exposed sections were mainly the upper part of the Datil volcanic pile and younger basaltic andesites. Younger Santa Fe beds were derived from fault blocks in which uplift, coupled with erosion and strong rotation, had exposed the prevolcanic section. As the uplifts continued to rise (and new uplifts were born), the lower part of the basin fill was progressively deformed.

Where the Popotosa and upper parts of the Santa Fe Group are separated by an angular unconformity and lithologic compositions contrast, distinction is easy. However, where the younger Santa Fe beds rest on the fanglomerate of Ladron Peak or where the younger Santa Fe has been derived from uplifts exposing mainly volcanic rocks, such as the Bear Mountains, major problems exist in picking the upper contact of the Popotosa Formation. Sediments derived during the main pulse of deformation (latest Miocene and/or Pliocene) were probably moved towards the centers of the present basins by reworking of earlier fans as uplift continued; then sedimentation encroached on the ranges as uplift slowed. Hence, the angular unconformities and compositional differences evident along the basin margins probably grade basinward into disconformities separating beds of similar composition. The upper contact of the Popotosa Formation may be gradational over a considerable interval in the subsurface of modern basins.

The youngest known Popotosa is interbedded with, and overlaps, rocks of the Socorro Peak volcanic center. A K-Ar date of 10.7 m.y. from a trachyandesite on the highest point of Socorro Peak (Burke and others, 1963) and a K-Ar date of 11.7 ± 0.6 m.y. from a dike in the Luis Lopez manganese district (Willard, 1971) indicates a late Miocene age for Socorro Peak volcanism. These volcanic rocks overlie a playa facies of the Popotosa Formation and are partly interbedded with, and partly overlapped by, coarse fanglomerates. All have been strongly elevated by the Socorro-Lemitar uplift.

Miocene Paleobasins in Northern Dona Ana County

Two intrarift basins of Miocene age have been partly reconstructed in northern Dona Ana County (Fig. 6). Neither basin is wholly preserved as part of the modern landscape, having been segmented into smaller intrabasin horsts and grabens in latest Miocene and/or Pliocene time. The location and trend of the paleobasins is based on studies of thickness, composition and facies distribution of the basin fills, which are assigned to the pre Plio-Pleistocene (pre-Camp Rice) part of the Santa Fe Group (Kottlowski, 1953; Hawley and others, 1969). Such studies also have shown that different fault block source areas were raised sequentially, and some repeatedly, from earliest Miocene to Pliocene time.

Formation rank subdivisions of the pre-Camp Rice part of the Santa Fe Group (Fig. 7) from oldest to youngest are: 1) lower Miocene transitional strata, mostly fanglomerate, that, near basin centers, grade down into tuffaceous sedimentary rocks of the upper Thurman Formation (Kelley and Silver, 1952; Seager and Hawley, 1973); the Thurman in turn interfingers downward with Uvas Basaltic Andesite (26 m.y.); 2) lower to middle Miocene Hayner Ranch Formation, mostly fanglomerate; 3) middle to upper Miocene Rincon Valley Formation, fanglomerate near basin margins, locally containing Selden Basalt (9 m.y.), grading to gypsiferous playa or alluvial flat deposits basinward. Near the center of paleobasins the three formations are conformable, but along basin margins the Hayner Ranch and Rincon Valley Formations overlap older units, often producing striking unconformities.

Oldest, largest and deepest of the two paleobasins is reconstructed from exposures of basin fill in the Rincon Hills and Tonuco uplift. Figure 6 shows the location of this basin and adjacent source uplifts and Figure 7A is a diagrammatic cross section across the basin. All three formations are generally conformable, totaling 4,000 ft to 5,000 ft in thickness. The deposits grade from fanglomerate in the lower two-thirds to playa or alluvial-flat sediments at the top. On the south side of the basin, in the Tonuco uplift, composition of clasts indicates that Eocene andesitic rocks exposed along the eastern rim of the Goodsight-Cedar Hills depression were the source rocks during deposition of the transitional strata. In Hayner Ranch time rhyolitic detritus from the Cedar Hills became important as well. Major contribution of Uvas Basaltic Andesite and Bell Top ash-flow tuffs from the Cedar Hills and Sierra de las Uvas characterize Rincon Valley deposition. In contrast, on the north side of the basin in the Rincon Hills, transitional strata and Hayner Ranch Formation contain very coarse boulder fanglomerate derived largely from the Sierra de las Uvas, while the younger Rincon Valley fanglomerate facies was derived mostly from Paleozoic rocks in the Caballo uplift. The Rincon Valley Formation locally overlaps mineralized (barite-fluorite-manganese) fault blocks of older Santa Fe strata with angular unconformity. These fault blocks were probably active along paleobasin margins during deposition of the Santa Fe Group.

This old basin clearly connects the Jornada del Muerto basin with the Palomas basin (Fig. 6), and deposits of similar thickness and age may be present in each of these basins. The two basins are separated today by a narrow intrarift horst, comprised of old rift deposits, trending southeastward between the Rincon Hills and San Diego Mountain. Thus, the Rio Grande rift in the restricted sense visualized by Kelley (1952) and other workers does not appear to end at Hatch but bends sharply eastward into the southern Jornada del Muerto, then turns southward. Southwest of Bishop Cap, the Mesilla bolson continues the trend of linked, en echelon rift basins southward to Mexico. (Tectonic Map of Rio Grande Region, in pocket). Batholithic roots of the Goodsight-Cedar Hills depression may have deflected rift structures around the Sierra de las Uvas.

A somewhat younger paleobasin developed in middle to late Miocene (Rincon Valley) time over what was previously a structurally high area between Sierra de las Uvas and the Jornada del Muerto basin. The basin is filled with fanglomerate of the Rincon Valley Formation that overlies Eocene-Oligocene volcanic rocks. From the Sierra de las Uvas, known deposits extend eastward to the Radium Springs area; the basin surface probably was graded to the floor of the Jornada del Muerto basin east of Radium Springs. The northern edge of the basin merges with the older, deeper basin just described. Rincon Valley playa and alluvial-flat strata exposed in the Tonuco uplift, Rincon Hills and along the northeastern side of the Sierra de las Uvas are common to both basins. Figure 6 shows the location and source areas of this basin and Figure 7B is a cross section across the basin.

Exposures of this younger basin fill are widespread, particularly in intrabasin uplifts such as the East and West Selden Hills and Cedar Hills, and in their intervening grabens. Thicknesses are generally less than 1,000 ft, thinning to near zero eastward. Clast compositions indicate the principal source areas were the Sierra de las Uvas and Cedar Hills, although thickness and structural reconstructions suggest that the Cedar Hills block was eventually buried by the basin fill. No clasts from such prominent modern fault blocks as the East and West Selden Hills, Tonuco uplift or Robledo Mountains are known within this basin. These uplifts are young intrarift fault blocks pushed up through older basin fill.

In the Selden Canyon area two basaltic flows are interbedded in the Rincon Valley fanglomerate. Named Selden Basalt (Seager and others, 1975), these flows apparently spread over a comparatively small part of the toe slope of the fans that drained eastward from the Cedar Hills-Sierra de las Uvas area. A potassium argon date of 9 m.y. from one flow establishes the late Miocene age of at least part of the Rincon Valley Formation; older parts of the formation may be as old as middle Miocene.

CULMINATION OF RIFTING

Disruption of the Popotosa Basin

Rifting was greatly accelerated in Socorro County in latest Miocene and/or Pliocene time after the eruptions at Socorro Peak (10-12 m.y. ago). The Popotosa playa and fanglomerate deposits on which these volcanic rocks rest now crop out at elevations as much as 2,000 ft above the present floodplain of the Rio Grande along the axis of the Socorro-Lemitar uplift (Fig. 5). The Bear Mountains may be even younger. They form a little-eroded, west-dipping hogback capped by basaltic andesites and fanglomerates which were earlier deposited on the floor of the Popotosa basin. On the Skylab photo (Fig. 4), this range resembles a turned-up lip of the basin floor like one might see on the edge of a giant mudcrack. Note the consequent drainage and lack of mature dissection characteristic of the other ranges. Playa deposits of lower Miocene Popotosa are exposed on its northwestern flank and the fanglomerate of Dry Lake Canyon, shed off the north end of the ancestral Magdalena Range before its downfaulting by the San Augustin rift, extends two-thirds of the way up its dip slope. (This resembles a giant fan on the Skylab photo, but it is a fan not related to the Bear Mountains.)

Segmentation of the Popotosa basin occurred over a long interval of time, in an irregular manner, complicated by bifurcation of the Rio Grande rift through the basin (Chapin 1971a), and culminated in latest Miocene and/or Pliocene time with changes both in rate and style of deformation. The earliest intrabasin uplift was the ancestral Magdalena Range (Figs. 3, 5) which was a major source of sediment for the Popotosa Formation. This uplift occurred after deposition of fanglomerate and playa deposits interbedded with the La Jara Peak Basaltic Andesite in the northwest corner of the basin (see section on Uplift of the Colorado Plateau) and before bifurcation of the rift. The andesitic fanglomerate of Dry Lake Canyon was shed off the west slope of the ancestral Magdalena Range into the Milligan Gulch graben. The fanglomerate of Dry Lake Canyon was derived almost entirely from the La Jara Peak Basaltic Andesite but not from the Bear Mountains, because: 1) The fanglomerate of Dry Lake Canyon extends at least 9 mi south of the Bear Mountains to beyond U.S. Highway 60, 2) the Bear Mountains are not sufficiently eroded to provide the necessary volume of material, 3) transport directions in the fanglomerate of Dry Lake Canyon (based on pebble imbrications) point to the downfaulted north end of the Magdalena Range, and 4) the fanglomerate of Dry Lake Canyon extends well up onto the dip slope of the Bear Mountains and is conformable with the underlying La Jara Peak Basaltic Andesite. The fanglomerate of Dry Lake Canyon interfingers westward with fanglomerates containing mostly ash-flow tuff clasts derived from the more deeply eroded Gallinas uplift which forms the western margin of the Popotosa basin.

Simultaneously with westward deposition of the fanglomerate of Dry Lake Canyon, a major piedmont slope built eastward from the ancestral Magdalena Range into the area now occupied by the Socorro-Lemitar Range and the type locality of the Popotosa. Thick playa deposits, now uplifted along the Socorro-Lemitar axis, accumulated along the toe of this piedmont slope. Transport directions in Popotosa fanglomerate and transition facies along the Socorro-Lemitar axis (Fig. 5) are predominantly from the west (Bruning, 1973).

The Ladron Mountains were repeatedly uplifted and shed fans southward and eastward into the Popotosa basin. Pebble counts in both fanglomerate and transition facies in the type locality show an increase in clasts of Precambrian and Paleozoic rocks towards the Ladron Mountains (Bruning, 1973, pls. 2A, 2C, 2D), beginning near the base of the exposed Popotosa section. The Ladron Mountains were strongly uplifted and shed a major fan system (the fanglomerate of Ladron Peak) into the basin after the accumulation of several hundred to several thousand feet of strata of largely volcanic composition from sources to the west. Thicknesses and stratigraphic relationships are not entirely known in the type locality because of faulting and partial overlap by beds of the upper Santa Fe Group. The Ladron Mountains were again strongly uplifted during the latest Miocene and/or Pliocene culmination of rifting and were a major source for younger sediments of the Santa Fe Group.

The ancestral Magdalena Range was partly buried by its own debris prior to rejuvenation in latest Miocene and/or Pliocene time. Coarse fanglomerates crop out in the South Baldy area at elevations near 10,600 ft, on the mesa east of Water Canyon at elevations of 8,000 ft and less, and on the southeast side of Magdalena Peak at an elevation of 7,200 ft. Other factors than faulting may be involved in these differences in elevation but they give some indication of the magnitude of late Miocene to Holocene faulting and rotation within the Magdalena Mountains; much greater displacements occurred on range-bounding faults.

Sometime after lavas were erupted onto playa muds at Socorro Peak (10-12 m.y. ago), the style of deformation changed to thin-skinned distension (Anderson, 1971) characterized by strong rotation of fault blocks above normal faults whose dips must decrease rapidly with depth. The Popotosa basin was fragmented into parallel horsts and grabens with relatively uniform spacing of 11 to 14 mi. Rocks of Precambrian to Miocene age were uplifted from the floor of the Popotosa basin through several thousand feet of basin fill and strongly rotated to form tilted fault-block mountains. Dips of 40 to 70 degrees are common in the Lemitar Range and in the modern Magdalena Range north of Kelly. Conformable dips between strongly tilted Popotosa beds and underlying formations, together with disruption of playas along the Socorro-Lemitar axis, indicate that uplift and rotation occurred after deposition of most, if not all, of the Popotosa Formation. Erosion truncated upturned Popotosa strata along the mountain flanks; later burial of these surfaces by fans of the upper

Santa Fe Group formed conspicuous angular unconformities.

A hinge line between thin-skinned, rotational deformation to the east and conventional horst and graben structure to the west, extends from the west flank of the modern Magdalena Mountains in the Kelly district (Fig. 5) north-northwestward to the Bear Mountains. Between this line and the edge of the Milligan Gulch graben, the ancestral Magdalena uplift has undergone little rotation as evidenced by the relatively horizontal pre-La Jara Peak (24 m.y.) erosion surface, partially exhumed over many square miles, and the essentially undeformed rhyolite flows (14 m.y.) south of Magdalena Peak. Between this line and the Rio Grande, rotation of fault blocks generally varies between 20 and 70 degrees. Gravity slide blocks are common along the frontal escarpments of the Socorro-Lemitar Range (R. M. Chamberlin, oral commun., 1975) and the Ladron Mountains (G. O. Bachman, oral commun., 1975) and may be present elsewhere. Transverse faults separate segments of fault blocks which have undergone markedly different rotations.

That portion of the original Popotosa basin east of the Rio Grande was uplifted, the basin-fill sediments eroded, and the highly faulted floor of the basin exhumed over an area about 12 mi wide east-west, and extending from the south edge of the Albuquerque basin to the Jornada del Muerto basin, a north-south distance of about 35 mi. This exhumed basin floor is conspicuous in the complexity of its faulting and its relatively low elevation (see Tectonic Map of the Rio Grande Region, in pocket, and the Skylab photo, Fig. 4). Transport directions in Popotosa deposits west of the Rio Grande are predominantly from the west and the major playa deposits along the Socorro-Lemitar axis indicates that this area was recurrently the lowest part of the basin floor. The Popotosa basin must have extended east of its playas for an appreciable distance since fans derived from the east have not been observed to interfinger with the playa deposits. The anomalous tectonic and geomorphic character of the belt of low foothills east of the Rio Grande and the preservation of thick sections of volcanic rocks from the Datil-Mogollon field within the foothills belt suggests that this was the basin floor. Late Cenozoic uplift exhumed the basin floor and helped produce the illusion of a "Socorro constriction."

The latest-Miocene and/or Pliocene culmination of rifting accelerated bifurcation of the Rio Grande rift along its San Augustin arm. Earlier evidence of the bifurcation consists mainly of alignment of early Miocene (21-23 m.y. ago) basaltic andesite stratovolcanoes along the margins of the San Augustin rift (Elston and others, 1970, Fig. 3; Tectonic Map of the Rio Grande Region, in pocket). Major northeast-trending grabens in the Magdalena area apparently did not form until after eruption of rhyolitic flows (14.3 ± 1.0 m.y., Weber and Bassett, 1963) from the Magdalena Peak dome. The vent is exposed on the east side of Magdalena Peak (Figs. 4, 5) about 1.5 mi southeast of the main bounding fault of the San Augustin rift. The rhyolitic lavas flowed southward for as much as 10 mi, but not northward into the San Augustin rift which must, therefore, be younger. Also, flow directions deduced from pebble imbrications in the Popotosa Formation yield no evidence of a graben trending northeastward across the basin; rather, the transport directions were consistently from west to east towards the north-trending playas now exposed along the Socorro-Lemitar axis. Therefore, it appears that the major grabens marking the San Augustin rift formed sometime during the latest Miocene and/or Pliocene acceleration of rifting. The 0.8 to 1.5 m of left-lateral, oblique-slip movement (Chapin, 1971a) on the bounding faults of the San Augustin rift in the Magdalena area reflects westward movement of the Colorado Plateau block in response to rapid spreading of the Rio Grande rift.

Disruption of Miocene Paleobasins in Northern Dona Ana County

Culmination of rifting apparently took place in Dona Ana County in latest Miocene and/or Pliocene time, after eruption of the Selden Basalt (9 m.y.) but before deposition of ancestral Rio Grande (Camp Rice) and related deposits 2 to 3 m.y. ago. Breakup of the broad paleobasins resulted in the formation of numerous, narrow, closely spaced intrabasin fault blocks such as the East and West Selden Hills, Robledo Mountains, Tonuco uplift, Rincon Hills, and their intervening grabens. Continuing uplift of older fault blocks such as the Caballo, Sierra de las Uvas and Cedar Hills during late Miocene-Pliocene time is indicated by offset of the Rincon Valley Formation along boundary faults. Nearly all of these ranges are comprised partly of uplifted paleobasin deposits and all essentially acquired their modern dimensions during this period. Except for thin late Pliocene and Pleistocene fanglomerate (Camp Rice Formation), no sedimentary record of the latest Miocene to Pliocene deformation is known. In fact, Plio-Pleistocene (Camp Rice) fanglomerate lies across broad, pedimented surfaces that truncate uplift margins and range-boundary faults, as well as late Miocene basin deposits. It is clear that the late Miocene to latest Pliocene interval was not only a period of major uplift, but also of subsequent widespread erosion, including pedimentation. Presumably the missing sediments were carried out of this area by some as yet undocumented river system of middle? to late Pliocene age, perhaps to be deposited in deep late Pliocene and Pleistocene basins in southernmost New Mexico, West Texas, and northern Mexico (J. W. Hawley, personal communication).

The sedimentary deposits and structures of Miocene and Pliocene age indicate a sequential development of late Tertiary uplifts and basins in the Las Cruces area. Uplifts like the Sierra de las Uvas and Cedar Hills apparently have great antiquity, dating back at least to the earliest part of the Miocene. Broad, deep paleobasins formed adjacent to these uplifts and were filled largely by detritus from them and from remnant Oligocene volcano-tectonic features such as the eastern margin of the Goodsight-Cedar Hills depression. Intermittent uplift of the Cedar Hills and Sierra de las Uvas throughout the Miocene and Pliocene is indicated by the stratigraphy of bolson fill as well as by structural features. On the other hand, the southern Caballo Mountains apparently were initially uplifted in middle to late Miocene time, while uplifts such as the Rincon Hills, Tonuco uplift, East and West Selden Hills, and probably Robledo Mountains are the product of latest Miocene and Pliocene faulting. The latest Tertiary faulting disrupted the older paleobasins and created the modern system of comparatively narrow, closely-spaced fault blocks in northern Dona Ana County.

Post late Pliocene uplift has not been spectacular. Offset or warping of Plio-Pleistocene deposits ranges from a few to perhaps 300 ft, the latter displacement along the eastern side of the Robledo Mountains. Much of this movement can be dated no closer than post middle Pleistocene. Late Quaternary fault scarplets, a few feet high, have been mapped in the Hatch area. These suggest uplift continuing to the present, perhaps on a diminishing scale.

Discussion

Was the latest Miocene and/or Pliocene surge of block faulting, which so profoundly affected the early basins of the Rio Grande rift and initiated the modern landscape, a peak of tectonism or is faulting and uplift continuing at a similar high, or even higher, rate? Should this section have been entitled "Acceleration of Rifting" instead of "Culmination of Rifting"? This question cannot be resolved with certainty because of the scarcity of data and the possibly episodic nature of tectonism, but it is worth pondering.

Evidence suggesting a culmination of rifting in latest Miocene and/or Pliocene time may be summarized as follows:

1) The present configurations of uplifts, basins, and the Rio Grande were largely established during this interval. Middle to late Pliocene and Pleistocene surfaces are related to these geomorphic elements and the late Pliocene-Pleistocene ancestral Rio Grande flowed approximately along its present route in New Mexico (Debrine and others, 1963, Fig. 2; Seager and Hawley, 1973; Seager and others, 1975; Hawley, Fig. 2, this guidebook).
2) The San Augustin arm of the rift appears to have been inactive for some time. Stearns (1962) reported that there was no evidence of tectonic activity in the San Augustin graben since the Wisconsin Lake San Augustin. In the Magdalena area, faulting parallel to the main stem of the Rio Grande rift has superimposed a north-trending structural grain across the San Augustin rift.
3) Total offset on range-bounding faults during the past 10 m.y. is relatively great compared to what could be extrapolated from the maximum observed offset of late Pliocene and Pleistocene axial river deposits and geomorphic surfaces. Hawley (this guidebook) reports that total displacement of lower Pleistocene and upper Pliocene beds in the Las Cruces area may locally exceed 300 ft. Axial river deposits of similar age along the west side of the Rio Grande in the Socorro area are as much as 600 ft above the present flood plain. Assuming that half of the 600 ft is due to entrenchment by the Rio Grande and half to tectonic movements yields a figure of 300 ft of uplift in 2 m.y., a figure similar to that reported by Hawley for the Las Cruces area. In the 10 m.y. since Socorro Peak volcanism, this rate of displacement would yield a total uplift of about 1,500 ft. Crude calculations indicate that offsets along frontal faults of major rotated blocks, like the Magdalena and Lemitar Ranges, during the past 10 m.y. are on the order of 10,000 to 15,000 ft. At least 8,000 ft of displacement has occurred on faults bounding the San Diego Mountain block in the Las Cruces area where Precambrian rocks now protrude through strongly tilted playa deposits of the Rincon Valley Formation (Fig. 6, 7).
4) More importantly, 2 to 3 m.y. old axial river deposits of the ancestral Rio Grande (Camp Rice Formation) lie across truncated intrabasin horsts in the San Diego Mountain-Rincon Hills area (Seager and others, 1971; Seager and Hawley 1973), yet these deposits are little deformed in spite of the fact that the same horsts uplifted and exposed strongly tilted early basin fill (Rincon Valley and older formations).
5) In general, dips in early basin fill (Popotosa and Hayner Ranch Formations) tend to be steep (20 to 60 degrees), whereas dips in the upper basin fill (upper Santa Fe Group, Camp Rice Formation) tend to be relatively gentle.

Evidence suggesting that rifting has continued at a rate comparable to that in latest Miocene and/or Pliocene time may be summarized as follows:

1) Abundant fault scarps cut late Pliocene and Pleistocene surfaces in the Socorro area (Sanford and others, 1972) and are characteristic of the Rio Grande rift along its entire length.
2) Terrestrial heat flow is high with a distinct anomaly along the western margin of the rift (Reiter and others, 1975).
3) Volcanism accelerated sharply about 5 m.y. ago (Fig. 9) and has remained active into Holocene time. However, there may be a 3 to 5 m.y. lag between the onset of an extensional episode and the acceleration of volcanism. Regional extension began in the Magdalena area at about 29 m.y. ago but large-scale basaltic andesite volcanism did not begin until about 24 m.y. (see section on Beginning of Regional Extension). Major basaltic andesite volcanism began in the Las Cruces area about 26 m.y. ago. The pulse of uplift and block faulting which disrupted the Miocene basins of the Socorro and Las Cruces areas must have begun shortly after eruption of the Selden Basalt (9 m.y.) and the Socorro Peak volcanic rocks (10-12 m.y.) in order to have thoroughly segmented the basins before deposition of late Pliocene beds which are related to near modern topography and show little deformation. Thus, block faulting may have peaked in the Pliocene but we are still near the peak of the resultant, later volcanism.

The change in structural style from conventional horsts and grabens to thin-skinned distension during the latest Miocene and/or Pliocene fragmentation of the Popotosa basin is of particular interest concerning evolution of the Rio Grande rift. Anderson (1971, p. 43) concluded that the extreme distension he observed in southeastern Nevada was:

> .. a surficial feature of a crustal belt that was subjected to a brief episode of tensional rifting. Rifting at subjacent levels along the belt was compensated for by emplacement of plutons. The surficial rocks were stretched and thinned over the plutons."

Sanford and others (1973) report the presence of a sharp discontinuity underlain by material of very low rigidity at a depth of 18 km beneath Socorro. The disconformity was traced northward for a distance of about 60 km (37 mi) during which its depth increased to about 30 km. Very high terrestrial heat flow (as much as 11.5 HFU) has been measured in the Socorro Peak area (Sanford and others, op. cit.; M. A. Reiter, oral commun., 1975). Thus, the Socorro area seems to fit Anderson's model in both structural and geophysical characteristics.

In the Las Cruces area, Decker and Smithson (1975) and Decker and others (this guidebook) report an unusually high heat flux and a positive Bouguer gravity anomaly. Their interpretive cross-sections show crustal thinning, a pillow of low-density upper mantle, and either a 9 km upwarp at the crust-mantle interface or a shallow, sill-like basaltic pluton. C. A. Swanberg (this guidebook) has interpreted high temperatures of ground water in the San Diego Mountain area from studies of Na, K, and Ca concentrations.

The Socorro and Las Cruces areas are the only localities along the Rio Grande rift where uplift and thin-skinned distension have elevated horsts through several thousand feet of Miocene sedimentary rocks near the centers of basins. Strong rotation of horsts, tilting of flanking strata, and truncation by erosion have exposed great thicknesses of basin fill. Major breaks in the sedimentary record and spectacular angular unconformities exist between deposits of late Pliocene to Pleistocene age and those of late Miocene or older age. Other basins of the Rio Grande rift, which escaped thin-skinned fragmentation, have undergone nearly continuous sedimentation.

Thus, the Socorro and Las Cruces areas are anomalous and we must ask whether the culmination of rifting apparent in these localities is valid elsewhere.

Scott (1975) reports that uplift and canyon cutting was greatly accelerated in the Southern Rocky Mountains in Pliocene time but that local Quaternary uplift probably did not exceed 100 m. Near Salida, Colorado, the major west-northwest-trending cross fault which separated the upper Arkansas basin from the San Luis basin, underwent 1 to 2 km of movement after deposition of beds containing a 7 m.y. old Ash Hollow fauna (Taylor 1975). In the Espanola basin, the middle to late Miocene portion of the Santa Fe Group (well-exposed, but only representing the east half of the basin) represents relatively continuous and uniform bolson sedimentation. But beginning in late Miocene or early Pliocene time, sedimentation became more variable, both in composition and mode of deposition, and several important unconformities developed (Galusha and Blick, 1971, Fig. 9, 10; Kim Manley, oral commun., 1975). Relatively undeformed ancestral Rio Grande deposits of the Puye Formation and the basalt capping Black Mesa, both dated at about 3 m.y. by Kim Manley (oral commun., 1975), establish a late Pliocene limit on the main period of deformation. Dating of basalt flows, geomorphic surfaces, and axial river deposits in central New Mexico by Bachman and Mehnert indicates that the main pulse of rifting was over by late Pliocene time (G. O. Bachman, oral commun., 1975).

BEGINNING OF THROUGH DRAINAGE— THE ANCESTRAL RIO GRANDE

The history of the Rio Grande is a subject of considerable controversy and one to which a great deal of recent work has been devoted. A detailed discussion of the Quaternary history of the Las Cruces area has been presented elsewhere in this guidebook by J. W. Hawley. Much less is known about the late Pliocene and Quaternary history of the Socorro area, but G. O. Bachman, H. H. Mehnert, and Michael Machette of the U.S. Geological Survey are currently mapping and dating late Cenozoic deposits and surfaces in this area. Papers by Denny (1941) and DeBrine and others (1963) provide a starting point for the Socorro area. Only a brief summary will be attempted here.

Most of the late Cenozoic history of the Rio Grande rift has been one of bolson sedimentation under arid to semi-arid conditions in closed basins. The "sand-filled tubs" of Bryan (1938) are a series of structurally aligned basins which lacked a master drainage until sometime in latest Miocene or Pliocene time. The oldest known axial river deposits which can unequivocally be related to an ancestral Rio Grande are late Pliocene in age. DeBrine and others (1963, Fig. 2) published a map of part of the Socorro Valley showing a belt of outcrops of "axial river sands and gravels interfingered with floodplain silts and clays" which parallel the east side of the present Rio Grande for about 16 mi and average about 1.5 mi in width. Needham (1936) reported that fossil vertebrates found in these axial river deposits were identified as late Pliocene in age by C. L. Gazin. J. W. Hawley (oral commun., 1975) considers the faunal assemblage to be of probable Blancan age. The highest of these axial river deposits is only 200 to 250 ft above the present floodplain of the Rio Grande. Along the west side of the Socorro Valley, axial river sands are exposed at elevations as much as 600 ft above the present Rio Grande. One such deposit underlies a remnant of the basalt flow of Black Mesa, near the perlite mine 2.5 mi southwest of Socorro. K-Ar dating of this flow is in progress by Bachman and Mehnert.

J. W. Hawley (this guidebook) reports that ancestral Rio Grande deposits can be followed nearly continuously along the river valley from Socorro to south of El Paso. In southern New Mexico and in the El Paso area, these deposits are known as the Camp Rice Formation (Strain, 1966) and considered to be uppermost Santa Fe Group. The age of the Camp Rice Formation has been established on the basis of vertebrate faunas, volcanic ash correlations, and paleomagnetic measurements to extend from more than 2.0 m.y. ago to less than 0.6 m.y. (see summary in Seager and others, 1975, and Hawley, this guidebook). The base of the Camp Rice is extensively exposed in the Rincon and Sierra Alta Quadrangles (Seager and Hawley, 1973; Seager and others, 1975) where it rests on a widespread erosion surface truncating tilted basin fill (Hayner Ranch and Rincon Valley Formations) and older rocks. Widespread deposition of the Camp Rice Formation ceased in late middle Pleistocene time and the Rio Grande subsequently eroded deeply into its earlier deposits. Integration of through drainage to the Gulf of Mexico by capture of the ancestral upper Rio Grande at El Paso is thought to have caused the abrupt change in flow regime. (Kottlowski, 1958; Ruhe, 1962, 1967; Strain, 1966; Hawley and Kottlowski, 1969).

A fission-track date of about 3 m.y. (Kim Manley, oral commun., 1975) on an ash bed near the base of the Puye Formation in the Espanola basin established a late Pliocene age for an ancestral Rio Grande in northern New Mexico. It appears, then, that integration of drainage along the Rio Grande rift occurred late in the Pliocene and at about the same time along the various segments of the rift. However, this story is based upon the recognition and dating of deposits left by an aggrading river. How long the river existed before major aggradation began is a question that cannot yet be answered. As the integrating stream worked south, its initial deposits in a given basin might have been removed by entrenchment, consequent upon lowering of base level, when the stream entered the next basin. Preservation of axial river deposits probably did not become common until the stream's longitudinal profile approached equilibrium. Also, the ancestral Rio Grande might have infiltrated into one, or more, of the actively subsiding northern basins of the rift until a combination of uplift in the headwaters and climatic changes provided sufficient water for it to escape to the south.

Since the change from internal drainage and bolson sedimentation to through drainage along the Rio Grande occurred near the end of the latest Miocene and/or Pliocene culmination of rifting, a cause and effect relationship might be anticipated. Drainage in central Colorado east of the Continental Divide has been generally eastward across the north-trending structural grain since the carving of an erosion surface of regional extent and low relief in the late Eocene (Epis and Chapin, 1973, 1975). Exceptions are the upper Arkansas River above Salida (in the upper Arkansas Valley segment of the Rio Grande rift) and the Rio Grande after it leaves the San Juan Mountains and turns southward down the San Luis Valley. East-trending late Eocene, Oligocene, and early Miocene paleovalleys described by Epis and Chapin (1968, 1973, 1975), Chapin and others (1970), Lowell (1971), Scott (1973, 1975), Scott and Taylor (1975), Taylor (1973, 1974, 1975), Taylor and others (1975) indicate that the ancestral South Platte and Arkansas Rivers maintained general eastward courses in spite of diversions by Oligocene volcanism and Neogene block faulting. An east-trending ancestral Rio Grande probably did the same until rapid uplift of the Sangre de Cristo Mountains diverted it southward along the deepening Rio Grande trough. Thus, it was probably the great barrier of the late Cenozoic Sangre de Cristo Mountains, which stretch uninterrupted for 230 mi from Salida, Colorado to near Santa Fe, New Mexico, that gave the Rio Grande rift an exotic river that could integrate drainage along its en echelon chain of basins.

SUMMARY AND CONCLUSIONS

The late Cenozoic histories of the Socorro and Las Cruces areas are similar. When integrated with data from other localities along the Rio Grande rift, the following conclusions can be drawn:

1) Regional extension began about 29 m.y. ago. Its first effect was to break the roofs of Oligocene batholiths and to allow the ascent of numerous shallow plutons.
2) Three to five million years after the beginning of regional extension, large volumes of basaltic andesite lavas were erupted and interbedded with fanglomerates in structurally controlled basins. The basaltic andesites have calc-alkalic affinities, high Sr^{87}/Sr^{86} ratios, and are related to the middle Tertiary volcanic episode. An extensive veneer of basaltic andesite flows spread over the Datil-Mogollon volcanic field between about 26 and 20 m.y. ago.
3) The Colorado Plateau began to rise about 24 m.y. ago and shed debris into a broad basin in the Socorro area.
4) The early basins of the Rio Grande rift were broad downwarps as much as 40 mi in width. They received several thousand ft of bolson sediments between early Miocene (24-26 m.y.) and late Miocene (9-10 m.y.) time. The basins are filled with complex deposits characterized by intertonguing of alluvial-fan, piedmont-slope, and alluvial flat-playa facies plus compositional facies caused by differences in source area.
5) Sometime after 9 or 10 m.y. ago, in latest Miocene and/or Pliocene time, uplift and block faulting was sharply accelerated along the Rio Grande rift. In the Socorro and Las Cruces areas, thin-skinned distension fragmented the early broad basins by uplift of closely spaced, strongly rotated, intrabasin horsts. A major gap in the sedimentary record exists in these areas between strongly tilted lower basin fill of late Miocene and older age and relatively flat-lying deposits of Plio-Pleistocene age. Elsewhere along the rift, sedimentation was relatively continuous.
6) The Socorro and Las Cruces areas are anomalous. They are the only areas along the Rio Grande rift where horsts have been elevated through several thousand feet of late Cenozoic sedimentary fill near the centers of basins. The combination of thin-skinned distension, high heat flow, and other geophysical anomalies suggests the possibility of major intrusions into the rift structure. Geothermal exploration seems warranted in these areas.
7) Rifting is continuing, but at a slower rate than during the latest Miocene and/or Pliocene culmination. Basalt flows and sedimentary deposits of late Pliocene and younger age are relatively undeformed.
8) The modern landscape was born during the latest Miocene and/or Pliocene culmination of rifting. Older basins are not evident in the modern landscape and can only be reconstructed by stratigraphic studies of the basin fill. The "Socorro constriction" is an illusion produced by the modern topography.
9) Through drainage was integrated along the Rio Grande rift in the waning stages of the latest Miocene and/or Pliocene culmination of rifting. The earliest known axial river deposits of an ancestral Rio Grande are late Pliocene (2-3 m.y.) in age. They are little deformed, rest on strongly tilted early basin fill in the Las Cruces area, and were deposited along a route similar to the present Rio Grande. Rapid uplift of the Sangre de Cristo Mountains may have deflected an east-flowing stream southward along the Rio Grande rift to yield an exotic stream and integrated drainage.
10) Bimodal basalt-rhyolite volcanism began about 14 m.y. ago. The earliest effects were the construction of volcanic piles where major northeast-trending lineaments intersected the Rio Grande rift at Magdalena Peak, Socorro Peak, and the Jemez Mountains. Basaltic volcanism was sharply accelerated about 5 m.y. ago; basaltic fields and individual flows dotted the Rio Grande rift from southern Colorado to the Mexican border after this time. The peak of basaltic volcanism may have lagged 3 to 5 m.y. behind the culmination of rifting, just as basaltic andesite volcanism did behind the initial rifting.
11) Use of the term "fundamentally basaltic" as proposed by Christiansen and Lipman (1972) is misleading. It lumps early Miocene calc-alkalic basaltic andesites with late Miocene and younger basalts. The relative lull in volcanism between about 20 and 14 m.y. ago suggests that two different thermal regimes were involved. The first was related to the middle Tertiary calc-alkalic fields and the overprinting of regional extension across them produced calc-alkalic basaltic andesites. The second is a new thermal regime related to the Rio Grande rift and to major northeast-trending lineaments. True basalts and lesser quantities of rhyolite characterize the late Miocene to Holocene volcanism.

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