



Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico--A summary

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CENOZOIC DOMINO-STYLE CRUSTAL EXTENSION IN THE LEMITAR MOUNTAINS, NEW MEXICO: A SUMMARY

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INTRODUCTION

The Lemitar Mountains are located in central New Mexico near the axis of a north-trending zone of crustal extension known as the Rio Grande rift (Chapin and Seager, 1975; Cordell, 1978). Detailed geologic mapping of the Lemitar Mountains (Chamberlin, 1976, 1978, 1982) has revealed a complex structural pattern dominated by subhorizontal to moderately east-dipping, dip-slip, normal faults that repeat over and over a strongly west-tilted sequence of Oligocene volcanic strata (fig. 1, A-A', B-B'). Abrupt changes in thickness of basaltic-andesite lavas and angular unconformities between adjacent ash-flow tuffs locally occur across these low-angle normal faults. Restoration of the ash-flow sheets to their original horizontal positions allows only one reasonable kinematic interpretation—the subhorizontal faults were high-angle normal faults bounding simultaneously rotating blocks in middle to late Oligocene time (31-27 m.y. ago).

I have previously referred to this simultaneous rotation and dip-slip displacement of subparallel fault blocks as domino-style rifting because in cross section the subequally tilted blocks look similar to a train of fallen dominoes (Chamberlin, 1978). The term domino-style extension may(?) be relatively new but the concept is not, and can be found in several discussions of extended terranes in the Basin and Range province (Emmons and Garrey, 1910, fig. 15; Thompson, 1960, fig. 3).

Based on detailed mapping and 30,000 m of drill holes in the Yerington district of Nevada, Profett (1977, fig. 15) has elegantly documented simultaneous rotation and displacement of originally high-angle, domino-like (gently curved) normal faults in an area that has undergone more than 100 percent extension. Although the fault planes are gently curved (3-7°/km), Profett's palinspastic cross sections demonstrate that the faults have been rotated (domino-style) to their present subhorizontal attitude. The recognition of rotated fault surfaces, either planar or gently curved, is a key aspect of domino-style extension, which is not found in most discussions of imbricate, listric normal faulting that tacitly assume the fault surfaces are fixed in space (see Anderson, 1971).

Figure 2 illustrates another important aspect of domino-style normal faulting, which is that after about 30 degrees of rotation the original domino faults are no longer in a favorable orientation for displacement as gravity shears. Continuing crustal extension must then form a second set of high-angle domino faults, which is coaxially superimposed on the first set. Buried low-angle faults in the Yerington district (Profett, 1977) and the Lemitar Mountains strongly support this aspect of Morton and Black's (1975) hypothetical model.

It must be emphasized that the concept of domino-style faulting is at best only a first-order approximation of the crustal extension process. In the real crust, vertical and lateral changes in ductility, preexisting structural grain or lack thereof, isostatic adjustments, magmatic intrusions, normal and reverse drag adjacent to faults, and other factors can, and do, create departures from the simple model of domino blocks (fig. 1).

The purpose of this summary article is to briefly describe structural features observed in the Lemitar Mountains and to interpret from them the late Cenozoic structural evolution of the area. In addition, palin-

spastically restored cross sections are presented which allow a reasonable estimate of the amount and rate of extension in the Lemitar Mountains area.

GEOLOGIC SETTING

The Lemitar Mountains lie near the axis of the Rio Grande rift where extensional strain, accumulated over the last 30+ m.y., is approximately 200 percent. This severe crustal extension is expressed primarily by strong rotation of Oligocene and early Miocene strata (fig. 3). Although widely covered by younger basin fill, it is apparent that extension and tilting of older strata generally decrease to the east and west away from the Lemitar Mountains. From a high vantage point (fig. 3) one can look across strongly tilted Oligocene and underlying Paleozoic strata in the Lemitar Mountains to the Colorado Plateau (Riley area) where equivalent strata are tilted only 5-15 degrees and extension is relatively minor. Yet swarms of basaltic dikes, which yield late Oligocene-early Miocene ages, also occur along the margins of the Plateau (Chapin and Seager, 1975) and indicate that crustal extension began there about the same time it did in the Lemitar Mountains (S. M. Cather, 1983, oral commun., has found evidence for basaltic volcanism as early as 33 to 36 m.y. in the Riley area, but dikes of this age have not yet been dated).

Many similar observations lead to the conclusion that the rate of extension generally increases toward the axis of extension, also an area of high heat flow. Thus the strong tilting and complex structure of the Lemitar Mountains is primarily a function of its axial location in the rift (fig. 2). Seemingly rapid periods of extension contemporaneous with nearby silicic volcanism (Chamberlin, 1978) may be relatively minor perturbations and the overall axial rate of extension may be essentially constant. More data is needed to test the merits of steady state versus episodic extension on a large scale. Small-scale observations in the Lemitar Mountains do suggest local variations in the rate of extension.

Other factors important in the geologic setting of the Lemitar Mountains include: (1) basement structural grains related to Precambrian, late Paleozoic, and Late Cretaceous-early Tertiary periods of deformation (Chapin and Seager, 1975); (2) the Laramide Sierra uplift which once spanned most of the rift in the Socorro area (Cather, this guidebook); (3) Oligocene calderas to the southwest that blanketed the Lemitar area with numerous sheets of ash-flow tuff (Osburn and Chapin, this guidebook); (4) development of a broad Miocene basin which included the Lemitar-Socorro Mountains area as part of its distended floor (Bruning, 1973; Chapin and Seager, 1975; Chamberlin, 1981); and (5) a period of strong epeirogenic uplift about 4-7 m.y. ago (Chapin, 1979) which rapidly exhumed the *preexisting* tilted block structure of the Lemitar-Socorro Mountains from under a relatively thin alluvial blanket that existed across the ranges about 10 m.y. ago.

The most significant difference between high-angle domino faulting that began 30 + m.y. ago in the Lemitar Mountains and the high-angle normal faults that generally outline the modern ranges may be a wider

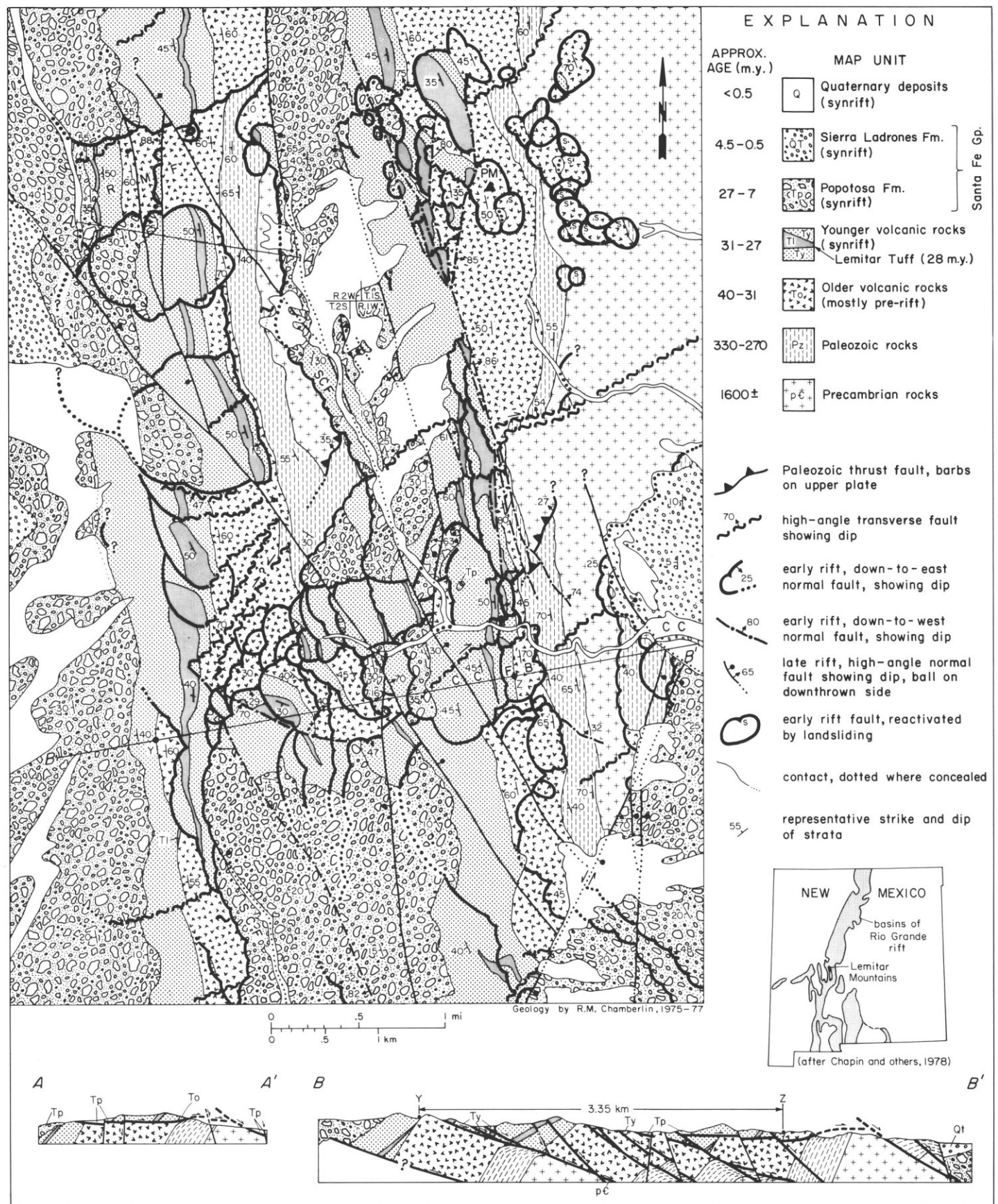


Figure 1. Generalized geologic map and cross sections (true scale) of the central Lemitar Mountains (modified after Chamberlin, 1982). PM=Polvadera Mountain, RMF=Red Mountain fenster, SCF=Silver Creek fault, CC=Corkscrew Canyon, CCFB=Corkscrew Canyon fault block.

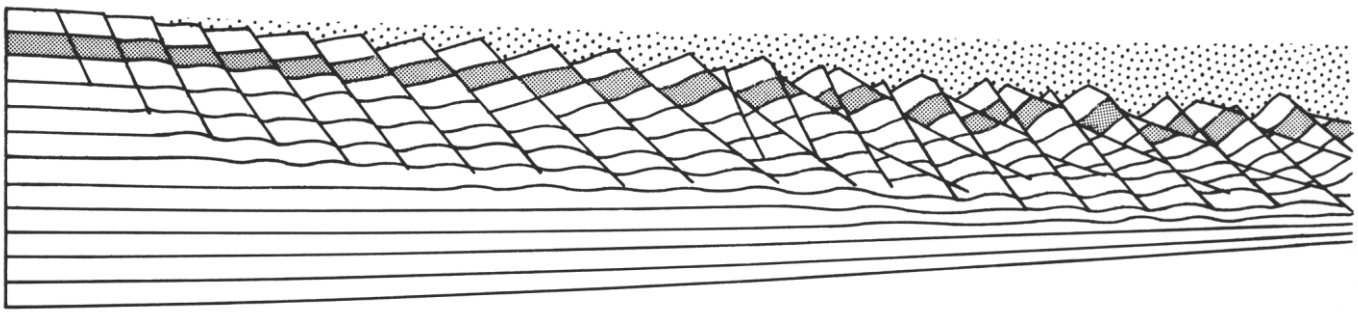


Figure 2. Morton and Black's (1975) hypothetical model for progressive crustal attenuation in the Afar depression of Ethiopia. Stippled area has been added to illustrate basin fill, which should also exhibit increasing tilts and complexity of normal faulting toward the rift axis (on right) and with time. This cross section could also be labeled progressive domino-style crustal extension in the Socorro area of the Rio Grande rift.

spacing of the younger faults (although active faults may go unrecognized within the range blocks; Machette, 1982). For details on the geologic setting of the Socorro-Lemitar Mountains area, see Chamberlin (1980, 1981), Chapin and others (1978), Chapin and Seager (1975).

STRATIGRAPHY

More than a decade of detailed geologic mapping in the Socorro-Magdalena area has firmly established a regional Cenozoic stratigraphic column keyed to distinctive and well-dated ash-flow tuffs, plus numerous dates of volcanic units interbedded with basin fills (Osburn and Chapin, 1983). It is the finely divided character of the Oligocene outflow section (Table 1) that has clearly revealed high-angle normal faulting contemporaneous with volcanism in the Lemitar Mountains. Ash-flow sheets not only provide a readily datable, essentially horizontal datum representing an instant of geologic time, but also cast a mold of the paleotopography immediately prior to their eruption. The compositionally zoned 28-m.y.-old Lemitar Tuff is extremely revealing of paleotopography because the crystal-poor lower member (light gray) preferentially filled in topographic lows, which were then quickly covered by the more sheet-like, crystal-rich upper member (dark red). Thus, in the field and on detailed maps (Chamberlin, 1982), one can see the

effects of 28-m.y.-old fault scarps, 10-60 m high, adjacent to faults that now displace the Lemitar Tuff by hundreds of meters. Even the generalized map of Figure 1 illustrates gross thickness variations of the Lemitar Tuff (generally reflected by outcrop widths), which were controlled by contemporaneous faulting.

Along the south side of section line B-B', knifelike edges of the Lemitar Tuff define the south edge of a broad northeast-trending paleovalley as much as 90 m deep. The deepest part of this transverse valley is controlled by northeast-trending high-angle faults that are preferentially downthrown to the north. The absence of erosional features in basaltic lavas below the Lemitar Tuff and the essentially uneroded top of the Lemitar Tuff, which was buried by more basaltic lavas, strongly supports the structural origin of this transverse sag. Abrupt northward increases in thickness of the lower Lemitar Tuff also occur across these transverse faults and clearly indicate that the faults predate the Lemitar Tuff.

Although much more subtle, it is also possible to visualize two north-trending strike valleys, which deepened to the west, by examining the east-west outcrop patterns of Lemitar Tuff near section line B-B' (fig. 1). Note that the absence of the Lemitar Tuff at point Y on B-B' locally defines the east edge of one strike valley. Whereas, about 60 m of

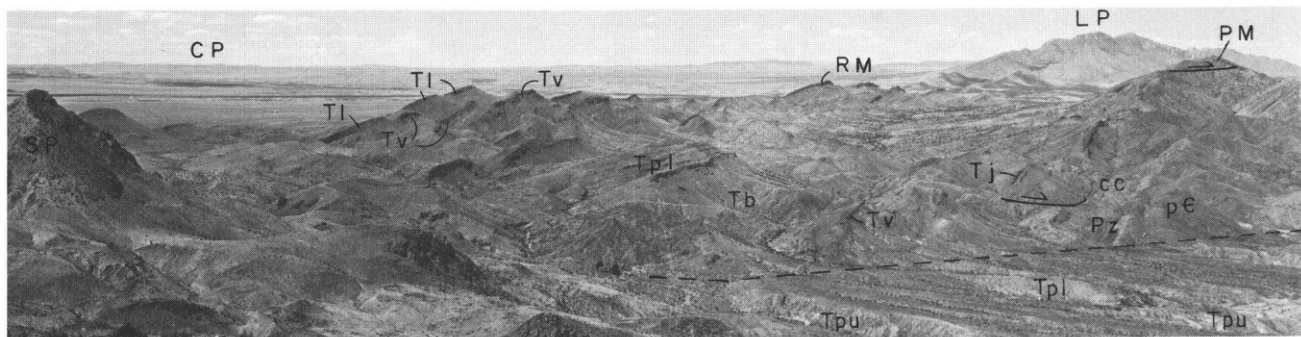


Figure 3. View of the Lemitar Mountains looking northwest from the top of Socorro Peak. SP = Strawberry Peak, CP = Colorado Plateau, RM = Red Mountain, LP = Ladron Peak, PM = Polvadera Mountain, CC = Corkscrew Canyon. Hogbacks of Oligocene ash-flow tuffs, which generally dip 45 to 70 degrees to the west, are the most prominent indication of the large extensional strain (200%). On the west flank of the range, a slightly offset hogback of 28-m.y.-old Lemitar Tuff (Tl) unconformably overlies distinctly offset hogbacks of 31-m.y.-old Vicks Peak Tuff (Tv), which is broken by northeast-trending transverse faults. Wedge-shaped prisms of basaltic-andesite lavas form slopes between the Lemitar and Vicks Peak hogbacks. In the south-central part of the range, a prominent angular unconformity separates early Miocene (20-27 m.y. old) mudflows and conglomerates of the lower Popotosa Formation (Tpl) from the underlying strongly tilted basaltic-andesite lavas (Tb) and Vicks Peak Tuff (Tv). Light-colored Paleozoic limestone and shales (Pz) showing true dips of 60-70 degrees and dark-colored Precambrian metamorphic rocks (pE) underlie the Oligocene volcanic pile along the east flank of the range. Subhorizontal early rift faults underlie Polvadera Mountain and a hogback of La Jencia Tuff (Tj) south of Corkscrew Canyon; note strong warping of Paleozoic strata adjacent to latter fault. Southeast of the high-angle range-bounding fault (dashed line), faulted and pedimented exposures of lower and upper (Tpu) Popotosa Formation dip about 25 degrees to the southwest under the 12-m.y.-old rhyolite dome of Strawberry Peak, which is not noticeably tilted. Photo by G. R. Osburn.

Table 1. Nomenclature, thickness, and approximate radiometric ages (Osburn and Chapin, 1983) for major stratigraphic units in the Lemitar Mountains. Informal divisions of younger and older volcanic rocks are the same as in Figure 1. Wavy line indicates major unconformity. Intervals of La Jara Peak Basaltic Andesite are informally referred to as lower, middle, and upper tongues. Thicknesses are estimated to the nearest 30 m from cross sections of Chamberlin (1982, Pl. 2).

Approximate age (m.y.)	Stratigraphic Unit
	Quaternary deposits, 0-30 m
4.5-0.5	Sierra Ladrones Fm, 0-300 m
	Popotosa Fm, 0-1350 m
20-7	upper, 0-900 m
27-20	lower, 0-450
	younger volcanic rocks, 150-750 m
27	South Canyon Tuff, 0-90 m
	La Jara Peak Basaltic Andesite, 0-330 m
28	Lemitar Tuff, 0-90 m
	La Jara Peak Basaltic Andesite, 0-150 m
	older volcanic rocks, 690-750 m
31	Vicks Peak Tuff, 60-90 m
	La Jara Peak Basaltic Andesite, 0-30 m
	La Jencia Tuff, 120-180 m
33	Hells Mesa Tuff, 90-150 m
	Granite Mtn, tuff of, 30 m
39-33	Spears Fm, 270-330 m
	Baca Fm, 0-30 m
	Paleozoic rocks, 120-450 m
	Abo Fm, 0-60 m
	Madera Lms, 60-210 m
	Sandia Fm, 60-180 m
	Kelly Lms, 0-30 m
	Precambrian rocks

Lemitar Tuff, exposed immediately to the east of the adjacent gently dipping early-rift fault, defines the west side of the next strike-oriented paleovalley. Similar abrupt variations in thickness, angular unconformities, and facies changes that were associated with contemporaneous normal faulting have been observed in the Miocene Popotosa Formation and the Plio-Pleistocene Sierra Ladrones Formation. See Chamberlin (1980) for detailed descriptions of these relationships.

EARLY RIFT DOMINO FAULTING

All fault traces shown on Figure 1 with a bold line are down-to-the-east, early rift, domino faults. Fault traces are poorly exposed in most areas and defined primarily by juxtaposition of stratigraphic units. Dips of these subhorizontal to moderately east-dipping domino faults, as shown in cross section (fig. 1, A-A', B-B'), are based on nearby observation of fault surfaces or the expression of fault traces across topography. Since local topographic relief is mostly less than 100 m, the overall trend of a fault trace, over a distance of 0.5 to 1.0 km, is a reasonable approximation of the strike of the fault surface. Dips shown in cross section are considered to be within 5 degrees of true dip. Small

scale cusps on low-angle fault traces usually represent V's across shallow drainages.

Age Relationships

Two ages (or stages) of early rift domino faults are generally recognized in the map area: (1) subhorizontal faults of late Oligocene to early Miocene age that form elliptical or circular fault traces, and (2) moderately east-dipping (25-45°) faults of middle to late Miocene age that exhibit numerous cusps and are generally throughgoing (north-trending). High-angle (60-70°), down-to-the-east, late rift faults (fig. 1), which may represent a third domino set, are discussed later. Fault stages 1 and 2 above are not divided on the map because they cannot always be clearly distinguished on the basis of dip.

Clear examples of stage-1 faults are the elliptical block south of Red Mountain fenster (RMF) and the Corkscrew Canyon fault block (CCFB) (fig. 1). As shown in cross section, both faults are essentially horizontal and control abrupt changes in thickness of the adjacent late Oligocene—early Miocene strata (Table 2). These thickness changes coupled with systematic decreases in dip, from older to younger strata, clearly demonstrate simultaneous rotation and displacement of the stage-1 domino faults. Palinspastic reconstructions of the synrift strata to their original horizontal attitudes (figs. 4, 5) demonstrate that these horizontal faults were active high-angle faults in late Oligocene to early Miocene time (31-20 m.y. ago). Stratigraphic relationships along the west side of the Corkscrew Canyon fault block indicate that this 500-m-displacement fault became essentially inactive about 27 m.y. ago and was unconformably buried as an east-facing (-30° dip) buttress by mudflow deposits of the basal Popotosa Formation (fig. 5c). Similar buttress unconformities are also present southwest of the Corkscrew Canyon fault block where two large domino faults appear to die out southward into a broad exposure of the lower Popotosa Formation (for details see Chamberlin, 1982, Pl. 1).

Examples of stage-2 domino faults are the Silver Creek fault, named by Bruning (1973), and a moderately east-dipping (25-40°) unnamed fault that juxtaposes Paleozoic rocks against Precambrian rocks near the mouth of Corkscrew Canyon (fig. 1). The Silver Creek fault locally cuts the upper Popotosa Formation of middle to late Miocene age and the unnamed fault is locally buried by the basal Sierra Ladrones Formation which may be of latest(?) Miocene age or Pliocene age.

Cross-cutting relationships of stage-2 faults superimposed on stage-

Table 2. Variation in dip and thickness of synrift stratigraphic units from the upthrown footwall block to the downthrown hangingwall block of the Red Mountain fenster (from Chamberlin, 1982, Pl. 2). Upper, middle, and lower basaltic andesites are tongues of the La Jara Peak Basaltic Andesite. The zero thickness for the Lemitar Tuff, upper basaltic andesite, and lower Popotosa Formation all represent truncation by a paleovalley of upper Popotosa age (Chamberlin, 1982, Pl. 1). Dips of equivalent strata are essentially the same from footwall to hanging

avg. dip	Unit (Table 1)	footwall	hangingwall
35°	lower Popotosa Fm	0-60 m	180-210 m
35-50°	upper basaltic andesite	0-60 m	270-330 m
50°	Lemitar Tuff	0-30 m	30-60 m
50-60°	middle basaltic andesite	150-180 m	120-180 m
60°	Vicks Peak Tuff	90 m	90 m
60°	lower basaltic andesite	0 m	30 m

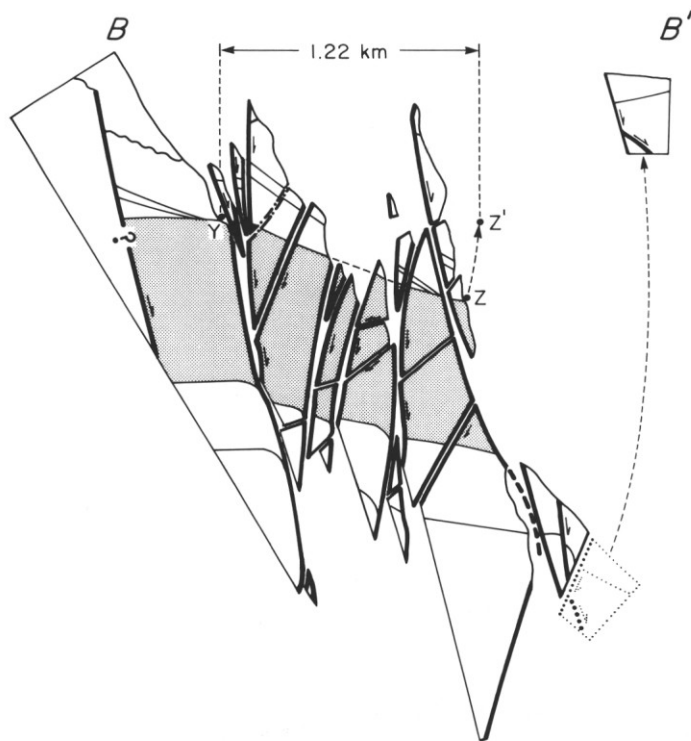


Figure 4. Cut and paste restoration of cross section B-B' (fig. 1) to original pre-rift continuity of older volcanic rocks (shaded, To of fig. 1). Restoration made by systematically unroofing and untilting superimposed fault blocks of present-day section. The indicated eastward downwarping is attributed to normal drag between the closely spaced fault blocks. A minor component of apparent crustal shortening created by the warping has been removed by projecting Z to the horizon (Y-Z') along an arc radiating from the hinge at Y.

1 faults are locally well defined; however, they may also be misinterpreted as splaying relationships of a contemporaneous fault zone. About 0.8 km south of point Z on Figure 1, a moderately dipping (45°) fault clearly displaces a subhorizontal fault about 60 m down to the east. The younger (steeper) fault trace appears to take on the 300 m displacement of the older fault where the two are superimposed (see Chamberlin, 1982). This additive relationship of cross-cutting fault traces causes the *apparent* displacement (stratigraphic throw) of the Silver Creek fault to vary from 2100 m near the center of the range, where it is superimposed on subhorizontal faults equivalent to those at the Red Mountain fenster, to its actual displacement of about 900 m near the southwest corner of the map area. East of the Red Mountain fenster, the south margin of two large-displacement (450 m, 750 m), shovel-shaped faults that dip about 10° to the east is truncated by the Silver Creek fault, all of which are in turn truncated by a high-angle late-rift fault. Note that the actual displacement of the Silver Creek fault (900 m), plus the throw on the older shovel-shaped faults (450 m, 750 m), is equal to the apparent stratigraphic throw of the Silver Creek fault (2100 m) where it is superimposed on these older faults.

Some subhorizontal faults near Polvadera Mountain have been reactivated by gravity sliding where steep erosion surfaces have cut across the lowest part of the fault plane. Small closed depressions, as much as 10 m deep and commonly filled by Quaternary alluvium, occur at the detachment point of the reactivated blocks and demonstrate their recent movement (fig. 1).

Geometry of Domino Blocks

In map view, high-angle normal faults typically zigzag across the countryside, locally make right-angle bends, and may locally intermesh to form a polygonal fabric dominated by the overall strike of the faults

(see Thompson, 1960, fig. 2; Machette, 1982, fig. 1). When strongly rotated to subhorizontal attitudes, zigzagging faults and abrupt bends in faults may combine with the modern erosion surface to form shovel-shaped fault blocks and transverse-oriented fensterlike areas. Transverse-oriented right-angle bends in the originally high-angle faults produce steep-sided blocks similar to old-fashioned coal shovels, whereas zigs (or zags) form spade-shaped blocks that may appear as gently curved troughs or shallow V-shaped troughs. If the Red Mountain fenster (fig. 1) is viewed as an originally east-facing zig, then the spade-shaped fault block immediately to the south was originally a west-facing zag. This zigzag relationship continues to the south; however, the transverse margins of the blocks become increasingly steep as they approach a northeast-striking zone of high-angle transverse faults. These sharp bends in the domino faults have retained their original steep dips because they are roughly perpendicular to the axis of rotation (north-northwest).

Trough axes of the shovel-shaped faults trend east-northeast, parallel to the regional direction of extension. Although rarely exposed, slickensides associated with the shovel-shaped blocks consistently plunge gently to the east-northeast, regardless of the related surfaces' orientation (Chamberlin, 1982). In other words, the shovel-shaped faults exhibit gently plunging (rotated) dip-slip slickensides near their trough axes and gently plunging (rotated) pseudo-strike-slip slickensides on their steep-sided transverse margins. In some areas, transverse faults may also act as extensional tear faults, which separate a more extended domain from a less extended domain; however, this relationship is not apparent in the Lemitar Mountains (see discussion of fig. 2-46.6, this guidebook).

The geometry of early domino blocks evidently reflects the structural grain and character of the underlying Precambrian and Paleozoic rocks. Several transverse faults along the eastern flank of the range are either parallel to, or coincident with, major lithologic boundaries in the Precambrian terrane (McLemore, 1980), a relationship which strongly suggests a Precambrian ancestry. Some transverse faults also exhibit opposing senses of movement where they pass from Paleozoic rocks into the overlying volcanic sequence, which suggests that they are reactivated Laramide faults. In contrast, a Paleozoic thrust fault, which originally dipped about 40 degrees to the north-northeast, has not been reactivated by rifting, presumably because of its unfavorable orientation.

Down-to-the-west early rift faults, which are shown on Figure 1 by a dash-dot line, represent relatively minor displacement (30-300 m) antithetic faults within the prevailing down-to-the-east domino field. A prominent zone of early rift antithetic faults extends from about 1 km northwest to about 3 km southwest of Polvadera Mountain (fig. 1). The early antithetic faults have been rotated westerly with the domino blocks to the present attitude of high-angle reverse faults. Transverse faults generally bound the north and south end of the antithetic fault zone. In combination with the Silver Creek fault, the antithetic fault zone essentially forms a strongly west-tilted graben. Development of this rotated graben is attributed to an underlying coarse-grained plutonic basement (granite and gabbro; McLemore, 1980), which apparently broke into conjugate (opposing) fault blocks because of its relatively isotropic character.

The downdip geometry of early domino faults may be planar or gently curved (listric). However, the subequal tilt ($\approx 5^\circ$) from footwall to hanging wall of several subhorizontal faults (displacements of 0.5-1.2 km) does not permit downdip curvatures of greater than 5-10 degrees per kilometer (equivalent to arcs with radii of 6-11 km; see Wernicke and Burchfiel, 1982, for discussion of listric versus planar block rotations). As illustrated in cross section (fig. 1, A-A', B-B'), subhor-

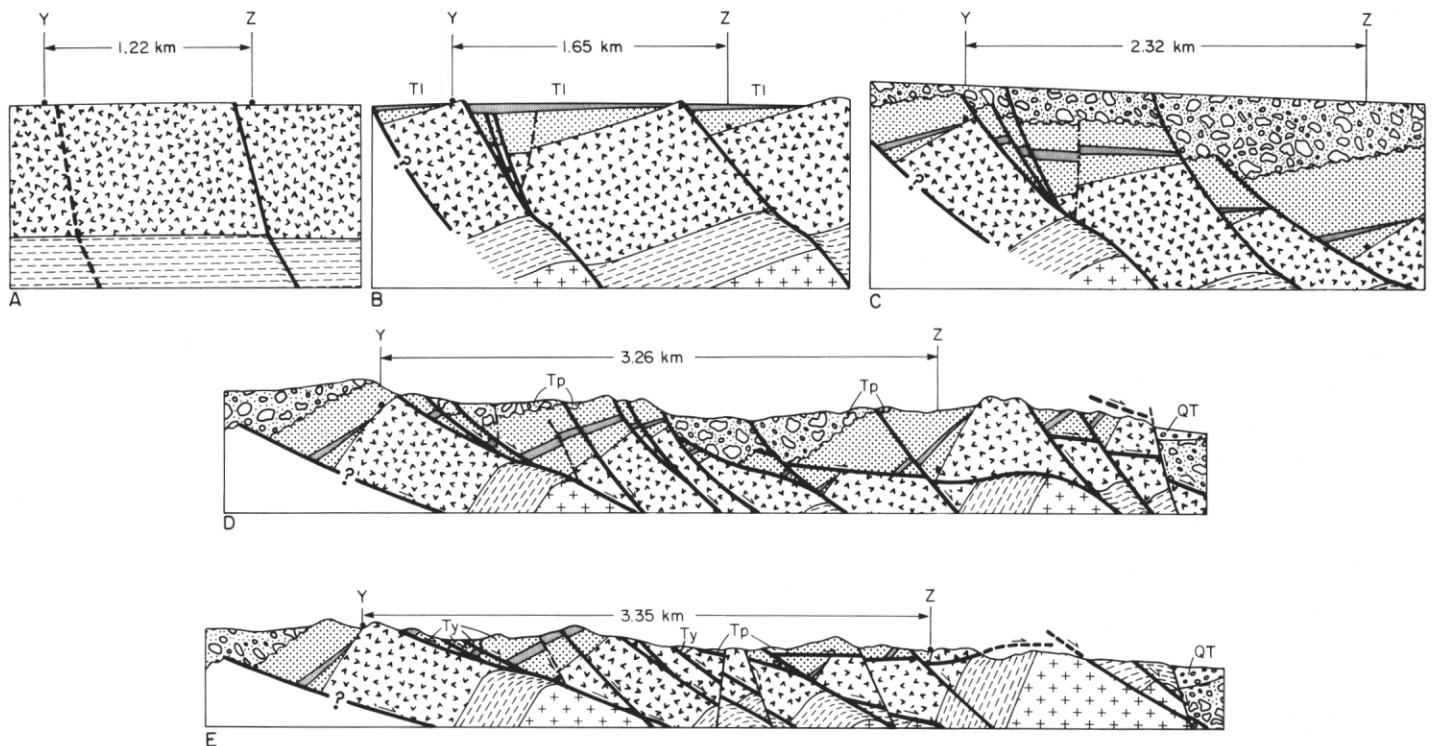


Figure 5. Palinspastic reconstructions of cross section B-B' (fig. 1) illustrating progressive domino-style crustal extension in the Lemitar Mountains area: (A) 31 m.y. ago, onset of domino-style faulting; (B) 28 m.y. ago, Lemitar Tuff (Tl) flows over tilted domino blocks largely filled in with basaltic-andesite lavas; (C) circa 20 m.y. ago, early domino blocks rotated as much as 30 degrees become inactive and are unconformably buried by mudflow deposits of lower Popotosa Formation; (D) circa 5 m.y. ago, continued extension in middle to late Miocene time (20–5 m.y. ago) has superimposed a second generation of domino faults on early inactive blocks (epeirogenic uplift coupled with continuing high-angle faulting has partly exhumed the range block from under basin fill) represents topographic disruption of the Popotosa basin; (E) present, accelerated erosion associated with epeirogenic uplift and continuing high-angle faulting concentrated along east flank of range has tilted main range block about 5–10 degrees west since 5–10 m.y. ago. See Figure 1 for symbols identifying stratigraphic units.

zonal domino faults commonly turn abruptly upward where they intersect the underlying Paleozoic section. This clearly represents an abrupt downward flattening, or deflection, of the original high-angle faults (fig. 5a), which was most likely caused by the relatively ductile character of interbedded shales, mudstones, and micritic limestones near the top of the Paleozoic section.

Tilting of Domino Blocks

Representative attitudes of strata shown in Figure 1 are based on more than 500 measurements on bedding or compaction foliations in tuffs (Chamberlin, 1982). Most of the indicated westerly dips reflect progressive tilting of domino blocks since about 31 m.y. ago (Table 2). Some exceptions are: (1) unusually low westerly dips (40°) in Paleozoic rocks caused by drag adjacent to subhorizontal faults (fig. 1, A-A', B-B'), and (2) unusually low westerly dips (10°) in the lower Popotosa Formation, south of B-B' (fig. 1), which reflect eastward primary dips adjacent to early Miocene fault scarps (fig. 5c). Measured dips in the apparently conformable sequence of older volcanic rocks (To, fig. 1) often vary as much as 10 degrees, even after obvious effects of local drag adjacent to faults are eliminated. Thus, angular unconformities are best defined by numerous outcrop attitudes coupled with the topographic expression of the divergent layers (see fig. 3).

The dominant strike of rotated strata is between due north and N 20° W. Departures of greater than 30° from the prevailing strike are locally associated with drag along transverse structures.

The most convincing evidence of progressive domino-style extension in the Lemitar Mountains is the incremental decrease in westerly dips of Cenozoic strata with decreasing age. In order of decreasing age,

major Cenozoic units and their representative westerly dips in the map area are: Vicks Peak Tuff (31 m.y.), 55–70°; Lemitar Tuff (28 m.y.), 40–50°; South Canyon Tuff (27 m.y.), 35–40°; lower Popotosa Formation (27–20 m.y.) 30–35°; and upper Popotosa Formation (20–12 m.y.), 20–25°. Continuing extension and rotation of strata is indicated by 10–15° westerly dips of the Socorro Peak Rhyolite (12–7 m.y.) and by 0–10° westerly dips of the Sierra Ladrones Formation (4.5–0.5 m.y.), exposed to the south and east of the map area, respectively (Chamberlin, 1980, 1981). This 55 to 70 degrees of divergence between late Oligocene and Pleistocene strata is primarily accommodated by numerous minor angular unconformities within formations (expressed as wedge-shaped formations) and locally by prominent angular unconformities between formations. These angular relationships suggest relatively rapid periods of rotation and extension in late Oligocene to early Miocene time (31–20 m.y. ago) and in late Miocene time (12–7 m.y. ago) contemporaneous with peaks in volcanism and high heat flow (Chamberlin, 1978). However, numerous local unconformities also indicate essentially continuous faulting and rotation of blocks in the Lemitar-Socorro mountains since 31 m.y. (for details see Chamberlin, 1980). Recent discussions of the Socorro regional geology with C. E. Chapin and G. R. Osburn have pointed out that conspicuous angular unconformities in the upper Cenozoic section occur at different stratigraphic levels in different places. Therefore, the prominent angular unconformities in the Lemitar Mountains area (fig. 3) may be of only local significance. The apparent late Miocene—early Pliocene culmination of rifting described by Chapin and Seager (1975) may be more an expression of regional uplift than a pulse of rapid regional extension.

Another expression of local variations in block rotation is found in the previously described rotated graben between the Silver Creek fault

and the antithetic fault zone west of Polyvadera Mountain. Unusually low westerly dips and local easterly dips within this rotated graben suggest that the down-to-the-west faults may be strongly curved listric faults. Another block of easterly dipping strata, which occurs outside the map area on the northeast flank of the range, is also associated with a zone of down-to-the-west antithetic faults (Machette, 1979, unpublished map). The apparent scissors-like rotation between domino and antithetic (graben) blocks is accommodated by high-angle transverse faults. An example of a much larger zone of scissors-like transverse faults is the Socorro transverse shear zone of Chapin and others (1978), which separates fields of tilted blocks undergoing rotation in opposite directions.

LATE RIFT FAULTING

The modern basins and ranges of the Socorro area were formed in late Miocene to early Pliocene time (ca. 7-4 m.y. ago) by continued high-angle normal faulting and regional uplift (Chapin and Seager, 1975; Chapin, 1979). The character of late-rift structures is best defined in the Socorro and La Jencia Basins, to the east and west of the Lemitar Mountains, respectively. Gravity maps (Sanford, 1968), measured westerly dips of 0-10° in Plio-Pleistocene basin fills (Chamberlin, 1980), and major down-to-the-east fault zones along the west sides of the basins (Machette, 1982, fig. 1) all support the interpretation of these modern basins as broad, west-tilted fault blocks. Antithetic (down-to-the-west) late-rift faults are observed in the basins, but in the Lemitar and Socorro ranges high-angle, down-to-the-west faults appear to be subordinate in number and amount of displacement. Cumulative down-to-the-east displacement along the Socorro Canyon fault zone (Machette, 1982), which locally bounds the eastern flank of the Lemitar Mountains, is estimated to be about 300 m since 4 m.y. ago (Chamberlin, 1982, Pl. 2).

Late-rift faults shown on Figure 1 are all high-angle normal faults that dip steeply (60-80°) in the direction of the downthrown block. The late faults are considered here to be primarily of Pliocene and Pleistocene age because they locally cut the Sierra Ladrones Formation (as at the mouth of Corkscrew Canyon) and because they commonly offset gently dipping early rift faults. Most late-rift faults exhibit small displacements (30-90 m) and generally cut steeply dipping beds at a small angle. Therefore, the late-rift faults are often only well defined where they displace older faults. Throughgoing traces of late-rift faults (fig. 1) are mostly projections between widely spaced control points and should not be regarded as well defined. Overprinting of high-angle faults on low-angle faults is well displayed along the west side of the Corkscrew Canyon fault block and near the center of cross section BB'. A complex interlocking pattern of blocks is apparent here.

The high-angle fault which bounds the southeast flank of the range clearly cuts across the early rift domino blocks within the range. Again, this superimposed relationship creates apparent stratigraphic throws along the range-bounding fault which represent the cumulative displacement within older blocks plus its own true displacement. Near Corkscrew Canyon, the apparent stratigraphic throw on this fault is about 2 km but near Strawberry Peak (south of map) the same fault has an apparent throw of 300 m. Gravity maps (Sanford, 1968) and the essentially constant relief along the range front indicate that the 300 m displacement is a more reasonable approximation of actual displacement.

AMOUNT AND RATE OF EXTENSION

Structure section B-B' (fig. 1) is reasonably well constrained by surface observations of fault-plane attitudes, dips of strata, and thickness variations of synrift strata. In addition, this cross section is drawn approximately parallel to the direction of extension as indicated by rotation of strata, trough axes of shovel-shaped fault blocks, and slickenside observations. As shown in Figure 4, sequential restoration of this cross section indicates that points Y and Z, which are now 3.35

km apart, were only about 1.22 km apart when crustal extension began about 31 m.y. ago. This represents a 175 percent increase in cross-sectional length parallel to the direction of extension, or an extension factor of 2.75 times original length. Similar reconstructions of other east-west cross sections across the Lemitar Mountains (Chamberlin, 1982, Pl. 2), suggest that extension increases from about 75 percent at the south end of the range to more than 250 percent near the north end of the range. However, this variation is considered to be more an expression of varying control, or lack of control, on the dip of faults, than a real lateral variation in the amount of extension. A reasonable estimate of crustal extension across the Lemitar range, as a whole, is considered to be 200 ± 50 percent.

Palinspastic reconstructions of cross section B-B', shown in Figure 5, allow reasonable order-of-magnitude estimates of the rate (or rates?) of extension across the Lemitar range since the onset of extension. Taking these reconstructed cross sections at face value, the indicated rates of extension are: 0.14 mm/yr from 31-28 m.y. ago, 0.08 mm/yr from 28-20 m.y. ago, 0.06 mm/yr from 20-5 m.y. ago and 0.02 mm/yr from 5 m.y. ago to present.

The greatest source of error inherent in these calculated rates of extension is the uncertainty in the actual time period represented between cross sections. Also the seemingly minor amount of extension in the last 5 m.y. is clearly not representative because the cross section does not include the zone of active high-angle faults along the east flank of the range. Reconstructed sections 5A and 5B are considered to be the best constrained with respect to change in length ($\pm 10\%$) and time (± 1 m.y.). The combination of these potential errors indicates possible rates of extension of as much as 0.24 mm/yr to as little as 0.10 mm/yr. Thus errors in rates of extension calculated here are considered to be at least ± 50 percent. The apparent rate of extension of 0.08 mm/yr over the time period 31 to 5 m.y. ago (5A to 5D) is also considered to be reasonably accurate because the longer time span reduces the effect of uncertain ages.

Geophysical studies summarized by Cordell (1978) clearly demonstrate that the Rio Grande rift is associated with a band of high-heat flow. A simplistic conclusion from this observation is that, like taffy, hot rocks are stretched more easily than cold rocks.

Based on this simple conclusion and above estimated rates of extension in the Lemitar Mountains, I suggest that supracrustal extension along the axis of the rift near Socorro has occurred at a relatively constant rate of 0.1 ± 0.05 mm/yr, since 30 m.y. ago. Local angular unconformities suggest accelerated periods of domino-style crustal extension contemporaneous with silicic volcanism from 31 to 20 m.y. ago and 12 to 7 m.y. ago. The second period is less distinct and may grade into late high-angle faulting and tilting of blocks.

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