A tectonic redefinition of the Southern Rocky Mountains

GORDON P. EATON *

Texas A. & M. University, College Station, TX 77843 (U.S.A.)

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Abstract


The Southern Rocky Mountains of the Western United States, physiographically defined and described by N.M. Fenneman nearly 60 yrs ago, are tectonically redefined and extended. They are shown to constitute the crestal range of a mammoth, continental, arch-like feature here named the Alvarado ridge. Its axis trends south from Casper, Wyoming at least as far south as El Paso, Texas, beyond which the ridge begins to lose morphological identity. Maximum elevations along the crest of the ridge exceed 4.2 km. The summit ranges are bordered on either side by gently sloping rises that extend outward for at least 1300 km, falling to elevations of less than 400 m. Modest rift structures along the ridge axis continue beyond the southern terminus of the mountains before playing out. A major sediment-filled axial graben exists over the southern two-thirds of the ridge, but equivalent parts of it farther north were stripped of their Neogene fill by erosion in the headwaters areas of the Colorado and North Platte rivers.

The maximum elevation of earlier Laramide mountains in this area has been estimated to have been no more than 2 km in Colorado, half that of the present range. Related topography was nearly obliterated by erosion prior to late Eocene time. Lateral stream planation produced a southeast-sloping, major late Eocene erosion surface across the region that had what was probably an isostatically adjusted, average maximum elevation of less than 900 m. Present day elevations and relief on the ridge crest are the result of steep crestal normal faulting, pronounced block uplift, and regional arching, with extensional strain limited to an axial corridor less than 200 km wide. This episode of mountain building began in middle Miocene time (17 to 12 Ma), culminating in latest Miocene and early Pliocene time, between 7 and 4 Ma ago.

Debris from the newly elevated range (the Southern Rocky Mountains, sensu lato) was shed along the full length of the Neogene Alvarado ridge down parts of both rises, as well as into its medial graben. The uplifted and tilted east rise (the Great Plains ramp) has an extensive aggradational cover that spread eastward to distances of 700 km and more in middle Miocene to earliest Pliocene time. Its fluviatile, lacustrine and eolian sediments are undergoing dissection today, but a sufficient portion remains to define the unmodified profile of the east rise, as well as the original length of the ridge. It is coincidentally similar in configuration and scale to the west rise of the mid-Atlantic ridge. The topography of the crestal mountain ranges on both structures is also remarkably similar.

The Southern Rocky Mountains are as high as the Alps, but are not the product of lithospheric compression and crustal thickening. Rather they reflect profound epeirogenic uplift driven by lithospheric thinning and accompanied by extensional strain and differential vertical jostling along the crest of the ridge.

* Present address: Office of the President, Iowa State University, Ames, IA 50011, U.S.A.
Introduction

Previous definitions of the Southern Rocky Mountains and Rio Grande rift

On Sunday, August 29, in the year 1540, Captain Hernando de Alvarado and a light scouting party of twenty men, under field orders from General Francisco Vásquez Coronado, struck eastward across the eastern Colorado Plateau from the Indian village of Hawikuh, on the upper Zuni river near the Arizona–New Mexico border, and began a march across what has long since been defined as part of the Rocky Mountains (Fig. 1). Their initial route of travel took them eastward and gently upward across low dipping sedimentary strata of Triassic, Jurassic, and Upper Cretaceous age [the geologic features described here are illustrated by Dane and Bachman (1965), and in Hawley (1978)], then across the malpais surface of a many-kilometers-wide series of Quaternary, subalkaline basalt flows. Farther east, they probably passed between Putney Mesa and Cebolleta Mesa which have Tertiary basalt caps. In doing so, they entered a swarm of north-northeast and north-trending normal faults of small displacement that define what is here regarded as the western tectonic border of the crestal region of a giant continental ridge; physiographically, they were still on the high, west-sloping Colorado Plateau.

At Acoma Pueblo, the Alvarado party turned northeast and after crossing another swarm of north-northeast trending normal faults of some-what greater displacement in the Rio Puerco fault zone, between the north-striking Lucero uplift on the south and the right-stepped, en echelon, Nacimiento uplift on the north, they descended into the Albuquerque–Belen structural basin in the upper Rio Grande Valley and encamped near the river between the sites of Sandia and Bernalillo on Tuesday, September 7. They had entered a different physiographic setting and the axial graben of the ridge. Not long before reaching the river, they must have passed north of the Albuquerque volcarfes, a north-trending alignment of large Quaternary cinder cones and their apron of olivine tholeiite flows on the graben floor.

The party eventually pushed around the north-ern end of the east-tilted fault block of the north-striking Sandia Mountains and proceeded into the southern foothills of the massive, horst-like, Sangre de Cristo Mountains, as far as the pueblo of Cicuye, near the townsite of Pecos, New Mexico. They were now close to the eastern margin of the crest of the ridge. In mid-winter, 1541, Alvarado’s commander, General Coronado, appeared at Cicuye and in late May, after returning from a camp to the west, he, Alvarado, and their party started down the Pecos river. A few days later, they climbed eastward out of its southeast-trending valley and proceeded up onto the vast, gently east-sloping High Plains (Day, 1940), thus completing one of the earliest European crossings of the Southern Rocky Mountains and the upper parts of both of the opposed, gently outward-sloping surfaces that constitute the rises of the ridge. They continued down the east rise, almost to the site of Abilene, Texas.

In the context of the widely accepted physiographic definitions and province boundaries of Fenneman (1928, 1931), this Spanish exploring party barely touched the Rocky Mountain system, and then only in passing the Sandias and entering the southern Sangre de Cristo Range, for according to Fenneman, the whole of the Rocky Mountain system ends at the southern tip of the Sangre de Cristo Mountains, south of which crestal elevations and topographic relief are lower than they are to the north. To the south lies the northern embayment of the easternmost part of his Basin and Range province (Fig. 2).

The basic thesis of this paper is that the Southern Rocky Mountains, here redefined as a tectonic ridge crest, extend well to the south, at least as far as El Paso, Texas (Fig. 1), as do their bordering rises. As will be demonstrated in sequence, Fenneman’s physiographic definition of the range, while topographically arguable, is fundamentally inadequate from a structural point of view. It is also unsupportable from a geophysical vantage point (as described in a companion paper: Eaton, 1986). From this point on, then, we will use the term Southern Rocky Mountains, sensu lato, to refer to the newly-defined province that constitutes the crestal region of what will henceforth be referred to as the Alvarado ridge. Based on this redefini-
Fig. 1. Index map of the southeastern part of the U.S. Cordillera of western North America. The heavy line identifies the border of the Southern Rocky Mountains, sensu lato, the crestal province of the Alvarado ridge, as defined in this paper. Also shown is the drainage pattern of its interior and its bordering rises. Small rectangles identify the locations of the tectonic maps shown in Figs. 10 and 11. The shaded area in the southern two-thirds of the crestal province identifies all that is left of axial graben fill deposits. Their area of occurrence is actually smaller than that shown here, for these deposits are longitudinally divided by large bedrock horsts that are not shown. Within the area of these deposits, shown by lighter shading, is the chain of structural-hydrologic basins along the upper Rio Grande which Bryan (1938) named the "Rio Grande depression". The routes of three early observers are shown as long dashed lines: Hernando de Alvarado (for whom the ridge is named) and his commander, Coronado, 1540; Alvar Nuñez Cabeza de Vaca (whose course of travel is less certain), 1535; and John C. Fremont, 1844. Routes are from Day (1940), DeVoto (1952) and Goetzmann (1966). States are labelled as follows: AZ—Arizona, CO—Colorado, KS—Kansas, NB—Nebraska, NM—New Mexico, OK—Oklahoma, TX—Texas, UT—Utah and WY—Wyoming.
Fig. 2. Physiographic subdivisions of the western United States, according to Fenneman (1928, 1931). A heavy line marks the border of the Alvarado ridge crest. Fenneman's provinces are labelled as follows: A—Northern Rocky Mountains, B—Great Plains, C—Central Lowland, D—Columbia Plateau, E—Middle Rocky Mountains, F—Wyoming Basin, G—Southern Rocky Mountains (sensu stricto), H—High Plains subdivision of the Great Plains (note the correspondence of its latitudinal range to that of the Southern Rocky Mountains, sensu lato), J—Basin and Range, K—Colorado Plateau, and M—Coastal Plain. States are labelled as in Fig. 1, with the following additions: ID—Idaho, MT—Montana, NV—Nevada, ND—North Dakota, and SD—South Dakota.

tion, the exploring party of Hernando de Alvarado may not have been the first of European origin to see or cross the Southern Rocky Mountains and Alvarado ridge. That distinction could belong to a much smaller group of Spaniards, led by Alvar Nuñez Cabeza de Vaca, whose route of travel is less certain and, for that reason, whose name it is not proposed be appended to the ridge (see an interpretive reconstruction of the Cabeza de Vaca route in Fig. 1).

How are the Southern Rocky Mountains to be redefined in this new context? In preparing his classic volume, *Physiography of Western United States*, half a century ago, Fenneman (1931) described these mountains as follows:

"...the mountains of the Southern (Rocky Mountains)
province are not strictly contiguous with those of other provinces (of the Rocky Mountain System) though certain low anticlines are continuous across the gaps and low isolated mountains stand on the plateau in central Wyoming where the belt of deformation crosses (the deformation referred to here is of Laramide age)... There is also a difference in character... The ranges of the...(Southern Rocky Mountains)... are, for the most part, linear features, the main crests being on structural uplifts generally flanked by outward-dipping strata making hogback foothills. In the Northern (Rocky Mountain) province such division into orographic units is almost wholly wanting. Most of the larger mountain masses there are not linear and they have neither axial crest nor monoclinal foothills...” (pp. 92–93).

“...The Southern Rocky Mountain province consists mainly of broad, elevated, north-south strips of granite generally flanked by steeply dipping sedimentaries...” (p. 93)

“...Colorado is crossed by two granite belts... separated by structural depressions...” (p. 110).

“...extensive areas may be found in which the mountain tops rise to an almost uniform level (that of a late Eocene erosion surface, described by Epis and Chapin, 1975)... Some of the ruggedest mountain areas do not rise above this plateau level and are plainly carved from it...” (pp. 96–97).

“Some of (the) higher mountains have rounded tops with only moderate summit slopes, such as occur on old mountains much subdued (by erosion)... Such summit forms may give way abruptly to... oversteepened, often nearly vertical slopes...” (p. 98).

Fenneman’s (1931) descriptions are apt and they call attention to features that help to distinguish tectonically the Southern Rocky Mountains from the Middle and Northern Rocky Mountains. They also help to define the characteristics of the crestal region of a continental ridge. Each a ridge is an elongate, but very broad, regional crustal arch with concave flanks, surmounted by sharply elevated crestal mountains which bracket, in their interior, an axial graben and axial valleys. The longitudinal drainage courses of these valleys are marked by thermal springs and related hydrothermal deposits of fluorite (Waring, 1965, fig. 2; Van Alstine, 1976; Eaton, 1984, fig. 6). The topographic floor of the graben is underlain by coarse clastic sediments interbedded with basalts flows and rhyolitic tuffs. Coeval sediments and volcanic rocks are found on the uppermost rises. The sediments are derived by erosion of the rugged crestal ranges. Finally, there is an obvious continuity of deformed Precambrian basement rocks across the entire width of the ridge, including the graben floor.

In describing what he regarded as the southern terminus of his Southern Rocky Mountains Province, a feature of little significance in the present redefinition, Fenneman wrote:

“The Sangre de Cristo Range is a steep... uplift, granite cored... From... lat. 37°30'... it extends straight south for 140 miles where it ends abruptly, and with it ends the Rocky Mountain System... West of the south end of the Sangre de Cristo Range and (westward) beyond the Rio Grande, almost on the 107th meridian, is a parallel range, the Nacimiento and Jemez Mountains. These... are not unlike the Sangre de Cristo in structure and character. Though similar mountains farther south are included in the Basin and Range province, it has seemed best to include these in the Southern Rocky Mountain province because of their close association...” (pp. 104–105).

Fenneman thus gave a hint of the essential tectonic arbitrariness of his southern, apparently purely physiographic, province boundary. It was left to a contemporary to stitch two like pieces together. In doing so, Bryan (1938) shifted the central focus from the quasi-parallel mountain belts to the structural depressions between them. Because the northernmost of these depressions began in southern Colorado, the feature he identified was offset considerably southward from part of Fenneman’s Southern Rocky Mountains, their axes coinciding over only part of the length of each.

Bryan employed the term “Rio Grande depression” to describe a series of structurally-aligned, narrow, linked basins through which the Rio Grande passes, descending from the high San Luis Valley in Colorado, well within Fenneman’s Southern Rocky Mountains Province, to El Paso, Texas, well within his Basin and Range province. He recognized the tectonic origin and common age (Miocene and Pliocene) of the basin-fill sediments along the river’s course, as well as the history of structural rejuvenation of the bordering ranges.

Thirty-three years later, Chapin (1971) presented a version of the Rio Grande rift that showed it to begin in the uppermost Arkansas Valley, above Leadville, Colorado, north of Bryan’s (1938) northern terminus, and after having broadened into a series of parallel basins and tilted horsts south of the latitude of Socorro, New Mexico, tentatively playing out a short distance below El Paso, Texas, near the southern end of the Franklin...
Mountains (Fig. 1). Chapin (1971) noted, however, that if one used the criteria of rift-related sedimentation, an argument could be made for extending the structure at least 110 km farther southeast.

Tectonic redefinition

A special volume devoted to the Rio Grande rift was published a short time later (Riecker, 1979). Of significance to our thesis here is a paper in that volume by Tweto (1979a). He argued that while the principal, sediment-filled grabens of the Rio Grande rift may terminate northward near Leadville, Colorado, major normal faults with large Neogene displacement and massive mountain ranges that are essentially young, structural horsts, and intervening valleys that are grabens or half grabens, continue northward and north-northwestern across the whole of Colorado. He pointed out that the Rio Grande rift is but one element of a much larger (extensional) tectonic domain that had its tentative beginnings in Oligocene time (28-29 Ma ago in the north and 30-32 Ma ago in the south, according to the data of Chapin and Seager, 1975; Tweto, 1979a; Price and Henry, 1984). Pronounced steep normal faulting of large displacement, block uplift and significant erosion began in middle Miocene time, however, with the most significant pulse of uplift in late Miocene and early Pliocene time (Chapin and Seager, 1975; Taylor, 1975).

The Neogene tectonic history of this region is remarkably similar to that of the Great Basin (compare Lipman, 1981 with both Eaton, 1982 and Zoback et al., 1981). In both areas, an early phase of southwest-directed, high horizontal extensional strain accompanied by pronounced stratal rotations was followed by a west or west-northwest-directed phase of extension dominated by low horizontal extensional strain, markedly less stratal tilting, and appreciably greater vertical displacement. The Southern Rocky Mountains we see today are the result of the latter phase of this extensional deformation which resulted from lithospheric thinning. Profound uplift and bold block faulting took place less than 20 Ma ago, with its strongest pulse between 12 and 4 Ma ago.

The present topography and the geologic data of Knight (1953) and Blackstone (1975) suggest that, as a tectonic feature, the Southern Rocky Mountains continue north of the structures described by Tweto (1979a) into Wyoming. Normal faulting there apparently occurred mostly in post-middle Miocene time. The full length of the redefined Southern Rocky Mountains thus runs from central eastern Wyoming southward to the west thumb of Texas.

Neither Fenneman's, nor Bryan's, nor Chapin's original north and south termini for the feature sometimes viewed as a mountain range and sometimes as a rift valley with bordering ranges (Figs. 1 and 2) is thus wholly satisfactory from a geographic or tectonic point of view. Further confusion results from the presence of major Laramide structures that one sees preserved in this and adjoining regions, and which, in places, are distinguished with difficulty from spatially coincidental structures that were formed in the great regional Neogene ridge uplift and crest-localized block faulting that followed the Laramide orogeny.

How, then, does one define a coherent tectonic whole? Coherence is based on first-order topography and on middle Miocene and younger structures and sedimentary and volcanic history.

First-order topography

Figure 3 shows the topography of the region smoothed by a moving 45' X 45' average on a 15' grid (Diment and Urban, 1981). The smoothed topography defines the north and south terminations of the ridge crest rather sharply, as well as the prominent east flank of the crestal mountains and the north trend of the Alvarado ridge as a whole. The west flank is less obvious in this figure, for the range is bordered on the west by topography as high as, or, in a very few places, higher than, the crest of the linear mountains with which we are here concerned. Its geographic definition, based on structure and local topography, is described below in the latter part of the section on geologic characteristics.

The north and south terminations of the ridge deserve brief comment. To a small degree, the
rendering of both was subjective. Topography was the prime criterion employed in drawing these parts of the boundary of the crestal region. Both the smoothed topography of Fig. 3 and the more detailed topography depicted by U.S. Geological Survey 1:500,000 scale topographic maps of Wyoming, New Mexico and Texas were employed. Neither termination of the ridge crest is tapered in plan, as one might intuitively expect. On the north, the province splays out, instead, even as it dies out. I believe this to reflect the effect of an inherited mechanical crustal anisotropy expressed by the array of earlier Laramide structures that developed there and that are shown below in Fig. 9.

The south end is more problematic, for the axial rift system broadens south of Albuquerque (see Fig. 1) and coeval extensional structures (both rift basins and normal faults) continue for many tens of kilometers beyond El Paso, along, and adjacent to, the Rio Grande. The high bordering topography that defines the range at the south end terminates as shown in Fig. 3, however, and the normal faults and rift basins that farther north strike generally due north make a sharp 45° bend to the southeast below El Paso and the faults begin to decrease in throw. Here, as at the north end of the ridge, there seems to be an implication of an inherited mechanical anisotropy of Laramide age and mild rejuvenation of earlier structures.

The east flank or border of the Southern Rocky Mountains, sensu lato, faithfully follows the 105th meridian from 32°N to 43°N. Locally, along it, but in abundance west of it, is a family of normal faults with demonstrable late Cenozoic movement. Together, these phenomena define a whole that has coherent and consistent regional topography, structure and age. It includes terrain ranging in average elevation from 1400 m to 3800 m, most of

Fig. 3. Smoothed topography and major normal faults of the crest and uppermost rises of the Alvarado ridge. (Smoothing based on 45' by 45' moving average on 15' grid centers). The range begins on the north at 43°N, in southeastern Wyoming (WY), and trends due southward, its eastern margin closely following the 105th meridian, to below 32°N, in the west thumb of Texas (TX). Normal faults are of two types: (1) those of known or inferred Neogene age (many of them show evidence of known or suspected Quaternary movement, as well); and (2) those either of unknown age of last movement or of pre-Neogene age. Note that the eastern margin of the range is neither a fault nor a fault-line scarp over most of its length. Data from Blackstone (1975), Cohee (1961), Diment and Urban (1981), Howard et al. (1978), and Tweto (1978).
Fig. 4. Distribution of Miocene and Pliocene sedimentary rocks on the Alvarado ridge. a. Generalized distribution map. Deposits shown here are divided by location into two groups: (1) narrow axial deposits, such as those filling the structural depressions along the midline of the ridge crest; and (2) broad alluvial aprons and their erosional remnants on the gentle rises flanking the ridge crest. The latter are of fluvial, lacustrine and locally, eolian, origin and near the ridge crest are locally interbedded with rhyolitic tuffs and/or basalt flows, petrologic markers of extensional strain. Distribution from King and Beikman (1974).
Fig. 4b. Details of erosional remnants of these deposits in northern Colorado (many of these outcrops are not included in diagram a). The isolated outcrops on the west rise are all that remain of an original cover that probably was almost as extensive as that on the east rise, as seen in diagram a. Formation identification, from west to east, as follows: BP—Browns Park; NP—North Park; T—Troublesome; DU—Dry Union; and O—Ogallala. The ridge crest proper lies between Craig on the west and Boulder and Golden on the east. Data from Tweto (1979b).
it above 1900 m. Individual mountain crests and flanks have strong north-trending components of strike, as do the strikes of the late Cenozoic extensional faults that bound them.

Other features contributing to a geologic demonstration of tectonic coherence and illustrated below (Figs. 11 and 8) are elongate, north-trending (to northwest-trending, en echelon, right-stepping) exposures of structurally elevated Precambrian basement rocks and a sharply defined drainage network that includes well-developed axial drainage and east and west flank drainages. Present, too, are well-preserved axial basin fills and remnants of sheet-like alluvial aprons of Miocene and Pliocene erosional debris on the rises flanking the mountains, parts of them interbedded with rhyolitic tuffs and, locally, with basalt flows (Figs. 4a and b).

**Syntectonic depositional history**

The local stratigraphic nomenclature applied to the fill of the axial basins along the midline of the Alvarado ridge varies from south to north. On the southern part of the ridge, in New Mexico, the principal units are those of the Santa Fe Group and its equivalents, the Tesuque, Chamita, Abiquiu, Picuris and Los Pinos formations of Miocene age. In the upper Arkansas and upper Blue River grabens of Colorado, the fill is referred to as the Dry Union Formation. Farther north, it is the early to late Miocene Troublesome Formation and more northerly yet, the middle Miocene North Park Formation (Izett, 1975; Tweto, 1975). The coeval, sheet-like sedimentary covers on the rises are known by still other names (Browns Park on the west and Arikaree and Ogallala on the east). Izett (1975) presented a correlation chart of all the units identified in the north. Collectively, they represent a span of time from 29 to 4.5 Ma ago, but we are here particularly interested in those sediments of middle Miocene and younger age.

The Browns Park Formation (26 to 8 Ma ago), on the northern part of the west rise, reached eastward into the area of the ridge crest where it is preserved in Neogene grabens and asymmetric half grabens west of the Park Range. The unit is cut both by a swarm of basaltic dikes and a linear band of basalt plugs within the crestal area. In the northwestern corner of North Park, northwest of Walden, Colorado (Fig. 4b), the name Browns Park has been applied to sandstones beneath the North Park Formation that are lithologically similar to the Arikaree Formation on the east rise (see below). This same stratigraphic relationship has been observed along the North Platte River, north of Saratoga, Wyoming, 50 km north of the Colorado border (Izett, 1975).

The sedimentary apron on the east rise of the Alvarado ridge is especially well preserved owing to profound calichification. It extends continuously for more than 700 km east of the crest, but originally extended farther. Its upper surface has been modified only slightly in the past 4 to 5 Ma. The stratigraphic units constituting this apron are the early Miocene Arikaree Formation and late Miocene to early Pliocene Ogallala Formation (Izett, 1975). These units rest unconformably on Laramide-age sedimentary rocks in the north and on Permian, Triassic and Jurassic rocks in the south. Paleogene rocks are seen on the upper rise east of the Alvarado ridge only in three widely separated areas close to the mountain front, but they are found in abundance over much of the Great Plains farther north, in the area east of the Laramide Northern Rocky Mountains.

The Arikaree is well sorted, fine grained and of Cenozoic volcanic rock provenance. Much of the material was probably derived from ash erupted in the Great Basin, far to the west, but locally some may also have been derived by erosion of the great Oligocene, calc-alkaline volcanic fields that formed on the late Eocene erosion surface in the corridor that was to become the summit of the ridge (Epis and Chapin, 1975; Steven, 1975). In contrast, the overlying Ogallala Formation is coarser, more poorly sorted and of Precambrian basement provenance. It varies in thickness up to nearly 200 m and consists of interbedded gravels, sands, silts and clays. It is made up of fluvialite and lesser lacustrine and eolian components.

The oldest Ogallala sediments include piedmont pediment veneers, valley fill deposits and coalesced fan alluviums (Hawley, 1984) that record the initial stages of uplift of the Alvarado ridge. Statements concerning the span of age of
the formation suggest variation in initial deposition with location on the east rise. Thus, Izett (1975) reported that Ogallala deposition in Colorado began 17 Ma ago, but farther south, in west Texas, the oldest Ogallala sediments appears to be only 12 Ma old or so. The youngest of these sediments in Texas, like those farther north, are between 4 and 5 Ma old, hence, of early Pliocene age. It is not clear as to whether the difference in initial times of deposition is real or not, only that uplift began sometime in middle Miocene time and resulted in the shedding of coarse fluvial sediments derived from the ridge crest down the east rise. Downslope progradation led to the development and growth of a very wide alluvial apron or gigantic bajada.

The development of caliche in the upper part of the Ogallala section and stratigraphic evidence of local eolian activity both suggest an increasing tendency toward aridity in the region east of the rising ridge crest. Simultaneously, precipitation and runoff on the uppermost west rise and crest must have increased and, even today, it is higher there than on the upper east rise: 40-50 cm vs. 30-40 cm. The potential for broad erosional stripping of deposits on the rising west flank of the ridge has, therefore, probably been somewhat greater since uplift, owing to rising westerly air masses discharging much of their moisture content on the west side of the ridge crest.

In northern Colorado, the sedimentary mantle on the west rise consists of widely scattered, large erosional remnants of the Browns Park Formation (Fig. 4b). It is as much as 550 m thick and consists of fluviatile and eolian sandstones interbedded with basalts. According to Izett (1975), an Arikaree-like sandstone occurs in the lower part of the formation. Izett asserted that the Browns Park Formation formerly covered very large areas, buried topographic highs, and extended from high on the flanks of the ranges into and across adjacent basins. The scattered remnants shown in Fig. 4b tend to support this view, but the age of the oldest part of the section appears to predate the beginning of ridge uplift, as recorded by initial Ogallala deposition on the east rise farther south. Larson et al. (1975) suggested that part of Browns Park time was characterized by deposition in broad, shallow basins nourished by small, ephemeral streams. They indicated that regional uplift perhaps did not begin until 10 Ma ago, but they also noted in their description of the unit that the basal conglomerate of the formation consisted of Precambrian basement debris that coarsened eastward toward the Park Range, suggesting strong relief in earlier times. This range developed first as a Laramide block uplift and was strongly rejuvenated in Neogene time, but the basal conglomerate could represent the existence either of residual Laramide topography or an episode of Oligocene uplift following Eocene bevelling of Laramide topography. It is probable that the 60-km-wide Steamboat basin in which the early Browns Park sediments accumulated was genetically similar to other broad extensional basins of latest Oligocene and early Miocene age farther south in the region, e.g., the Popotosa basin of central New Mexico (identical age of initial deposition at 26 Ma; Chapin and Seager, 1975).

To the south, in Arizona, the Bidahochi Formation of late Miocene and Pliocene age (6.7-4.1 Ma) is probably also part of the youngest west rise cover. It consists of a lower lacustrine member with interbedded rhyolitic tuff, a volcanie middle member of trachybasalt (as noted above, the older Browns Park Formation is also cut by and interbedded with basalt), and a fluviatile upper member consisting of cross-bedded sandstones interbedded with rhyolitic tuffs (L.D. Fellows, written commun., 1985). Together, the maximum thickness of these units is no more than 250 m. Before approximately 5 Ma ago, the Colorado Plateau apparently had an undrained, saucer-like topographic configuration, owing to rim uplifts adjoining vast areas of extension to the west, southwest, and east, creating the potential for lake impoundment and lacustrine sediment accumulation in earliest Bidahochi time.

The preserved stratigraphic record of the Alvarado ridge thus provides a wide range of dates for the initiation of ridge uplift, all of them of middle to late Miocene age: roughly 17, 12, 10, and 7 Ma. The youngest date may not be a reliable indication of the beginning of uplift, for older sediments may have been stripped from the Colorado Plateau portion of the west rise before
the oldest Bidahochi sediments were ponded and deposited. It is a matter deserving further study.

Near its axis, the full length of the crest of the Alvarado ridge is marked locally by scattered eruptive masses of basalt. They are of Miocene and younger age and are unimpressive in their volume. Their occurrence is of major genetic significance, however, for they indicate extension of the lithosphere that was localized along the ridge crest.

**Topographic aspects of the Southern Rocky Mountains and Alvarado ridge**

**Relationship of the redefined province to the North American Cordillera**

Because the mountains surmounting the Alvarado ridge are a part of the North American Cordillera, the argument for their tectonic uniqueness and coherence is furthered with an identification of topographic features that set them apart from other elements of the Cordillera. Figure 5 is a generalized topographic map of the Cordillera between latitudes 20°35' and 60°40'N, a strike distance of almost 6000 km. The Cordillera's overall trend in this stretch is north-northwest and the long axis of the figure is oriented parallel to that trend.

The high terrain of western North America, defined here as the region above 1000 m in elevation, has twice the width in its U.S. portion than it does in either Mexico or Canada. The area of terrain above 2000 m is also much greater in the United States, especially in the eastern part of the Cordillera. Most of the sub-region under discussion lies above 2000 m. There are large tracts above 3000 m and numerous peaks and ridges above 4000 m. Save for Alaska, it is regionally the highest part of the North American Cordillera, and as high as the celebrated Alps. It lies east of an imaginary curvilinear axis drawn to connect the highest parts of the Cordillera of Canada and Mexico.

The orientation of the crest and east rise of the Alvarado ridge relative to the rest of the Cordillera is anomalous. Both the 1000 and 2000 m contours, as well as the Continental Divide near its axis, trend due north, rather than north-northwest, an azimuthal discrepancy with the whole of the Cordillera of 21° (see inset). The ridge has thus developed as a mammoth young topographic feature cutting across the easternmost part of the principal late Mesozoic-early Tertiary Cordilleran topographic grain at an oblique angle.

**The concept of a continental ridge and rise**

The focus of many investigations of lithospheric rifts has been on the rift valleys and their related crustal structure. To the extent that mountain ranges are observed to occur in association with rift valleys, they have tended to be regarded as “shoulders”, “bordering ramparts”, or “rim uplifts”, i.e., features of secondary interest and significance. In addition, the pair of rises that bracket them and which together constitute a regional arch, have received the appellation “plateau uplift” or “topographic swell”. It is a central argument of this paper that all of these features of the Alvarado ridge were created at the same time by the same process and that the ridge, as a whole, is the more significant feature, not the rift valley at its axis, although that valley provides the principal clue as to the nature of the local stress field.

The rifted Southern Rocky Mountain province and its rises are part of a broad, coherent structure that is at least 2500 km wide from the toe of one rise to the toe of the other. It is grossly similar in general topographic form to a spreading ocean ridge, despite a significant difference in origin. The topography of the concave rise on either side of a continental ridge does not represent systematic thermal subsidence of once higher terrain generated at the ridge crest, hence, the morphologic similarity between oceanic and continental ridges is in significant part coincidental. A specific interpretation of the origin of the Alvarado ridge (lithospheric thinning) is provided in a companion paper (Eaton, 1987).

**Ridge and rise topography**

Figure 6 shows a set of topographic profiles drawn across the crest of the Alvarado ridge 1° of latitude apart. These profiles all cross the north-
ern, higher part of the ridge. Each was drawn with a vertical exaggeration of approximately 100:1 and each is overlain by a similar profile of like vertical exaggeration crossing some part of the Mid-Atlantic ridge. Four of these paired profiles are centered on the ridge crest (Figs. 6a–d), but the fifth is drawn from the axial graben out to a distance of 900 km on the rises that flank the crestal mountains of both ridges.

The profiles in Fig. 6 demonstrate a remarkable, but coincidental, similarity in first-order morphology between a continental ridge and a slowly spreading oceanic ridge. There is an absence of a water load in the continental case. The cross-sectional dimensions of width and height of the crestal ranges, themselves, are the same, as are the topographic relief and slopes. These latter similarities are probably related to common fault processes and are perhaps little altered by the water load in the oceanic case. One can see that in aligning the crestal peaks in Fig. 6e, the concave rises of the paired profiles track one another faithfully for distances of hundreds of kilometers. Only their local relief is different, that of the ocean floor being greater and more irregular. If an adjustment were made for the effect of the water load in the oceanic case, however, the two sets of profiles would not coincide, though they would have a similar form. The oceanic profile would stand higher at its crest and the rises would have steeper regional slopes.

An additional comparison is somewhat instructive (see Fig. 7). Topographically, the Alvarado ridge is far more like those first-order symmetrical features that develop at divergent oceanic plate boundaries than like continental mountain ranges created by relative plate convergence and lithospheric compression and stacking. On the left of Fig. 7a–d is a series of four profiles, two of them crossing the Alvarado ridge. On the right (Fig.

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**Fig. 5.** Generalized topography of the North American Cordillera in Canada, the United States and Mexico (from American Association of Petroleum Geologists, 1977). Throughout much of the 6000 km stretch shown here the Cordillera is relatively narrow and of north-northwest trend. By contrast, the Southern Rocky Mountains, sensu lato, outlined schematically by the heavy rectangle on the east, display a contrasting trend and have a higher average elevation. The Continental Divide follows its western half. The pattern of major river drainage, shown only in and around the subject province, is illustrated in greater detail in Figs. 1 and 8.
7e–h) are profiles across collisional and non-collisional convergence zones and their associated mountain ranges. The topographic asymmetry of the latter is as systematic and well-developed as the bilateral symmetry of the ridges in Fig. 7a and b.

There appears to be little trace of the topographic effect of the earlier Laramide compression on the first-order topography of the Southern Rocky Mountains in either Figs. 6 or 7. Not even the profile across the collision-produced Himalayas (Fig. 7e), drawn purposefully at a location where they are relatively narrow, is quite similar. There is an absence of paired rises flanking the Himalayas and the gentle terrain on the two sides is of contrasting elevation, a high plateau occurring on the north.

In addition to the topographic contrast between the Alvarado ridge and convergence-produced mountain ranges, geologic evidence indicates that the Laramide Southern Rocky Mountains had been largely obliterated before Neogene time, well before extension and related uplift began. Epis and Chapin (1975) argued that the compressional Laramide Rockies probably never stood very high because rapid erosion in Late Cretaceous, Paleocene and Eocene time kept pace with mountain uplift. Tweto (1975) suggested that the Laramide mountain crests may have stood only 1000 to 2000 m above sea level and local basins in which their erosional debris accumulated, between 300 and 600 m. The cumulative Laramide structural relief is much greater, of course, because of the integrating effects of repeated uplift over time, that uplift driven in part by isostatic response to persisting erosion. The stratigraphic record indicates that thousands of meters of Precambrian, Paleozoic and Mesozoic rocks were stripped from the Laramide uplifts.

Fig. 6. Topographic profiles across the crest of the Alvarado ridge (AR) and Mid-Atlantic ridge (MR). Vertical exaggeration is 100:1. Because the west rise of the latter better matches the east rise of the former, all profiles of the Mid-Atlantic ridge are reversed, east for west, as permitted by the genetic bilateral symmetry of spreading ocean ridges. The profiles of the Alvarado ridge can be identified by virtue of the heavier line weight and smaller data sampling interval employed in plotting them. Individual figures are as follows: (a) AR, 40°N; MR, 15°N; (b) AR, 39°N; MR, 17°30'N; (c) AR, 38°N; MR, 27°30'N; (d) AR, 37°N; MR, 35°N; and (e) AR, 36°N; MR, 35°N. The profiles in a–d are centered on the crestal ranges and extend outward only 400 km or so. In (e), the Rio Grande rift and its oceanic counterpart were placed at the left edge of the figure so that the bordering escarpments and nearly 900 km of the adjoining rises could be compared.
Fig. 7. Smoothed topographic profiles across major mountain ranges of the world. At the top, on the left, are two symmetrical profiles developed across divergent tectonic plate boundaries in the ocean; on the right are asymmetric profiles developed at, and near, convergent plate boundaries both on continents and at ocean margins. The vertical exaggeration in all profiles is 100:1. In the case of those convergent boundary profiles that cross young, calc-alkaline volcanic chains related to active subduction, care was taken to avoid crossing the high volcanic edifices. Individual figures are as follows: (a) Mid-Atlantic ridge along 45°S; (b) Mid-Atlantic ridge along 29°N; (c) Alvarado ridge along 36°N (the Wasatch Mountains, near the west edge of this figure, were also elevated in Neogene time as the eastern rim uplift of the Great Basin extensional province, farther west); (d) Alvarado ridge along 33°N; (e) the Himalayas of Asia; (f) the Andes of western South America; (g) the central Alps of Southern Europe; and (h) central Japan.
both as they developed and after compression and related uplift had ended.

At the close of the Laramide episode (middle Eocene time), lateral stream planation bevelled nearly all of the region, producing a pediment surface of low relief across uplifts and basins, alike. This is the now-high erosion surface described by Fenneman (1931, and in quotation, above) and analyzed by Epis and Chapin (1975) and Scott (1975). Paleobotanical evidence (MacGinitie, 1953; Leopold and MacGinitie, 1972) suggests that at the time of its development this surface had an average maximum elevation of no more than 900 m. Even so, part of that elevation must have reflected isostatic response to the events that had preceded and accompanied development of the surface. Epis and Chapin (1975) cite regional evidence to the effect that the surface sloped gently southeastward toward the Gulf of Mexico with an average gradient of about 0.5 m/km. It must have merged imperceptibly with what is now a Great Plains region since mantled with Neogene erosional debris and tilted due eastward in late Cenozoic time at a steeper slope.

Scott (1975) asserted that this erosion surface is probably the only widespread Cenozoic surface of low relief in the Southern Rocky Mountains and that large variations in elevation between parts of it, originally mistaken for a series of different surfaces, are simply the result of Neogene block faulting and differential uplift. He believed that the surface extended northward into central Wyoming, as described there by Knight (1953) and Denson and Harshman (1969). Epis and Chapin (1975) described other evidence for its apparent presence in western Colorado and New Mexico (citing, among others, the observations of Steven et al., 1967, and Schmitt, 1933). Other geologists have since found evidence for what appears to be additional, local erosional bevelling in Oligocene time, with Miocene sediments filling paleo-stream valleys of that age (B.H. Bryant, pers. commun., 1985).

With the onset of localized extension in late Oligocene and early Miocene time and notable uplift in middle Miocene time that continued into early Pliocene time, parts of the Neogene Southern Rocky Mountains rose nearly 3000 m. Remnants of the late Eocene pediplain are now found at elevations as high as 3800 m. In addition, erosional remnants of fluidal, ash-flow tuffs that swept southeastward across it in Oligocene time are, owing to the later development of major grabens and horsts, found at high and low elevations, alike (Epis and Chapin, 1975). The maximum pulse of uplift appears to have occurred in latest Miocene and earliest Pliocene time (7–4 Ma ago). This uplift was not accomplished by crustal thickening, for the crust varies little in its thickness from the area of the range crest on the highest part of the ridge all of the way across the region of the sloping Great Plains and part of the Central Lowlands (see Eaton, 1987, fig. 8).

Today the apron of Miocene and Pliocene erosional debris that was shed eastward from the rising Neogene Southern Rocky Mountains locally exceeds 2000 m in elevation in its westernmost reaches. It therefore stands as high as, or higher than, the crest of the Laramide Southern Rocky Mountains that preceded it. Continued uplift since the end of Ogallala time has resulted in the deep incision of valleys such as those of the Arkansas, South Platte, and Pecos rivers and exhumation of the eroded edges of upturned pre-Cenozoic strata. Large volumes of the Arikaree and Ogallala formations, especially those closest to the mountains, have been removed by erosion save at the north end of the range, in southeasternmost Wyoming, where they still lap up onto the erosion surface that bevels the Precambrian basement (Fig. 4) as "The Gangplank" followed by Union Pacific Railroad and U.S. Interstate Highway 80. At this locality, and at two others farther south, one near Castle Rock, Colorado (40 km south of Denver), and the other near the Colorado–New Mexico line, there is minimal Neogene structural topographic relief between the upper edge of the Great Plains (east rise) sedimentary and volcanic cover and the top of the mountain front, a few tens to a few hundreds of meters at most. An even larger part of the west rise cover probably has been stripped from the Colorado Plateau and Wyoming Basin physiographic provinces, as a result of higher precipitation and runoff on the west side of the ridge.

Lateral progradation of the widespread alluvial
apron on the east side of the ridge required topographic gradients there that would provide sufficient energy for sediment transport of coarse clastic debris out to distances of many hundreds of kilometers. Subsequent local erosion of this cover in Pliocene and later time is suggestive of recurring uplift involving the whole of its region of occurrence.

Axial valleys and axial drainage

A characteristic feature of the summit regions of slowly spreading oceanic ridge-rise complexes is the axial valley. We have seen that the sediment-filled Rio Grande depression occupies the medial portion of the southern two-thirds of the Alvarado continental ridge crest, hence, it is important to examine the northern one-third.

North of the point where the upper Rio Grande enters the San Luis Valley from the west, at Del Norte, Colorado (Fig. 8), the Neogene graben in which it flows southward continues northward for another 80–90 km, to Poncha Pass. North of this pass, marked by an oblique, transverse structural zone (see Fig. 3), is another aligned graben of Neogene age, similar in nature, but much narrower than San Luis Valley. In it the upper Arkansas river flows south to its east-trending canyon of escape from the range, north of the Wet Mountains. This graben continues northward to Tennessee Pass.

The stippled zone in Fig. 8 identifies the full extent of the axial drainage of the Southern Rocky Mountains. It marks a series of right-stepping, en echelon rivers that begin on the south with the south-flowing Rio Grande. Next northward is...
south-flowing San Luis creek and then the south-flowing upper Arkansas river. East of Tennessee Pass, the axial drainage continues north of Hoosier Pass with the north-flowing Blue river and a facing tributary of the Colorado, the south-flowing Big Muddy. They enter the southwest-flowing Colorado river from opposite sides near Kremmling, Colorado.

Major faults with Neogene movement flank the Blue river (Tweto, 1979a), one of them a normal fault of considerable displacement, the other, a reactivated Laramide thrust. The valley is a half graben that has been largely stripped of its sedimentary fill. Near-source Neogene conglomerates are preserved as small patches faulted against Precambrian basement rocks (the small outcrops between Breckenridge and Kremmling labelled DU and T in Fig. 4b). According to Tweto (1979a), they once filled the valley.

The bedrock floor (the base of the valley fill) of the Blue river valley ranges in elevation from roughly 10,000 ft (3050 m) at the foot of Hoosier Pass to a little less than 7500 ft (2285 m) near Kremmling. Farther south, the highest parts of the top of the Neogene fill of the Rio Grande graben between the Colorado–New Mexico line and Tennessee Pass range in elevation from more than 11,000 ft (3350 m) on the east side of the San Luis valley, southeast of Alamosa, Colorado, to a little more than 10,000 ft (3050 m), at the upper end of the Arkansas valley. The top of the fill probably stood at least that high in the Blue river valley and if it had been preserved from almost complete erosion by: (1) that major axial tributary of the powerful Colorado river, the Blue; and (2) by a valley glacier, it would have extended the appearance of a right-stepped, sediment-filled Rio Grande rift or graben, bordered by horsts, northward at least to Kremmling.

North of Willow Creek Pass, in the broad, high, flat-floored valley of North Park, the north-flowing North Platte river begins its long journey to the Missouri river, which it joins south of Omaha, Nebraska, far down the east rise. Its headwaters drain the northern end of the Southern Rocky Mountains and the northern part of the east rise. The middle Miocene North Park Formation once covered the floor of North Park and was also deposited northward along the ancestral North Platte river, according to Izett (1975). A readily made Laramide basin thus served as part of the axial valley system during and after Neogene uplift and extension.

Most of the axial drainage of the Southern Rocky Mountains flows to the Gulf of Mexico. For a short stretch, however, between Hoosier and Willow Creek Passes (both of which mark an eastward jump in the Continental Divide), axial drainage is to the west and southwest, to the Gulf of California, as is the drainage of the west rise.

There is a systematic array of streams that flow east and west down (or through) the steep flanks of the crestal ranges and down the gentle rises that border them, some for distances of many hundreds of kilometers. On the west, (Fig. 8) from north to south, are the west-flowing Bitter, Little Snake, Yampa, White, Colorado, Gunnison, Dolores, San Juan, Pueblo, Largo and Gila rivers. On the east (Figs. 1 and 8), are the Niobrara, the east-flowing portion of the North Platte, the South Platte, (between the two branches of the Platte is east-flowing Lodgepole Creek, which is not shown) the Republican, the Solomon and the Saline (neither is shown), Smoky Hill, Arkansas, Purgatoire, Cimarron, North Canadian, Canadian, Red, upper Brazos, and upper Colorado (of Texas) rivers. Not all of these streams head up in the crestal ranges. Some originate on the rise of the Great Plains province, notably in its High Plains subdivision, east of the cover-beheading valleys of the much larger South Platte, Arkansas, upper Canadian and Pecos rivers. They have incised themselves 100 m and more below the original surface of the High Plains, but the effect of this incision is only local.

Figure 8 also illustrates the course of the Continental Divide through the region. It marks the western, shoulder-like crest of the Alvarado ridge over most of its length. Only in the source area of the Colorado river, a stream that has cut through the western crest of the range, is the Divide displaced eastward. Beyond both the north and south ends of the Southern Rocky Mountains, the Continental Divide turns more toward the interior of the North American Cordillera, as Fig. 5 indicates.
Figure 8 also shows the spatial distribution of the highest peaks (or clusters of peaks) in the Southern Rocky Mountains. These are mountains exceeding 12,000 ft or 3650 m in elevation. The distance from the northernmost of these, north of latitude 41° N, to the southernmost, at the head of the Hondo river, south of latitude 34° N, is 930 km. The great bulk of the high peaks occur in a belt 600 km long, however, between 35°45' and 40°45' N latitudes. Those peaks that exceed 14,000 ft (or 4270 m) in elevation are restricted to a belt only 375 km long, all of it in Colorado. That state claims some 53 peaks in excess of 14,000 ft, but none is higher than 14,500 ft (4420 m). They thus represent a crude concordance of peak elevations that has a variance relative to sea level of less than 5%. These elevations dwarf Tweto's (1975) estimate of 2000 m for the highest of the Laramide Rocky Mountains in Colorado and MacGinitie's (1953) determination of an elevation of less than 900 m for the widespread late Eocene pediment surface.

Not all of the high peaks in Fig. 8 lie within the Southern Rocky Mountains, sensu lato. The large cluster of peaks at the western head of the Rio Grande represent local topographic eminences in the middle to late Cenozoic San Juan volcanic field, most of which lies just off the ridge crest on the upper west rise (see Fig. 3). These mountains were included in Fenneman's (1931) definition of the Southern Rocky Mountains. They are not the peaks of basement-cored block uplifts bordered by normal faults, however, but are part of a large constructional pile of volcanic rocks of intermediate composition. They were extruded onto the post-Laramide erosional surface that crossed the site of the Southern Rocky Mountains. The major peaks in the San Juan volcanic field stand as high as the peaks on the ridge crest today for two reasons: (1) continued isostatic uplift of their bulk in response to erosion, owing to the relative buoyancy of their underlying light, shallow crustal batholith (Steven, 1975; Steven and Lipman, 1976); and (2) as an area of already-high constructional relief prior to the latest episode of lithospheric thinning and regional uplift, they have been elevated along with the rest of the upper part of the continental rise (including the Colorado Plateau) west of the ridge crest.

Structural characteristics

Structural setting and history

Figure 9 illustrates the regional structural setting within which the Southern Rocky Mountains, sensu lato, developed. Outcrop traces of thrust faults, the axes of major compressional folds and structural basins, and uplifts of Laramide (and older) age strike northwest to north-northwest, at angles of 20° to 60° with the axis of the ridge crest. Although it is not shown in Fig. 9, some of these structures continue into the interior of the crestal province and were involved in its uplift (see Fig. 10). Their northwest orientation finds explanation in the plate tectonic models of Coney (1978) and Chapin and Cather (1981). Northeast compression was strongly oblique to what was to become the north–south axis of the Southern Rocky Mountains, sensu lato.

Chapin and Cather (1981) argued that the direction of Laramide compression was east-northeast from 80 to nearly 55 Ma ago and that it changed to northeast sometime around 55 Ma ago. Following hypotheses first put forward by Kelley (1955) and Baltz (1967), they postulated that a north-trending zone of profound right-lateral, convergent shear existed along the site of the Southern Rocky Mountains late in Laramide time (approximately late Paleocene and early Eocene time). The evidence and arguments for their interpretation, which has since been extended and refined by Chapin (1983), consists both of a north-trending, en echelon swarm of north-northwest striking compressional folds (Fig. 10c), and a like-trending series of narrow, en echelon Eocene basins (Chapin and Cather, 1981, fig. 1). North–south Laramide shortening in the Wyoming Basin and Middle Rocky Mountain provinces, west of the Southern Rocky Mountains, and an absence of such shortening in the stable continental interior to their east was considered as further evidence of a north–south zone of horizontal shear, as was an apparent north–south offset of at least 100 km in the generally west-trending magnetic anomalies arising from sources in the Precambrian basement (Chapin, 1983, fig. 8). The length of this north–south zone was il-
Illustrated by Chapin (1983, fig. 1) with a sketch map showing a series of postulated, north-trending, right-slip Laramide faults. It extends from southern New Mexico to east-central Wyoming, thus running the full length of the ridge crest today.

If such a zone of shear actually existed throughout the province in late Laramide time, it developed in a region that had been structurally anomalous since Proterozoic time. Tweto (1975, 1979a), and Chapin and Seager (1975) all argued, as had others before them, that there was a north to northwest-trending zone of recurring structural highs stretching from southern New Mexico to Wyoming in this region, both in Laramide and pre-Laramide times. These highs shed sediments into local basins, the sedimentary fills of which are well preserved in the stratigraphic record (see Chapin and Seager, 1975, fig. 2). Tweto (1979a) also suggested that many of the normal faults along which extension and uplift have taken place in Neogene and Quaternary time originally may have been strike-slip and high-angle reverse faults of Precambrian, late Paleozoic or Laramide ancestry. The site of mountain building from which today’s range rose was thus apparently predetermined by the presence of older structures and probably also by the effect of Oligocene magmatism. The former provided local to regional-scale mechanical inhomogeneities in the crust and the latter, a thermally-induced rheological anomaly.

The older tectonic events in the region set the stage for a profound new mountain range in Neogene time. While extensional strain came into being across two regions within the Cordillera between 105°W longitude and 120°W longitude (Eaton, 1979, fig. 2a; 1982, figs. 2f and g), all of it in a brief time (early to late Oligocene), followed by extensional deformation that continued into the Holocene, it produced locally contrasting re-

![Regional Structural Setting](image-url)
suits: a major mountain range atop a giant ridge that carries the Continental Divide through New Mexico, Colorado and southern Wyoming and a very broad region of distributed extension (the Great Basin) farther west. Given the great width of this region of discontinuous extension, one may

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**Fig. 10.** Tectonic maps of the west border region of the summit of the Alvarado ridge. a. Normal faults in southwestern New Mexico (after Ratte' et al., 1979). b. Folds in north-central New Mexico; monoclines are labelled as follows: A—anticlinal bend; and S—synclinal bend (after Baltz, 1967). c. Mafic dikes (heavy lines) and normal faults, same area and data source as in b. d. Folds and thrust faults in northwestern Colorado (after Tweto, 1979b). e. Dikes (heavy lines), volcanic plugs (circled dots), basalt flows (stippling) and normal faults, same area and data source as in d. Selected north to north-northeast-trending normal faults are rendered with a heavier line weight and shaded for emphasis.
ask how the western boundary of the structural ridge crest under discussion (and the associated extensional strain) is to be defined? To answer this question, we look now at some tectonic details.

Geographic definition of the western border of the ridge crest

Figure 10 consists of a series of tectonic maps illustrating key elements of the structural geology.
of the ridge crest's western border region. Unlike its eastern border, which drops abruptly (along sharp structural warps and discontinuous fault, fault-line and predominantly erosional scarps) to the eroded upper edge of the Great Plains rise, the western edge of the mountain province is adjoined by other high mountains and plateaus such as the San Juan Mountains and the White River and Colorado plateaus.

Although pronounced local elevations, steep

![Map of Dikes and Normal Faults](image)

Fig. 10c. For legend see p. 183.
bounding mountain slopes and north-south trends of slopes were the elements followed in drawing part of the western boundary, late Cenozoic extensional structures played a more important role, particularly in those areas where they crossed major topographic sags or bridged major topographic re-entrants. Miocene and younger normal faults, basaltic dikes, cinder cones and/or lava fields, some having well-defined local feeders, and rhyolitic dikes and plugs (together, the bimodal petrogenic associates of crustal extension) were also used in drawing the border in some places, as described below.

Figure 10a shows the distribution of normal faults in a part of southwestern New Mexico dominated by Cenozoic volcanic rocks. It borders the west side of the Rio Grande Valley. The highest terrain is a broad, north-trending mountain range (the Black Range) west of the towns of Chloride and Hillsboro. Two observations are of importance here:

1) Structurally higher, older rocks, including

![Map Diagram](image-url)
Paleozoic sedimentary rocks and lower Tertiary (?) andesites and latites, locally much altered, are exposed in this range, but throughout much of the rest of the map area (the topographically-lower Basin and Range Province in the southern quarter excluded), the surface rocks are younger rhyolites, andesites and basaltic andesite flows, interbedded with clastic sediments and rhyolitic ash flows of Oligocene and Miocene age.

(2) The strike of normal faults in this high terrain is essentially due north, whereas to the west the dominant strike directions are northeast (in the north) and west-northwest (in the south).

The western, structural border of the Alvarado ridge crest at this latitude was drawn, therefore, along the west edge of the array of north-trending normal faults and structurally higher pre-Oligocene rocks.

Moving northward, Figs. 10b and c are tectonic maps of an area in northern New Mexico. In the

Fig. 10e. For legend see p. 183.
Fig. 11. Basement exposures on the Alvarado ridge crest and west rise. a. Block uplifts of Precambrian basement rocks along the whole of the Southern Rocky Mountains, sensu lato. b. Their relation (shown by light shading) to Neogene structural basins (dark shading) and extensional faults in the east border region in central Colorado (from Bayley and Muehlberger, 1968; Tweto, 1978).
sotropy that developed as a result of north-north-
east to northeast-directed compression in Laram-
ide and earlier times and a generally west-di-
rected Neogene extensional strain ($\sigma_1$ was ori-
ented first southwest, then west to west-northwest;
Lipman, 1981); and (2) exhumation of low, ero-
sionally-residual, northwest-trending Laramide
mountain blocks that may have been buried by
Oligocene volcanic rocks and Miocene continental
sedimentary and volcanic rocks.

In Fig. 11b, the pattern of young normal faults
appears to reflect the first of these effects. Some
of them strike north to north-northwest, parallel
to the general trend of the province and ap-
proximately perpendicular to the direction of
spreading, but a great many strike northwest. In
the eastern half of Fig. 11b, the north to north-
northwest-striking faults cut across the eastern
ends of the northwest-striking faults and appear to
be younger. Some of the northwest-striking faults
occur in north-northwest-trending, en echelon
swarms that do not appear to be the result of
regional, left lateral shear, as their map pattern
might at first seem to suggest (Wilcox et al., 1973).

Moore (1973) and Ranalli and Tanczyk (1975)
have observed that major plate divergence struc-
tures around the world tend to be dominated
statistically by the development of north-trending
ridges and rises, reflecting east-west directed litho-
spheric extensional strain. This is also true for the
crestal region of the Alvarado ridge, but the struc-
ture there has been strongly influenced in its de-
velopment by pre-existing crustal structures of
contrasting strike, an influence generally lacking
in the development of ocean ridges which involve
mechanically much simpler new lithosphere. The
first order topography of the Alvarado ridge (Fig. 3)
is the topography of significance insofar as the
origin of the Southern Rocky Mountains is con-
cerned.

Plate tectonic models that attempt to explain
the structural evolution of this region are to be
found in Coney (1978), Eaton (1979, 1982), Lip-
man (1981) and Chapin and Cather (1981). An
interpretation of the Alvarado ridge as the pro-
duct of regional lithospheric thinning and axially-
localized lithospheric stretching is provided in a
companion paper (Eaton, 1987).

Conclusions

The Southern Rocky Mountains constitute the
crest of a mammoth continental ridge with gentle,
concave flanks. It carries the Continental Divide
northward across New Mexico and Colorado into
Wyoming. Unlike the rest of the North American
Cordillera, the Alvarado ridge trends due north.
As a whole, this ridge spans parts of five physio-
graphic provinces. Fenneman's (1928) definition
of the Southern Rocky Mountains is judged to be
geo logically inadequate, for in all its fundamental
characteristics, these mountains are at least 60%
longer than he defined them, extending southward
from what he proposed to be their southern
termination, as far as El Paso, Texas. Earlier-
formed late Paleozoic and late Mesozoic–early
Cenozoic mountains on the site of the ridge crest
had been erased by pediplanation and a period of
tectonic quiescence and crustal stability had set in
before local extensional strain began in Oligocene
time. After an initial period of mild crustal thin-
ing and local stretching along what was to be-
come the crestal corridor of the ridge, the processes
of steep normal faulting, profound block uplift,
and the development of flanking rises began in
late Miocene time and continued into early Plio-
cene time. Mild crustal extension along the axial
corridor accompanied by active faulting has con-
tinued into the Holocene. A pronounced mechani-
cal anisotropy inherited from earlier tectonic ac-
tivity gave rise locally to secondary structural
overprinting during thermostectonic uplift. The
Southern Rocky Mountains in Colorado are twice
as high as their compressional predecessors and as
high as the Alps of Europe, marking them as one
of the great orographic and tectonic features of
the North American continent.

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referred to as the Alvarado ridge have been greatly
influenced by the observations and opinions of
investigators who have spent several lifetimes
pondering its various puzzles. Some of them are
acknowledged by reference to their published
works, but others who have counselled me, argued
with me, and pointed me toward bits of evidence that have tended to substantiate or refute elements of a prototype of the definitional model presented here, deserve special mention: Bruce Bryant, Charles Chapin, Paul Morgan, William Seager and Richard Taylor. I am indebted both to Chapin and to William Muehlberger for reviews and suggestions that have led to substantial improvements in the manuscript.

References


New

Schmitt, H., 1933. Summary of the geological and metallogenic
Riecker, R.E. (Editor), 1979. Rio Grande Rift: Tectonics and
Knight, S.H., 1953. Summary of the Cenozoic history of the
Assoc. Guideb., 8th Annu. Field Conf., Laramie Basin,
Wyo. and North Park, Colo., pp. 65–76.
Larson, E.E., Ozima, M. and Bradley, W.C., 1975. Late Ceno-
zoic basic volcanism in northwestern Colorado and its
implications concerning tectonism and the origin of the
Colorado River system. In: B.F. Curtis (Editor), Cenozoic
History of the Southern Rocky Mountains. Geol. Soc. Am.,
Mem., 144: 155–178.
Lipman, P.W., 1980. Cenozoic volcanism in the western United
States: Implications for continental tectonics. In: Continen-
Lipman, P.W., 1981. Volcano-tectonic setting of Tertiary ore
deposits, Southern Rocky Mountains. In: W.R. Dickinson
and W.D. Payne (Editors), Relations of Tectonics to Ore
Deposits in the Southern Cordillera. Ariz. Geol. Soc. Dig.,
MacGinitie, H.D., 1953. Fossil plants of the Florissant beds,
Paleontol., 198 pp.
Moore, G.W., 1973. Westward tidal lag as the driving force of
plate tectonics. Geology, 1: 99–100.
Oligocene volcanism in Trans-Pecos Texas: Timing the
transition from Laramide compression to Basin and Range
Ranalli, G. and Tanczyk, E.I., 1975. Meridional orientation of
grabens and its bearing on geodynamics. J. Geol., 83:
526–531.
Ratte
Stotelmeyer, R.B. and Meeves, H.C., 1979. Mineral re-
sources of the Gila Primitive Area and Gila Wilderness.
Riecker, R.E. (Editor), 1979. Rio Grande Rift: Tectonics and
pp.
Schmitt, H., 1933. Summary of the geological and metallogenic
history of Arizona and New Mexico. In: Ore Deposits of
the Western States. Am. Inst. Min. Met. Eng., New York,
pp. 316–326.
Scott, G.R., 1975. Cenozoic surfaces and deposits in the South-
ern Rocky Mountains. In: B.F. Curtis (Editor), Cenozoic
History of the Southern Rocky Mountains. Geol. Soc. Am.,
Mem., 144: 227–248.
southern New Mexico, west Texas, and northern Chihuahua.
In: R.E. Riecker (Editor), Rio Grande Rift: Tectonics and
87–106.
Steven, T.A., 1975. Middle Tertiary volcanic field in the South-
ern Rocky Mountains. In: B.F. Curtis (Editor), Cenozoic
History of the Southern Rocky Mountains. Geol. Soc. Am.,
Mem., 144: 75–94.
Juan volcanic field, southwestern Colorado. U.S. Geol.
Surv., Prof. Pap., 958: 35 pp.
Steven, T.A., Mehnert, H.H. and Obradovich, J.D., 1967. Age
of volcanic activity in the San Juan Mountains, Colorado.
In: Geological Survey Research. U.S. Geol. Surv., Prof. Pap.,
575: D47–D55.
Taylor, R.B., 1975. Neogene tectonism in south-central Col-
orado. In: B.F. Curtis (Editor), Cenozoic History of the
Southern Rocky Mountains. Geol. Soc. Am., Mem., 144:
211–226.
Tweto, O., 1975. Laramide (Late Cretaceous–Early Tertiary)
orogeny in the Southern Rocky Mountains. In: B.F. Curtis
(Editor), Cenozoic History of the Southern Rocky Moun-
Tweto, O., 1978. Tectonic map of the Rio Grande rift system
in Colorado. In: J.W. Hawley (Compiler), Guidebook to
Rio Grande Rift in New Mexico and Colorado. N.M. Bur.
Min. Miner. Resour. Circ., 163, Sheet 1, Scale 1:1,000,000.
In: R.E. Riecker (Editor), Rio Grande Rift: Tectonics and
Magmatism. Am. Geophys. Union, Washington, D.C.,
33–56.
Tweto, O., 1979b. Geologic map of Colorado. Scale 1 : 500,000.
U.S. Geol. Surv. map.
Van Alstine, R.E., 1976. Continental rifts and lineaments asso-
ciated with major fluor spar districts. Econ. Geol., 71:
977–987.
Waring, G.A., 1965. Thermal springs of the United States and
other countries of the world—a summary. U.S. Geol. Surv.,
Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the Western
407–34.