



Cenozoic tectonic evolution of the Las Cruces area, New Mexico

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CENOZOIC TECTONIC EVOLUTION OF THE LAS CRUCES AREA, NEW MEXICO

by

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INTRODUCTION

The Las Cruces area (Fig. 1) is within the Rio Grande rift, both in the original restricted sense described by Bryan (1938) and Kelley (1952), and in the broader sense suggested by Chapin (1971). The present topography is dominated by intra-rift uplifts and basins of late Cenozoic age, but these are superimposed upon a variety of older, very different tectonic features of middle Tertiary and Laramide age. My objective in this article is to describe important tectonic elements of different ages to illustrate the evolution of tectonic styles and patterns through the Cenozoic.

Published work and unpublished ideas of many geologists were drawn from in assembling this summary. Among these, studies by Darton (1928), Dunham (1935), Kelley and Silver (1952), Kottlowski (1953, 1960), De Hon (1965), Reeves (1969), Ruhe (1967), Gile, Hawley and Grossman (1970), Dane and Bachman (1965), Bachman and Myers (1968), and Hawley and Kottlowski (1969) were used to supplement mapping by Seager and others (1971), Clemons and Seager (1973), Seager and Hawley (1973), Seager, Clemons and Hawley (1975), Clemons (1975), Seager (1975), and Seager and Clemons (1975). Unpublished data from and discussions with John Hawley, C. E. Chapin, R. E. Clemons, W. E. Elston, F. E. Kottlowski, J. M. Hoffer, E. M. P. Lovejoy, LeRoy Corbitt, Clyde Wilson, and L. H. Gile comprise a basis on which much of the tectonic evolution of the area is interpreted.

Three major stages in the evolution of the area are recognized: Laramide uplift, middle Tertiary (Eocene-Oligocene) volcano-tectonics, late Tertiary (Miocene-Holocene) volcanism and rifting.

LARAMIDE TECTONICS

In the Las Cruces area structures of Laramide age are preserved beneath less deformed, late Eocene volcanic rocks. The intervening erosion surface is widespread and truncates older rocks ranging in age from Late Cretaceous to Precambrian. Conspicuous angular unconformities, particularly along the Rio Grande between the Caballo Mountains and Las Cruces, permit reconstruction of major Laramide uplifts, smaller folds, and faults of both large and small displacement. In the Fra Cristobal Mountains similar structures are Late Cretaceous in age according to Kelley and McCleary (1960), but in north-western Dona Ana County they can not be dated more closely than pre-late Eocene, post-Permian, but are very clearly Laramide in character.

Figure 2 shows an interpretation of the late Eocene subcrop in south-central New Mexico. The figure shows three major north-trending uplifted areas of Laramide age. Eocene or latest Cretaceous rocks overlying Precambrian in the core of each uplift demonstrate erosion of 6,000 to 9,000 ft of Mesozoic and Paleozoic rocks from the uplifts during or following Laramide

midde deformation. Clearly, the present structurally high position of large areas of Precambrian rocks within the Rio Grande rift is partly accounted for by Laramide uplifts.

Structures associated with the Laramide uplifts are well-displayed in the Caballo, Fra Cristobal, and Robledo Mountains, and at San Diego Mountain (Tonuco uplift). Abrupt flexing of beds and associated small thrusts, and cascade folds are common in Paleozoic strata of the Caballos (Kelley and Silver, 1952). Similar features, as well as basement thrusting, have been found at San Diego Mountain (Seager and others, 1971) and in the Fra Cristobal range (McCleary, 1960). All of these structures indicate eastward transport, away from structurally highest parts of Laramide uplifts. A major east-trending pre-late Eocene normal fault with about 1,500 ft displacement is exposed in the Robledo Mountains. This fault is interpreted to be a Laramide cross-fault that displaces the southern nose of the Laramide uplift in that area.

Flexures and thrusts associated with Laramide uplifts of south-central New Mexico are interpreted to be flank monoclines and marginal upthrusts similar to those that border many of the broad, anticlinal uplifts of the Colorado Plateau and southern Rocky Mountains (Eardley, 1962, 1968). Similarly, the southern New Mexico uplifts were probably broad anticlines with steep, locally thrust flanks, though clearly they were not as complex nor as large as those in the Rocky Mountain region. Laramide basins probably are represented by the Jornada del Muerto in the latitude of Truth or Consequences, and perhaps by the Sierra Blanca basin (Kelley and Thompson, 1964). Other Laramide uplifts may eventually be recognized from studies in the Franklin-Organ-San Andres chain; Laramide-type structures are already known in some (Franklins, E. M. P. Lovejoy, personal communication). If these ranges had a Laramide history of uplift, the structurally high Precambrian rocks in the middle of the Rio Grande rift would not be such an enigma.

The base of the Tertiary section is represented in many places by limestone conglomerate derived from the Laramide folds. These conglomerates and associated redbeds, named Love Ranch Formation by Kottlowski and others (1956), are post-orogenic and range from a few feet to about 2,000 ft in thickness. They are mainly locally derived fan deposits but may include talus adjacent to uplifts. The erosion surface on which the conglomerates were deposited exhibits considerable relief; 1,000 ft or more can be demonstrated on the flanks of some Laramide uplifts. Elsewhere, the surface appears to be comparatively flat.

Small amounts of andesitic detritus is present in most outcrops of the basal Tertiary conglomerates. The conglomerates generally grade upward into overlying andesitic strata of late Eocene age.

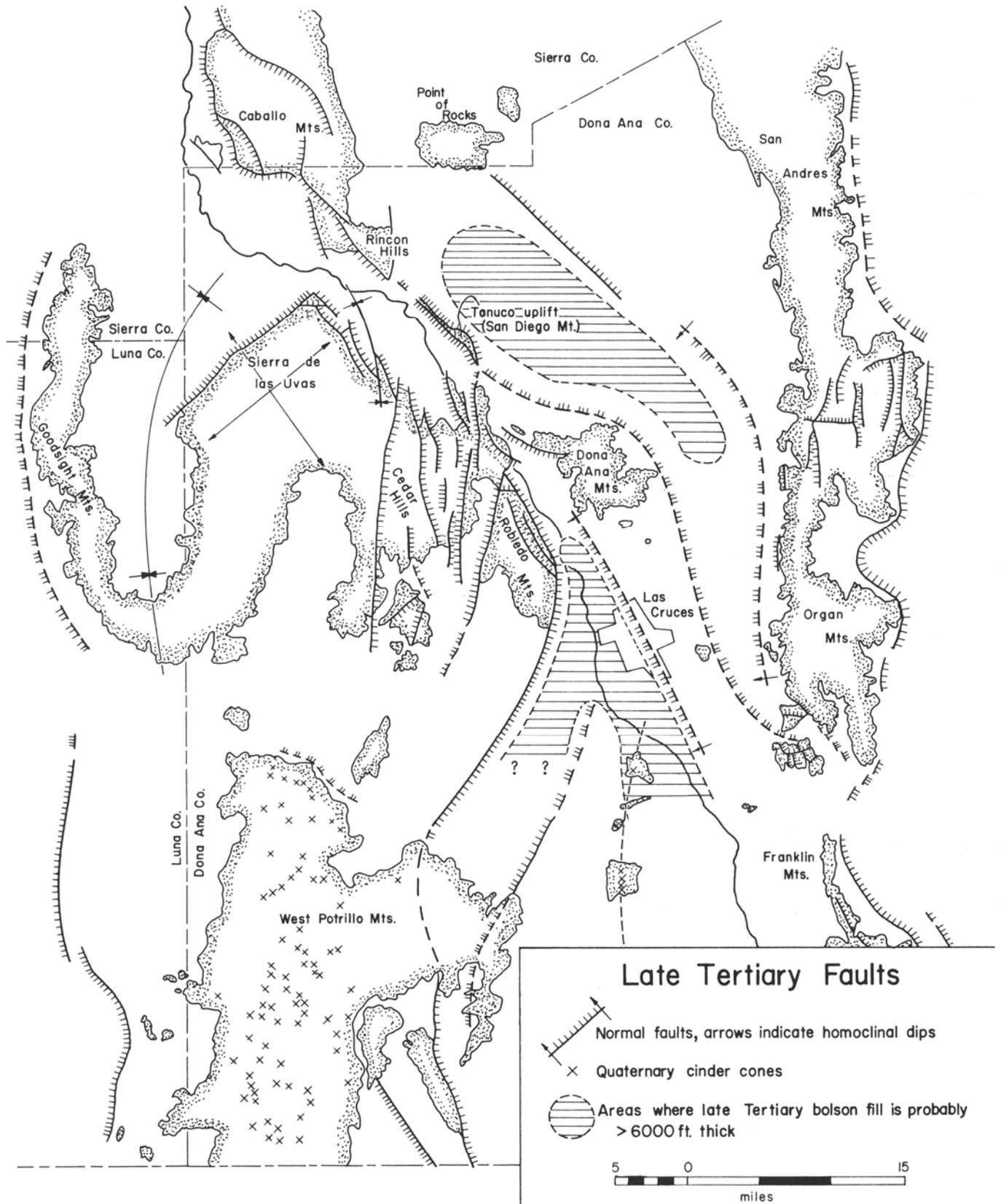


Figure 1. Late Tertiary fault pattern in central southern New Mexico.

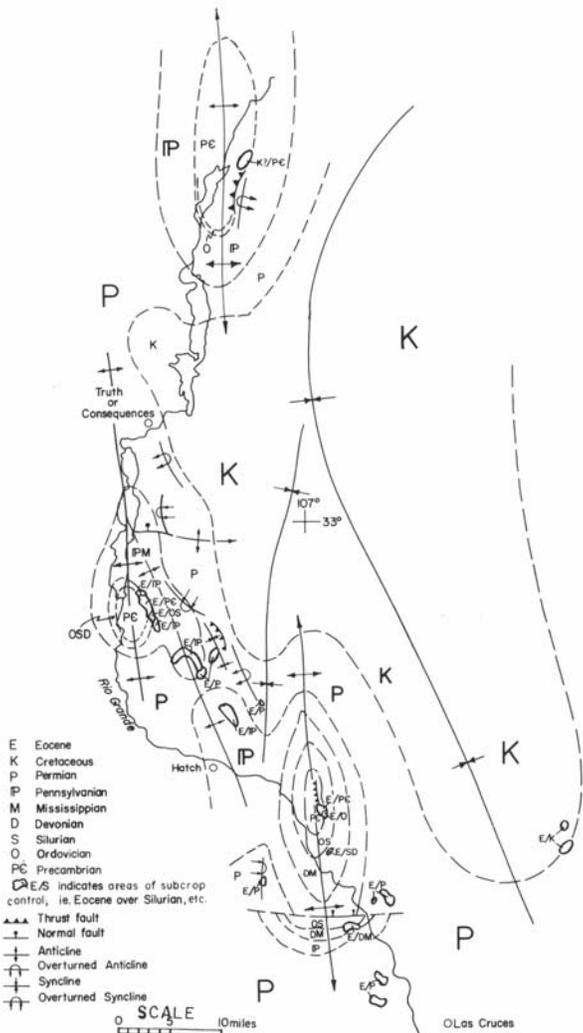


Figure 2. Interpreted late Eocene subcrop map between Las Cruces and the Fra Cristobal Mountains. Laramide uplifts are interpreted to be basement block uplifts with marginal up-thrusts and associated flexures.

MID-TERTIARY VOLCANO-TECTONICS

Middle Tertiary (late Eocene-Oligocene) volcanism is represented by two volcanic sequences, a late Eocene sequence of predominantly andesitic volcanic rocks and associated plutons, and an Oligocene sequence of predominantly silicic volcanic rocks and related plutons. The two sequences are separated by a regional unconformity representing about 3 to 8 m.y.

Eocene Volcanism

In the Las Cruces area Eocene volcanics are predominantly andesitic epiclastic rocks and lesser amounts of andesite flows that grade downward into the fanglomerates just described. They generally are about 2,000 ft thick and probably represent a widespread apron of fluvial and laharc deposits around one or more volcanic centers in the area. The epiclastic rocks, called Palm Park Formation in northern Dona Ana

County, and Orejon Andesite in the Organ range, appear to interfinger westward with andesite and latite of the Rubio Peak Formation (Elston, 1956). Collectively, these formations comprise a thick and widespread, apparently simple, plateau-like sequence of deposits within which very few vent areas or any other kinds of structures, except small subvolcanic sills and an occasional small stock, have been recognized.

Facies distribution of Palm Park beds in northern Dona Ana County and the presence of an andesitic stock in the Dona Ana Mountains suggest that an andesite volcano, now eroded to its roots, existed in that area. Lava flows and coarse-grained laharc breccias containing clasts similar to the stock crop out adjacent to the stock, but these grade outward through channelform laharc breccia beds to fine-grained, basin-center deposits exposed now in the Sierra de las Uvas-southern Caballo region. The stock may be an unroofed magma chamber, the source of at least part of the Palm Park Formation. Similar small stocks and laccoliths are also known near El Paso (Hoffer, 1969, 1970; Lovejoy, personal communication), although volcanic rocks are not present. Other than a northerly alignment, no structural control of these plutons is apparent.

Oligocene Volcano-Tectonics

Oligocene ash-flow tuffs, or locally basalts, overlie Eocene rocks on a widespread disconformity, representing perhaps 3 to 8 m.y. of no geologic record. Although probably not as extensive as the older andesitic strata, the early to middle Oligocene ash-flow sheets spread over considerable areas of the Las Cruces region from their sources in major vent zones or cauldrons. Associated with source structures are notable amounts of intrusive rocks, especially flow-banded rhyolite and monzonite, and lesser amounts of basalt and andesite. Four major volcano-tectonic features are associated with Oligocene ash-flow sheets, and 3 are source cauldrons or vent zones (Fig. 3).

Goodsight Cedar Hills Depression

The Goodsight-Cedar Hills depression (Seager, 1973) is an asymmetric, north-trending elliptical basin about 50 mi long and 25 mi wide located in northwestern Dona Ana County and adjacent areas. The depression is partly filled with 5 ash-flow tuff sheets (Bell Top Formation) that collectively represent about 90 mi³ of rhyolitic magma. An additional 165 mi³ of epiclastic strata are interbedded with the Bell Top ash-flow tuffs, and more than 100 mi³ of Uvas Basaltic Andesite of latest Oligocene and early Miocene age caps the sequence. Along the axis of the depression in the eastern Sierra de las Uvas area, maximum thickness of the depression fill is more than 1,800 ft. Figure 4 is a diagrammatic east-west section through the depression.

Only the eastern boundary of the depression is structurally controlled. Ash-flow tuff, epiclastic and basaltic andesite units thin gradually northward, westward and southward from the basin axis. The eastern boundary, however, comprises a several mile wide faulted zone, within which at least 25 rhyolite intrusions and other types of volcanic vents have been recognized. This north-trending vent zone is called Cedar Hills vent zone and is described separately. The eastward movement of most of the ash-flow tuff units in the depression apparently was blocked by these vent features, particularly the rhyolite intrusions, so that only one of the ash-flow tuffs is found on the

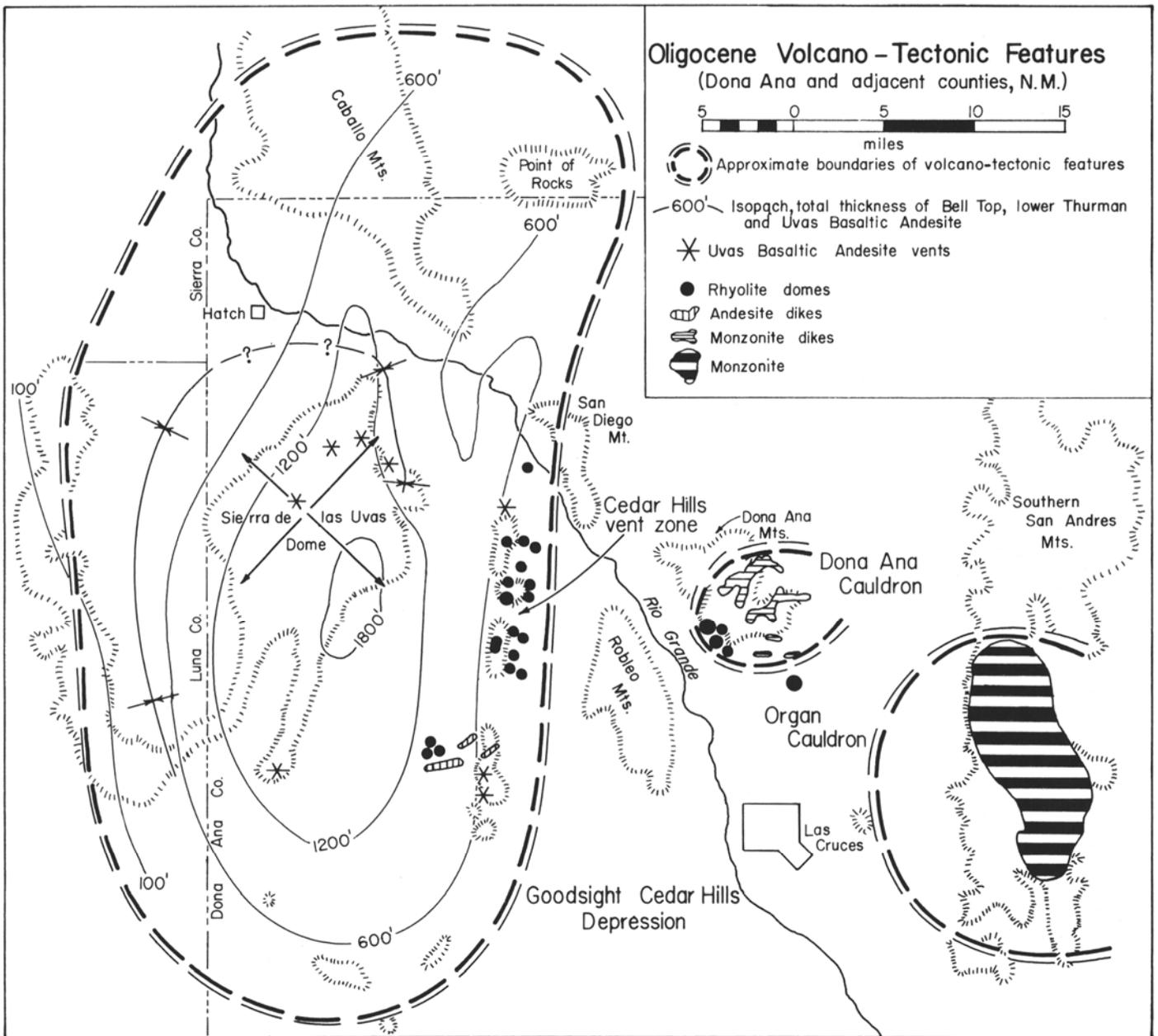


Figure 3. Oligocene volcano-tectonic features near Las Cruces.

raised rim of the depression east of the vent zone. This tuff (tuff 3) erupted from the vent zone prior to rhyolite intrusions and spread radially away from the vent. The source of the other tuffs in the depression is unknown. Because they appear to be largely, if not entirely, confined to the depression, they presumably erupted from some place within it. Sources of Uvas Basaltic Andesite are concentrated near the center of the basin and within the Cedar Hills Vent zone. The Uvas and its vents are related to initial break-up within the Rio Grande rift, hence are considered with the rift.

The Good sight-Cedar Hills depression persisted as a tectonic feature throughout nearly all of Oligocene time. It clearly is not a short lived cauldron of the classic Valles or Toba types. Yet its volcano-tectonic origin seems clear in that subsidence was contemporaneous with and probably consequent on ash-flow tuff eruption and concurrent sedimentation. The struc

ture may be transitional in character between a partly developed cauldron on the east side and a simple, large fault trough. Inasmuch as it is elongated parallel to the Rio Grande rift, it may be viewed as a precursor to Basin and Range structure in the area.

Cedar Hills Vent Zone

The Cedar Hills vent zone along the eastern margin of the Good sight-Cedar Hills depression comprises a belt of intrusive rocks and various volcanic vent features at least 20 mi long and up to 4 mi wide. The vent zone trends nearly north except at its southern end where it swings toward the southwest. This change in strike may be associated with the southeastern margin of the Good sight Cedar-Hills depression. The vent zone was the source of part of the volcanic fill in the adjacent depression.

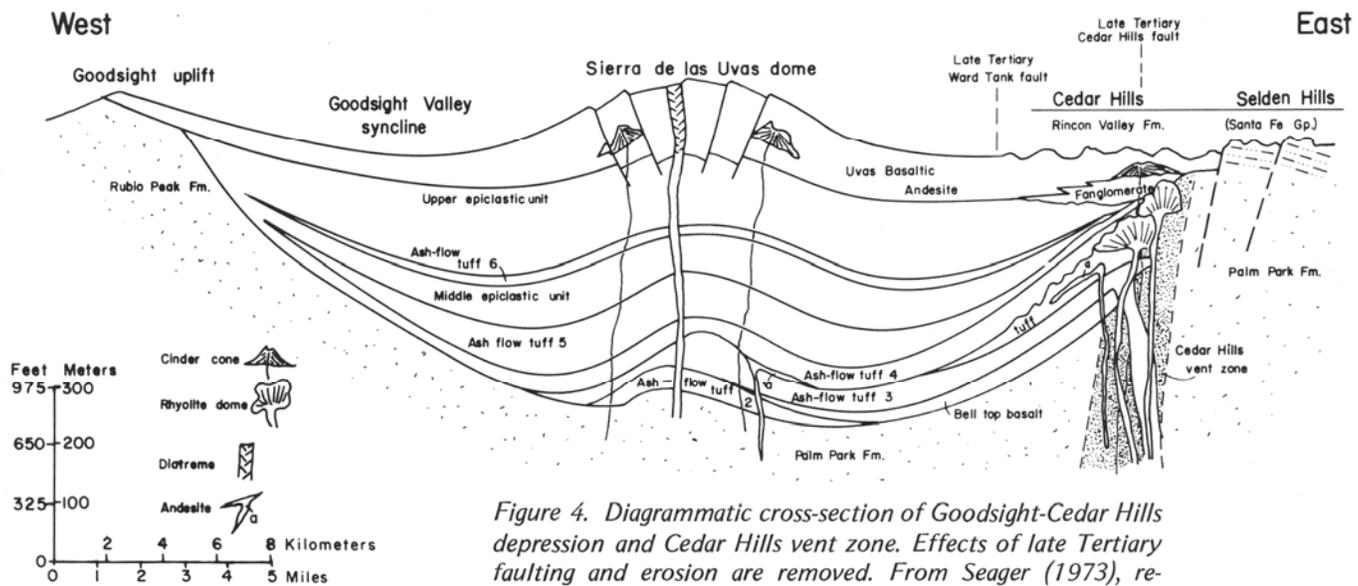


Figure 4. Diagrammatic cross-section of Goodsight-Cedar Hills depression and Cedar Hills vent zone. Effects of late Tertiary faulting and erosion are removed. From Seager (1973), reprinted by permission of Geol. Soc. America.

Much of the volcanic activity in the vent zone has been dated at 33 to 35 m.y. old, but volcanic activity in the zone also occurred about 26 m.y. ago, and perhaps at 9 m.y. ago. Most of the middle Oligocene (Bell Top) volcanism is in the form of flow-banded rhyolite domes, now eroded to their roots, that were emplaced following eruption of ash-flow tuff 3. Twenty five domes have been mapped, as well as a diatreme, tuff cone, collapsed area, and an ignimbrite dike of ash-flow tuff 3. These features apparently formed a formidable barrier to the eastward spread of younger ash flows and basalt flows in the Goodsight-Cedar Hills depression; almost none of the flows or basin fill are found east of the vent zone. At least 6 andesite or basaltic andesite vents have been mapped along the zone; some are in the form of buried cinder cones, some in the form of dikes or plugs. Uvas Basaltic Andesite vents, about 26 m.y. old, comprise half of these. The remainder are sub-volcanic andesite plutons, about 33 to 35 m.y. old, that are within the Bell Top Formation. Selden Basalt flows, about 9 m.y. old, are interbedded in Santa Fe fanglomerates in Selden Canyon. The basalts are nearly restricted in areal extent to the vent zone, and may have been erupted from it, but specific sources of the basalt have not been found.

Dona Ana Cauldron

Most of the southern half of the Dona Ana Mountains are carved from the Dona Ana rhyolite, an ash-flow tuff sequence more than 2,500 ft thick. The tuff and associated rhyolitic to monzonitic intrusive rocks are about 33 to 37 m.y. old, according to K-Ar dating. Differences in mineralogy of the ash-flow tuffs from place to place suggest that the formation is a multiple flow unit, but a simple cooling history is indicated by gradational contacts, both vertically and laterally. The formation is not present in the Bell Top Formation to the west, nor has it been recognized in the Organ Mountains to the east. Thus, it appears to be a local, thick puddle of ash-flow tuff, areally restricted to the Dona Ana Mountains.

The great thickness of the formation and its limited areal extent, as well as most of the associated rocks and structures, demand that the sequence be interpreted in terms of a cauldron model. The cauldron is about 5 to 8 mi in diameter,

and boundaries are marked by flow-banded rhyolite, monzonite porphyry, and other intrusive rocks, and locally by structurally high pre-cauldron rocks outside the intrusive belts. Within the cauldron up to 1,000 ft of sedimentary rocks containing large landslide blocks, and interbedded ash-flow tuffs and rhyolite flows overlie the Dona Ana rhyolite, and apparently filled the cauldron as it continued to subside. Much of this cauldron fill is in structurally low positions near the cauldron margin, locally even filling marginal grabens. These may represent moat deposits. Intrusive rocks that occupy the cauldron boundary and also the edges of a second, smaller cauldron nested within the larger, all transect both Dona Ana rhyolite and the younger cauldron or moat fill.

There is no obvious resurgent structural dome. Indeed, a basinal structure centered on the smaller cauldron is defined by foliation and bedding. However, structurally high, faulted, and intruded pre-cauldron rocks are present near the center of the cauldron. In the same area Dona Ana rhyolite is structurally 1,000 ft or more higher than younger moat (?) deposits. These relations may indicate resurgence of the cauldron floor, perhaps contemporaneously with monzonite and flow-banded rhyolite intrusive activity.

The cauldron is of particular interest because of its deep erosion. The highest peaks in the range are formed on monzonite porphyry dikes. Assuming these rocks crystallized at least 1,000 ft beneath the surface, then the present level of erosion is 1,000 to 3,000 ft below the original surface of the cauldron. At this level, pre-cauldron rocks are extensively exposed, especially along the cauldron margins and in the resurgent (?) central area. Intrusive ignimbrite dikes, the roots of flow-banded rhyolite domes, monzonite bodies, including a large laccolith that may have surfaced to produce volcanic activity, all are revealed. In short the internal fabric of a cauldron down to at least 3,000 ft below the original surface is in view.

Organ Cauldron

A cauldron source of Oligocene volcanics in the Organ Mountains is inferred from several lines of evidence. First, an impressive thickness of silicic volcanics is exposed. At least

1,000 ft of basal ash-flow tuffs (Cueva Tuff) is followed upward by at least 2,000 ft of flow-banded rhyolite and ash-flow tuff (Soledad Rhyolite). These units appear to be gradational, representing one magmatic cycle. Second, they appear to be areally restricted. They comprise much of the southern Organ Range but are missing in outcrops to the south, west and north. Very great changes in thickness accompanied by pinching out of many ash-flow units takes place over short distances within the Organs, suggesting proximity to a source. Third, the volcanic pile has the configuration of a structural basin, probably the result of subsidence. Detailed mapping, chemical studies, and absolute dating may reveal that the northerly elongated Organ batholith, dated 32 m.y., is comagmatic with the volcanics, and may be of resurgent origin into the cauldron fill. Structurally high Paleozoic rocks at Bishop Cap, Tortugas Mountain and near Organ may represent cauldron walls, with the lowlands between these rocks and the Organ volcanics a cauldron moat, much modified by late Tertiary block faulting. Gravity maps between Bishop Cap and Tortugas Mountain support the interpretation of an arc-shaped buried cauldron rim facing the southern Organ Range. At Bishop Cap the "cauldron facies" of Soledad Rhyolite units are in fault contact with an escarpment of Paleozoic rocks that also faces the Organ Range.

LATE TERTIARY RIO GRANDE RIFT

As is the case elsewhere (Christiansen and Lipman, 1972; Lipman and others, 1972; Bruning and Chapin, 1974; Chapin and others, 1974) eruptions of copious amounts of basaltic andesite in latest Oligocene and earliest Miocene time appears to coincide with the change from silicic volcanism to active extension within the Rio Grande rift and Basin and Range province. In northern Dona Ana County, Uvas Basaltic Andesite, 26 m.y. old, is associated with major through-going rift faults, and with bolson fanglomerates, so that dating of initial rifting can be demonstrated. Evolution of the rift through late Tertiary time is recorded by Miocene and Pleistocene sedimentary and volcanic rocks of the Santa Fe Group.

Uvas Basaltic Andesite

Uvas Basaltic Andesite flows up to 800 ft thick are largely confined to the Good sight-Cedar Hills depression, with thin flows overlapping the western margin. Several vent features have been recognized in the Sierra de las Uvas where flows are thickest and most numerous. These relations probably mean that the Uvas Basaltic Andesite formed a broad, shield-like volcanic edifice, comprised largely of thin flows, and centered along the axis of the Good sight-Cedar Hills depression (Seager, 1973). In the Sierra de las Uvas, basaltic andesite flows interfinger downward with sedimentary rocks that contain Bell Top ash-flow tuffs; in the Rincon Hills the basaltic andesite also interfingers with thick overlying tuffaceous strata that grade upward into Santa Fe fanglomerate. Thus, nearly continuous deposition from early Oligocene to early or middle Miocene time in the depression appears to record the transition from Oligocene volcanism into rifting.

In the Cedar Hills area initial faulting in the rift can be closely estimated. In that area an exhumed Uvas cinder cone lies across and apparently was constructed on the Cedar Hills fault, one of the large, through-going rift faults in the region. Flows from that cone interfinger southward with thick fanglomerate derived from flow-banded rhyolite in the Cedar Hills

fault block (Fig. 5). These relations indicate that rift faulting was in progress at least 26 m.y. ago, and that basaltic andesite volcanism and early rifting overlapped in time.

Sierra de las Uvas Dome

The Sierra de las Uvas dome, the most prominent structural feature in the Sierra de las Uvas, formed near the middle of the Good sight-Cedar Hills depression and within the area where the Uvas Basaltic Andesite shield, as well as older ash-flow tuffs, are thickest (Fig. 3). The dome is about 10 mi in diameter and shows structural relief of about 2,000 ft. Its crestal region is complexly faulted by an axial graben system that bifurcates on the northwestern flank. The dome is bordered on the west and east by synclinal moats, and an extension of the moat is inferred beneath the Hatch-Rincon valley on the basis of opposing dips in Oligocene rocks on both sides of the valley.

The dome is interpreted to have formed by resurgent magma. This is suggested by dimensions typical of other resurgent domes, by the axial graben system, whose geometry suggests uplift by vertical movements, and by the bordering moat-like synclines. The uplifted area contains several Uvas vents, including one at the summit of the dome. Perhaps resurgence was caused by silicic magma, although no post-Uvas intrusives are known from the dome area, nor has erosion yet cut deep enough to confirm the presence of a stock or batholith beneath the dome. A nearly circular 200 gamma aeromagnetic low is coincident with the dome.

The timing of uplift of the dome has not been closely established, but it appears to antedate most of the major rift faults of the region and post-date the Uvas Basaltic Andesite. Thick tuffaceous sandstones (upper Thurman Fm.) directly overlie the Uvas Basaltic Andesite in the moat area north of Hatch; these suggest that both dome uplift and moat subsidence began immediately following eruption of the Uvas. Fanglomerates derived from the Sierra de las Uvas first appear, however, more than 1,400 ft above the Uvas Basaltic Andesite in the moat. These fanglomerates may indicate rapid doming at this time, or they may reflect an early stage of rifting around, and block uplift of, the Sierra de las Uvas. In the Cedar Hills region, of course, rifting was in progress during eruption of the Uvas, and the Sierra de las Uvas dome is clearly younger than those faults. Available evidence suggests that eruption of Uvas Basaltic Andesite, uplift of the Sierra de las Uvas dome, and initial faulting within the Rio Grande rift were penecontemporaneous events.

Early Rift Basins

Evolution of the rift throughout the Miocene is interpreted largely from the nature and distribution of bolson fill of the Santa Fe Group. In northern Dona Ana County these deposits are subdivided into 3 formations: 1) basal transitional strata of early Miocene age, mostly fanglomerates about 400 ft thick that grade downward into fine-grained moat (?) deposits of the upper Thurman Formation; 2) Hayner Ranch Formation of early to middle Miocene age, mostly red fanglomerate and sandstone, and 3) Rincon Valley Formation of middle to late Miocene age, brown fanglomerate containing the Selden Basalt, age 9 m.y., as well as playa and alluvial flat deposits. Local angular unconformities and boulder fanglomerate wedges within and between formations testify to repeated uplift, erosion and deposition within the rift during the Miocene.



Figure 5. Tectonic map of the Cedar Hills area. Uvas Basaltic Andesite (26 m.y.) cinder cone was constructed on the Cedar Hills fault. Flows from the cinder cone inter-finger southward with rhyolite boulder fanglomerate derived from the uplifted Cedar Hills block. This is interpreted to mean that active rifting was in progress in this area 26 m.y. ago.

These formations were originally deposited in broad, early rift basins that are no longer part of the landscape (Fig. 6). The basins were segmented into smaller intrarift basins and horsts in latest Miocene and Pliocene time. Exposures of the old basin fill are present now in such uplifts as the Rincon Hills, Tonuco uplift and Cedar Hills.

The oldest among the early basins apparently extended northwestward through the present Hatch Valley and southern Caballo Mountains. It contains nearly 3,500 ft of transitional and Hayner Ranch fanglomerate capped by 1,350 ft of Rincon Valley playa and fan deposits. Nearly all of the transitional and Hayner Ranch strata are derived from the Sierra de las Uvas and eastern rim of the Goodsight-Cedar Hills depression, thus demonstrating the antiquity of those structures. The composition of Rincon Valley fanglomerates near the Caballo Mountains and Cedar Hills, however, indicate that by 9 m.y. ago those uplifts became important sources of clastics delivered to the basin.

A second basin containing only Rincon Valley bolson fill, as well as the Selden Basalt, developed in late Miocene time between the Sierra de las Uvas and Radium Springs area. This broad basin trended nearly north and probably overlapped at its northern end with the basin just described. It was filled by volcanic detritus from the eastern Sierra de las Uvas and Cedar Hills. No detrital material from such prominent modern fault blocks as the Robledo, East or West Selden Hills, or Dona Ana Mountains is present.

Late Miocene and Pliocene Rifting

Faulting in the Rio Grande rift apparently culminated in latest Miocene and Pliocene time, after eruption of the Selden Basalt but before latest Pliocene and Pleistocene fan deposits and associated fluvial sediments were formed. The broad, older intrarift basins were segmented into narrow, closely spaced intrabasin horsts and grabens. Uplifts like the Rincon Hills, Tonuco, East and West Selden Hills, Robledo Mountains, and Cedar Hills formed within the older basins, and the older basin deposits now form part of most of those uplifts. Major displacement of the Rincon Valley Formation by movement along boundary faults is obvious on all of these uplifts. Continued uplift of the Sierra de las Uvas during latest Miocene and Pliocene also can be demonstrated by major offset of the Rincon Valley Formation along boundary faults. Thus, the development of modern fault block topography in the rift (Fig. 1) is a comparatively recent event. Although some uplifts were initially outlined as early as 26 m.y. ago and show by their sedimentary record evidence of continuing uplift throughout the late Tertiary, others were raised to their present position wholly or largely between 9 and about 2 m.y. ago. In the case of both old and young fault blocks, uplift appears to have culminated in Pliocene time. Except for comparatively thin fanglomerate of latest Pliocene and Pleistocene age, no sedimentary record of this major period of uplift is known.

LATE PLIOCENE, PLEISTOCENE AND HOLOCENE TECTONIC EVOLUTION OF THE RIFT

Late Pliocene and Pleistocene fan and fluvial deposits overlie an extensive middle to late Pliocene erosion surface that truncates many kinds of rocks of varying ages. In many places widespread pediments truncate range boundary faults that

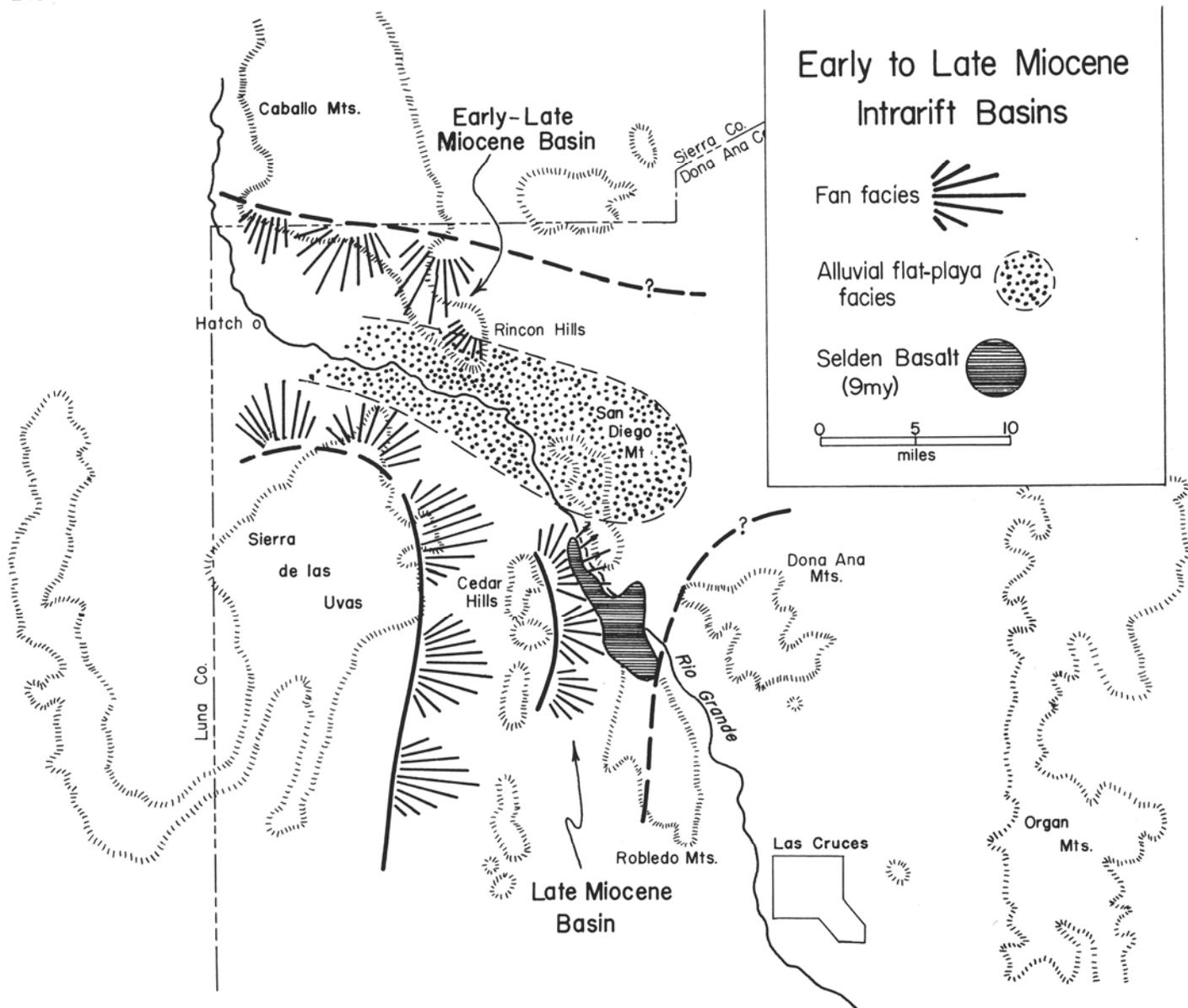


Figure 6. Early to late Miocene intrarift basins in north-central Dona Ana County. The basins were segmented into intrabasin uplifts and horsts in latest Miocene or Pliocene time.

show evidence of hundreds, locally thousands, of feet of displacement in latest Miocene or Pliocene time. Clearly, extensive erosion as well as uplift characterized the last few million years of the Tertiary. Sedimentary deposits resulting from this erosion are not known and presumably were carried out of the area by some as yet undocumented river system, perhaps to be deposited in deep, rapidly subsiding basins known in extreme southern New Mexico, trans-Pecos Texas and northern Chihuahua (J. W. Hawley, personal communication).

Initial evidence of a through-going river system is in the late Pliocene and early Pleistocene fluvial deposits of the Camp Rice Formation (Strain, 1966; Hawley and others, 1969). In the Las Cruces area the oldest of these deposits demonstrate that the river once flowed along the axis of the graben west of the Robledo uplift. Somewhat younger and thicker Camp Rice fluvial deposits are restricted to areas east of the Robledos. Pleistocene movement along the east Robledo fault as well as downwarping of the Mesilla Valley may have diverted the course of the river toward the east, where it has remained to

the present (J. W. Hawley, personal communication).

Uplift of the ranges has continued into the Quaternary. At least 16 faults in the Las Cruces region show evidence of movement during the last half million years, most by offset of middle Pleistocene fan surfaces producing piedmont scarps a few to perhaps 100 ft high. Locally stratigraphic separation of Pleistocene beds may approach 300 ft or more. A few fault scarps 2 to 3 ft high in the Hatch area displace very young erosion surfaces and may be late Quaternary in age.

SYNTHESIS

Three major stages in the tectonic evolution of the Las Cruces area are recognized: 1) Laramide uplift; 2) Eocene-Oligocene andesite and rhyolite volcanism; 3) late Tertiary block faulting in the Rio Grande rift. These stages also are generally recognized elsewhere in New Mexico and southern Colorado (Chapin, 1974; Chapin and others, 1974).

Laramide uplifts appear to be generally similar in geometry to Laramide foreland uplifts of the Rocky Mountains and Colorado Plateau, though probably smaller in scale. Available control suggests the north to north-northwest trending uplifts are en echelon and that the structurally highest, most deeply eroded folds lie in a belt near the present course of the Rio Grande. Many major late Tertiary rift uplifts nearly coincide with their Laramide predecessors, suggesting that the position of some late Tertiary tectonic features was inherited from or governed by the orientation of Laramide structures.

Eocene andesitic and Oligocene silicic volcanic rocks overlie bevelled Laramide uplifts and basins. Eocene strata and flows show little evidence of structural control, being characterized by widespread aprons of epiclastic rocks and flows with local small stocks or other subvolcanic plutons. Oligocene volcanics and plutons, on the other hand, are generally related to cauldron sources, conspicuous vent zones or fault basins. The northerly alignment or elongation of many of these volcano-tectonic features suggests that an extensional stress field of regional dimension developed in southern New Mexico by at least 35 m.y. ago. The stress field may have been a precursor to the more active extension that developed in early Miocene time, culminating in the Rio Grande rift. If so, the middle Oligocene extension represents a transition in southern New Mexico from the apparently non-extensional regime of Eocene time to the block faulting of early Miocene to Pleistocene time.

The transition to active rifting in Dona Ana County is marked by the change from silicic to basaltic andesite volcanism about 26 m.y. ago. Near Las Cruces rift faulting contemporaneous with basaltic volcanism can be demonstrated. Evolution of the rift through the Miocene is characterized by the development of broad, local basins, some oblique to the present structural grain. Five thousand feet or more of bolson deposits accumulated in these basins, which were segmented into narrow, closely spaced intrabasin uplifts and grabens in latest Miocene and Pliocene time.

Composition of the bolson fill indicates a sequential development of uplifts in the region. Some, like the Sierra de las Uvas, show evidence of considerable antiquity and a long history of repeated uplift, while others, like the Rincon Hills, Tonuco uplift and probably the Robledo Mountains, appear to have been raised only in latest Cenozoic time. Rifting apparently culminated during the latest Miocene and Pliocene, although it has continued on an apparently diminishing scale throughout the Pleistocene and Holocene. Basaltic volcanism comprises an important aspect of the rifting, especially during the Pleistocene, and to a lesser extent the Miocene, in the Las Cruces area.

Although the north-trending rift structures are basically a product of east-west extension, other factors may have locally controlled the orientation of rift faults. Among these, a pre-existing basement grid fracture system is important as demonstrated by Ramberg and Smithson (1975). Similarly, the north-trending Laramide structural grain apparently exerted an important influence on the orientation and positioning of some major rift structures. Finally, several Oligocene volcano-tectonic features affected the rift pattern. Among these, some subsidence fractures or vent zones associated with cauldron margins also became the sites of late Tertiary block faulting (Cedar Hills vent zone; Emory Cauldron, see Elston, Seager, and Clemons, this guidebook).

The trends of other rift faults apparently were modified by

structural or lithologic inhomogeneities of volcano-tectonic origin in the crust, such as the Sierra de las Uvas dome, its subjacent moat, and some cauldron complexes of the region. The trends of rift faults tend to diverge around features such as these instead of transecting them.

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