Large-scale geomorphology and fission-track thermochronology in topographic and exhumation reconstructions of the Southern Rocky Mountains

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ABSTRACT

Long-term landscape evolution is the integrative sum of constructive rock-uplift processes and destructive erosional processes. For the Southern Rocky Mountains, it has been proposed that Phanerozoic rock uplift and erosion have been influenced by crustal structure that was inherited from the time of assembly of the continent in the Proterozoic. This paper compares large-scale geomorphology and long-term rock exhumation histories in three distinct crustal terranes to assess possible differences in Laramide and post-Laramide deformation of the Southern Rocky Mountains. We analyze modern topographic data and fission-track thermochronology for several portions of the Southern Rockies with distinctly different post-Laramide geologic histories and estimate the amount of Laramide and post-Laramide rock uplift. The areas of investigation include: (1) the Colorado Front Range, an area of regional elevated heat flow in the Yavapai province; (2) the New Mexico Taos Range, a region of localized high heat flow throughout the late Tertiary and Quaternary along the Rio Grande rift in the Mazatzal province; and (3) the New Mexico Sierra Nacimiento, a region of localized high heat flow in the Quaternary associated with the Jemez Mountains, also in the Mazatzal province. Both the Taos Range and Sierra Nacimiento lie in proximity to the Jemez lineament, which is thought to be a significant Proterozoic structural feature that has influenced Quaternary volcanism along its trend.

We utilize and test a dimensionless topographic index called the *ZR* ratio, which is the ratio between mean elevation and mean relief, as a quantitative measure of the differences in orogen-scale topography. Digital topography (DEM) and GIS software (ARC/INFO) allow for the rapid determination of this ratio at various length scales. Our results show that the Taos Range has the lowest *ZR* ratio (most rugged topography), and the Sierra Nacimiento has the highest ratio (least rugged topography). Fission-track thermochronology results show that a partial annealing zone (PAZ) is preserved in the Front Range and the northern portion of Sierra Nacimiento (the region incidentally not on the high-heat flow Jemez lineament); both the Taos Range and the southern portion of Sierra Nacimiento have had the PAZ removed by erosion. Reconstructed amounts and timing of rock denudation based on the fission-track data are consistent with the *ZR* ratios in that the most rugged topography exhibits the greatest and most recent denudation, whereas the least rugged topography experienced far less denudation, most of which occurred immediately after the Laramide orogeny.

Fission-track thermochronology and geomorphic results support an overall model of significant crustal thickening during the Laramide orogeny, followed by relatively low and differential rates of rock uplift, erosional exhumation, and isostatic rebound. Specific regions of greater post-Laramide rock exhumation and rugged topography are highly correlated with regions of known localized high heat flow and late Cenozoic volcanism, a finding consistent with the hypothesis that at least locally, the high mean elevation of the Southern Rockies is supported by a buoyant mantle. Both the style of Laramide deformation and subsequent magmatic input from a low-velocity, buoyant mantle may have been influenced by older crustal structure. All three factors, Proterozoic crustal structure, Laramide deformation, and post-Laramide uplift, appear to play an important role in the ability of streams to integrate through the Rocky Mountain foreland. As rates of erosion are strongly tied to local relief of well-drained landscapes, stream integration at the large scale may explain the correlation between long-term denudation rates and modern topographic ruggedness (*ZR* ratio), and be the limiting factor in the processes driving rock uplift in the post-Laramide Southern Rockies.

KEY WORDS: Rocky Mountains, Laramide orogeny, landform evolution, apatite fission-track, thermochronology, geomorphology, exhumation.

INTRODUCTION

The Front Range is a highland of disordered crystalline rocks, for the most part resistant schists and granites, whose greater original mass long ago suffered more or less complete planation, depression and burial under a heavy series of strata.... The region northwest of Denver was then broadly up-arched into a high altitude, the broad crest of the arched peneplain forming the present crest of the Front Range at altitudes of ten to twelve thousand feet, while the higher monadnocks that chance to stand on or near the crest reach altitudes of fourteen thousand feet or more ... (Davis, 1911, p. 31).

Ever since Davis introduced the concept of a southern Rocky Mountain "peneplain", geologists have strongly debated the roles that Laramide deformation, post-Laramide tectonism, late Cenozoic epeirogeny, and climate have played in shaping the landscape of the U.S. western interior. It has been proposed (Karlstrom and Humphreys, this issue) that the evolution of the lithosphere of the southern Rocky Mountains is governed by a complex, but resolvable, interaction between crustal structure and mantle processes. Here we hypothesize that topography and surficial geomorphic processes represent the surface manifestation of this interaction between crustal structure and mantle processes. Large-scale landscape evolution, which is the long-term integrative effect of topography delicately adjusting to constructive rock-uplift processes and destructive rock-exhumation processes, is one indication of the changes in deep-seated lithospheric processes through geologic time. Our goals in this paper are to provide some fundamental understanding of the nature, extent and limitations of geomorphic and fission-track data and how we envision using these data to bridge the gap between long-term landscape evolution and long-term lithospheric processes. Specifically, we wish to work toward a prediction of the amount of exhumation, constrained by fission-track thermochronology, and evolution of topography constrained by spatial analyses of DEMs, for the Laramide and post-Laramide Rocky Mountains. Together these data will be used to investigate the influence of ancient crustal structure on later tectonic events, namely, the Laramide orogeny, regional extension associated with the Rio Grande rift, and Neogene landscape evolution. In presenting these goals, we anticipate generating new insights on the nature and timing of Laramide and any post-Laramide deformation of the Southern Rockies.

GEOLOGIC, GEOMORPHIC, AND PHYSIOGRAPHIC SETTING

The Southern Rocky Mountain physiographic province is a rugged upland of the U.S. western interior. The province lies roughly between 35°–42° N latitude and 110°–105° W longitude, stretching from southern Wyoming to northern New Mexico (Fig. 1). A regional topographic map of the U.S. western interior shows that the Southern Rocky Mountains stand as one of four major regions of high mean elevation, the others being the Yellowstone area of northwestern Wyoming, the St. George igneous trend in central Utah, and the Rio Grande rift in New Mexico and southern Colorado (Fig. 1). A common geophysical feature to all of these regions is buoyant, low-velocity mantle (Grand, 1994; Humphreys and Dueker, 1994a, 1994b), manifest as Quaternary volcanism along the St. George trend and at Yellowstone, and as active continental rifting (the Rio Grande rift) through the southern Rocky Mountains. Important in this paper is the zone of high heat flow and Quaternary volcanism associated with the Jemez lineament (Fig. 1), which is thought to be a significant Proterozoic structural feature. The Jemez lineament forms the southern edge of the broad boundary zone between the Yavapai and Mazatzal Proterozoic provinces (Karlstom and Humphreys, this issue); the northern edge of the boundary zone roughly parallels the Jemez lineament and is located south of the Front Range. The strong spatial correlation between buoyant, low-velocity mantle (Grand, 1994; Humphreys and Dueker, 1994a, 1994b) and high mean elevation (Fig. 1) forms the basis for our hypothesis that the dynamic interaction between crustal structure and mantle processes is manifest in the Cenozoic history of rock uplift, exhumation of rocks, and ultimately in the topography.

The Southern Rocky Mountain highlands, which stand at elevations above 2500 m, are surrounded by landscapes that are at least 500 m lower (Fig. 1). The transition from the uplands to adjacent lowlands occurs rather abruptly along the northern, eastern, and southern boundaries of the province at locations coincident with the Cheyenne belt in southern Wyoming, the Front Range escarpment, and Jemez lineament, respectively. The best known physiographic feature of the Southern Rockies is the Rocky Mountain erosion surface, an upland surface of low relief presumably formed by fluvial erosion following Laramide deformation (Davis, 1911; Epis and Chapin, 1975; Chapin and Cather, 1983; reviewed in Gregory and Chase, 1994). The core of the debate surrounding the Cenozoic tectonic evolution of the Southern Rockies centers on whether this erosion surface was (1) created by progressive lowering and rounding of divides of a formerly high-standing Laramide upland as the landscape was reduced to near sea level (Davis, 1911; Love, 1970), (2) created near sea level as fluvial erosion kept pace with the uplift of rock during Laramide deformation (Epis et al., 1980), or (3) created at high elevation (2 to 2.5 km) by a climate and hydrology that favored the reduction of relief in the uplands (Gregory and Chase, 1994). The implications of the first two hypotheses require post-Laramide uplift (Steidtmann et al., 1989) of the Southern Rockies to place the erosion surface at its present elevation and create the substantial relief around the province margins; the third hypothesis requires post-Laramide erosional exhumation of Laramide structures with the modern relief attributed solely to differences in rock erodability (Leonard and Langford, 1994; Chapin and Cather, 1994) and the local effects of Pleistocene glaciation. Effects of regional climatic changes throughout the Cenozoic undoubtedly had important (Chapin and Kelley, 1997), but poorly understood, effects on the Southern Rocky Mountain landscape. A less seasonal, less stormy early Cenozoic climate pattern (Barron, 1989) that may have favored chemical weathering and transport-limited processes changed to a more seasonal, more stormy late Cenozoic pattern including monsoonal-like precipitation that favors mechanical weathering, and weathering-limited processes.

At three locations along the Front Range, the escarpment between the Southern Rockies and the Great Plains is masked by fingers or “gangplanks” of sedimentary deposits of the High Plains that rise gradually to virtually onlap the crystalline rocks (Scott, 1975; Chapin and Cather, 1994). Locally, important stratigraphic relationships between these Cenozoic alluvial deposits and volcanic rocks can be used to reconstruct a late Cenozoic history of land-surface deformation and fluvial incision. For example, the southernmost gangplank is located in northeastern New Mexico. Here, numerous late Cenozoic fluvial deposits shed from the Sangre de Cristo Mountains are complexly interbedded and juxtaposed on geomorphic surfaces with volcanic deposits of the Raton-Clayton (30 ka to 8.77 Ma; Stroud and McIntosh, 1996) and Ocate (800 ka to 8.3 Ma) volcanic fields (Scott, 1975, 1989; O’Neill and Mehnert, 1988; Scott and Pillmore, 1993). Other simple, yet profound regional stratigraphic relationships further constrain the events that have driven post-Laramide landscape evolution for the southern Colorado-northern New Mexico region. Paleocene and Eocene deposits that are preserved under the three “gangplanks” have been eroded from the remainder of the eastern margin of the Southern Rocky Mountain province. Furthermore, despite voluminous Oligocene to early Miocene volcanic activity associated with the Mogollon-Datil, San Juan, Latir, Spanish Peaks and Ortiz volcanic fields, virtually no volcaniclastic sediments of that age are preserved on the New Mexico or southern Colorado Great Plains. It is likely that sediments of this age have been removed by erosion given that the middle Tertiary volcanic fields have been deeply exhumed, with the plutons now exposed at the surface.

Beginning in the late middle Miocene and proceeding through the late Miocene, the High Plains began aggrading thin, but widespread, coarse-grained alluvial deposits called the Ogallala Formation. The precise genesis of the Ogallala Formation remains unclear, but it probably represents a period of valley aggradation (Elias, 1942; Leonard and

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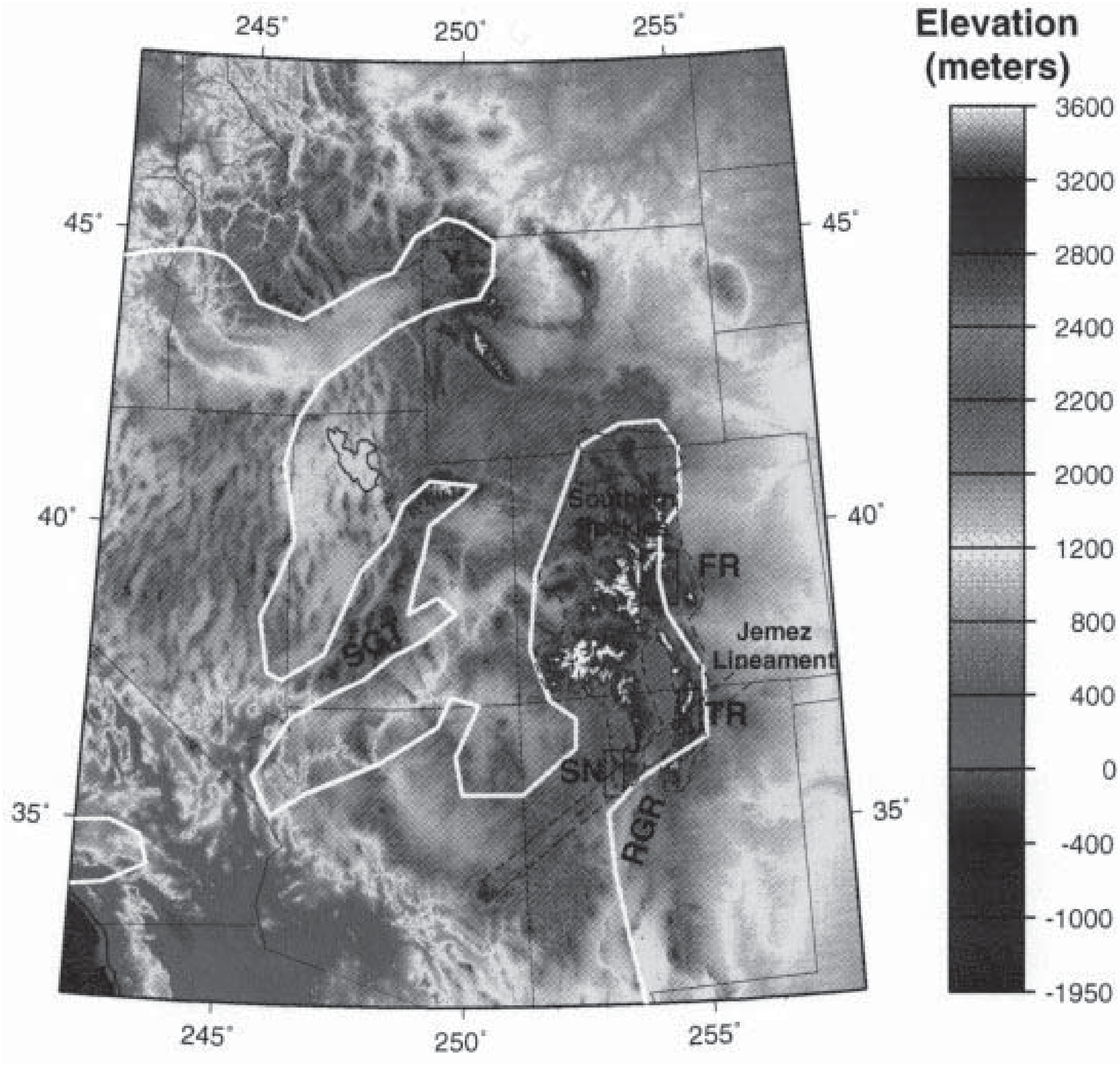

Figure 1. Topographic map of the western United States illustrating the high mean elevation of the Southern Rocky Mountains (dashed irregular line). Labeled boxes outline location of topographic and fission-track analyses presented in this paper; SN = Sierra Nacimiento, TR = Taos Range, FR = Front Range. Parallel dashed straight lines mark the location of the Jemez lineament, a region of Neogene-Quaternary high heat flow and volcanism; J = Jemez Mountains. Other regions of Quaternary volcanism include the Saint George trend (SGT), Yellowstone (Y), and Rio Grande rift (RGR). The high mean elevation of the entire U.S. western interior reflects a topography dynamically supported by a low-velocity, buoyant mantle, outlined by the thick white line (Grand, 1994; Humphreys and Dueker, 1994a).

Frye, 1978) and transport of detritus in response to post-Laramide tectonic and/or epeirogenic rejuvenation, or climatically driven increased mechanical erosion of the Southern Rockies. The fact that the Ogallala Formation represents a period of sediment transport across the Great Plains is an important consideration in the role of post-Laramide tectonic deformation of the Southern Rockies. No thick accumulations of the Ogallala Formation occur in eastern New Mexico or southeastern Colorado (the region immediately adjacent to Rio Grande rift uplift), an observation consistent with the lack of a crustal downwarp to preserve the detritus shed from the Southern Rockies during the late Tertiary.

CONCEPTS

Conceptual Models for Long-term Lithospheric Evolution and Landscape Response

Reconstruction of Cenozoic crust–mantle interactions for the Southern Rocky Mountains from a study of long-term landscape evolution represents a classic inverse problem (Fig. 2). The geomorphologist and fission-track thermochronologist begins with: (1) topography (mean relief, mean elevation), (2) short-term rates of landscape incision from stratigraphy and fluvial sediment yields, and (3) long-term rates of landscape exhumation from stratigraphy and interpretations of fission-track age and length distributions. In the end these data can really only answer two questions: (1) what is the history of rock uplift and cooling? and (2) what has been the evolution of the mean relief of the landscape through time? It is then the task of the tectonicist to interpret these results in terms of changes in crustal thickness and/or crust-mantle interactions. Geomorphic and fission-track thermochronologic data sets are complex and integrate the effects of many lithospheric processes over long periods of time. These data do not reflect a unique lithospheric process or series of processes. For example, at the large scale, all of the world's great orogens are high and steep despite the fact that they lie in highly variable plate tectonic settings. At the more local scale, topographic differences such as the presence or absence of plateaus might offer some insight into the precise processes of rock uplift. It is on these differences that the geomorphologist and fission-track thermochronologist must focus.

Landscapes are the geomorphic expression of constructive rock-uplift processes and destructive rock-exhumation processes, but these processes are difficult to parameterize in a useful way. England and Molnar (1990) examined surface uplift and rock uplift as possible parameters for representing the forcing of the geomorphic system; however, neither of these parameters isolates the tectonic source from the erosional response. Process-based models with spatial dimensions (e.g., Willgoose et al., 1991; Beaumont, et al., 1992; Tucker and Slingerland, 1994; Howard et al., 1994; Slingerland et al., 1994) are commonly used to represent geomorphic and rock-uplift processes. Simpler approaches would be to reconstruct the landscape incrementally by restoring denuded sediments back to their drainages (Hay et al., 1989; Pazzaglia and Brandon, 1996) or to analyze the spatial dimensions of topography with the aim of isolating the deformation signal (Summerfield and Hulton, 1994; Weissel et al., 1994). At the core of these simple approaches are three important assumptions: (1) that any given column of crustal material contains some portion that can be removed by erosion, a portion called the erodible thickness of the crust or *ETC* (Pazzaglia and Brandon, 1996); (2) that external geologic or plate tectonic forces collectively define a crustal "source" term that can change *ETC*; and (3) that the mean rate of mechanical erosion of a crustal column is proportional to its mean elevation above base level (Ruxton and McDougall, 1967; Ahnert, 1970; Stephenson, 1984; Pinet and Souriau, 1988; Hay et al., 1989; Harrison, 1994; Pazzaglia and Brandon, 1996).

The flux of crustal source into an orogen can be visualized as the input to the system from deep-seated tectonic or epeirogenic processes. Conversely, the erosion flux from a mountain belt can be viewed as the system output, which in our case, is driven by exhumation processes. *ETC* and topography tell us about the balance between those two fluxes. It is useful here to look at source history for a simpler view of the system input. The generalized examples in Figure 3 (cf. Allmendinger, 1986) illustrate how various tectonic and epeirogenic processes are distinguished by their crustal source histories. In theory, each source history will produce its own characteristic erosional response (Fig. 3; Schumm and Rea, 1995) that can be inferred from the record of syn-deformational fluvial stratigraphy and geomorphic surfaces in and adjacent to the Southern Rockies.

In practice, the source history is complicated by a combination of processes. For example, Figure 3a is a schematic view of Laramide deformation of the Southern Rockies, where horizontal contraction led to crustal thickening. In this case, the increase

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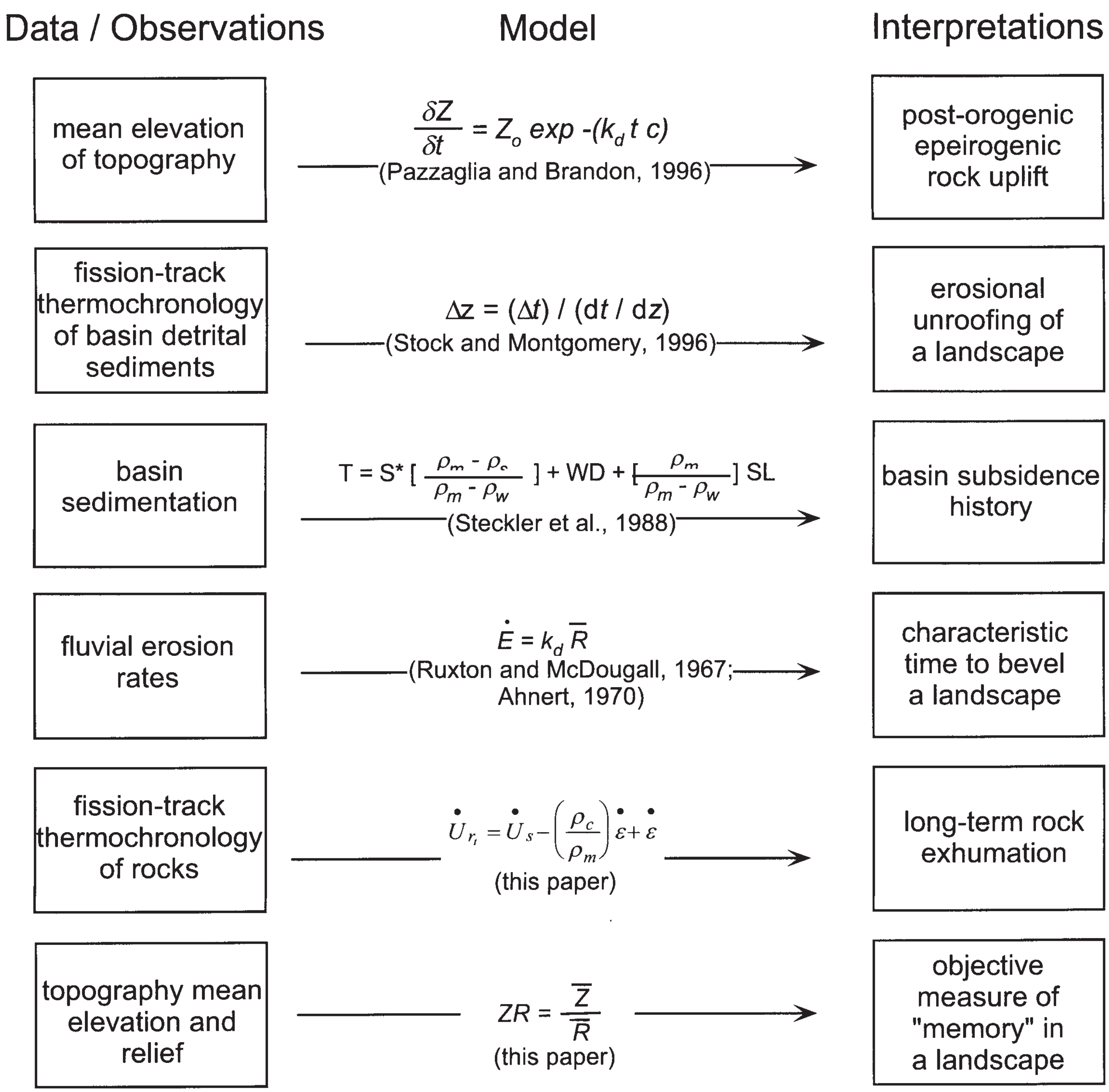

Figure 2. Some proposed models linking data and interpretations of long-term landscape evolution.

in source with time is an isostatic response to the increase in crustal thickness.

The second example (Fig. 3b) shows continental rifting. In this case, the source history is governed by two processes, transient thermal buoyancy responding to the rise of hot asthenospheric mantle, and thinning of the crust by horizontal stretching. During the early stages of rifting, the combination of thermal buoyancy and lithospheric thinning might result in an increase in source, but with time, the loss of thermal buoyancy would result in source ultimately dropping below zero, reflecting the permanent result, a thinned crust. The transition from positive to negative source is governed by the time constant for the thermal relaxation of the rift zone. Much of the western United States has responded in the manner illustrated in Fig. 3b, creating the Basin and Range. This scenario also applies to the Rio Grande rift, although the rift is superimposed on previously thickened, high-standing crust like that shown in Figure 3a.

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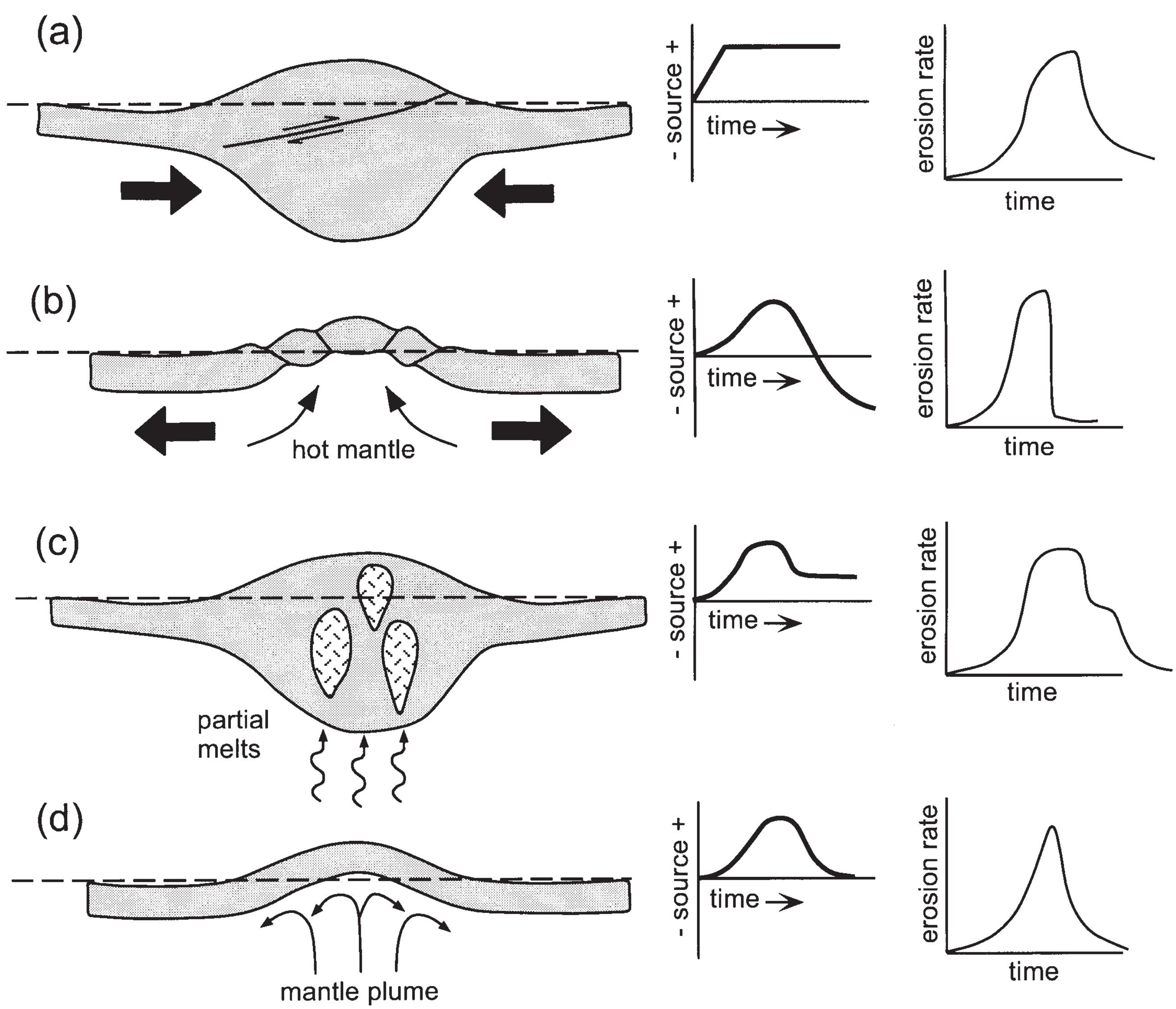

Figure 3. Simple illustration of the source histories associated with four generic tectonic settings (from Pazzaglia and Brandon, 1996). ***A***, Contraction, such as in continent-continent collisions; example of Laramide deformation. ***B***, Extension, such as that of the Basin and Range or at rift margins. ***C***, Magmatism accompanied by significant mantle-derived plutonism; example of Laramide plutonism. ***D***, Asthenospheric flow giving rise to dynamically-supported topography; example of a possible mechanism for post-Laramide deformation of the Southern Rockies. Note the characteristic functions of source and exhumation rate, ($\dot{\varepsilon}$) (wrt time), for these four different geologic settings. For (***A***), the initial increase in $\dot{\varepsilon}$ is followed by an exponental decrease, a signature of consuming a low-density root and subsequent isostatic adjustment. For (***B***), the initial increase in $\dot{\varepsilon}$ is followed by a rapid decrease because topography is destroyed by the rift subsidence process, not erosion. For (***C***), the erosional response is complex, reflecting both erosional isostatic responses of (***A***) and thermal isostatic responses of (***B***). For (***D***), the increase and decrease in $\dot{\varepsilon}$ is symmetric, following the symmetric increase and decrease in source (and topography) associated with a buoyant, low-velocity mantle plume.

The third example (Fig. 3c) shows emplacement of mantle-derived intrusives, which locally occurred during syn- and post-Laramide deformation of the Southern Rockies. In this case, both heat and mass are added to the crust, resulting in an initial high and positive source. Once again, thermal relaxation would lead to a loss of thermal buoyancy and a partial decrease in source. But note that in this case, the source remains positive because of the increased thickness of the crust following emplacement of the intrusion, and possibly because the extraction of basaltic material from the mantle causes the remaining mantle to be more buoyant.

The last example (Fig. 3d) illustrates dynamic topography of Gurnis (1992) where the topography is dynamically supported by forces associated with the flow of the mantle. A characteristic of this process is that source is completely recovered with the removal of the dynamic support. As a consequence, the source quickly returns to zero. This scenario illustrates a possible mechanism to drive late Cenozoic deformation for the Southern Rockies. Conceivably, a dynamic mantle west of the Southern Rockies resulted in crustal thinning and formation of the Basin and Range in the late Tertiary and Quaternary, whereas a different crustal response following continued westward movement of North America over the same dynamic mantle may have created the contemporary, mantle-supported high topography of the Southern Rockies.

Fission-track Thermochronology

The four conceptual crustal source histories illustrated in Figure 3 will result in different long-term rock exhumation histories, and subsequently, different reconstructions of long-term landscape evolution. Fission-track analysis is a proven method for determining the thermochronologic history of rocks and interpreting their often complex exhumation histories. Fission-track annealing in apatite is controlled primarily by temperature and the chemical composition of the apatite [tracks in chlorapatite completely anneal at higher temperatures (140 °C) than those in fluorapatite (120 °C); Green et al., 1986; Green, personal communication, 1996]. In a relatively stable geological environment where temperatures vary uniformly as a function of depth, apatite fission-track (AFT) age and track lengths decrease systematically with depth (Fig. 4a; Naeser, 1979, Fitzgerald et al., 1995). 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 (Fig. 4a). The AFT ages of detrital grains in sedimentary rocks at shallow depths (temperatures < 70 °C) are 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. The AFT ages in basement rocks at shallow depth (temperatures < 70 °C) reflect the cooling history of the basement prior to the period of stability, and, as with sedimentary rocks, the mean track lengths would be relatively long (> 13 µm).

In the temperature range known as the partial annealing zone (PAZ), which is between 60–70 °C and 120–140 °C, depending on the composition of the apatite, the AFT ages and track lengths are reduced compared to the original AFT ages and lengths. Mean track lengths in the PAZ are typically 8 to 13 µm. Finally, at temperatures above 120 to 140 °C, tracks that are formed are quickly destroyed and the fission-track age is zero. If, after a period of relative stability, the crust is rapidly cooled during exhumation related to a tectonic event, the fossil PAZ may be exhumed and the time of cooling and the paleodepth of the top or bottom of the PAZ can be estimated (Fig. 4b; Gleadow and Fitzgerald, 1987). If the tectonically disturbed area cools rapidly (> 5 °C/m.y.), the mean track lengths in rocks that are at the base of the fossil PAZ (below the break-in-slope on the age-depth profile) are generally > 14 µm, and the AFT ages from below the base of the exhumed PAZ can be used to estimate the timing of the onset of exhumation. If the rock column cools more slowly during uplift and/or erosion, the mean track length at the base of the fossil PAZ is typically < 14 µm, and the apparent AFT age more loosely constrains timing of the initiation of cooling (Foster and Gleadow, 1992).

Recently, Kamp and Tippett (1993), Fitzgerald et al. (1995), and Stock and Montgomery (1996) demonstrated that AFT analysis can be a powerful tool in evaluating the tectonic and exhumation history of mountain systems in convergent settings. Using the elevation of the base of the PAZ, the timing of exhumation recorded below the PAZ, estimates of mean surface elevation before and after a tectonic event, and estimates of paleogeothermal gradients and surface temperatures (Savin, 1977), these authors were able to constrain surface uplift, rock uplift, and exhumation. We adopt and modify the approach of Fitzgerald et al. (1995). AFT analyses return the timing and thickness of an exhumed vertical column of crust. Exhumation of rocks (ε) can be accomplished by extensional tectonic (Selverstone, 1988) or erosional processes; here we consider erosional exhumation only. The rate of uplift of the Earth's surface ($\dot{U}_S$), measured in

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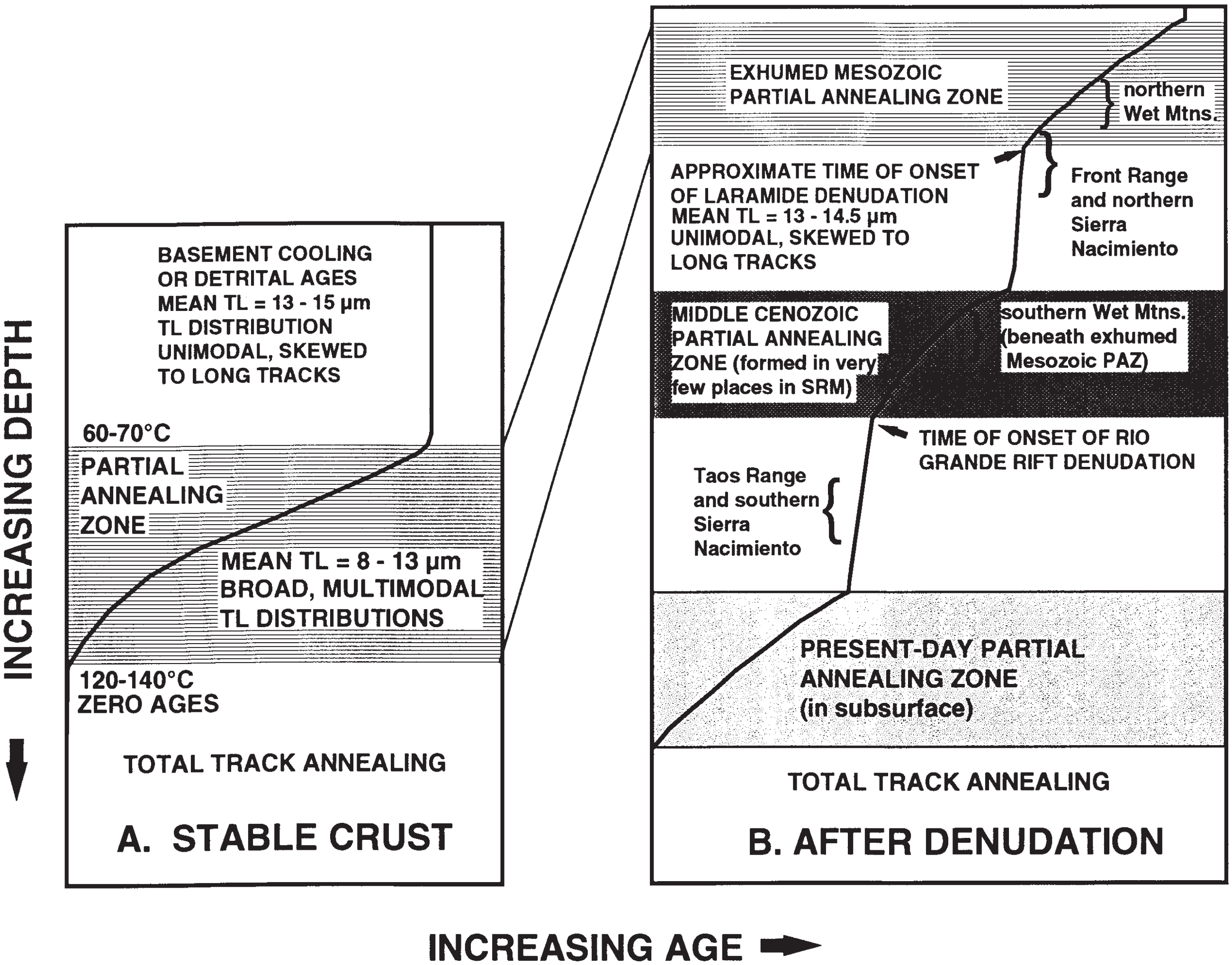

Figure 4. Diagrammatic relationship of fission-track age and length as a function of depth at time of maximum burial during the Mesozoic (***A***) and after exhumation (***B***). Diagram described in the text. TL = track length. Representative portions of the AFT age-depth curve that are preserved in the Front Range and Wet Mountains are shown for reference.

meters, reflects the difference between the rate of rock uplift ($\dot{U}_r$), in essence the source term of Figure 3, and the rate of rock exhumation ($\dot{\varepsilon}$), measured in length per unit time,

$$\dot{U}_S = \dot{U}_r - \dot{\varepsilon} \qquad \text{(England and Molnar, 1990)} \quad (1).$$

Here we use the dot notation to denote rates. Two fundamentally different processes contribute to rock uplift: isostatically-driven rock uplift ($\dot{U}_{r_i}$) and tectonically-driven rock uplift ($\dot{U}_{r_t}$),

$$\dot{U}_r = \dot{U}_{r_i} + \dot{U}_{r_t} \qquad (2).$$

The interaction between isostatically and tectonically driven rock uplift in active orogens is complex and intimately linked to the rates and style of erosional exhumation (Beaumont et al., 1992). Over short spatial wavelengths, the isostatic component is further complicated by flexural effects. We simplify our case, the Southern Rocky Mountains, by assuming that there is no rock uplift attributed to crustal thickening (Fig. 3a) and that flexural effects are minimal. The total amount of exhumation determined by AFT analysis in the Southern Rocky Mountains applies to the duration of the Laramide orogeny and subsequent. It is an implicit assumption that most of the tectonically driven rock uplift occurred during the Laramide orogeny and most of the isostatically driven rock uplift is post-Laramide; however, we could use regional geologic relationships, where appropriate, to argue for isostatic rock uplift during the Laramide orogeny and vice versa. During the Laramide orogeny and subsequent time the rate of isostatically-driven rock uplift, assuming no flexural effects is:

$$\dot{U}_{r_i} = c\,\dot{\varepsilon} \quad (3),$$

where c is a compensation ratio for Airy isostasy determined by crustal and mantle densities,

$$c = \rho_c / \rho_m \quad (4)$$

and ρ_c is 2700 kg/m^3 and ρ_m is 3400 kg/m^3. For settings where regional geologic relationships can independently constrain the rates of surface uplift, the rates of tectonically-driven rock uplift can be estimated by combining equations (1) through (4)

$$\dot{U}_{r_t} = \dot{U}_s - \left(\frac{\rho_c}{\rho_m}\right)\dot{\varepsilon} + \dot{\varepsilon} \quad (5).$$

To illustrate the role that AFT exhumation data can play in determining the Laramide and post-Laramide history of the Southern Rocky Mountains, consider the hypothesis that the post-Laramide Southern Rockies were beveled by erosion to a mean elevation near sea level (Davis, 1911; Love, 1970) to create the Rocky Mountain erosion surface. Figure 3a shows that removal of crust above base level (above the dashed line) will immediately result in isostatic rebound of the crustal column because the crustal thickening associated with Laramide shortening produced a low-density crustal root that protrudes into the upper mantle. The density difference between average crustal material (ρ_c = 2700 kg/m^3) and average upper mantle (ρ_m = 3400 kg/m^3) means that only about 20 percent of the total thickness of a crustal column will stand above base level; the rest of the column remains in the root. If the Laramide orogeny created an average of 2 km of topography, 8 km of crustal root would have to be created to support that topography. Conversely, to remove 2 km of Laramide topography, 10 km of crust would have to be consumed. That is, the post-Laramide Southern Rockies would have an *ETC* of approximately 10 km. The implication of this post-Laramide history is significant exhumation of rocks, a history that would be well-recorded in the amount of exhumation determined from fission-track thermochronology. In contrast, if post-Laramide erosion has not beveled topography to near sea level, creating instead the Rocky Mountain erosion surface at high elevation (reviewed in Gregory and Chase, 1994), much less rock exhumation is necessary. The calculated exhumation based on fission-track thermochronology would be expected to be much less than in the case where the Southern Rockies were beveled to sea level, as discussed later in this paper.

The "Memory" of Landscapes

The two rock-exhumation scenarios outlined above, clearly distinguishable in fission-track thermochronology histories, nonetheless have both been developed to explain a topographic and geomorphic feature—the Rocky Mountain erosion surface. This leads to the obvious question as to what useful information, if any, could a geomorphic or topographic analysis of the Southern Rockies provide regarding its post-Laramide tectonic history. Landscapes have "memory." Individual ranges in the Southern Rocky Mountains were all uplifted during Laramide crustal thickening 80–40 Ma, but since that time, they have experienced different geologic histories. In some cases, such as in the Front Range of Colorado, that geologic history has favored preservation of the Rocky Mountain erosion surface. In other words, the Front Range retains evidence of the rock uplift and rock-exhumation events during the Laramide. In contrast, other ranges such as the Sangre de Cristo Mountains of south-central Colorado and north-central New Mexico have seen a post-Laramide geologic history that has all but destroyed the original Laramide uplift and the Rocky Mountain erosion surface. Although Laramide faults and folds are preserved within the range, the modern topography has little "memory" of Laramide uplift and deformation. Instead, the Sangre de Cristo Mountains have been strongly reshaped by post-Laramide (rift-related) rock uplift and exhumation. A key question should be asked to help unravel these different geologic histories: Can the topographic "memory" in a landscape be quantified? In other words, can geomorphic and topographic data such as mean elevation and mean local relief of a range be quantified by a simple, dimensionless parameter such that the Front Range has a quantifiably different topography than the Sangre de Cristo Mountains? Below we present some data that argue that under the appropriate geologic constraints, topography can in fact be quantified to reflect the degree of "memory" in a given landscape.

PRELIMINARY RESULTS

The ZR Ratio

We present a geomorphic approach for evaluating differences in topography and topographic evolution that might be relatable to Laramide and post-Laramide tectonic events. Here we choose three mountain ranges that lie in three different Proterozoic crustal terranes: (1) the Colorado Front Range in the Yavapai province; (2) the Taos Range in the Mazatzal province north of the Jemez lineament; and (3) Sierra Nacimiento in the Mazatzal province straddling the Jemez lineament (Fig. 5). All three ranges share common rock types (to a first-order) and rock-uplift histories during the Laramide orogeny; however, their post-Laramide geologic histories have varied considerably. We recognize that local differences in rock type and climate play a role in determining the post-Laramide topography of these regions. Perhaps more importantly, regional geomorphic considerations such as the relative degree and timing of drainage integration through the Rocky Mountain foreland contribute significantly to long-term landscape evolution. At this stage of our research, we have not yet addressed the relative contributions of post-Laramide tectonics, climate, local rock type, and drainage integration. We will assume that changes in climate and the effects of local rock type are subordinate to post-Laramide tectonics and drainage integration, which tend to be highly correlated (Summerfield, 1991; Summerfield and Hulton, 1994).

The drainage basin is the fundamental unit of the fluvial landscape (Ritter et al., 1995). Geometric characteristics of the master channel and its tributary network within a drainage basin, collectively referred to as drainage basin morphometry, have long been recognized to contain basic information regarding the basin's geologic and hydrologic setting and its evolution (Horton, 1945; Melton, 1958; Abrahams, 1984). Of particular interest to regional tectonic interpretations, relief morphometry such as the hypsometric integral applied across many adjacent drainage basins, has proven useful in quantitatively or semi-quantitatively describing how a landscape expresses variable rates of rock uplift or subsidence (Schumm, 1956; Strahler, 1952; Gardner, et al., 1987; Hack, 1973; Bull and McFadden, 1977; Merritts and Vincent, 1989; Montgomery and Dietrich, 1994; Burbank et al., 1996). We wish to explore the utility of a particular relief morphometric parameter that relates mean local elevation to mean local relief at the scale of a mountain range, and is designed to capture the local ruggedness of a landscape (Formento-Trigilio and Pazzaglia, *in press*). Previous applications of a similar relief parameter (Burbank et al., 1996) have proven useful for characterizing threshold hillslopes in regions of very high rates of tectonic uplift, as well as for indicating topography that is either anomalously flat or steep with respect to its mean elevation above sea level. Insofar that landscape ruggedness at the mountain range scale is controlled by the major valley spacing and the extent to which a drainage net fills a basin (Melton, 1958), we view a relationship between mean local relief with respect to mean elevation as a potentially useful measure of the degree of drainage integration and as a reflection of regional rates of rock exhumation by fluvial processes (Summerfield, 1991; Summerfield and Hulton, 1994).

Rapid relief morphometric calculations of topography involve measuring mean local relief and mean local elevation on a rasterized grid of elevation data. The elevation information, available from the U.S. Geological Survey DEM database, has a horizontal spatial resolution of 30 m and a vertical resolution to the nearest meter (actually closer to 3 m). The data are entered into a rasterized lattice format in ARC/INFO and projected into a UTM projection coordinate system. Local mean elevation is calculated from:

$$\bar{Z} = \sum_{n} Z_r / n \qquad (1),$$

where $\bar{Z}$ is mean elevation in meters, ΣZ_r is the sum of elevation values within a circle of radius r, and n is the number of elevation values within a circle of radius r. By moving a circular window of radius r, where r is measured as the number of cells in the lattice, across the DEM a new lattice of local elevation, in essence a low-pass filtered version of the original data, is produced. Sensitivity analyses (Formento-Trigilio and Pazzaglia, *in press*) have shown that a circle of radius (r) = 34 cells, effectively 1 km given that the original lattice spacing is 30 m, provides an effective filter to characterize local mean elevation that is significantly different from the original topography, but not over-representative of the long wavelengths. Similarly, local mean relief is calculated from:

$$\bar{R} = (Z_{max} - Z_{min})_r \qquad (2),$$

where $\bar{R}$ is local mean relief in meters, Z_{max} is the maximum elevation within a circular window of radius r, and Z_{min} is the minimum elevation in a circular window of radius r. When the radius of the circular window evaluating mean local relief is the same as that for mean local elevation, a dimension-

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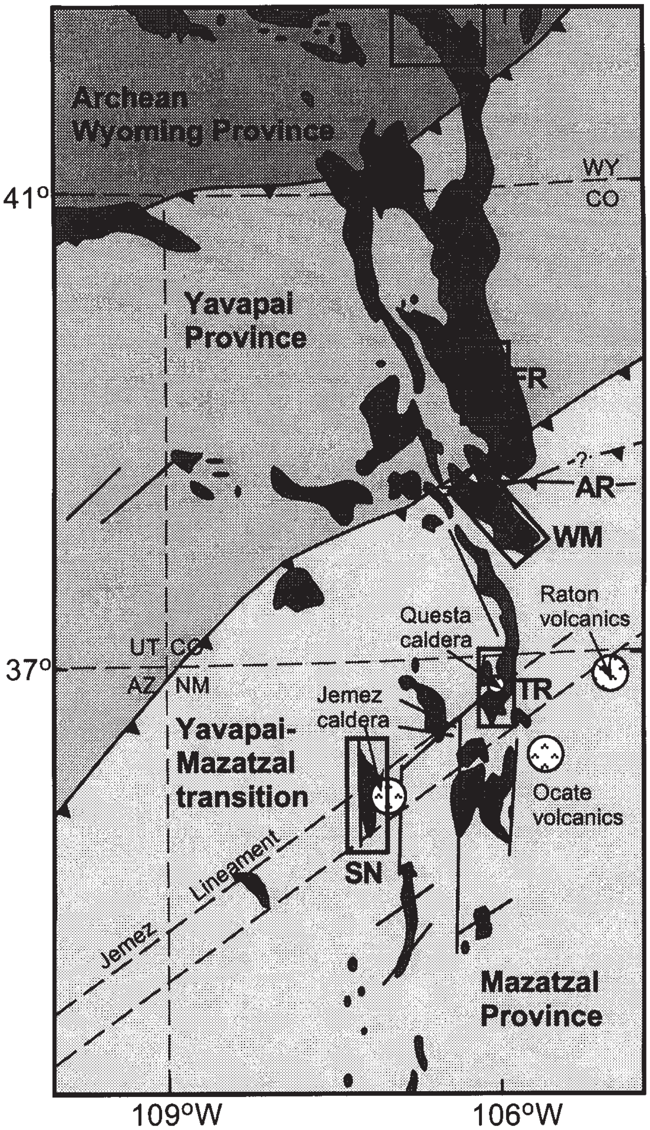


Figure 5. Major Precambrian crustal boundaries in the Southern Rocky Mountains (Karlstrom and Bowring, 1993). Darkest shading represents outcrop of Proterozoic rocks. Studied ranges, Sierra Nacimiento (SN), Taos Range (TR), Front Range (FR), Wet Mountains (WM), and Laramie Range (LR) are outlined by boxes. AR is the Arkansas River. Note the wide blocky character of Laramide uplifts in the Yavapai province and Archean Wyoming province versus the predominantly long, narrow character of Laramide uplifts in the Mazatzal province. The boundary between Yavapai and Wyoming provinces is the Cheyenne belt.

less parameter, the mean elevation to mean relief (*ZR*) ratio can be calculated:

$$ZR = \overline{Z}/\overline{R} \qquad (3; \text{Fig. } 6).$$

Division of a morphometric parameter sensitive to rates of rock uplift and exhumation (mean relief) into a constant (mean elevation) effectively normalizes the relief for the conditions of regional base level. As such, the *ZR* ratio is very sensitive to anomalously flat or steep topography and contains useful information regarding the degree of drainage integration. For example, the *ZR* ratio of the Tibetan Plateau interior would be a very large number, given the low ruggedness of that landscape attributed to the high mean elevation and virtual lack of any local relief. The lack of relief is directly attributed to the fact that the Tibetan Plateau is very arid and internally drained, conditions that lead to few streams, shallow fluvial valleys, and very low rates of rock exhumation by fluvial processes despite the high rates of rock uplift throughout the late Cenozoic. In contrast, a well-drained landscape such as the Olympic Mountains of Washington State has a relatively low *ZR* ratio of approximately 1. This *ZR* ratio is indicative of a rugged landscape with a high drainage density where mean local elevation and mean local relief are highly correlated (and nearly equivalent) with concomitant high rates of erosional exhumation by fluvial processes that are equal and opposite to rates of rock uplift.

For the Southern Rocky Mountains, calculation and comparison of the *ZR* ratio of Sierra Nacimiento, the Taos Range, and the Front Range will be used to interpret the relative ruggedness as a function of drainage integration, placed in the context of long-term rates of erosional exhumation determined by fission-track thermochronology (Table 1). Our analysis is preliminary and best viewed in the context of exploring the utility of a simple relief morphometric parameter, in this case the *ZR* ratio, to quantitatively describe the role that relative drainage integration plays in erosional exhumation of the Laramide uplifts. Implicit in our methodology is the assumption that the Precambrian rock types underlying the observed ranges are similar. We will leave rigid statistical analysis of the differences in the *ZR* ratio throughout the Southern Rocky Mountains for future work when we have a larger subset of ranges to evaluate.

AFT Results

Introduction

The role of the Proterozoic crustal terranes in influencing the Laramide and post-Laramide evolution of the Southern Rockies can be considered when we place the *ZR* ratios of our three mountain ranges in the context of their long-term Laramide and post-Laramide exhumational histories. Mountain blocks with high *ZR* ratios (more subdued to-

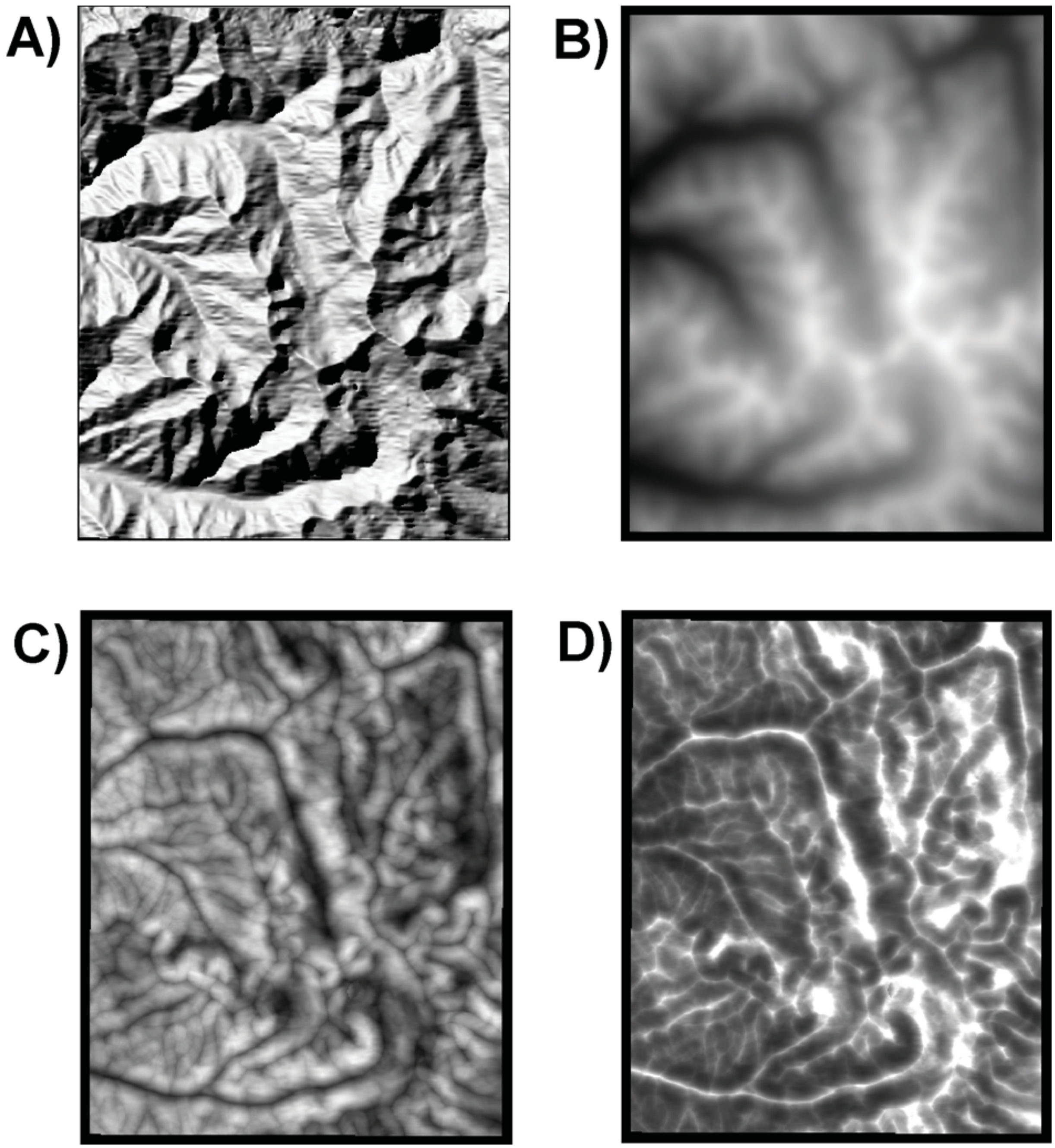


Figure 6. Examples of the topographic analysis. ***A***, Raw 30 m-resolution digital elevation data of the Wheeler Peak quadrangle in a shaded hillslope portrayal. ***B***, Filtered topography using a moving circle window with radius = 0.25 km; mean elevation (*Z*) of this quadrangle is 3341 m. High elevations in white, low elevations in black. ***C***, Filtered local relief using a moving circle window with radius = 0.5 km; relief ranges from 28 to 374 m and has a mean value (*R*) of 198 m. High relief areas in white, low relief areas in black. ***D***, The *ZR* ratio for this quadrangle is produced by dividing grid of (***C***) into grid of (***B***). Regions of anomalously flat topography are in white. These flat regions correspond to formerly glaciated valley bottoms and illustrate the caution that must be exercised in interpreting topography solely in the context of rates of rock uplift. The *ZR* ratio, using a window radius of 0.5 km, ranges from 8 to 102 and has a mean value of 18 for this quadrangle. Sensitivity analyses have demonstrated that a window of this size is typically too small to convincingly discriminate differences in topography. Data in Table 1 reflect a moving circle window radius of 1 km, which results in a *ZR* ratio of 5 for the same quadrangle. Appreciate that if (***D***) had more white color, as is the case for the Front Range and Laramie Range, the *ZR* ratio would be higher.

Table 1. Summary of the relationship between landscape roughness and the *ZR* ratio determined from 30 m DEM data using a moving window radius of 1 km. See Formento-Trigilio and Pazzaglia (*in press*) for a complete presentation of *ZR* ratio sensitivity analyses.

Mountain range	Mean elevation *Z* (m)	Mean relief *R* (m)	Mean slope (°)	*ZR* [1]	Long term exhumation rate (km/m.y.)
Archean Craton					
Laramie Mountains[2]	2326	149	4.3	15	~ 0.09 (?)[3] (50 Ma)
Yavapai					
Front Range	2810	425	12	7	0.12-0.17 (67 to 37 Ma)
Mazatzal					
Wet Mountains	3103	636	17.6	5	(?)
Sierra Nacimiento, north of Jemez lineament	2981	315	8.9	10	0.12-0.15 (58 to 30-24 Ma)
south of Jemez lineament	2555	330	9.4	8	0.2 [4] (< 1 Ma)
Taos Range	3376	632	17.5	5	0.14-0.28 [5] (16-6 Ma)

1 = *ZR* ratios are rounded off to one significant figure.
2 = DEM data used for this range are the USGS 3arcsec data with horizontal resolution of 90 m.
3 = Denudation rate is very poorly constrained as the age of the Rocky Mountain surface for the Laramie Mountains is poorly known and may range from Eocene to late Miocene age. Exhumation data from Cerveny (1990).
4 = Quaternary rate of fluvial incision determined by fluvial terraces (Formento-Trigilio and Pazzaglia, *in press*).
5 = see text disscussion for assumptions made in these exhumation extimates.

pography) and abundant Laramide (40-70 Ma) or older AFT ages like the Front Range and northern Nacimiento Mountains provide insight into exhumation associated with Laramide deformation. Mountain ranges with lower *ZR* ratios (more rugged terrain) and late Eocene to late Miocene AFT ages like the Taos Range section of the Sangre de Cristo Mountains are associated with flank uplifts adjacent to the Rio Grande rift.

Front Range–Wet Mountains

We find differences in the style and amount of Laramide deformation and exhumation in the Proterozoic rocks that straddle the northern margin of the wide Yavapai-Mazatzal boundary zone (Fig. 5). The margin is defined as the northern limit of 1.6-Ga deformation and its location is poorly constrained in central Colorado. Our structural datum is the base of an uplifted AFT partial annealing zone of pre-Laramide age (Kelley and Chapin, 1995, 1997, *in press*). The base of the fossil PAZ, which separates samples with AFT ages >100 Ma and short mean track lengths (10–12 µm) from samples with AFT ages of 50 to 75 Ma and longer mean track lengths (12–14 µm), formed at a depth of about 4 km when the area now occupied by the Front Range was at sea level near the end of Mesozoic time (e.g., Fig. 4a). The PAZ has since been disrupted by faulting and folding associated with Laramide and post-Laramide tectonism. AFT data from the southern Front Range indicate that the center of the range moved vertically with respect to the mountain flanks during Laramide deformation. AFT ages at low elevation along both the eastern and western margins of the Front Range are >100 Ma and the mean track lengths are short. In contrast, AFT ages of 50 to 75 Ma are prevalent in canyon bottoms within the range, with the ages generally decreasing toward the center of the range. Furthermore, the elevation of the base of the PAZ increases from 1762 m near the mouth of Waterton Canyon to 2400 m near Bailey, Colorado (Fig. 7). The elevation of the base of the PAZ is 2600 m on the south side of Pikes Peak and 3500 m on Mount Evans (Kelley and Chapin, 1997). Faults that accommodated the transition between the laterally thrusted mountain flanks and the vertically uplifted center of the range have been identified using AFT data on either side of northwest-striking faults that intersect the canyons dissecting the Front Range.

A schematic cross section of the internal structure of the Front Range based on the AFT data from the Waterton Canyon/North Fork South Platte river traverse (Fig. 7) is shown in Figure 8. This cross section is representative of the Front Range from Golden Gate Canyon just north of Golden, Colorado, south to the Arkansas River, completely within the Yavapai province. The style of Laramide deformation changes north of Golden Gate Canyon, which is roughly coincident with the Colorado mineral belt, another crustal structure of presumed Proterozoic ancestry. The Golden thrust fault, a range-bounding fault south of Golden, swings east into the Denver Basin, back-thrusts involving Phanerozoic sedimentary rocks become common, and no AFT ages >100 Ma are found in the Proterozoic rocks along the eastern margin of the Front Range. All the AFT ages are 40 to 70 Ma, implying greater amounts of Laramide denudation along the eastern range front in the northern Front Range compared to the southern Front Range.

Constraints on the total amount of exhumation, surface uplift, and rock uplift across the Front Range since the end of Cretaceous time can be determined from modern elevation of the base of the PAZ (Fitzgerald et al., 1995). The present mean elevation of the Front Range is approximately 2.5 km. The paleomean surface elevation near the end of the Mesozoic was sea level, but sea level was at least 150 to 200 m higher compared to today, so the total mean surface uplift is on the order of 2.3 km. The establishment of a PAZ indicates pre-Laramide relative tectonic stability at or near the end of the Mesozoic, so a typical geothermal gradient for a stable craton of 25 °C/km is used. By using these assumptions and noting the present elevations of the base of the fossil PAZ in the Front Range, we find that the total rock uplift, which is rock movement with respect to sea level, is generally 6 to 6.6 km, with a low of 5.9 km near the mouth of Waterton Canyon and a high of 7.5 km for Mount Evans (Table 2, Fig. 7). Total mean exhumation ranges from 3.5 to 5.2 km, with most values clustering at 3.6 to 4.3 km. From equations (2) through (4), the total isostatic and tectonic components of rock uplift are 2.9 to 4.2 km and 2.9 to 3.3 km, respectively. The Rocky Mountain erosion surface existed prior to the eruption of the 36.7-Ma (McIntosh and Chapin, 1994) Wall Mountain Tuff , which rests on and preserves the surface in the southern Front Range. If we accept that the erosion surface is the same age everywhere under the Wall Mountain Tuff, most of the exhumation occurred between 67 and 37 Ma, yielding exhumation (erosion) rates of 0.12 to 0.17 km/m.y.

Samples for AFT analysis were also collected at low elevation along the highway paralleling the Arkansas River (Fig. 7), which approximately follows the northern edge of the boundary zone between the Yavapai and Mazatzal provinces. Along the western one-third of the traverse the AFT ages are 55 to 78 Ma with mean track lengths of 13 to 13.5 μm, characteristic of samples from below the base of the PAZ. In contrast, along the eastern two-thirds of the profile (east of Echo Park), the ages are 92 to 173 Ma with mean track lengths of 10 to 12 μm, indicative of samples within the PAZ. The exposure of a fossil PAZ to the east and Laramide-age samples from below the PAZ at higher elevation to the west mimic the pattern seen in the Front Range, although the width of the zone of older AFT ages is much broader along the Arkansas River (20 km here compared to 1.5 to 5 km to the north). The core and eastern flank of a Laramide uplift is exposed in this profile, and the western flank of the uplift has been disrupted by late Cenozoic faulting associated with the Rio Grande rift along the borders of the Wet Mountain graben and the Sangre de Cristo Mountains.

The Wet Mountains (Fig. 7), which lie south of the northern margin of the Yavapai-Mazatzal boundary (Fig. 5), differ from the Front Range and the Arkansas River traverse in that the base of the Mesozoic fossil PAZ found to the north is not exposed in the Wet Mountains. 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 exhumation in this area was comparable to that along the eastern margin of the Front

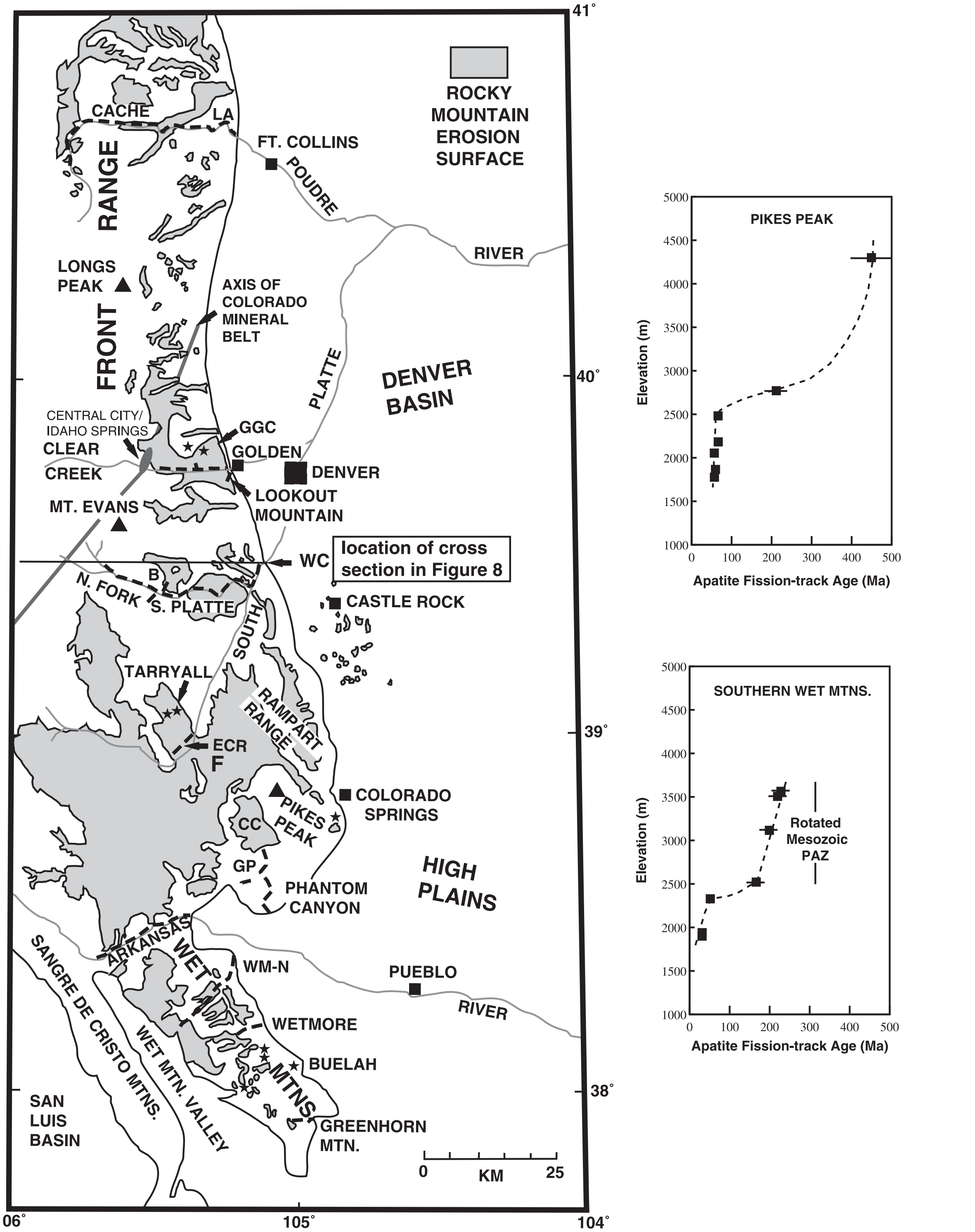


Figure 7. Index map showing fission-track sample traverses (dashed lines), isolated sample localities (stars), geographic areas mentioned in text, and distribution of Rocky Mountain erosion surface (shaded). Traverses from north to south are: Golden Gate Canyon (GGC), Lookout Mountain/Clear Creek, Waterton Canyon (WC)/north fork of the South Platte River, Tarryall Reservoir/Elevenmile Canyon Reservoir (ECR), Phantom Canyon, Garden Park (GP), Arkansas River, Wet Mountains-north (WM-N), Wetmore, and Greenhorn Mountain. Location of reconnaissance traverse along Cache la Poudre River also shown. F = Florissant fossil beds and CC = Cripple Creek volcanic field. Distribution of Rocky Mountain erosion surface (shaded pattern) from Coleman (1985); note remnants of Rocky Mountain surface on High Plains near Castle Rock. Location of Colorado mineral belt from Bryant et al. (1981).

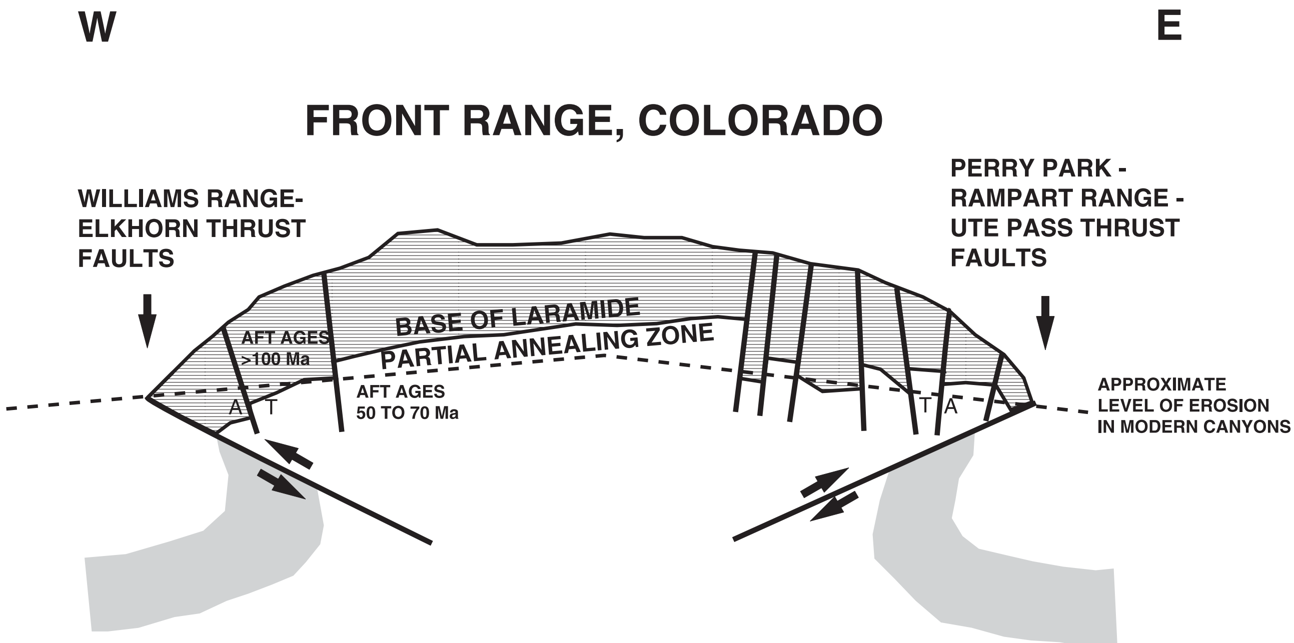


Figure 8. Schematic cross-section showing geometry of faults and disruption of base of PAZ by Laramide deformation in the Waterton Canyon/north fork of the South Platte River portion of the Front Range.

Range (Kelley and Chapin, 1995; 1997). Since 50- to 70-Ma AFT ages are not found in the Wet Mountains, the amount of vertical Laramide uplift and erosion was less compared to areas to the north, suggesting that lateral thrusting rather than vertical uplift dominated the style of early Laramide deformation in this area. The change in style of Laramide deformation between the Front Range (vertical uplift in the core, lateral thrusting on the margins) and the Wet Mountains (lateral thrusting only) roughly coincides with the northern extent of Yavapai-Mazatzal boundary zone. This change also corresponds with a marked transition in modern topography from a broad mountain range in the case of the Front Range to more segmented, narrower, and more rugged ranges in the southern Wet Mountains and northern Sangre de Cristo Mountains.

Table 2. Summary of rock-uplift and exhumation calculations for the Front Range and Sierra Nacimiento.

Area	PAZ Elevation (m)	Rock Uplift (km)	Exhumation (km)
Centennial Cone	>2645	6.6	4.3
Waterton Canyon (mouth)	1762	5.8	3.5
Waterton Canyon (W of Floyd Hill fault)	1900	5.9	3.6
Mount Evans	3500	7.5	5.2
Bailey	2400	6.4	4.1
Pikes Peak	2600	6.6	4.3
	2000	6.0	3.7
Northern Nacimiento Mtns.	2500	6.5	4.1

AFT ages in the southern Wet Mountains vary from about 230 Ma for Proterozoic rocks collected a short distance below the summit of Greenhorn Mountain to approximately 30 Ma at the lowest elevation. The shape of the age-elevation profile for the southern Wet Mountains is representative of a rotated pre-Laramide PAZ and the top portion of an uplifted post-Laramide PAZ (Fig. 7). Only two examples of post-Laramide PAZs have been found in Colorado and New Mexico, one in the southern Wet Mountains and one at high elevation in the Magdalena Mountains near Socorro, New Mexico. The geometry of the age-elevation profile implies that Miocene uplift and erosion in the southern Wet Mountains began about 30 ± 5 Ma, which is contemporaneous with the development of the Rio Grande rift. Rift development has caused northward tilting of the Wet Mountains, as indicated by the higher elevation of the Rocky Mountain erosion surface at the south end of the range compared to the northern part of the mountain block. Furthermore, the Rocky Mountain erosion surface is more highly dissected at the southern end of the range (Fig. 7) Thus, systematic changes in both the fission-track data and the topography across the Wet Mountain region seem to coincide with the transition across the northern edge of the Yavapai-Mazatzal boundary.

Taos Range–Sangre de Cristo Mountains

AFT ages of 18.5 ± 3.4 Ma to 34.2 ± 5.9 Ma from Proterozoic rocks and early Miocene intrusives in the vicinity of Wheeler Peak (Fig. 9) reflect cooling of this part of the Taos Range during the early phases of Rio Grande rift deformation following the emplacement of the Lucero pluton (LP, Fig. 9) at about 18 Ma (Kelley, 1990). Late Miocene exhumation of the southwest margin of the Costilla Mountain block in the northern part of the Taos Range is indicated by 6.5- to 13.8-Ma AFT ages (Fig. 9). In general, the AFT ages increase from west to east away from the rift toward the center of the range (Fig. 9) and with increasing elevation (Fig. 10). An exception to this trend occurs in the vicinity of Comanche Creek (Fig. 9), where 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. 9 and 10). A down-to-the-west normal fault mapped by Lipman and Reed (1989) lies between the sample localities. These results, along with AFT ages determined for sedimentary rocks in the Raton Basin to the east (Kelley and Chapin, 1995), suggest that in this area the east side of the range has been brought up with respect to the center of the range during extension.

In contrast to the other mountain ranges examined in this study, no AFT ages >60 Ma or evidence of an uplifted PAZ have been found in the Taos Range. The oldest AFT age is 48 ± 4 Ma in a downdropped fault block on the east side of the Costilla Mountains. Although Laramide-age structures are preserved in this range (southeastern corner of Fig. 9), the more recent exhumation history and topographic development of this area are dominated by rift-related tectonism. Lack of a PAZ and a temporally variable geothermal gradient associated with the Questa caldera makes it difficult to determine reasonable rates of exhumation in the Taos range. The cooling rates between 60-120° derived from the data for most samples are 5–10 °C/Ma. Assuming a gradient of 35 °C/km, typical of rift gradients, and that cooling is exhumation-related only, we estimate exhumation rates between 0.14–0.28 km/m.y. during the middle to late Miocene.

The AFT ages along the Southern Rocky Mountain–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 Sangre De Cristo Mountains near Las Vegas, New Mexico (Kelley and Chapin, 1995). In addition, the amount of volcanism along the boundary between the provinces increases toward the south. Oligocene to Miocene AFT ages in the mountain blocks on the east side of the Rio Grande rift and on the High Plains may be attributed to exhumation of at least 2 km of Mesozoic to early Cenozoic sedimentary rocks during a period of elevated heat flow as the Rio Grande rift began to form. Other lines of evidence supporting a minimum of 2 km of exhumation along the east side of the Sangre de Cristo Mountains in the middle Cenozoic include the profound unconformity between the late middle Miocene to late Miocene Ogallala Formation and Cretaceous to Permian rocks in eastern New Mexico, the exposure of early Miocene to Oligocene plutons (e.g., Spanish Peaks and Capitan) with a modern relief of 1 km above the surrounding plains, and elevated vitrinite reflectance values on the Great Plains (Broadhead and King, 1988; Close and Dutcher, 1990; Barker and Pawlewicz, 1989). Consequently, differential uplift along the Southern Rocky Mountain–Great Plains boundary in the late Oligocene to early Miocene appears to have been accommodated across the broad Yavapai–Mazatzal Proterozoic transition zone.

Sierra Nacimiento

Sierra Nacimiento (Fig. 11) is made up of at least two uplifted Proterozoic blocks with different topographic signatures and cooling histories. The northern section is wider in the E–W direction and coincides with San Pedro Parks, where late Oligocene to early Miocene Abiquiu Formation rests on a well-developed, east-dipping erosion surface that bevels Proterozoic to Paleozoic rocks currently

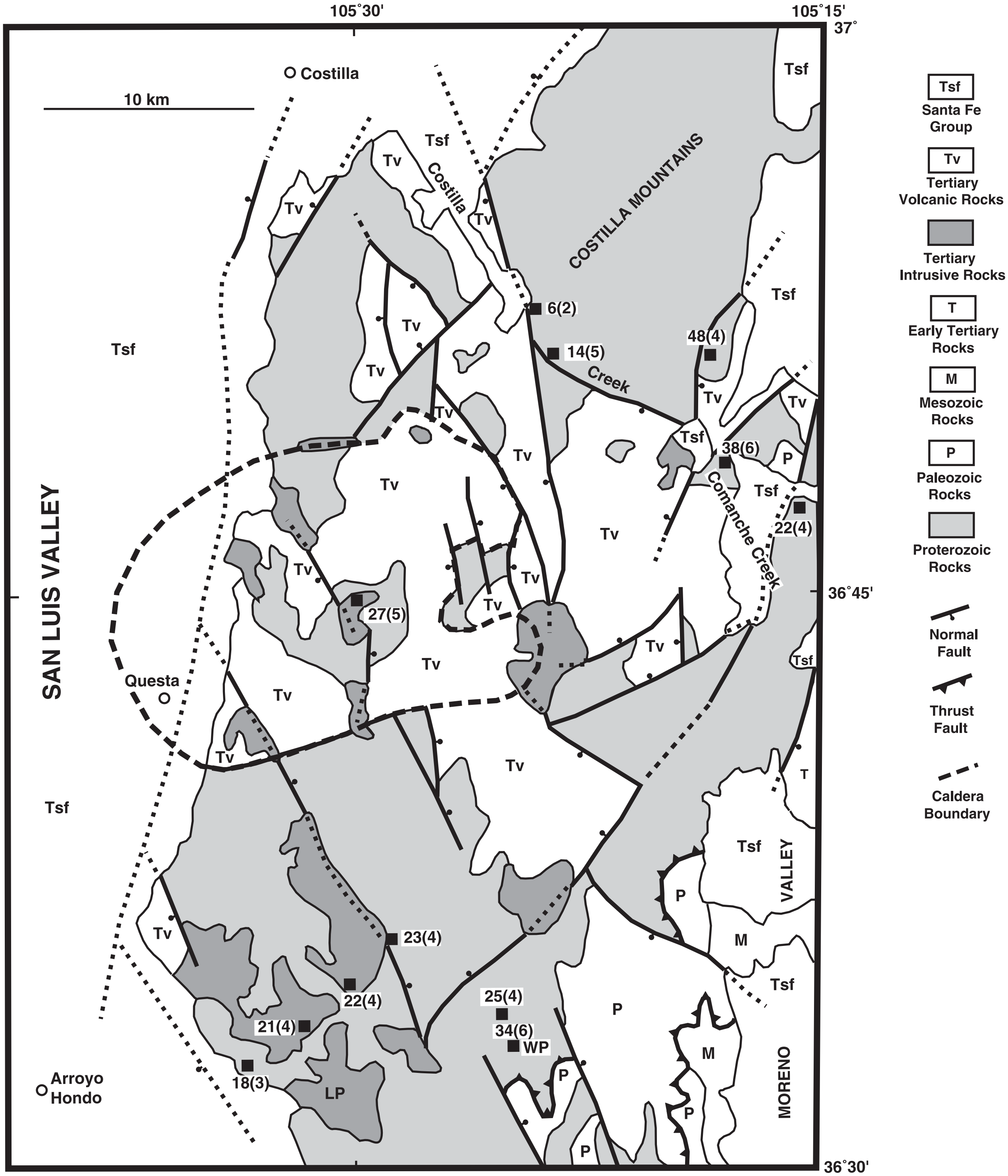


Figure 9. Simplified geologic map of Taos Range (after Lipman and Reed, 1989). WP = Wheeler Peak; LP = Lucero pluton. AFT age and standard error of the age are shown adjacent to sample localities (solid squares).

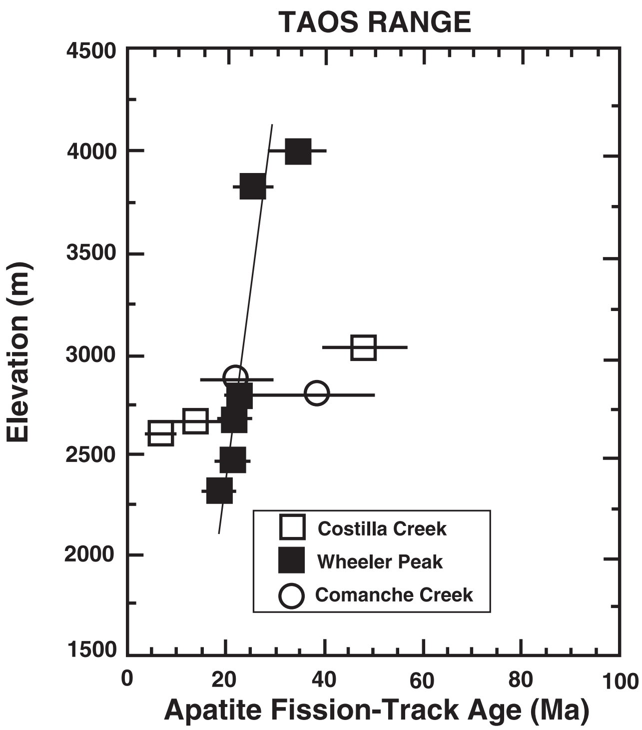


Figure 10. AFT age versus elevation plot for the Taos Range. Line is a least squares regression.

at elevations as high as 3300 m (10,800 ft) above sea level. AFT track length and age data on the south side of San Pedro parks in the vicinity of Nacimiento Peak (NP, Fig. 11) define the base of a fossil partial annealing zone (Fig. 12). The highest elevation samples on the traverse are within the PAZ, while the lowest elevation sample, based on its track length distribution (Fig. 12), is below the base of the PAZ. Since this area was near sea level at the time that the Cretaceous Pictured Cliffs Sandstone was deposited during the final retreat of the sea from this area at 76 Ma (Fassett and Obradovich, 1996), we can use assumptions similar to those discussed for the Front Range to estimate the amount of isostatic and tectonic rock uplift since the beginning of Laramide deformation.

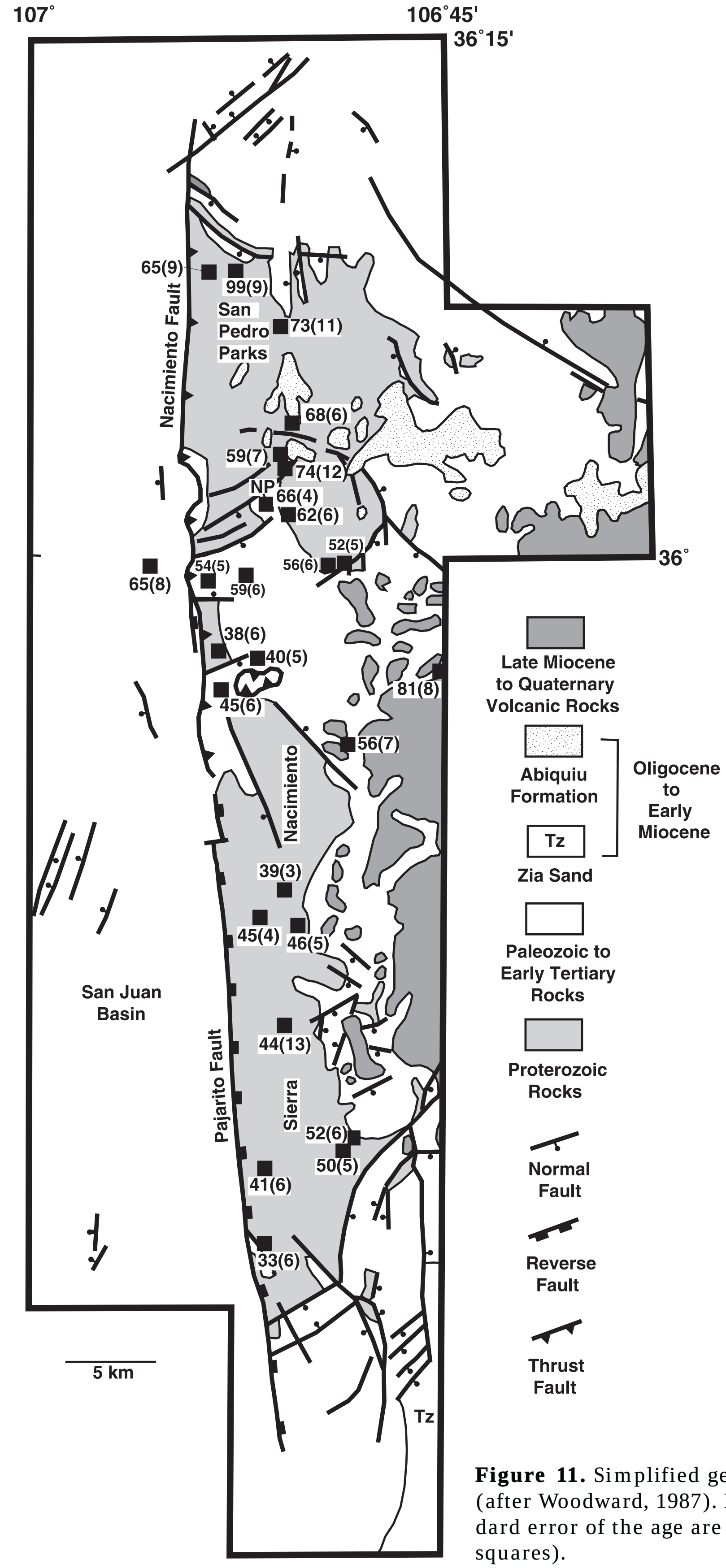
Surface uplift is about 2.1 km, rock uplift is 6.5 km, and total exhumation is approximately 4.1 km; these values are similar to those derived from the strongly uplifted core of the Front Range. Approximately 3.3 km of rock uplift could be attributed to isostatic processes. The remainder, or 3.2 km of rock uplift, is presumably of tectonic origin. The Nacimiento fault, which forms the western boundary of the northern block, is primarily a high angle structure with a component of lateral displacement (Woodward, 1987). The sedimentary record in the adjacent San Juan basin indicates relatively minor deformation in the vicinity of Sierra Nacimiento in Late Cretaceous to early Paleocene time. Evidence for significant uplift and erosion of the Nacimiento block is first evident in the Eocene San Jose Formation (Baltz, 1967). The AFT data indicate exhumation and cooling of Sierra Nacimiento began in the early Eocene, consistent with the development of a pronounced unconformity at the base of the San Jose Formation. The presence of the Abiquiu Formation (~28 Ma, Ingersoll et al., 1990) on the erosion surface in San Pedro Parks, which may be a southern correlative with the Rocky Mountain erosion surface, can be used to infer that most of the exhumation in this part of Sierra Nacimiento occurred prior to late Oligocene. Thus the exhumation rate between early Eocene and late Oligocene is approximately 0.12 to 0.15 km/m.y., again rates that are similar to those determined for the Front Range.

The southern margin of the boundary between the Yavapai and Mazatzal provinces corresponds to the southern extent of pre-1.7-Ga Yavapai rocks (Karlstrom and Humphreys, this issue). This margin generally coincides with the Jemez lineament, which marks the boundary between San Pedro Parks to the north and the southern Sierra Nacimiento. The southern Sierra Nacimiento is narrower in the east–west direction than the range to the north, the erosion surface is not preserved, and it is bounded on the southeast side by faults associated with the Rio Grande rift (Formento-Trigilio and Pazzaglia, *in press*; Fig. 11). This pattern is analogous, on a smaller scale, to the trends observed across the Front Range-Wet Mountain-Taos Range transition to the north. The AFT ages in the southern Sierra Nacimiento are 33 ± 4 to 46 ± 5 Ma and the mean track lengths are 13.0 to 13.8 mm. The base of the pre-Laramide PAZ is not present in the southern part of the range (Fig. 12). The absence of the erosion surface and the PAZ , as well as the younger AFT ages in the southern Sierra Nacimiento, suggest that the amount of exhumation increases toward the south in the range, an observation consistent with high measured rates of Pliocene and Quaternary fluvial incision and exhumation (Formento-Trigilio and Pazzaglia, *in press*).

DISCUSSION

Introduction

Topographic and AFT data provide useful constraints on the response of the landscape to crust–mantle interactions across Proterozoic terrane



boundaries. AFT-determined rock exhumation and *ZR* ratios indicate differences in the style and amount of Laramide uplift between the southern Front Range and the Wet Mountains, suggesting that the northern edge of the Yavapai–Mazatzal boundary may have influenced Laramide deformation in this area. Similar trends are seen across the southern margin of the Yavapai–Mazatzal boundary along the Jemez lineament in the Sierra Nacimiento. The boundary itself marks a north–south transition in the rates of post-Laramide (late Oligocene to early Miocene) rock exhumation along the eastern margin of the Southern Rockies. These observations are consistent with differential crustal response across the Yavapai–Mazatzal boundary to the current underlying low-velocity, buoyant mantle (Figs. 1 and 3d).

Crust–Mantle Interactions in the Yavapai Province

The preservation of a pre-Laramide fossil PAZ on the south side of Pikes Peak (Fig. 7) in an area where the Wall Mountain Tuff is preserved provides a unique opportunity to explore the relationship between the time–temperature information contained in the AFT age and track length data, and the amount of exhumation that occurred during (1) two phases of Laramide deformation, (2) the formation of the Rocky Mountain erosion surface, and (3) late Cenozoic landscape development (Kelley and Chapin, 1997). A break-in-slope on the age–elevation profile occurs at a modern elevation of approxi-

Figure 11. Simplified geologic map of the Nacimiento Mountains (after Woodward, 1987). NP = Nacimiento Peak. AFT age and standard error of the age are shown adjacent to sample localities (solid squares).

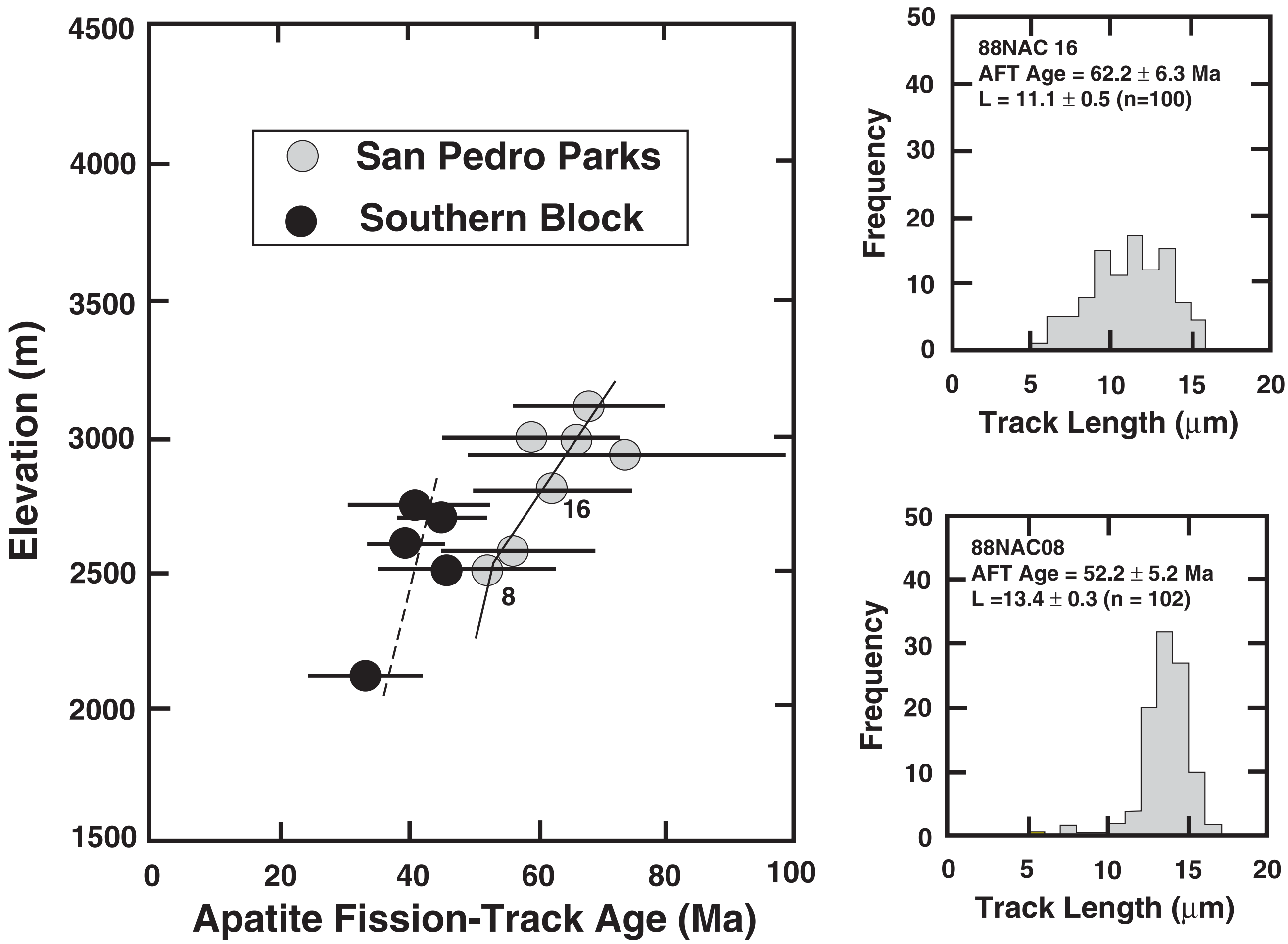


Figure 12. Age-elevation plot from Abo siltstone on Nacimiento Peak and Proterozoic rocks of Sierra Nacimiento. Track length distributions for highest elevation Proterozoic sample (88NAC16) and lowest elevation Proterozoic sample (88NAC08) in the vicinity of Nacimiento Peak are shown to the right and are keyed to the age-elevation plot. AFT age, standard error of age, mean track length, standard deviation of length, and number of confined tracks measured (in parentheses) shown on track length histogram for each sample. Solid line shows approximate location on the fossil PAZ; dashed line is the trend defined by samples below the PAZ in southern Sierra Nacimiento.

mately 2600 m. 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 is currently at an elevation of about 2900 m, only about 300 m above the inflection point on the age–elevation profile. The AFT data from the lower portion of the Phantom Canyon Road clearly show substantial cooling (exhumation) between 57 and 67 Ma; however, the mean track lengths of 12.1 to 12.8 mm and the broad unimodal track length distributions for these samples suggest that they did not cool rapidly through the PAZ.

The results can be used to infer that Pikes Peak area started cooling during the early phase of Laramide deformation. During this phase of deformation, we estimate from modeling the track length data (Corrigan, 1991; Kelley and Chapin, 1997) that the low-elevation rocks cooled from about 120 to 80-90 °C. This implies that the rocks moved from depths of 4 km to depths of 2.8 to 3.2 km (using a surface temperature of 10 °C after exhumation begins based on fossil leaf morphology; Gregory and Chase, 1994). Consequently, only 0.8 to 1.2 km of exhumation occurred in this area during the early phase of Laramide contraction (latest Cretaceous–early Paleocene), and the remaining 2.5 to 2.9 km of material has been removed since middle Paleocene time. This suggests that approximately 2.2 to 2.6 km of rock was removed during late Laramide deformation and the creation of the Rocky Mountain erosion surface. These events preceded the eruption of the Wall Mountain Tuff and the Cripple Creek lava flows, leaving only about 0.3 km of material to be stripped from this part of the Front Range in the Neogene and Quaternary. AFT data from the Waterton Canyon / North Fork South Platte River and Poudre River traverses indicate similar exhumation histories. AFT data from the Clear Creek area do not indicate the two-stage Laramide cooling history, but indicate instead rapid cooling starting early in the Laramide orogeny. The proximity of plutons of the Colorado Mineral belt appears to have affected the buoyancy of this part of the Front Range during Laramide deformation (e.g., Fig. 3c)

Recent seismic data (Sheehan et al., 1995) suggest no modern crustal root under the Colorado Rockies and crustal thinning beneath the Rio Grande rift. Consumption of a crustal root (presumably through erosion and crustal thinning) that likely formed during Laramide crustal thickening and the evolution of spectacular topographic relief in the western Front Range (e.g., Mt. Evans) appear to be relatively recent phenomena; otherwise, the PAZ and the Rocky Mountain erosion surface would not be preserved.

This complicated Laramide and post-Laramide exhumation history is further reflected in the geomorphology by a middle-range *ZR* ratio (Table 1); in essence, the topography of the Yavapai province has only a partial “memory” of Laramide deformation. The Yavapai province has experienced a broad, relatively slow epeirogenic uplift over tens of millions of years. This type of rock uplift has not favored dramatic, local base level falls and the concomitant regional drainage integration through the Rocky Mountain foreland. Central Colorado topographically resembles a plateau with locally deep valleys carved by both fluvial and glacial processes. In fact, we might expect the *ZR* ratio to be even higher, more similar to the Laramie Range, if both the high latitude and high mean elevation of the Front Range did not favor the development and maintenance of glaciers in the Pleistocene and the subsequent high local valley relief.

Crust–Mantle Interactions Along the Jemez Lineament

Topography and rock exhumation histories along the Jemez lineament illustrate spatial and temporal variations in the interactions between this complicated crustal suture and the underlying low-velocity, buoyant mantle. The Taos Range shows the most rugged topography and greatest degree of post-Laramide rock exhumation of our study areas (Table 1). These aspects are the results of crustal extension and high heat flow associated with the Rio Grande rift and Miocene volcanism at the Questa caldera (Fig. 5) and at least 500 m of Pliocene and Quaternary rift flank uplift (Menges, 1990). Unlike the Front Range, the Taos Range retains little evidence of the Laramide orogeny. Drainages are well integrated across rift-flank uplifts such as the Taos Range, which tend to be relatively narrow in Mazatzal province. The narrow character of these Mazatzal ranges stands in contrast to the relatively wide uplifts of the Yavapai province. The combination of recent, rapid uplift and a well-integrated drainage is manifest topographically in the steep slopes and lowest *ZR* ratio (Table 1).

Sierra Nacimiento exhibits aspects of both the Taos Range and the Front Range. Like the Taos Range, it is located in the Mazatzal province (straddling the Jemez lineament), it is directly associated with rift tectonism (Formento-Trigilio and Pazzaglia, *in press*) and high heat flow associated with the Jemez volcanic field, and it is a relatively narrow uplift (Fig. 5). In these respects, Sierra Nacimiento has a specific geomorphic expression, including a distinct, linear mountain front, more typical of post-Laramide rock uplift such as observed in the Taos Range. However, a flat range crest, the highest measured *ZR* ratio, and rock exhumation data (Table 1) suggest that the north end of the Nacimiento block probably shares characteristics more in common with the Front Range or the Laramie Range. In fact, the northern Sierra Nacimiento has a relatively high *ZR* ratio; in effect, its topography retains a strong “memory” of Laramide rock uplift.

In contrast, the southern portion of Sierra Nacimiento has been exhumed by accelerating rates of Pleistocene fluvial incision approaching 0.2 km / Ma (Formento-Trigilio and Pazzaglia, *in press*) and lacks a partial annealing zone. Not surprisingly, the southern Sierra Nacimiento lies astride the Jemez lineament and has experienced a greater degree of post-Laramide rock uplift than the northern Sierra Nacimiento. Where this post-Laramide rock uplift along the Jemez lineament has been active for tens of millions of years, such as across the Rio Grande rift (Taos Range), both the fission-track data and topography have little “memory” of Laramide deformation. Where the post-Laramide rock uplift has been active for less than two million years, that is, the southern Sierra Nacimiento, drainages have not had sufficient time to adjust to the abrupt falls in local base level and portions of the range still retain some “memory” of the Laramide landscape. *ZR* ratios for the southern Sierra Nacimiento are very similar to those observed for the Front Range. We would expect that with time and continued rock uplift along the Jemez lineament, topography in the southern Sierra Nacimiento would deviate from Front Range Yavapai-like character and begin to more closely mimic the topography characteristic of the narrow ranges in the Mazatzal province such as the Taos Range.

CONCLUSIONS

In very general terms, the low-velocity, buoyant mantle beneath the Southern Rocky Mountains (Fig. 1) appears to have driven spatially and temporally variable rates of post-Laramide rock (crustal) uplift across and along proposed Proterozoic crustal sutures (Fig. 13; Karlstrom and Humphreys, this issue). Youthful topography with little evidence of the Laramide orogeny (low *ZR* ratios) and relatively large amount of rock exhumation where a PAZ is not preserved are favored by Neogene rock uplift, a narrow uplifted range geometry, and a regionally well-integrated fluvial system. These conditions are most often met in the Mazatzal province. Old topography with a “memory” of the Laramide orogeny (high *ZR* ratios) and a relatively small amount of rock exhumation where a PAZ is preserved are favored by little post-Laramide rock uplift or rock uplift restricted to the Quaternary, wide, block-uplifted ranges, and a regional poorly-integrated fluvial system. These conditions are most often met in the Yavapai and Wyoming provinces. Locally along a proposed crustal suture, such as the Jemez lineament, a given Laramide range will show a spatially and temporally complex response of post-Laramide crustal uplift. Insofar that the Jemez lineament is a known zone of high heat flow, we propose that it can be used as a useful space for time substitution analogue to understand the broader effects that a low-velocity, buoyant mantle has on the entire Southern Rockies.

Although our combined fission-track and geomorphic data sets are currently rather limited, intriguing patterns have emerged regarding the style and amount of fluvial dissection along the eastern margin of the Southern Rockies in the vicinity of the proposed Proterozoic crustal boundaries. The Front Range preserves essentially only a Laramide exhumation history. AFT data from the eastern margin of the Front Range do not record the development of significant differential uplift between the High Plains and the Front Range during late Cenozoic time (Kelley and Chapin, 1995). One model that accounts for both the geologic and AFT evidence involves uplift of the Front Range during Laramide deformation, burial of its eastern margin and adjacent High Plains by as much as 1 km of early to middle Cenozoic sediments derived from the uplifted range, and the development of the Rocky Mountain erosion surface both on the Front Range and the High Plains in late Eocene time (Gregory and Chase, 1994; Leonard and Langford, 1994). Portions of the erosion surface were subsequently covered by the Wall Mountain Tuff and other volcanic rocks, resulting in local preservation of the surface. The sedimentary apron adjacent to the Front Range was deeply dissected during subsequent regional climatic changes, drainage integration, and/or regional uplift of the western U.S. in the late Cenozoic.

To the south, within the northern border zone between Proterozoic provinces, the Wet Mountains preserve both Laramide and rift-related cooling histories and the style of Laramide deformation is different than that observed in the Front Range. Topographically, the mountain ranges are narrower south of the transition, the erosion surfaces become increasingly dissected toward the south, and the *ZR* ratio decreases, perhaps reflecting collapse of a once broader uplift by rifting. Similarly, across the Jemez lineament, the northern Sierra Nacimiento preserves a record of primarily Laramide uplift and erosion, while both the topography and the cooling histories of the southern Sierra Nacimiento have been influenced by rift-related tectonism and late Cenozoic volcanism in the Jemez Mountains. The topography and the cooling histories in the Taos Range, which lies astride the Jemez lineament, and forms part of a rift-flank uplift, have clearly been overprinted by late Cenozoic rock uplift. These observed patterns lead us to speculate that the Proterozoic boundaries, which likely separate crustal blocks with different inherited structures and rock types, have influenced Laramide, post-Laramide (late Oligocene–early Miocene), and Rio Grande rift (post-Miocene) rock uplift and exhumation of the Southern Rocky Mountains. Although our analysis does not prove that these boundaries are important in controlling the structural and topographic evolution of this region, our results do not preclude their influence.

Our conclusions represent a gross oversimplification of a complex system heavily dependent upon the interaction between topography, exhumation, and rock-uplift processes. Active tectonic settings such as Taiwan (Lundberg and Dorsey, 1990), New Zealand (Adams, 1985), and the Olympic Mountains (Brandon et al., 1997) have a much greater amount

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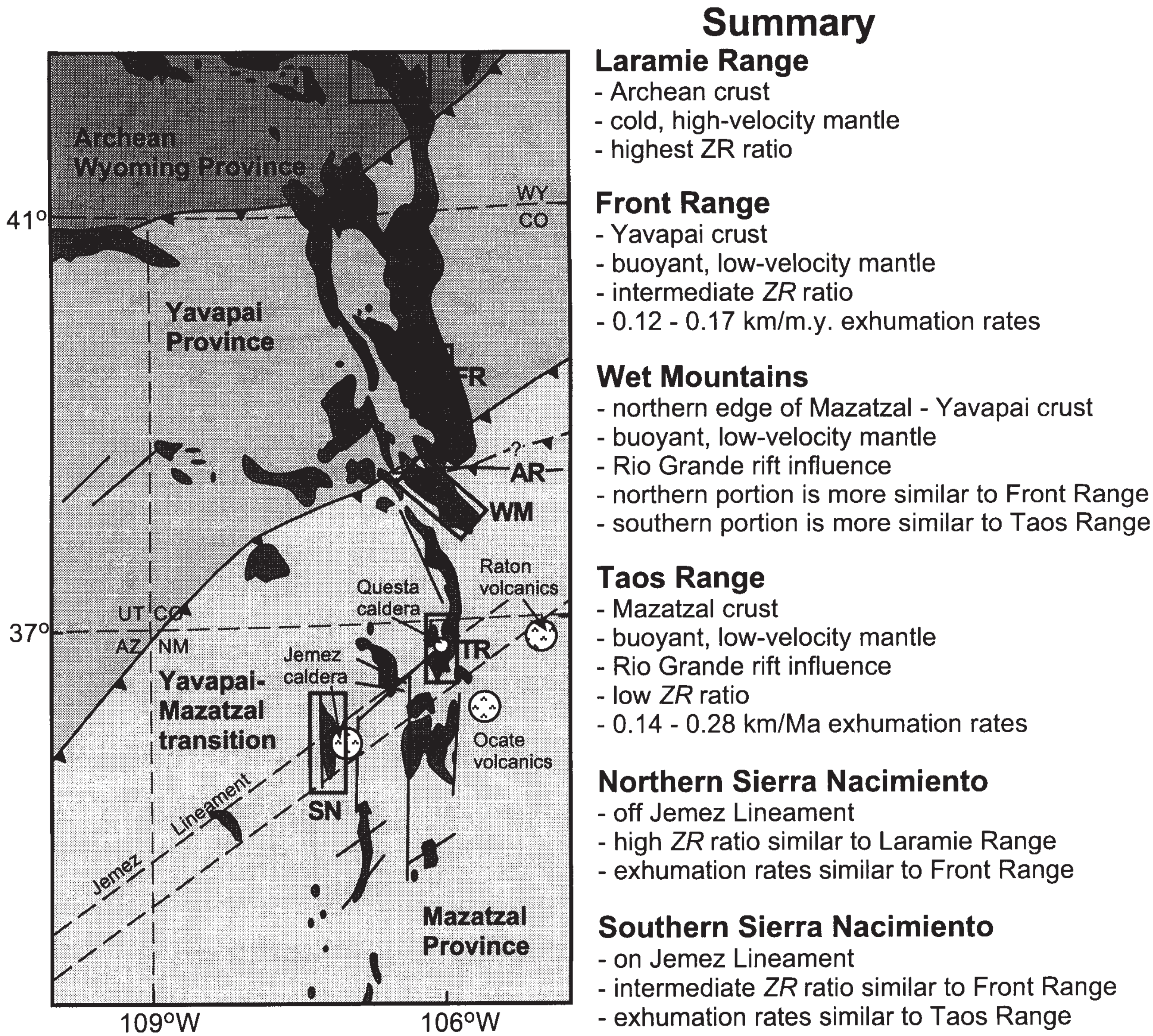

Figure 13. Summary of AFT ages and geomorphic evidence (*ZR* ratios) for selected ranges throughout the Southern Rocky Mountains in the context of major Precambrian crustal boundaries (Karlstrom and Bowring, 1993). Darkest shading represents outcrop of Proterozoic rocks. Location of studied ranges, Sierra Nacimiento (SN), Taos Range (TR), Front Range (FR), Wet Mountains (WM), and Laramie Range (LR) are outlined by the boxes. AR is the Arkansas River.

of rock uplift, and a much smaller component of isostatically driven rock uplift in comparison to the Southern Rocky Mountains. The very fact that the base of the PAZ is preserved attests to the relatively small degree of tectonic rock uplift during the Laramide and subsequent relatively large degree of post-Laramide isostatically or buoyant mantle-driven rock uplift. The poorly drained intracontinental setting represented by the Rocky Mountain foreland during the Laramide orogeny might explain the relatively small amount of exhumation. Seeing no effective way to remove mass by erosion and no compelling geologic evidence for regional extension, we conclude that Laramide deformation just stalled, resulting more in a plateau-like landscape than a jagged mountain belt.

Explaining the relatively large degree of post-Laramide uplift is more difficult. The geomorphic and AFT data (Fig. 2) cannot distinguish between true isostatically-driven rock uplift, that is rock uplift driven exclusively by the erosional removal of mass above a low-density crustal root (Fig. 3a), and an isostatic response to an underlying low-velocity buoyant mantle (Fig. 3d), essentially, an epeirogenic process. In this respect, what needs to be developed is a conceptual model that will allow for an inverse approach to deconvolve the topographic and AFT observations into their appropriate rock-uplift processes (Fig. 2).

In the future, we wish to better integrate our topographic analyses (the *ZR* ratio) with fission-track determined rock-exhumation histories. We envision a suite of unitless indices that consider both topographic and exhumation characteristics, normalized to rock type and drainage basin area, to be a far better indicator of the interaction between Proterozoic crustal terranes and a dynamic mantle. A more complete suite of AFT ages must be collected across the Southern Rockies, including uplifts in the Wyoming craton and the Cheyenne belt, and from drill holes in the adjacent High Plains. A most serious limitation in our current understanding of the problem is the relative importance that continental-scale changes in hydrology (climate) play in determining topographic form and long-term rates of exhumation. Clearly there are feedbacks between mean elevation and precipitation that we have not constrained. At present we will simply have to assume that continental-scale changes in climate and hydrology play a subordinate, or at least dependent, role to the changing rates of rock uplift.

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REFERENCES CITED

Abrahams, A., 1984, Channel networks, a geomorphological perspective: Water Resources Research, v. 20, p. 161-188.

Adams, J., 1985, Large scale tectonic geomorphology of the southern Alps, New Zealand, *in* Morisawa, M., and Hack, J. T., eds., Tectonic geomorphology: Boston, Allen and Unwin, p. 105-128.

Ahnert, F., 1970, Functional relationship between denudation, relief, and uplift in large mid-latitude drainage basins: American Journal of Science, v. 268, p. 243-263.

Allmendinger, R. W., 1986, Tectonic development, southeastern border of the Puna Plateau, northwestern Argentine Andes: Geological Society of America Bulletin, v. 97, p. 1070-1082.

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of the Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geological Survey Professional Paper 552, 101 p.

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.

Barron, E. J., 1989, Severe storms during Earth history: Geological Society of America Bulletin, v. 101, p. 601-612.

Beaumont, C., Fullsack, P., and Hamilton, J., 1992, Erosional control of active compressional orogens, *in* McClay, K. R., ed., Thrust tectonics: New York, Chapman Hall, p. 1-18.

Brandon, M. T., Roden-Tice, M. K., and Garver, J. I., 1998, Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State: Geological Society of America Bulletin, v. 110 (*in press*).

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

Bull, W. B., and McFadden, L. D., 1977, Tectonic geomorphology north and south of the Garlock fault, California, *in* Doehring, D. O., ed., Geomorphology in arid regions: Proceedings of the 8th Annual Geomorphology Symposium, State University of New York, Publications in Geomorphology, p. 115-138.

Burbank, D. W., Leland, J., Fielding, E., Anderson, R. S., Brozovic, N., Reid, M. R., and Duncan, C., 1996, Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas: Nature, v. 379, p. 505-510.

Cerveny, P. F., 1990, Fission-track thermochronology of the Wind River Range and other basement cored uplifts in the Rocky Mountain foreland [Ph.D. dissert.]: Laramie, University of Wyoming, 189 p.

Chapin, C. E., and Cather, S. M., 1983, Eocene tectonics and sedimentation in the Colorado Plateau-Rocky Mountain area, *in* Lowell, J. D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, p. 33-56.

___ 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G. R. and Cather, S. M. eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 5-23.

Chapin, C. E., and Kelley, S. A., 1997, The Rocky Mountain erosion surface in the Front Range of Colorado, *in* Bolyard, D. W., and Sonnenberg, S. A., eds., Geologic history of the Colorado Front Range: Denver, Colorado, Rocky Mountain Association of Geologists Symposium Guidebook, p. 101-114.

Close, J. C., and Dutcher, R. R., 1990, Update on coalbed methane potential of Raton Basin, Colorado: Society of Petroleum Engineers Paper 20667, p. 497-512.

Coleman, S. M., 1985, Map showing tectonic features of late Cenozoic origin in Colorado, U.S. Geological Survey Miscellaneous Investigations Series Map I-1566, scale 1:1,000,000.

Corrigan, J. D., 1991, Deriving thermal history information from apatite fission-track data: Journal of Geophysical Research, v. 96, p. 10,347-10,360.

Davis, W. M., 1911, The Colorado Front Range, a study on physiographic presentation: Annals of the Association of American Geographers, v. 1, p. 21-83.

Elias, M. K., 1942, Tertiary prairie grasses and other herbs from the High Plains: Geological Society of America Special Paper 41, 176 p.

England, P., and Molnar, P., 1990, Surface uplift, uplift of rocks, and exhumation of rocks: Geology, v. 18, p. 1173-1177.

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, *in* Curtis, B. F., ed., Cenozoic history of the Southern Rocky Mountains: Boulder, Colorado, Geological Society of America Memoir 144, p. 45-74.

Epis, R. C., Scott, G. R., Taylor, R. B., and Chapin, C. E., 1980, Summary of Cenozoic geomorphic volcanic and tectonic features of Central Colorado and adjoining areas, *in* Kent, H. C., and Porter, K. W., eds., Colorado Geology: Denver, Colorado, Rocky Mountain Association of Geologists, p. 135-156.

Fassett, J. E., and Obradovich, J. D., 1996, Subsidence/sedimentation rates as Campanian Pictured Cliffs Sandstone shoreline regressed across San Juan basin, New Mexico and Colorado based on five new $^{40}Ar/^{39}Ar$ ages spanning 2.5 m.y.: Geological Society of America Abstracts with Programs, v. 28, no. X?, p. 66.

Fitzgerald, P. G., Sorkhabi, R. B., Redfield, T. F., and Stump, E., 1995, Uplift and denudation of the central Alaska Range: a case study in the use of apatite fission-track thermochronology to determine absolute uplift parameters: Journal of Geophysical Research, v. 100, p. 20,175-20,191.

Formento-Trigilio, M. L., and Pazzaglia, F. J., 1998, Tectonic geomorphology of the Sierra Nacimiento, traditional and new techniques in assessing long-term landscape evolution in the Southern Rocky Mountains: Journal of Geology (*in press*).

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.

Gardner, T. W., and 11 others, 1987, Central America and the Caribbean, *in* Graf, W. L., ed., Geomorphic systems of North America, Centennial Special Volume 2: Boulder, Colorado, Geological Society of America, p. 343-402.

Gleadow, A. J. W., and Fitzgerald, P. G., 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.

Grand, S. P., 1994, Mantle shear structure beneath the Americas and surrounding oceans: Journal of Geophysical Research, v. 99, p. 11,591-11,621.

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., 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.

Gurnis, M., 1992, Long-term controls on eustatic and epeirogenic motions by mantle convection: GSA Today, v. 2, p. 141, 144-145, 156-157.

Hack, J. T., 1973, Stream-profile analysis and stream-gradient index: U.S. Geological Survey Journal of Research, v. 1, p. 421-429.

Harrison, C. G. A., 1994, Rates of continental erosion and mountain building: Geologische Rundschau, v. 83, p. 431-447.

Hay, W. W., Shaw, C. A., and Wold, C. N., 1989, Mass-balanced paleotopographic reconstructions: Geologische Rundschau, v. 78, p. 207-242.

Horton, R. E., 1945, Erosional development of streams and their drainage basins: Geological Society of America Bulletin, v. 56, p. 275-370.

Howard, A. D., Dietrich, W. E., and Seidl, M. A., 1994, Modeling fluvial erosion on regional to continental scales: Journal of Geophysical Research, v. 99, p. 13,971-13,986.

Humphreys, E. D., and Dueker, K. G., 1994a, Western U.S. upper mantle structure: Journal of Geophysical Research, v. 99, p. 9615-9634.

___ 1994b, Physical state of the western U.S. mantle: Journal of Geophysical Research, v. 99, p. 9635-9650.

Ingersoll, R. V., Cavazza, W., Baldridge, W. S., and Shafiqullah, M., 1990, Cenozoic sedimentation and paleotectonics of north-central New Mexico: Implications for initiation and evolution of the Rio Grande rift: Geological Society of America Bulletin, v. 102, p. 1280-1296.

Kamp, P. J. J., and Tippett, J. M., 1993, Dynamics of Pacific plate crust in the South Island (New Zealand) zone of oblique continent-continent convergence: Journal of Geophysical Research, v. 98, p. 16,105-16,118.

Karlstrom, K. E., and Bowring, S. A., 1993, Proterozoic orogenic history in Arizona, *in* Van Schmus, W. R., Bickford, M. E., and 23 others, eds., Transcontinental Proterozoic provinces, *in* Reed, J. C., and 6 others, eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 188-211.

Kelley, S. A., 1990, Late Mesozoic to Cenozoic cooling history of the Sangre de Cristo Mountains, Colorado and New Mexico: New Mexico Geological Society Guidebook 41, p. 123-132.

Kelley, S. A., and Chapin, C. E., 1995, Apatite fission-track thermochronology of Southern Rocky Mountain-Rio Grande rift—western High Plains provinces: New Mexico Geological Society Guidebook 46, p. 87-95.

___ 1997, Internal structure of the southern Front Range, Colorado, from an apatite fission-track thermochronology perspective, *in* Bolyard, D., and Sonnenberg, S.A., eds., Tectonic history of the Front Range: Denver, Colorado, Rocky Mountain Association of Geologists Symposium Guidebook, p. 19-30.

___ 1998, Denudational histories of the Front Range and Wet Mountains, Colorado, based on apatite fission-track thermochronology, *in* Evanoff, E., and Gregory, K., eds., Cenozoic history of Florissant area: Geological Society of America Special Paper (*in press*).

Leonard, A., and Frye, J. C., 1978, Paleontology of Ogallala Formation, northeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 161, 21 p.

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: The Mountain Geologist, v. 31, p. 45-52.

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.

Love, J. D., 1970, Cenozoic geology of the Granite Mountains area, central Wyoming: U.S. Geological Survey Professional Paper 495-C, 154 p.

Lundberg, N., and Dorsey, R., 1990, Rapid Quaternary emergence, uplift, and denudation of the Coastal Range, eastern Taiwan: Geology, v. 18, p., 638-641.

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.

Melton, M. A., 1958, Correlation structure of morphometric properties of drainage systems and their controlling agents: Journal of Geology, v. 66, p. 442-460.

Menges, C. M., 1990, Late Quaternary fault scarps, mountain-front landforms, and Pliocene-Quaternary segmentation on the range-bounding fault zone, Sangre de Cristo Mountains, New Mexico, *in* Krinitzsky, E. L., and Slemmons, D. B., eds., Neotectonics in earthquake evaluation: Boulder, Colorado, Geological Society of America, Reviews in Engineering Geology, v. 8, p. 131-156.

Merritts, D., and Vincent, K. R., 1989, Geomorphic response of coastal streams to low, intermediate and high rates of uplift, Mendocino triple junction region, northern California: Geological Society of America Bulletin, v. 101, p. 1373-1388.

Montgomery, D. R., and Dietrich, W. E., 1994, Landscape dissection and drainage area-slope thresholds, *in* Kirkby, J. I., ed., Process models and theoretical geomorphology: United Kingdom, John Chichester, p. 221-246.

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.

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.

Pazzaglia, F. J., and Brandon, M. T., 1996, Macrogeomorphic evolution of the post-Triassic Appalachian Mountains determined by deconvolution of the offshore basin sedimentary record: Basin Research, v. 8, p. 255-278.

Pinet, P., and Souriau, M., 1988, Continental erosion and large-scale relief: Tectonics, v. 7, p. 563-582.

Ritter, D. F., Kochel, R. C., and Miller, J. R., 1995, Process Geomorphology, 3rd Edition: Dubuque, Iowa, W. C. Brown, 539 p.

Ruxton, B. P., and McDougall, I., 1967, Denudation rates in northeast Papua from potassium-argon dating of lavas: American Journal of Science, v. 265, p. 545-561.

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.

Schumm, S. A., 1956, Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey: Geological Society of America Bulletin, v. 67, p. 597-646.

Schumm, S. A., and Rea, D. K., 1995, Sediment yield from disturbed earth systems: Geology, v. 23, p. 391-394.

Scott, G. R., 1975, Cenozoic surfaces and deposits in the Southern Rocky Mountains, *in* Curtis, B. F., ed., Cenozoic history of the Southern Rocky Mountains: Boulder, Colorado, Geological Society of America Memoir 144, p. 227-248.

Scott, G. R., 1989, Geologic and structure contour map of the Spinger 30' x 60' quadrangle, Colfax, Harding, Mora, and Union counties, New Mexico: U.S. Geological Survey Miscellaneous Investigations Map I-1705, scale 1:100,000.

Scott, G. R., and Pillmore, C. L., 1993, Geologic and structure-contour map of the Raton 30' x 60' quadrangle, Colfax and Union counties, New Mexico, and Las Animas County, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-2266, scale 1:100,000.

Selverstone, J., 1988, Evidence for east-west crustal extension in the eastern Alps: Implications for the unroofing history of the Tauern Window: Tectonics, v.7, p. 87-105.

Sheehan, A. F., Abers, G. A., Jones, C. H., and Lerner-Lam, A. L., 1995, Crustal thickness variations across the Colorado Rocky Mountains from teleseismic receiver functions: Journal of Geophysical Research, v. 100, p. 20,391-20,404.

Slingerland, R., Harbaugh, J. W., and Furlong, K. P., 1994, Simulating clastic sedimentary basins: Englewood Cliffs, New Jersey, Prentice Hall, 220 p.

Steckler, M. S., Watts, A. B., and Thorne, J. A., 1988, Subsidence and basin modeling at the U.S. Atlantic passive margin, *in* Sheridan, R. E., and Grow, J. A., eds., The Atlantic continental margin: U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. I-2, p. 399-416.

Steidtmann, J. R., Middleton, L. T., and Shuster, M. W., 1989, Post-Laramide (Oligocene) uplift in the Wind River Range, Wyoming: Geology, 17, 38-41.

Stephenson, R., 1984, Flexural models of continental lithosphere based on long-term erosional decay of topography: Geophysical Journal of the Royal Astronomical Society, v. 77, p. 385-413.

Stock, J. D., and Montgomery, D. R., 1996, Estimating paleorelief from detrital mineral age ranges: Basin Research, v. 8, p. 317-327.

Strahler, A. N., 1952, Hypsometric (area-altitude) analysis of erosional topography: Geological Society of America Bulletin, v. 63, p. 1117-1142.

Stroud, J. R., and McIntosh, W. C., 1996, The volcanic history and landscape evolution of the Raton-Clayton volcanic field, New Mexico: Geological Society of America Abstracts with Programs, v. 28, no. 6, p. A378.

Summerfield, M. A., 1991, Global geomorphology: Longman Scientific and Technical, co-published by John Wiley and Sons Inc., New York, 537 p.

Summerfield, M. A., and Hulton, N. J., 1994, Natural controls of fluvial denudation rates in major world drainage basins: Journal of Geophysical Research, v. 99, p. 13,871-13,883.

Tucker, G. E., and Slingerland, R. L., 1994, Erosional dynamics, flexural isostasy, and long-lived escarpments: A numerical modeling study: Journal of Geophysical Research, v. 99, p. 12,229 -12,243.

Weissel, J. K., Pratson, L. F., and Malinverno, A., 1994, The length-scaling properties of topography: Journal of Geophysical Research, v. 99, 13,997-14,012.

Willgoose, G., Bras, R. L., and Rodriguez-Iturbe, I., 1991, Results from a new model of river basin evolution: Earth Surface Processes and Landforms, v. 16, p. 237-254.

Woodward, L. A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 42, 84 p.

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