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APATITE FISSION-TRACK THERMOCHRONOLOGY OF SOUTHERN ROCKY MOUNTAIN–RIO GRANDE RIFT–WESTERN HIGH PLAINS PROVINCES

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Abstract—Apatite fission-track (AFT) thermochronology has been a useful tool in evaluating the tectonic and topographic evolution of the Southern Rocky Mountains, Rio Grande rift, and western High Plains provinces. AFT data from the Front Range and Wet Mountains document that little differential uplift has occurred in the late Cenozoic between the Southern Rocky Mountains and the High Plains in Colorado, except at the southern end of the Wet Mountains. AFT results support a model whereby the central portion of the Front Range was uplifted vertically and the eastern and western flanks of the range were thrust laterally during early Laramide compression. Only about 1 km of denudation occurred in the central Front Range during early Laramide deformation, while approximately 2.5 km of material was removed during late Laramide deformation and the development of the Rocky Mountain erosion surface. AFT ages from the east flank of the Rio Grande rift in the northern Sangre de Cristo Mountains of Colorado and the Sandia Mountains of New Mexico, as well as AFT data from the east side of the southern Sangre de Cristo Mountains and the High Plains of New Mexico, record early Oligocene to middle Miocene cooling. This cooling event is likely related to epeirogenic denudation of at least 2 km of Mesozoic to early Cenozoic sedimentary rocks during early extension in the Rio Grande rift. Widespread Oligocene volcanism in the rift and along the Southern Rocky Mountain–High Plains boundary may have regionally elevated the heat flow. An east-to-west increase in AFT age in the Sangre de Cristo Mountains between Las Vegas and Santa Fe, New Mexico (12–34 Ma along the Rincon Range–High Plains boundary; 44–74 Ma in the Santa Fe Range), when coupled with other geologic evidence, is used to unravel the complicated tectonic history of this area. Laramide deformation elevated the Santa Fe Range and the site of the Española Basin relative to the Rincon Range, where lateral thrusting dominated. Sediments shed from the Santa Fe area accumulated in areas now occupied by the eastern Rincon Range and on the High Plains. During the early phase of rift development, the highland to the west, including the Santa Fe Range to the west of the Picuris–Pecos fault, collapsed to form the Española Basin, allowing preservation of Laramide AFT ages in the Santa Fe Range. Epeirogenic uplift and erosion that was triggered by early rift extension occurred along the High Plains margin, stripping away the accumulated early Cenozoic sediments, Paleozoic to Mesozoic sedimentary rocks, and in some areas, Oligocene volcanic rocks. Denudation in the eastern Rincon Range was enhanced in some places by the development of minor down-to-the west normal faults and associated footwall uplift within the Sangre de Cristo Mountains. Much of the current elevation of the Santa Fe and Rincon Ranges is accommodated by faults activated during the late phase of extension *within* the range rather than along faults on the margins of the southern Sangre de Cristo Mountains.

INTRODUCTION

Over the past decade we have acquired more than 250 apatite fission-track (AFT) ages in the Southern Rocky Mountains, Rio Grande rift, and High Plains provinces. The data from the Rio Grande rift were published by Kelley et al. (1992), while the results from the Front Range, Wet Mountains, southeastern Sangre de Cristo Mountains and High Plains are reported by Kelley and Chapin (in press). Here, we present a summary of AFT results from each province, focusing on the general trends in this large data set. We will combine the AFT results with other geological evidence to discuss current ideas concerning the tectonic evolution of the area between Denver and Albuquerque with emphasis on new, intriguing results in the southeastern Sangre de Cristo Mountains and Pedernal Hills (Fig. 1).

FISSION-TRACK ANALYSIS

Fission-track annealing in apatite is controlled primarily by temperature and the chemical composition of the apatite (tracks in chlorapatites anneal more slowly than those in fluorapatites; Green et al., 1986). In tectonically stable areas where temperatures as a function of depth are now at a maximum, the AFT age and track lengths decrease systematically with depth (Naeser, 1979). At temperatures less than 60 to 70°C, tracks that are produced by the spontaneous fission of ^{238}U are retained, and annealing is relatively minor. The AFT ages in this interval are typically equivalent to or greater than the stratigraphic age of the rock unit and the mean track lengths are on the order of 13 to 15 μm. In the temperature range known as the partial annealing zone (PAZ), which is between 60–70°C and 120–140°C for the mineral apatite, the original AFT age and track lengths are reduced. Mean track lengths in the PAZ are generally 10 to 13 μm. Finally, at temperatures above 120 to 140°C, tracks that are formed are quickly annealed and the fission-track age is zero. If the stable crust is subsequently rapidly cooled (>5°C/Ma) during denudation (uplift and erosion) related to a tectonic event, the PAZ may be preserved so that the time of cooling and the paleodepth of the top or bottom of the PAZ can be estimated (Gleadow and Fitzgerald, 1987). If rocks cool rapidly through the PAZ, the mean track lengths in rocks that are at the base of the fossil PAZ are generally in the 13 to 15 μm range, and the AFT ages in this interval can be used to estimate the timing of the denudation. If the rock column cools more slowly during uplift and/or erosion, the mean track length at the base of the preserved PAZ is typically <13 μm, and the apparent AFT age more loosely constrains timing of the initiation of cooling (Foster and Gleadow, 1992).

FRONT RANGE/WET MOUNTAINS, SOUTHERN ROCKY MOUNTAINS, COLORADO

Late Cenozoic history

AFT data from the Front Range and Wet Mountains in central Colorado have proven useful in constraining the late Cenozoic topographic evolution of the Southern Rocky Mountains (SRM), which has been the subject of much debate. MacGinitie (1953) studied the Florissant flora, which overlies the 36.7 Ma Wall Mountain Tuff (McIntosh and Chapin, 1994) in a paleovalley on the Rocky Mountain erosion surface (Evanoff and Chapin, 1994) capping the Front Range west of Pikes Peak; he concluded that the flora grew at elevations on the order of 300 to 900 m during the late Eocene. Epis and Chapin (1975) proposed, on the basis of this interpretation, that the SRM developed moderate relief during Laramide deformation, that the mountains were eroded to a surface of low relief with an elevation of 300 to 900 m by approximately 35 Ma, and that the erosion surface was subsequently uplifted 1.5 to 2.0 km in the late Cenozoic. However, re-evaluation of the Florissant flora (Meyer, 1992; Wolfe, 1992; Gregory and Chase, 1992) implies that the SRM were at an elevation of 2.2 to 3.3 km during late Eocene and that the apparent uplift of the surface in the late Cenozoic is related to climatic rather than tectonic factors (Gregory and Chase, 1994). These findings alter the view of the topographic development of the SRM. The new

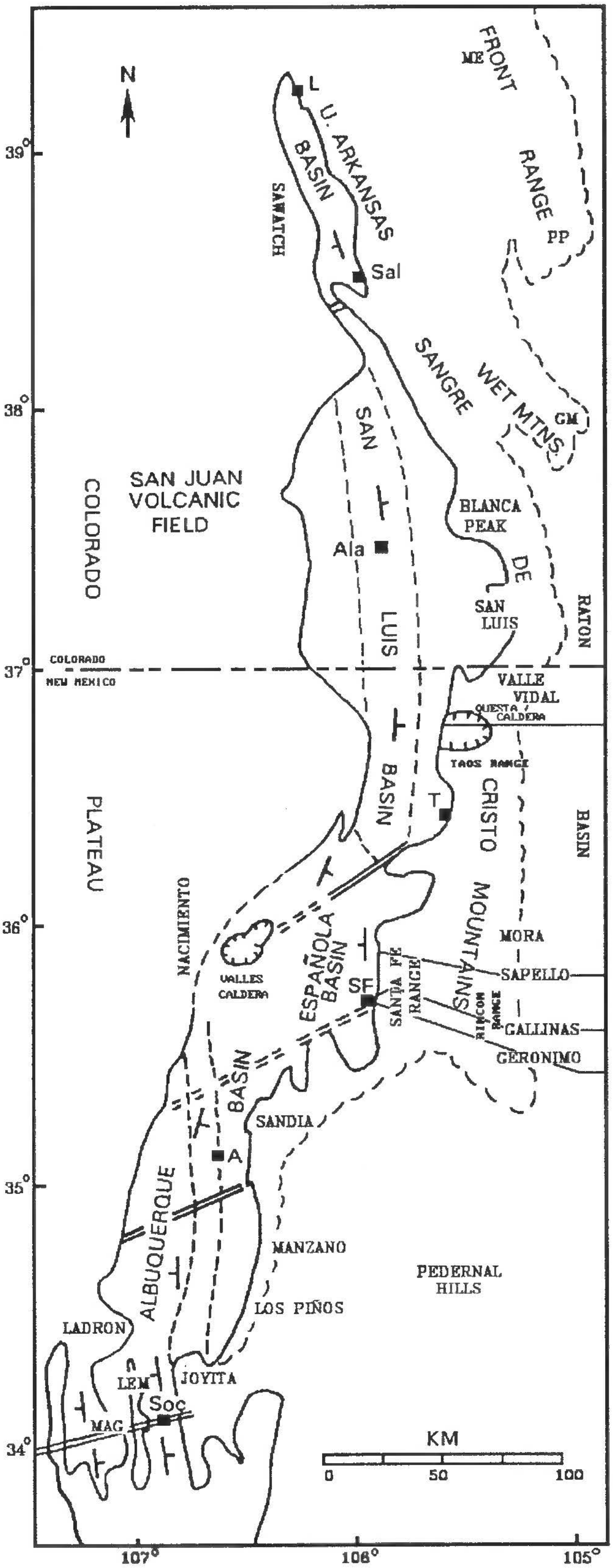

FIGURE 1. Index map showing locations of mountain ranges and sample traverses mentioned in text. MAG = Magdalena Mountains; LEM = Lemitar Mountains; PP = Pikes Peak; GM = Greenhorn Mountain. Towns are represented by squares: L = Leadville; Sal = Salida; Ala = Alamosa; T = Taos; SF = Santa Fe; A = Albuquerque; Soc = Socorro. Base map from Chapin (1988) showing the accommodation zones (double lines) separating half-grabens of opposite dip polarity. Locations of topographic profiles in Figure 7 are also shown.

interpretation suggests that the SRM attained their current elevation during Laramide crustal thickening and that the eastern front of the SRM was buried under sediments derived from the mountains. The present 500- to 1000-m east-facing escarpment along the eastern Front Range is therefore the result of differential erosion and removal of these sediments during the late Cenozoic (Leonard and Langford, 1994; Chapin and Cather, 1994). Remnants of these sedimentary deposits are preserved beneath the Wall Mountain Tuff in the vicinity of Castle Rock and under basaltic lava flows near Raton Pass (Chapin and Cather, 1994).

Based on the AFT results, the only area examined in this study that has undergone significant Neogene uplift and erosion relative to the High Plains is the south end of the Wet Mountains (Figs. 1, 2); this denudation is likely related to extensional tectonics of the Rio Grande rift. The AFT data from low elevations in the southern Wet Mountains implies that denudation in the southern Wet Mountains began about 25 ± 5 Ma (Kelley and Chapin, in press). Significant Neogene uplift is not recorded in the > 55 Ma AFT data for the eastern and southern flanks of the Front Range, suggesting that the Front Range–High Plains boundary owes its topographic relief to late Cenozoic erosional exhumation of Laramide structure rather than late Cenozoic faulting. A model that accounts for both the geologic and AFT evidence involves uplift of the Front Range during Laramide deformation to elevations similar to those observed today, burial of the margins by as much as 1 km of early to middle Cenozoic sediments derived from the mountains, and the development of an erosion surface both on the Front Range and the High Plains in the warm, equitable climate of the late Eocene. Portions of the Rocky Mountain erosion surface were subsequently covered by the Wall Mountain Tuff and other volcanic rocks, resulting in local preservation of the surface. In areas not protected by Eocene rocks, the surface continued to evolve so that in some places it is covered with Miocene rocks and is considered to be a Miocene-aged surface (O'Neill and Mehnert, 1988; Evanoff, 1990). The sedimentary apron adjacent to the Front Range was severely eroded following a climatic change at approximately 7 to 8 Ma that produced seasonal fluctuations in rainfall (summer "monsoon" season) and intense precipitation during thunderstorms.

Laramide deformation

The AFT data were also used to investigate the style and magnitude of Laramide deformation in the Front Range and Wet Mountains. AFT ages along the eastern margin of the Front Range near Golden are 100 to 270 Ma (Fig. 3) and a sample at the east base of Pikes Peak yielded an age of 171 ± 9 Ma. The ages > 100 Ma, and associated short mean track lengths (10 to 11.5 μm), represent a preserved PAZ that developed during burial under 2 to 2.5 km of Mesozoic sedimentary rocks (Bryant and Naeser, 1980). In contrast to the >100 Ma ages along the eastern margin, the base of the fossil PAZ and AFT ages of 57 to 67 Ma are exposed at low elevations in Phantom Canyon on the south side of Pikes Peak (Fig. 3). Bryant and Naeser (1980) found >100 Ma AFT ages along the western margin of the Front Range and an uplifted Laramide PAZ in the center of the range at Mt. Evans (Fig. 3). AFT data from the east side of the Front Range and the south side of Pikes Peak, as well as published AFT data from the western margin and the core of the range (Bryant and Naeser, 1980), indicate that the Mesozoic PAZ was warped and faulted during the Laramide orogenic event. The central portion of the Front Range was uplifted vertically relative to the margins, while the mountain flanks were thrust laterally along low-angle faults.

The AFT data are consistent with the "mushroom tectonics" model (Fig. 4) of Jacob (1983). Jacob (1983) and Jacob and Albertus (1985) presented convincing geologic and seismic-reflection evidence for low-angle thrusting along the east flank of the Front Range and northeastern margin of the Wet Mountains. Jacob (1983) pointed out that the surface traces of thrusts bounding the southern Front Range are nearly horizontal over a distance of approximately 90 km along strike. Other lines of evidence for low-angle thrusting cited by Jacob (1983) and Jacob and Albertus (1985) are (1) oil and gas seeps within the Proterozoic rocks of the Front Range, (2) the asymmetry of the Denver basin with the basin axis close to the mountain front indicating thrust loading of the basin, (3) the very low-angle nature of the Elkhorn thrust on the west side of the

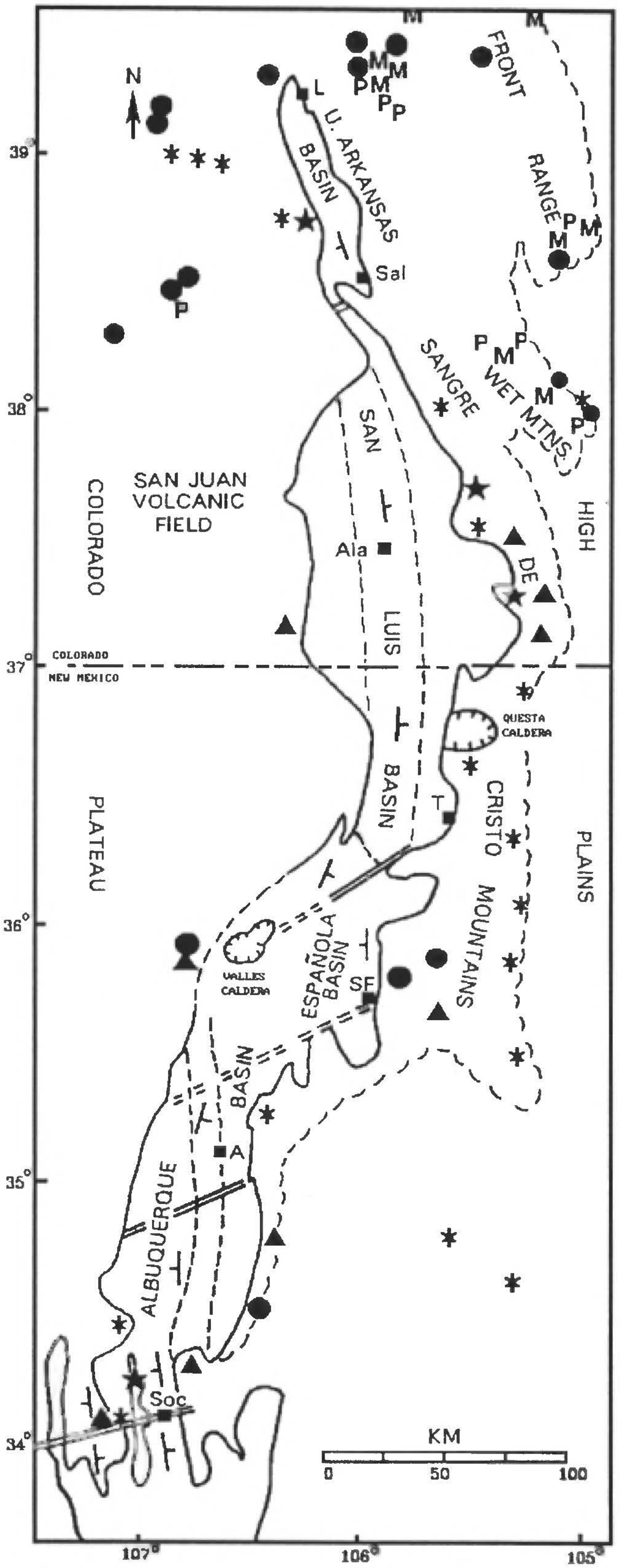

FIGURE 2. Regional map summarizing AFT age distribution in the northern and central Rio Grande rift, the Southern Rocky Mountains, and the High Plains. Base map from Chapin (1988) with abbreviations as described in Figure 1. Data from Church and Bickford (1971), Cunningham et al. (1977), Olson et al. (1977), Bryant and Naeser (1980), Lindsey et al. (1986), Shannon (1988), Kelley et al. (1992), Kelley and Chapin (in press). Stars for ages of 5 to 15 Ma, asterisks for 10 to 35 Ma, triangles for 20 to 40 Ma, solid circles for 40 to 80 Ma, M for ages 80 to 245 Ma, and P for ages 245 to 500 Ma.

range, as shown in cross-section on the Denver 1°x2° sheet (Bryant et al., 1981) and supported by the AFT dating of Bryant and Naeser (1980), and (4) interpretations of a seismic-reflection line acquired by Grant–Norpac along Jackson Creek Road west of Castle Rock in 1984.

The AFT ages of 140 to 300 Ma (older ages at high elevation) for the northern Wet Mountains can be used to infer that the amount of early Laramide denudation in this area was comparable to that along the eastern margin of the Front Range. Since the base of the PAZ (e.g., Phantom Canyon or Mt. Evans) is not exposed in the Wet Mountains, lateral thrusting rather than vertical uplift dominated the style of early Laramide deformation in this area. These results are consistent with the observation that the Wet Mountain thrust fault along the east side of the range is essentially horizontal (Jacob, 1983).

The relative amounts of denudation associated with early Laramide (Late Cretaceous–middle Paleocene) and late Laramide (late Paleocene to early Eocene) deformation in the Pikes Peak area can be constrained from the AFT data. Mean track lengths of 12.1 to 12.8 μm and the broad unimodal track length distributions for the 57 to 67 Ma samples on the south side of Pikes Peak (e.g., 92PP06, Fig. 3) suggest that they did not cool rapidly through the PAZ (1.5–2 °C/Ma). Assuming a surface temperature of 20°C (Savin, 1977) and a geothermal gradient of 25°C/km (modified from Bryant and Naeser, 1980), the inflection point on the south side of Pikes Peak was at a depth of about 4 km at the end of the Mesozoic. During early Laramide deformation, we estimate that the low elevation rocks cooled from about 120° to 80–90°C, which implies that the samples moved from depths of 4 km to depths of 2.8 to 3.2 km (using a surface temperature of 10°C after denudation begins; Gregory and Chase, 1992). Consequently, only 0.8 to 1.2 km of denudation occurred in this area during the Laramide event and the remaining 2.8 to 3.2 km of material has been removed since the Paleocene. The Rocky Mountain erosion surface under the 36.7 Ma Wall Mountain Tuff and the 30.9 to 32.5 Ma flows from the Cripple Creek volcanic field (K.D. Kelley et al., 1994) is currently at an elevation of about 2900 m, only about 300 m above the inflection point on the age-elevation profile. Consequently, approximately 2.4 to 2.8 km of rock was removed during late Laramide deformation and carving of the Rocky Mountain erosion surface prior to the emplacement of the Wall Mountain Tuff and the Cripple Creek lava flows. The remaining 0.3 to 0.4 km of material has been stripped in the late Cenozoic.

FLANKS OF THE NORTHERN RIO GRANDE RIFT, NEW MEXICO AND COLORADO

Kelley et al. (1992) examined the cooling histories of the mountain blocks forming the eastern and western margins of the northern Rio Grande rift using AFT analysis and they found several trends in the AFT data. First, the youngest AFT ages are generally found in the mountain ranges adjacent to the master faults that control the tilt of the half-grabens that form the northern rift (Fig. 2). Since the master fault systems commonly have large displacements (3 to 5 km), the mountain ranges with young AFT ages reflect flexural uplift, as well as tectonic and erosional denudation, during the late phase of rift development between 16 to 10 Ma. Flexural isostatic uplift is particularly rapid in promontories that project into rift basins at the junction of arcuate normal faults bounding the deep side of half-grabens (e.g., Ladron Mountains, Blanca Peak). Normal faulting on three sides caused the rapid tectonic denudation of these blocks.

The second trend in the data is found only in the northern Rio Grande rift of Colorado, where the AFT ages are youngest in the mountain blocks adjacent to the rift, and are progressively older away from the rift. This result is expected in light of the isostatic adjustments outlined above. However, as we will see in the subsequent discussion, the age pattern found in Colorado is not observed in New Mexico.

Third, because of denudation associated with rift flank development, uplifted PAZs with Paleozoic to Mesozoic AFT ages like those observed in the Front Range and Wet Mountains have been eroded from the ranges bounding the Rio Grande rift. Rocks that cooled during Laramide deformation (below the base of the PAZ) are found in the Santa Fe Range, the Nacimiento Mountains, and the Los Piños Mountains (Figs. 1, 2). The

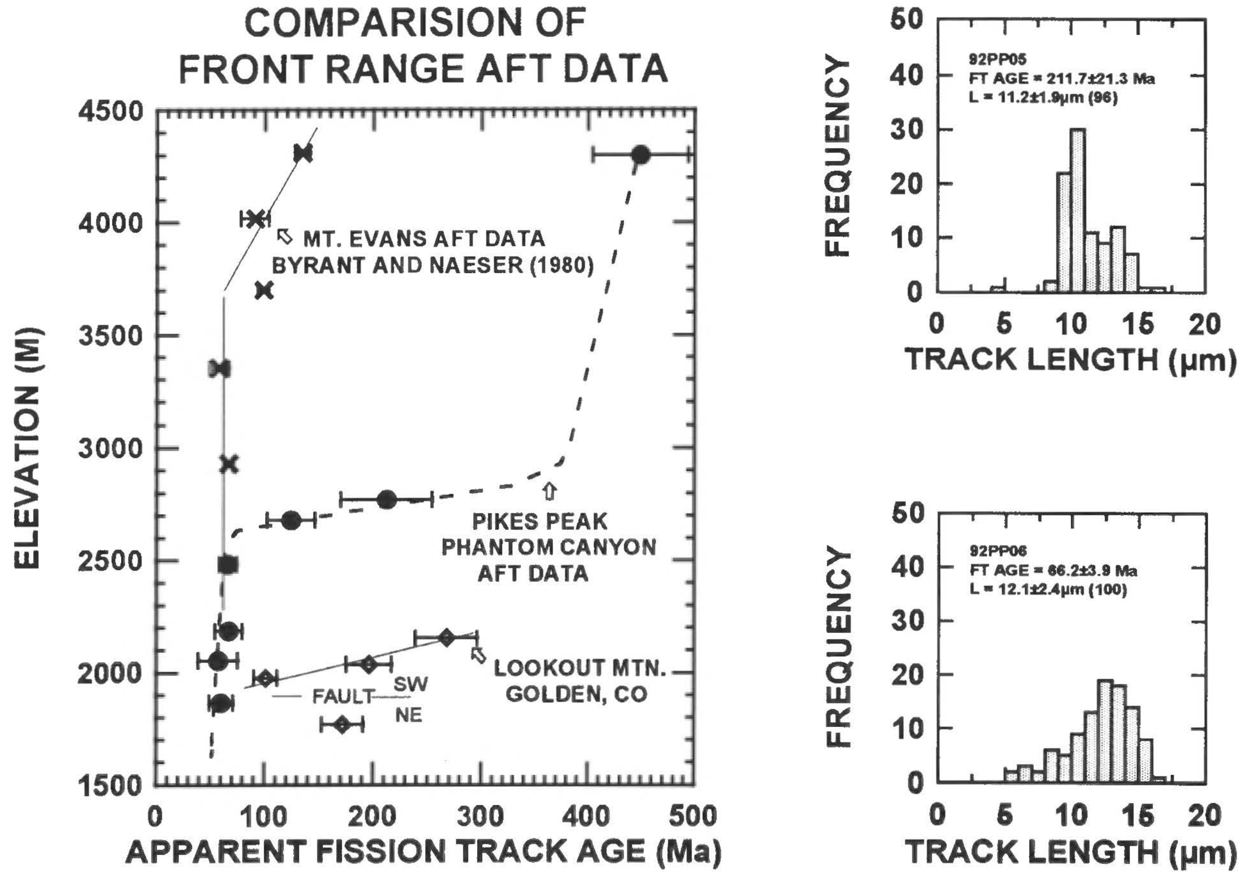

FIGURE 3. AFT ages plotted as a function of elevation for the Phantom Canyon–Pikes Peak profile (circles) and Lookout Mountain (Golden) traverse (diamonds). Two sigma error bars are plotted. AFT data from Mt. Evans (crosses; Bryant and Naeser, 1980) shown for comparison. Track length distributions for samples within (92PP05) and at base (92PP06) of uplifted PAZ are presented at right. Approximately 200 to 300 m of displacement along a northwest-trending-fault between the two lowest elevation samples at Lookout Mountain has disrupted the PAZ, bringing the southwest (SW) block up with respect to the northeast block (NE).

AFT ages from the Santa Fe Range are virtually identical to the AFT ages preserved at low elevation on the south side of Pikes Peak. Although the track length data for the Santa Fe Range indicate relatively slow cooling rates of about 2 to 3°C/Ma during early Laramide deformation (Kelley et al., 1992), this mountain block cooled more quickly than did Pikes Peak. Without the preservation of the base of the PAZ or the Rocky Mountain erosion surface, the total amount of Laramide denudation is not well constrained. Using assumptions like those for the Front Range concerning the geothermal gradient and surface temperature, Kelley et al. (1992) suggested that about 2 km of denudation is associated with early Laramide deformation in north-central New Mexico, which is significantly more than the 0.8 to 1.2 km of early Laramide denudation estimated from the AFT data for the Pikes Peak area.

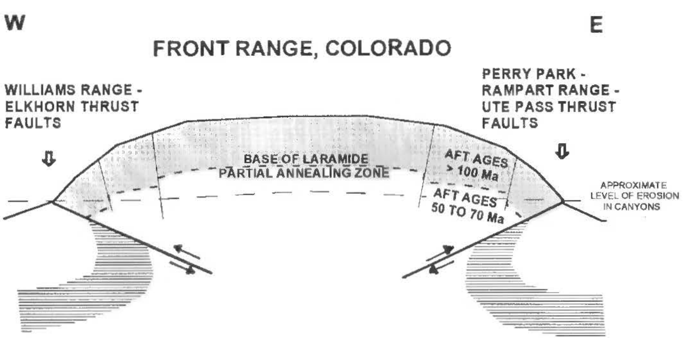

FIGURE 4. "Mushroom tectonics" model for the southern Front Range (no horizontal or vertical scale; after Jacob, 1983), which resembles a large flower-structure. The stippled area represents the uplifted PAZ with ages > 100 Ma, while the unshaded area immediately beneath the shaded area has AFT ages of 50 to 70 Ma. Areas shaded with horizontal lines schematically portray deformed sedimentary rocks.

Areas that cooled during late Laramide deformation and late Eocene erosion have been preserved at high elevation in portions of the northern Sangre de Cristo, Nacimiento, Manzano, and Magdalena Mountains (Figs. 1, 2). Cooling rates during this time interval are typically 2 to 4°C/Ma. The Rocky Mountain surface is preserved in a few places in the Sangre de Cristo Mountains under Oligocene to Miocene volcanic rocks and in the Brazos uplift. Although the Rocky Mountain erosion surface was largely removed in northern New Mexico during rift-flank uplift, it is likely that the low relief surface capping the Front Range and Wet Mountains formed over the Southern Rocky Mountain, High Plains, and Rio Grande rift provinces (Epis and Chapin, 1975).

Cooling of the crustal column and accompanying regional denudation related to rift development and, to a lesser degree, waning of regional volcanism is recorded in the Oligocene and early Miocene AFT ages in the northern Sangre de Cristo Mountains, Taos Range and Sandia Mountains (Figs. 2, 5). Cooling rates derived from track length data from these mountain blocks are generally 5 to 10°C/Ma (Kelley et al., 1992). Volcanism in southern Colorado and throughout New Mexico related to the transition between compressional and extensional stress regimes (Lipman, 1983a) was widespread during this time interval (Armstrong and Ward, 1991), with the peak of volcanism occurring at about 28 Ma. Volcanic centers active during the Oligocene to Miocene include the San Juan (Steven and Lipman, 1976), Latir (Lipman et al., 1986), and Great Plains margin (McLemore, this guidebook) fields (Fig. 5), as well as the Mogollon–Datil field (McIntosh et al., 1990) to the southwest. The heat flow was presumably somewhat elevated on a regional scale during this volcanism. The cooling observed in the AFT data from mountain blocks on the east side of the San Luis Basin and the northern Albuquerque Basin may have been enhanced by the waning of volcanism in the early

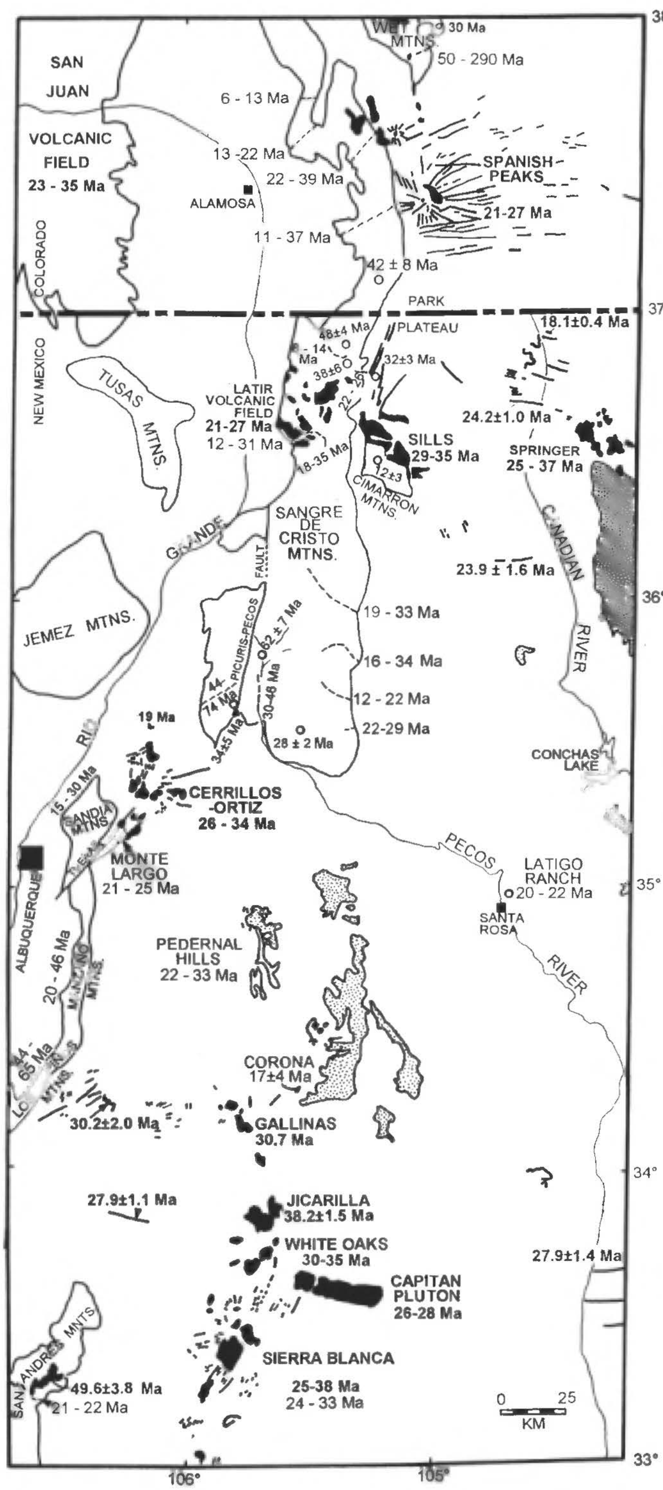

FIGURE 5. Regional map showing the location of AFT age profiles along the Southern Rocky Mountain–High Plains boundary in southern Colorado and northern New Mexico. The distribution of early to middle Cenozoic volcanic centers associated with the High Plains margin are also shown. The ages (bold numbers) and distribution of the volcanic centers are derived from Luedke (1993), McLemore (in press), Penn et al. (1994), Clemons (1982), and Tweto (1978). The Miocene Ogallala Formation is shown as the stippled pattern.

Miocene. However, the cooling is more likely related to epeirogenic denudation that affected the Rio Grande rift and the western High Plains, since many of the AFT ages predate the peak of volcanism. The topographic relief that developed during early rift denudation was not high, because tuffs from the San Juan volcanic field are found in the northern Sangre de Cristo Mountains (Kearney, 1983; Kelley et al., 1992), the Amalia Tuff from the Latir volcanic field is found up to 45 km away from the Latir volcanic field on both sides of the rift (Lipman, 1983b), and tuffs from calderas southwest of Socorro on the west side of the rift are found in the Joyita Hills on the east side of the rift.

Areas with AFT ages between 5 and 10 Ma (Fig. 2) reflect the combined effects of hydrothermal activity (Sawatch Range, San Luis area), volcanism (Lemitar Mountains) and rift-flank denudation. Cooling rates during the late phase of rift formation are high (5 to 15°C/Ma). About 2 to 3 km of uplift and erosion is related to the development of relief on the modern rift flanks, assuming a constant gradient of 30°C/km. Estimated denudation rates during rifting in areas largely unaffected by late Cenozoic volcanism are on the order of 200 to 300 m/Ma.

SOUTHERN SANGRE DE CRISTO MOUNTAINS–HIGH PLAINS, NEW MEXICO

O'Neill and Mehnert (1988) established the late Miocene to Pliocene tectonic and geomorphic history of the southern Sangre de Cristo Mountains (SDCM) and adjacent High Plains through detailed study of the geomorphic surfaces preserved beneath basalt flows of the Ocate volcanic field. They found that the development of a late Miocene erosion surface in the SDCM provided sediment for the Ogallala Formation in eastern New Mexico and west Texas (Fig. 5). The Ogallala Formation was deposited between approximately 12 and 5 Ma. It has been extensively eroded since 5 Ma so that broad valleys, particularly the Canadian and Pecos River valleys, separate erosional remnants of the Ogallala Formation on the High Plains from the source terranes in the SDCM.

Pre-Ogallala erosion was even more severe, but is difficult to document because early to middle Cenozoic sediments were completely stripped from the High Plains of New Mexico prior to Ogallala deposition. However, four lines of evidence, including the AFT cooling ages from this study, point to the removal of 2 to 3 km of Paleozoic to early Cenozoic rocks since the early Oligocene along the southern Rocky Mountain–High Plains boundary south of the Wet Mountains in Colorado. First, and most importantly, the Ogallala Formation rests upon a profound unconformity, such that its subcrop includes rocks of Permian to Late Cretaceous age on the High Plains of New Mexico and southern Colorado. Broad, ESE-trending paleovalleys that developed on this middle Cenozoic erosional surface were later filled with fluvial deposits of the Ogallala Formation (Gustavson and Winkler, 1988). During the late stages of Ogallala deposition, both paleo-uplands and paleovalleys on the erosion surface were covered by eolian deposits. Farther north, the Ogallala Formation truncates progressively younger rocks (Tweto, 1979). In the Colorado–Wyoming border area, the Ogallala Formation laps across Cretaceous, Eocene, Oligocene and early Miocene formations and onto the Precambrian core of the Laramie Range to cap the well-known "gangplank" (Knight, 1953; Moore, 1960).

The second line of evidence is the existence of middle to late Oligocene plutons with summit elevations that are more than a kilometer above the surrounding plains. These plutonic rocks must have been intruded into a significant thickness of Paleozoic to early Cenozoic sedimentary rocks. The 21 to 27 Ma (Smith, 1979; Penn et al., 1994) Spanish Peak stocks in south-central Colorado, which currently rise about 1 to 1.2 km above the adjacent plains, were probably covered by 1 to 1.5 km of material at the time of emplacement (Richard Smith, personal commun., 1994; Close and Dutcher, 1990). The Eocene Huerfano Formation crops out on the margin of the West Spanish Peak stock at elevations up to 3800 m (Johnson, 1969). The Huerfano Formation is as much as 600 m thick and overlies about 3000 m of latest Cretaceous and early Cenozoic orogenic sediments in the Raton Basin (Johnson and Wood, 1956). Similarly, the 28 Ma Capitan pluton (Campbell et al., 1994) in east-central New Mexico stands at least 1 km above the adjoining plains. Fluid inclusion data indicate that the Capitan pluton was intruded beneath at least 1 km of rock (Allen and McLemore, 1991; Campbell et al., 1994). Permian rocks now surround the base of Capitan Mountain; all younger rocks have been removed and the Ogallala Formation rests on Triassic and Permian rocks in southeastern New Mexico.

The third line of evidence is based on vitrinite reflectance values, which are unusually high in portions of the Raton, Estancia, Tucumcari and Permian basins (Broadhead and King, 1988; Broadhead, personal commun., 1994). Close and Dutcher (1990) suggested that the high coal rank in the east-central Raton Basin, well away from the thermal influences of the Spanish Peak intrusive center, is largely due to burial in an area with high heat flow (80 to 120 mWm^{-2}). Barker and Pawlewicz (1989) found elevated vitrinite reflectance values in the Permian basin of eastern New Mexico and west Texas that they attribute to Miocene rift-related tectonism.

AFT ages determined in this study provide the fourth line of evidence for major denudation along the Southern Rocky Mountain–High Plains border; these results show that denudation was in progress during the early Oligocene to middle Miocene. Samples were taken along five traverses in the eastern Rincon and Taos Ranges of the SDCM (Fig. 1). Most samples are from Proterozoic granitic rocks and Paleozoic sandstones that were transported eastward over Paleozoic to Mesozoic sedimentary rocks along west-dipping thrust faults during Laramide deformation. The Paleozoic to Mesozoic sedimentary rocks immediately to the east of the easternmost thrust faults are vertical to overturned, forming hogbacks that mark the western limb of the Raton Basin. The few AFT samples that were collected from sandstones in the hogbacks are shown as open circles on the age-elevation plots in Figure 6. The AFT ages to the west of the range-bounding faults (solid circles) are typically 12 to 30 Ma, the mean track lengths are long (13.6 to 14.4 μm), and the age-elevation profiles are generally steep (Fig. 6). The track length data and the age-elevation data (Fig. 6A, C, and D) indicate rapid cooling between middle Oligocene and middle Miocene.

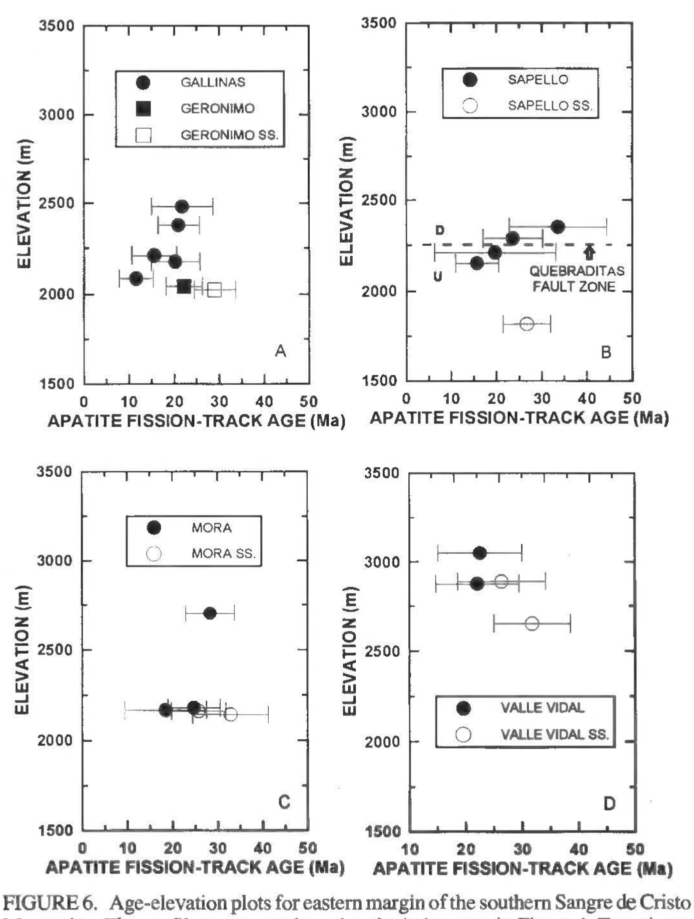

FIGURE 6. Age-elevation plots for eastern margin of the southern Sangre de Cristo Mountains. The profile names are keyed to the index map in Figure 1. Two sigma error bars are plotted. The solid symbols represent AFT ages from Proterozoic crystalline rocks and Paleozoic sedimentary rocks located to the west of the west-dipping, Laramide-aged thrust faults that form the eastern margin of the southern Sangre de Cristo Mountains. The open symbols are AFT ages from east-dipping to overturned Mesozoic to early Cenozoic sedimentary rocks that form hogbacks east of the Laramide thrust faults.

The cooling is likely related to denudation in an area with regionally elevated heat flow (note volcanic centers on High Plains margin on Fig. 5), as discussed in the previous section. At least 2 to 3 km of material (depending on the geothermal gradient and the amount of low thermal conductivity coal or shale in the removed section) has been eroded from this area since the early Oligocene. Since most of the late Cenozoic faults in the eastern Rincon Range have small displacements (Baltz and O'Neill, 1984), the denudation was largely accomplished by differential erosion of sedimentary rocks rather than by uplift along faults. The youngest AFT ages are commonly found on a topographic bench between the easternmost range-bounding thrust faults and the higher relief, central part of the SDCM (inverted triangle; Fig. 7). We propose that Paleocene to Eocene sedimentary rocks derived from Laramide uplifts to the west (Cather, 1992) may have buried the area now occupied by this topographic bench and the western High Plains, thus keeping temperatures above approximately 100 to 120°C. The early Cenozoic sedimentary rocks on this bench may have been analogous to the Poison Canyon, Cucharo and Huerfano Formations in the northern Raton Basin (Johnson and Wood, 1956; Johnson, 1969). The hypothetical package of early Cenozoic sediments south of the Cimarron Mountains, as well as some Mesozoic and Paleozoic sedimentary rocks and volcanic rocks from calderas to the west, may have been largely stripped away in the early Oligocene to middle Miocene. The eroded material bypassed the High Plains and may have contributed to the significant deltaic progradations found in the sedimentary rocks of the Texas Gulf Coast (e.g., Galloway et al., 1986).

One exception to the generalization concerning the steep age-elevation profiles in the eastern SDCM occurs in the structurally complex Sapello area, which has a low slope on its profile (Fig. 6). The two younger samples on this traverse were taken from the east side of the Quebraditas fault zone, a Laramide-aged thrust fault with late Cenozoic, down-to-the-west normal movement (Baltz and O'Neill, 1986). The two older samples are from the western, downthrown side of the fault. The Quebraditas fault zone forms the eastern boundary of the east-tilted Rociada half-graben, the southernmost in a chain of shallow (100–200 m of valley fill), east-tilted Neogene basins in the SDCM, including the Mora, Moreno, Valle Vidal and Comanche Creek valleys. Displacements on normal faults along the east sides of the Mora and Moreno valleys are estimated to be 100 to 300 m (Baltz and O'Neill, 1990; Colpitts and Smith, 1990). The AFT data can be used to imply that at least 300 m of offset has occurred across the Quebraditas fault.

The AFT ages from Mesozoic to early Cenozoic sandstones in the hogbacks just east of the range-bounding thrust faults are consistently older than the AFT ages to the west of the faults (Fig. 6). The probable cause for this pattern is the presence of chlorine-rich detrital apatite in the sandstones. Tracks in fluorapatite, which is the dominant type of apatite found in Proterozoic and Paleozoic rocks in New Mexico (Kelley et al., 1992), anneal at lower temperatures (100 to 120°C) than tracks in chlorapatite (140 to 150°C). Although we have not yet done chemical analyses of the apatite, many of the sandstone samples had distinct age populations, indicative of a chemical effect. Another possible interpretation of this age trend involves the cooling of the sandstones during groundwater recharge in the hogbacks (e.g., Ge and Garven, 1989). Further work is needed to distinguish between these possibilities.

Samples were also collected from the mafic and trondhjemitic rocks of the Pecos Greenstone belt exposed in the Pecos River valley in the center of the southern SDCM. One sample of Proterozoic diabase exposed in a small fault block near Cowles gave an age of 62 ± 7 Ma (Fig. 5). The remainder of the AFT ages along this profile are 30 to 46 Ma and do not strongly correlate with elevation or with north-south position along the traverse. Surprisingly, the AFT ages increase from the Great Plains toward the Rio Grande rift (Figs. 7, 8), a result that is opposite the AFT trends found in the northern rift in Colorado (Kelley et al., 1992). A possible scenario that may explain the age pattern is presented in the summary section of this paper. A less pronounced east-to-west age increase is observed in the isolated Proterozoic outcrops located near the Pedernal Hills and near Corona to the south of the SDCM (Fig. 5). The AFT ages from surface samples and drill cores in the Pedernal Hills range

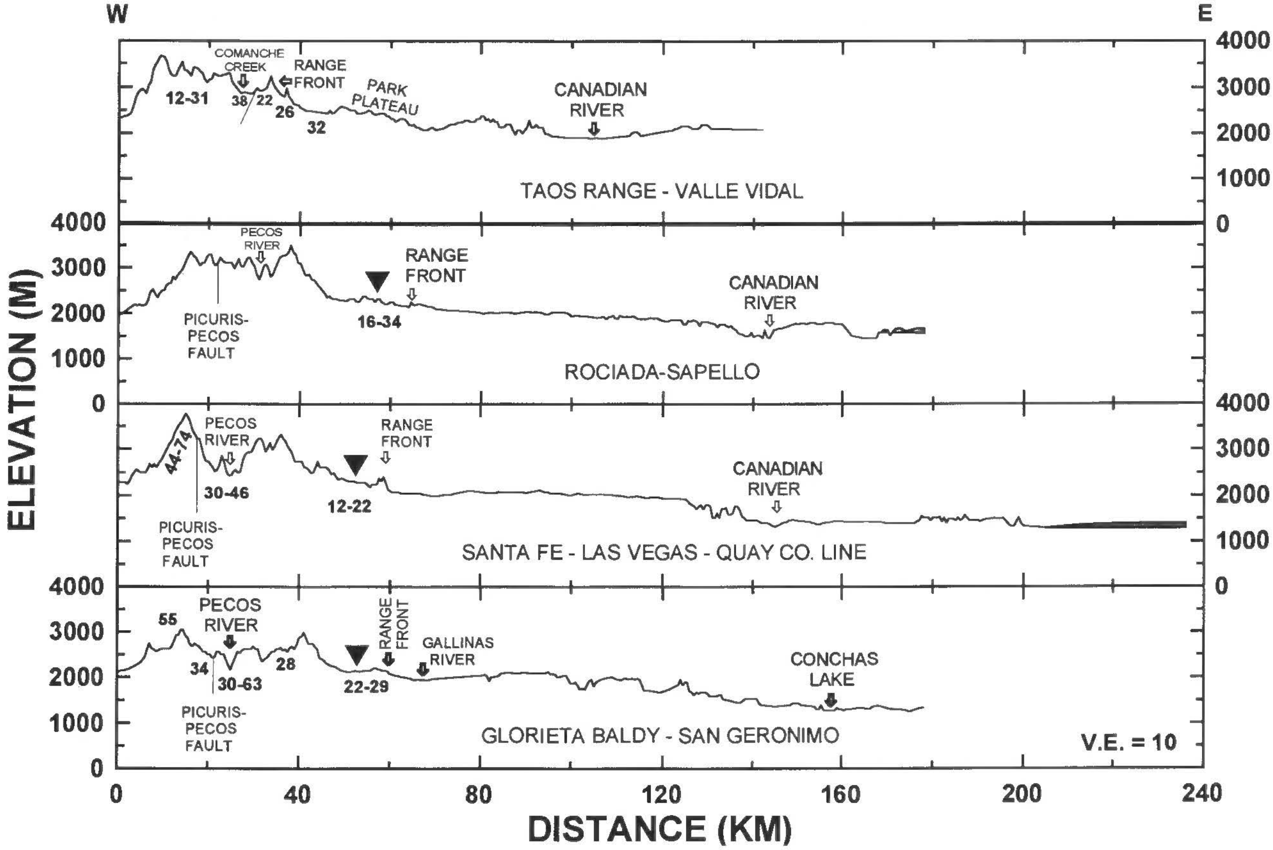

FIGURE 7. Topographic profiles across the eastern margin of the southern Sangre de Cristo Mountains. From north to south (top to bottom) the profiles roughly coincide with the Taos Range–Valle Vidal, Rociada–Sapello, Santa Fe Baldy–Gallinas Creek, and Glorieta Baldy–San Geronimo AFT data traverses. See Fig. 1 for locations. AFT age ranges in Ma shown for reference. Inverted triangle highlights the location of the topographic bench between the high SDCM and the easternmost, range-bounding thrust fault. Ogallala outcrops shown as shaded areas.

from 22 to 33 Ma, whereas a 17 ± 5 Ma AFT age was determined for the Corona outcrop. The area of anomalously young AFT ages extends eastward into the Tucumcari Basin. A series of four Pennsylvanian to Permian sandstones covering a depth interval of 534–2136 m was obtained from the Trans-Pecos Resources No. 1 Latigo Ranch C well (Fig. 5). Unfortunately only two of the sandstones at 1230 and 1351 m yielded apatite. The AFT ages for these sandstones are 22.3 ± 2.7 and 20.2 ± 3.0 Ma, respectively. The AFT ages are younger than expected, given the fact that the geothermal gradients in this area are 24 to 27°C/km (Reiter et al., 1975; Edwards et al., 1978), so that the modern temperatures for these sandstones are on the order of 30 to 36°C.

A systematic east-to-west age increase is not observed to the north in the Taos Range. The AFT age patterns observed in the western Taos Range are largely controlled by the thermal affects of the Latir volcanic field and subsequent denudation during the late phase of rifting (Kelley et al., 1992). The ages near the rift are young at low elevation (6 to 12 Ma) and increase to 35 to 48 Ma at high elevation (Fig. 5). The ages from the east side of the Taos Range change abruptly from 38 Ma for Proterozoic rocks in the Comanche Creek valley in the center of the range to 22 Ma for Proterozoic rocks just east of Comanche Creek (Figs. 5, 8). A down-to-the-west normal fault mapped by Lipman and Reed (1989) lies between the sample localities. The results suggest that the east side of the range has been brought up with respect to the center of the range during extension. Two sandstones in the Poison Canyon/Raton Formation from the western margin of the Raton Basin adjacent to the Taos Range give AFT ages of 26 to 32 Ma (Fig. 7), which are younger than the Cretaceous to Paleocene stratigraphic age of this unit. The sandstone AFT ages are likely older than the AFT ages from the Proterozoic rocks due to differences in apatite compositions between the rock types. The young AFT ages for the sandstones in the western Raton Basin indicate burial by an additional 1 to 2 km of early Cenozoic sediments and/or tuffs and flows from the Questa caldera in an area of elevated heat flow.

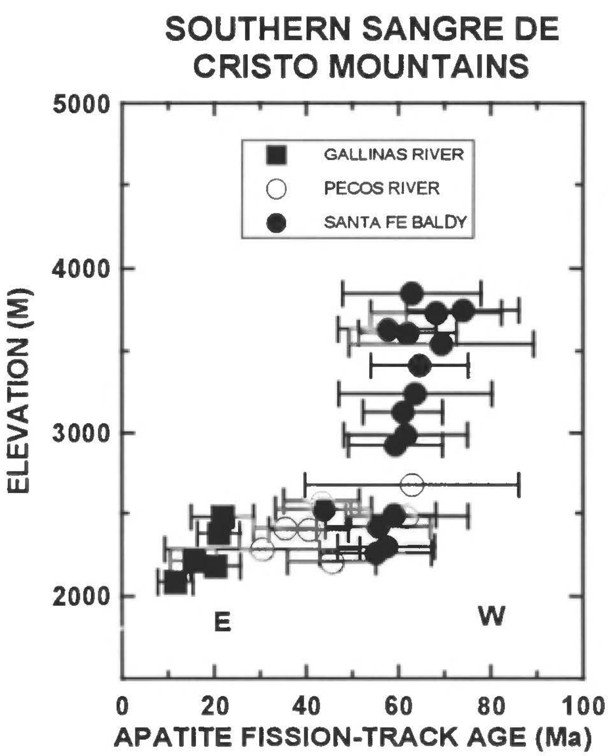

FIGURE 8. AFT age - elevation plot for an east-west traverse through the southern Sangre de Cristo Mountains between Santa Fe and Las Vegas, New Mexico. Two sigma error bars are shown.

SUMMARY

1. The AFT data support the recent ideas by Gregory and Chase (1992) and Leonard and Langford (1994) concerning the late Cenozoic topographic evolution of the Front Range. According to Gregory and Chase (1992), the Front Range attained elevations similar to those observed today during Laramide deformation. The eastern margin of the range was buried by sediments shed from the mountains. A high-elevation, low-relief surface developed on the Southern Rocky Mountains and adjacent High Plains. The modern topographic escarpment along the east side of the Front Range and northern Wet Mountains is the result of late Cenozoic erosion of Late Cretaceous and early Cenozoic sediments. A climatic shift toward monsoonal circulation and intense summer thunderstorms along the mountain front may have been responsible for the accelerated erosion.

2. New AFT data from the east side of the Front Range and the south side of Pikes Peak, as well as published AFT data from the western margin and the core of the range (Bryant and Naeser, 1980), indicate that the central portion of the Front Range was uplifted vertically during Laramide deformation, while the mountain flanks were thrust laterally along low-angle faults. The Front Range results may provide a useful model to guide petroleum exploration along the margins of basement-cored uplifts in frontier areas in South America and southeast Asia.

3. Using the track length and AFT age data for the low elevation samples on the south side of Pikes Peak and the position of the Rocky Mountain erosion surface with respect to our sample traverse, we estimate that a maximum of 0.8 to 1.2 km of denudation occurred in this area during early Laramide (Late Cretaceous–Paleocene) deformation and that 2.4 to 2.8 km of rock was removed during late Laramide (latest Paleocene–middle Eocene) deformation and Eocene erosion prior to the emplacement of the 36.7 Ma Wall Mountain Tuff and the 30.9 to 32.5 Ma Cripple Creek lava flows.

4. In the Rio Grande rift, the lack of uplifted PAZs like those seen in the SRM and the increase in age away from the rift in Colorado provide clear evidence of the large amount of denudation associated with rift flank development. Flexural uplift, as well as tectonic and erosional denudation, are important in the formation of the mountain ranges bordering the rift since the youngest AFT ages are found adjacent to the master faults of the asymmetric half-grabens.

5. The AFT ages along the SRM–High Plains boundary decrease southward, ranging from >100 Ma in the Front Range to 30 Ma in the southern Wet Mountains to 12–20 Ma in the southern SDCM. In addition, the amount of volcanism along the boundary between the provinces increases toward the south. The Oligocene to Miocene AFT ages in the mountain blocks on the east side of the Rio Grande rift and on the High Plains are likely due to epeirogenic denudation of Mesozoic to early Cenozoic sedimentary rocks during a period of elevated heat flow as the Rio Grande rift began to form.

6. The AFT ages in the Santa Fe Range and Rincon Range increase from east to west, indicating the complex nature of the tectonic evolution of this area. Laramide deformation elevated the Santa Fe Range and the site of the Española basin (Cather, 1992) relative to the Rincon Range, where lateral thrusting dominated (Baltz and O'Neill, 1984, 1986; Baltz, 1972). The lack of coarse, proximal deposits of Late Cretaceous to Paleogene age in the western Raton basin suggests that the Laramide mountain front was farther west than it is today. Sediments shed from the Santa Fe area accumulated on the site now occupied by the eastern Rincon Range and on the High Plains. During the early phase of rift development, the highland to the west, including the Santa Fe Range, collapsed to form the Española basin, allowing preservation of Laramide AFT ages in the Santa Fe Range (Kelley et al., 1992; Cather, 1992). Epeirogenic uplift and erosion triggered by early rift extension occurred on the High Plains margin, stripping away Paleozoic to Mesozoic sedimentary rocks and the accumulated early Cenozoic sediments from the eastern Rincon Range and High Plains. Denudation in the eastern Rincon and Taos Ranges was enhanced in some places by the development of minor down-to-the-west normal faults and associated footwall uplift within the SDCM. The modern topography developed during the late phase of extension. Much of the current elevation of the Santa Fe and Rincon Ranges is accommodated by faults within the range rather than along faults on the margins of the SDCM (Kelley, this guidebook).

7. The study of Barker and Pawlewicz (1989) illustrated the economic implications of SDCM–High Plains AFT results in understanding petroleum generation in basins on the High Plains. These authors used vitrinite reflectance versus depth curves to infer that temperatures were elevated in the Permian basin of eastern New Mexico and west Texas during the Miocene. They concluded that the elevated temperatures were the result of tectonic activity in the Rio Grande rift and that the higher temperatures caused renewed petroleum generation in the Permian basin.

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REFERENCES

Allen, M.S. and McLemore, V.T., 1991, The geology and petrogenesis of the Capitan pluton, New Mexico: New Mexico Geological Society, Guidebook 42, p. 115–127.

Armstrong, R.L. and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: the temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, p. 13,220–13,224.

Baltz, E.H., 1972, Geologic map and cross sections of the Gallinas Creek area, Sangre de Cristo Mountains, San Miguel County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-673, scale 1:24,000.

Baltz, E.H. and O'Neill, J.M., 1984, Geologic map and cross sections of the Mora River area, Sangre de Cristo Mountains, Mora County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-1456, scale 1:24,000.

Baltz, E.H. and O'Neill, J.M., 1986, Geologic map and cross sections of the Sapello River area, Sangre de Cristo Mountains, Mora and San Miguel Counties, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-1575, scale 1:24,000.

Baltz, E.H. and O'Neill, J.M., 1990, Third day road log from Angel Fire to Black Lake, Guadalupita, Mora, Rociada, and Sapello: New Mexico Geological Society, Guidebook 41, p. 67–96.

Barker, C.E. and Pawlewicz, M.J., 1989, Renewed petroleum generation related to Tertiary intrusion and increased heat flow, western Permian Basin, Texas and New Mexico: American Association of Petroleum Geologists Bulletin, v. 73, p. 331.

Broadhead, R.F. and King, W.E., 1988, Petroleum geology of Pennsylvanian and lower Permian strata, Tucumcari Basin, east-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 119, 75 p.

Bryant, B. and Naeser, C.W., 1980, The significance of fission-track ages of apatite in relation to the tectonic history of the Front Range and Sawatch Range, Colorado: Geological Society of America Bulletin, Part I, v. 91, p. 156–164.

Bryant, B., McGrew, L.W. and Wobus, R.A., 1981, Geologic map of the Denver 1° x 2° quadrangle, north-central Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I-1163, scale 1:250,000.

Cather, S.M., 1992, Suggested revisions to the Tertiary tectonic history of north-central New Mexico: New Mexico Geological Society, Guidebook 43, p.109–122.

Campbell, A.R., Heizler, M.T. and Dunbar, N.W., 1994, $^{40}Ar/^{39}Ar$ dating of fluid inclusions in quartz from the Capitan Pluton, New Mexico: PACROFI, v. 5, p. 11.

Chapin, C.E., 1988, Axial basins of the northern and central Rio Grande rift; *in* Sloss, L.L, ed., Sedimentary cover–North American craton: Boulder, Colorado, Geological Society of America, Decade of North American Geology, D-2, Chap. 8, p. 165–170.

Chapin, C.E. and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift: Geological Society of America, Special Paper 291, p. 5–23.

Church, S.E. and Bickford, M.E., 1971, Spontaneous fission-track studies of accessory apatite from granitic rocks in the Sawatch Range, Colorado: Geological Society of America Bulletin, v. 82, p. 1727–1734.

Clemons, R.E., 1982, New Mexico Geologic Highway Map, New Mexico Geological Society, scale 1:1,000,000.

Close, J.C. and Dutcher, R.R., 1990, Update on coalbed methane potential of Raton Basin, Colorado: Society of Petroleum Engineers Paper 206667, p. 497–512.

Colpitts, R.M. and Smith, C.T., 1990, Geology of the Moreno Valley, Colfax County, New Mexico: New Mexico Geological Society, Guidebook 41, p. 219–228.

Cunningham, C.G., Naeser, C.W. and Marvin, R.F., 1977, New ages for intrusive rocks in the Colorado mineral belt: U. S. Geological Survey, Bulletin 1395-C, 7 p.

Edwards, C.L., Reiter, M., Shearer, C. and Young, W., 1978, Terrestrial heat flow and crustal radioactivity in northeastern New Mexico and southeastern Colorado: Geological Society of America Bulletin, v. 89, p. 1341–1350.

Epis, R.C. and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post Laramide late Eocene erosion surface in the Southern Rocky Mountains: Geological Society of America, Memoir 144, p. 45–74.

Evanoff, E., 1990, Early Oligocene paleovalleys in southern and central Wyoming: evidence of high local relief on the late Eocene unconformity: Geology, v. 18, 443–446.

Evanoff, E. and Chapin, C.E., 1994, Composite nature of the "Late Eocene surface" of the Front Range and adjacent regions, Colorado and Wyoming: Geological Society of America, Abstracts with Programs, v. 26, p. 12.

Foster, D.A. and Gleadow, A.J.W., 1992, The morpho-tectonic evolution of rift-margin mountains in central Kenya: constraints from apatite fission-track thermochronology: Earth and Planetary Science Letters, v. 113, p. 157–171.

Galloway, W.E., Jirik, L.A., Morton, R.A. and DuBar, J.R., 1986, Lower Miocene (Fleming) depositional episode of the Texas coastal plain: Texas Bureau of Economic Geology, Report of Investigation 150, 50 p.

Ge, S. and Garven, G, 1989, Tectonically induced transient groundwater flow in foreland basin; *in* Price, R.E., ed., Origin and evolution of sedimentary basins and their energy and mineral resources: Washington, D.C., American Geophysical Union, Geophysical Monograph Series 48, International Union of Geodesy and Geophysics, v. 3, p. 145–158.

Gleadow, A.J.W. and Fitzgerald, P.F., 1987, Uplift history and structure of the Transantarctic Mountains: new evidence from fission track dating of basement apatites in the Dry Valleys area, southern Victoria Land: Earth and Planetary Science Letters, v. 82, p. 1–14.

Green, P.F., Duddy, I.R., Gleadow, A.J.W., Tingate, P.R. and Laslett, G.M., 1986, Thermal annealing of fission tracks in apatite, 1. A qualitative description: Chemical Geology (Isotope Geoscience Section), v. 59, p. 237–253.

Gregory, K.M. and Chase, C.G., 1992, Tectonic significance of paleobotanically estimated climate and altitude of the late Eocene erosion surface, Colorado: Geology, v. 20, p. 582–585.

Gregory, K.M. and Chase, C.G., 1994, Tectonic and climatic significance of a late Eocene low-relief, high-level geomorphic surface, Colorado: Journal of Geophysical Research, v. 99, p. 20,141–20,160.

Gustavson, T.C. and Winkler, D.A., 1988, Depositional facies of the Miocene–Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico: Geology, v. 15, p. 203–206.

Jacob, A.F., 1983, Mountain front thrust, southeastern Front Range and northeastern Wet Mountains, Colorado, *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, p. 229–244.

Jacob, A.F. and Albertus, R.G., 1985, Thrusting, petroleum seeps, and seismic exploration: Front Range south of Denver, Colorado; *in* Macke, D.L., and Maughan, E.K., eds., Rocky Mountain Field Trip Guide 1985: Society of Economic Paleontologists and Mineralogists, p. 77–96.

Johnson, R.B., 1969, Geologic map of the Trinidad quadrangle, south-central Colorado: U.S. Geological Survey, Miscellaneous Investigations Map I-558, scale 1:250,000.

Johnson, R.B. and Wood, G.H., Jr., 1956, Stratigraphy of Upper Cretaceous and Tertiary rocks of Raton Basin, Colorado and New Mexico: American Association of Petroleum Geologists, v. 40, p. 707–721.

Kearney, B.C., 1983, Volcanic stratigraphy and structure of the La Veta Pass area, northern Sangre de Cristo Mountains, south-central Colorado [M.S. thesis]: Dallas, Southern Methodist University, 67 p.

Kelley, K.D., Snee, L.W. and Thompson, T.B, 1994, Geology and geochronology of the Cripple Creek complex: Geological Society of America, Abstracts with Programs, v. 26, p. 22.

Kelley, S.A., 1995, Evidence for post-Laramide displacement on the Picuris–Pecos fault: New Mexico Geological Society, Guidebook 46.

Kelley, S.A. and Chapin, C.E., in press, Denudational histories of the Front Range and Wet Mountains, based on apatite fission-track thermochronology: Geological Society of America Special Paper, Geology of the Florissant region.

Kelley, S.A. and Duncan, I.J., 1986, Late Cretaceous to middle Tertiary tectonic history of the northern Rio Grande rift: Journal of Geophysical Research, v. 91, p. 6246-6262.

Kelley, S.A., Chapin, C.E. and Corrigan, J., 1992, Late Mesozoic to Cenozoic cooling histories of the flanks of the northern and central Rio Grande rift, Colorado and New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 145, 39 p.

Knight, S.H., 1953, Summary of the Cenozoic history of the Medicine Bow Mountains, Wyoming: Wyoming Geological Association Guidebook, Eighth Annual Field Conference, p. 65–76.

Leonard, E.M. and Langford, R.P., 1994, Post-Laramide deformation along the eastern margin of the Colorado Front Range—a case against significant faulting: Mountain Geologist, v. 31, p. 45–52.

Lindsey, D.A., Andriessen, P.A.M. and Wardlaw, B.R., 1986, Heating, cooling, and uplift during Tertiary time, northern Sangre de Cristo Range, Colorado: Geological Society of America Bulletin, v. 97, p. 1133–1143.

Lipman, P.W., 1983a, Tectonic setting of the mid to late Tertiary in the Rocky Mountain region; *in* Ranta, D.E., ed., The genesis of Rocky Mountain ore deposits: changes with time and tectonics: Denver, Colorado, Proceedings of the Denver Region Exploration Geologists Society Symposium, p. 125–131.

Lipman, P.W., 1983b, The Miocene Questa Caldera, northern New Mexico: relation to batholith emplacement and associated molybdenum mineralization; *in* Ranta, D.E., ed., The genesis of Rocky Mountain ore deposits: changes with time and tectonics: Denver, Colorado, Proceedings of the Denver Region Exploration Geologists Society Symposium, p. 133–147.

Lipman, P.W. and Reed, J.C., 1989, Geologic map of the Latir volcanic field and adjacent areas, northern New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-1907, scale 1:48,000.

Lipman, P.W., Mehnert, H.H. and Naeser, C.W., 1986, Evolution of the Latir volcanic field, northern New Mexico, and its relation to the Rio Grande rift, as indicated by potassium–argon and fission track dating: Journal of Geophysical Research, v. 91, p. 6329–6346.

Luedke, R.G., 1993, Maps showing distribution, composition, and age of early and middle Cenozoic volcanic centers in Arizona, New Mexico, and west Texas: U.S. Geological Survey, Miscellaneous Investigations Series Map I-2291-A., scale 1:1,000,000.

MacGinitie, H.D., 1953, Fossil plants of the Florissant Beds, Colorado: Carnegie Institution of Washington Publication, 198 p.

McIntosh, W.C. and Chapin, C.E., 1994, $^{40}Ar/^{39}Ar$ geochronology of ignimbrites in the Thirtynine Mile volcanic field, Colorado, *in* Evanoff, E. , ed., Late Paleogene geology and paleoenvironments of central Colorado: Geological Society of America Field Trip Guidebook, p. 23–26.

McIntosh, W.C., Sutter, J.F., Chapin, C.E. and Kedzie, L.L., 1990, High-precision $^{40}Ar/^{39}Ar$ sanidine geochronology of ignimbrites in the Mogollon–Datil volcanic field, southwestern New Mexico: Bulletin of Volcanology, v. 52, p. 584–601.

McLemore, V.T., in press, Great Plains margin (alkalic-related) gold deposits in New Mexico: New Mexico Geological Society, Guidebook 46.

Meyer, H.W., 1992, Lapse rates and other variables applied to estimating paleoaltitudes from fossil flora: Paleogeography, Paleoclimatology, Paleoecology, v. 99, p. 71–99.

Moore, F., 1960, Summary of Cenozoic history, southern Laramie Range, Wyoming and Colorado; *in* Weimer, R.J., and Haun, J.D., eds., Guide to the Geology of Colorado: Geological Society of America, Rocky Mountain Association of Geologists, Colorado Scientific Society, Field Trip Guidebook, p. 217–222.

Naeser, C.W., 1979, Fission-track dating and geologic annealing of fission tracks; *in* Jager, E., and Hunziker, J.C., eds., Lectures in Isotope Geology: New York, Springer–Verlag, p. 154–169.

Olson, J.C., Marvin, R.F., Parker, R.L. and Mehnert, H.H., 1977, Age and tectonic setting of lower Paleozoic alkalic and mafic rocks, carbonatites, and thorium veins in south-central Colorado: U. S. Geological Survey, Journal of Research, v. 5, p. 673–687.

O'Neill, J.M. and Mehnert, H.H., 1988, Petrology and physiographic evolution of the Ocate volcanic field, north central New Mexico: U.S. Geological Survey, Professional Paper 1478, 19 p.

Penn, B.S., Wendlandt, R.F., Simmons, E.C., Snee, L.W. and Unruh, D.M., 1994, Geochemical evolution of the Spanish Peaks intrusive rocks of south-central Colorado: Geological Society of America, Abstracts with Programs, v. 26, p. 58.

Reiter, M., Edwards, C.L., Hartman, H. and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geological Society of America Bulletin, v. 86, p. 811–818.

Savin, S.M., 1977, The history of the Earth's surface temperature during the past 100 million years: Annual Reviews of Earth and Planetary Science, v. 5, p. 319–355.

Shannon, J.R., 1988, Geology of the Mount Aetna cauldron complex, Sawatch Range, Colorado, [Ph.D. dissertation]: Golden, Colorado School of Mines, 434 p.

Smith, R.P., 1979, Early rift magmatism at Spanish Peaks, Colorado; *in* Riecker, R.E., ed., Rio Grande Rift: tectonics and magmatism: Washington D.C., American Geophysical Union, p. 313–321.

Steven, T.A. and Lipman, P.W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U.S. Geological Survey, Professional Paper 958, 35 p.

Tweto, O., 1978, Tectonic map of the Rio Grande rift system in Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, Sheet 1, scale 1:1,000,000.

Tweto, O., 1979, The Rio Grande rift system in Colorado; *in* Riecker, R.E., ed.,

Rio Grande Rift: tectonics and magmatism: Washington D.C., American Geophysical Union, p.33–56.
Wolfe, J.A., 1992, An analysis of present-day terrestrial lapse rates in the western conterminous United States and their significance to paleoaltitudinal estimates: U.S. Geological Survey, Bulletin 1964, 35 p.