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Shari A. Kelley

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LATE MESOZOIC TO CENOZOIC COOLING HISTORY OF THE SANGRE DE CRISTO MOUNTAINS, COLORADO AND NEW MEXICO

SHARI A. KELLEY
Department of Geological Sciences, Southern Methodist University, Dallas, Texas 75275

Abstract—Apatite fission-track (FT) data collected in the Sangre de Cristo Mountains adjacent to the northern Rio Grande rift of New Mexico and Colorado indicate that rocks now exposed in the eastern margin of the rift cooled during uplift and erosion in a complex, three-dimensional pattern. The Santa Fe Range portion of the Sangre de Cristo Mountains cooled during the early stage of the Laramide orogenic event (Late Cretaceous–Eocene). At least three portions of the range, the high elevation samples at La Veta Pass, Trinchera Peak and Wheeler Peak, cooled during the late stage of the Laramide event (Eocene) and during the development of a regional late Eocene erosion surface. In contrast, Blanca Peak and the lower elevation samples at La Veta Pass, Trinchera Peak and Wheeler Peak cooled during early extension of the Rio Grande rift and waning of regional volcanism in the late Oligocene and early Miocene. Cooling rates increased from the early phase of the Laramide event (3–4°C/Ma followed by 1°C/Ma) to the late phase of the Laramide event (3–4°C/Ma) to early development of the Rio Grande rift (5–9°C/Ma). Blanca Peak, which is located at the intersection of three normal faults bounding the deep side of a half-graben (San Luis basin), has cooled very rapidly (9°C/Ma). Tectonic denudation on three sides has possibly allowed unusually rapid isostatic uplift.

INTRODUCTION

The Southern Rocky Mountains in Colorado and New Mexico have experienced a long and complex geologic history, culminating with the compressional Laramide orogenic event beginning in late Cretaceous (Maastrichtian) and extending to late Eocene. A widespread surface of low topographic relief was carved across much of the area in the latest Eocene, and major volcanism occurred in the Oligocene. The Rio Grande rift, the extensional feature that bisects the Southern Rocky Mountains, began to form about 30 Ma and developed during two phases of regional extension (Chapin and Seager, 1975; Morgan et al., 1986). The early (30–18 Ma) northeast-southwest oriented phase of extension is characterized by the development of broad, shallow basins, low amplitude topographic relief, localized areas of strong extension along low-angle normal faults and the emplacement of large volumes of basaltic andesite lavas and rhyolitic ash-flow-tuffs. The later phase of extension (primarily 10–4 Ma) is characterized by the development of deep half-grabens, high topographic relief, the formation of widely spaced, high-angle, normal faults and the emplacement of alkali-olivine and tholeiitic basalts.

The principal objectives of this paper are to: (1) present new apatite fission-track ages for rocks exposed in the Sangre de Cristo Mountains in Colorado along the eastern margin of the northern Rio Grande rift; (2) reexamine published FT ages from the Sangre de Cristo Mountains; and (3) use these data to constrain the cooling and tectonic histories of this mountain range during Laramide compression and the early phase of rift formation.

INTERPRETATION OF FISSION-TRACK DATA

Consider apatite in a rock that cools from high temperatures during uplift and erosion. Fission tracks in apatite are constantly being produced at a rate that is controlled by the spontaneous fission decay constant for ^{238}U and are annealed at a rate controlled by the temperature. As cooling begins, the fission-track annealing rate is greater than the production rate, and no tracks accumulate in the mineral. As cooling proceeds, apatite passes through a temperature range (75–125°C; Gleadow and Duddy, 1981) where partially annealed tracks are retained. Finally, at low temperatures, fission tracks that are produced are retained, and annealing is minor. The partially annealed and fully retained tracks are all used to calculate an apparent age. The fission-track method "dates" the cooling of a rock through the closure temperature of approximately 100°C; it should be noted that the method does not necessarily date a discrete cooling event, but an interval of time (Crowley, 1990). The length of this time interval is dependent on the cooling rate.

Denudation rates from apparent fission-track ages

A simple method of determining approximate timing and rates of cooling due to uplift and erosion is based on the measurement of apatite fission-track ages as a function of elevation in a mountain range. Since rocks at higher present-day elevations cooled before rocks at lower present-day elevations, the apparent ages at higher elevations will be older. The ages at high elevation can be used as a minimum estimate of the initiation of denudation, and the difference in ages at the higher and lower elevations can be used to calculate apparent denudation rates. The apparent denudation rate will equal the absolute denudation rate only when: (1) the 100°C isotherm is horizontal during denudation; (2) the distance between the surface and the 100°C isotherm remains constant as denudation occurs (i.e., constant geothermal gradient); and (3) uplift equals erosion (Parrish, 1983). These assumptions are not always met.

A better approach to determining the cooling history of a mountain block involves using track-length measurements in combination with the apparent ages. Green et al. (1989) describe how length and age data can be used to determine quantitatively the thermal history experienced by a sample. Figure 1 illustrates qualitatively the use of track-length analysis in interpreting complex thermal histories. For example, a mineral that has cooled, then experienced mild reheating, then cooled again (Fig. 1a) will have a "mixed" age that dates neither the heating nor the subsequent cooling event. The tracks in a mineral that has been subjected to a short thermal pulse are not completely erased, but are significantly shortened, resulting in a population of short tracks. As the mineral cools following the thermal pulse, long tracks are again retained; thus a histogram of track length would have a bimodal distribution (Fig. 1b).

In contrast, a sample with a simple cooling history (Fig. 1c) would have a unimodal histogram. If the sample experienced slow cooling (1–4°C/Ma), the track-length distribution is skewed toward longer tracks (Fig. 1d). If the sample has cooled rapidly (5–>10°C/Ma; Fig. 1e), the track-length distribution would be relatively symmetric about long tracks (Fig. 1f). Finally, if the sample cooled very slowly (1°C/Ma) (Fig. 1g), so that it remained in the zone of partial stability for a long time, the histogram would be broad and multimodal (Fig. 1h).

The cooling histories determined from fission-track analysis (e.g., Green et al., 1989) from a set of samples collected along a traverse up a mountain can be used to determine denudation rates, assuming reasonable estimates of geothermal gradient during denudation are available.

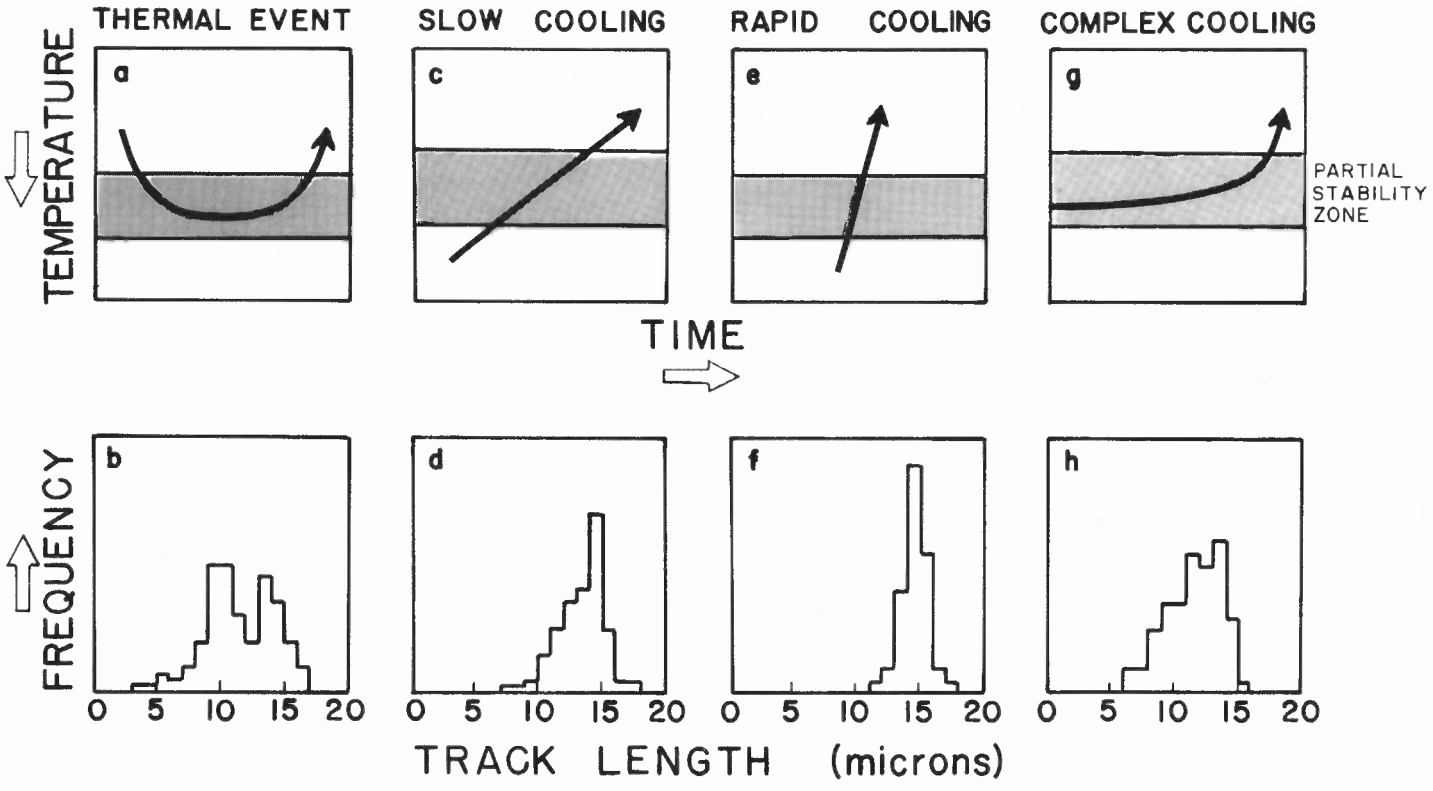


FIGURE 1. Hypothetical time-temperature curves and associated track-length distributions (after Gleadow et al., 1986).

PROCEDURES

Sixteen samples of Proterozoic crystalline rocks and Paleozoic sedimentary rocks were collected along three traverses through the Sangre de Cristo Mountains in Colorado (Fig. 2, profiles b, c and d; Fig. 3). The criteria used in locating the traverses included the occurrence of sufficient vertical relief and the presence of rock types containing adequate amounts of apatite for FT dating. Elevations of the samples were determined from U.S. Geological Survey 1:24,000 scale topographic maps to an estimated accuracy of ± 6 m.

Apatite was separated from the samples using standard heavy liquid (sodium polytungstate with a density of 2.95 gm/cm^3 and methylene iodide) and magnetic separation techniques. A total of 10 samples containing sufficient apatite were prepared for FT dating by the external detector method (EDM) (Naeser, 1979).

Apatite grains were mounted in an epoxy wafer, polished to expose the grains, and etched for 25 seconds in a 5 M solution of nitric acid to reveal the fission tracks. Twenty apatite grains were examined in each sample, where possible. The apatite grain mounts were then covered with muscovite detectors and sent to the Texas A&M Nuclear Science Center for irradiation. The neutron flux was calibrated with Fish Canyon and Durango age standards (accepted age of 27.9 $\pm$ 0.7 Ma for the Fish Canyon Tuff and 31.4 $\pm$ 0.5 for Durango apatite: Green, 1985) and Corning Glass CN-5.

Upon return from the reactor, each muscovite detector was removed from the grain mount and etched in 48% hydrofluoric acid for 13 minutes in order to reveal induced fission tracks. The muscovite detectors from the glass standards and the age standards were etched in hydrofluoric acid for 45 minutes and 13 minutes, respectively.

This paper also reports new track-length analyses from two traverses in the Sangre de Cristo Mountains in northern New Mexico (Fig. 2, profiles e and f). Earlier results from these traverses are presented in Kelley and Duncan (1986).

Calculation of FT ages and error statistics

Individual grain ages were calculated using the methods described by Naeser (1979) and Hurford and Green (1983). The Chi-squared statistic (Galbraith, 1981) is used to determine whether the individual ages belong to a single age population. Mixed ages caused by partial annealing, sediment provenance or sample contamination are indicated when the Chi-squared statistic does not pass at the 5% probability level.

If the individual grain ages pass the Chi-squared test, then a conventional age estimate using the sum of the spontaneous and induced counts for all the grains is calculated, and the errors in the age are computed using the methods of Galbraith and Laslett (1985). In this study all of the samples passed the Chi-squared test, and conventional ages are reported.

Fission-track length measurements

The track-length distribution in the apatite-grain mounts were measured using a microscope fitted with a 100$\times$ oil immersion lens, a drawing tube and a digitizing tablet. The system allows the track lengths to be measured to approximately ± 0.2 μm. Horizontal, well-etched, confined tracks (tracks completely enclosed within the crystal) were measured. Only grains with prismatic faces oriented parallel to the c-axis were examined.

Microprobe analyses

Green et al. (1986), upon examining apatites from sedimentary rocks, found that fission tracks in chlorine-rich apatite anneal more slowly than tracks in fluorapatite. Consequently, within a sample containing apatite from several sources, the older individual grain ages tend to be associated with grains of chlorine-rich apatite.

Apatites from many of the crystalline and sedimentary rocks from this study were analyzed using an electron microprobe. Two hypotheses are tested in this study. First, we want to determine if a correlation exists between mineral chemistry and individual grain age, particularly in the sedimentary rocks. Second, we want to determine if there is a correlation between the overall mineral chemistry of each sample and the conventional age for the sample in an attempt to identify chemical versus thermal controls on the ages of these geographically scattered samples.

The grains were analyzed with an electron beam accelerating voltage

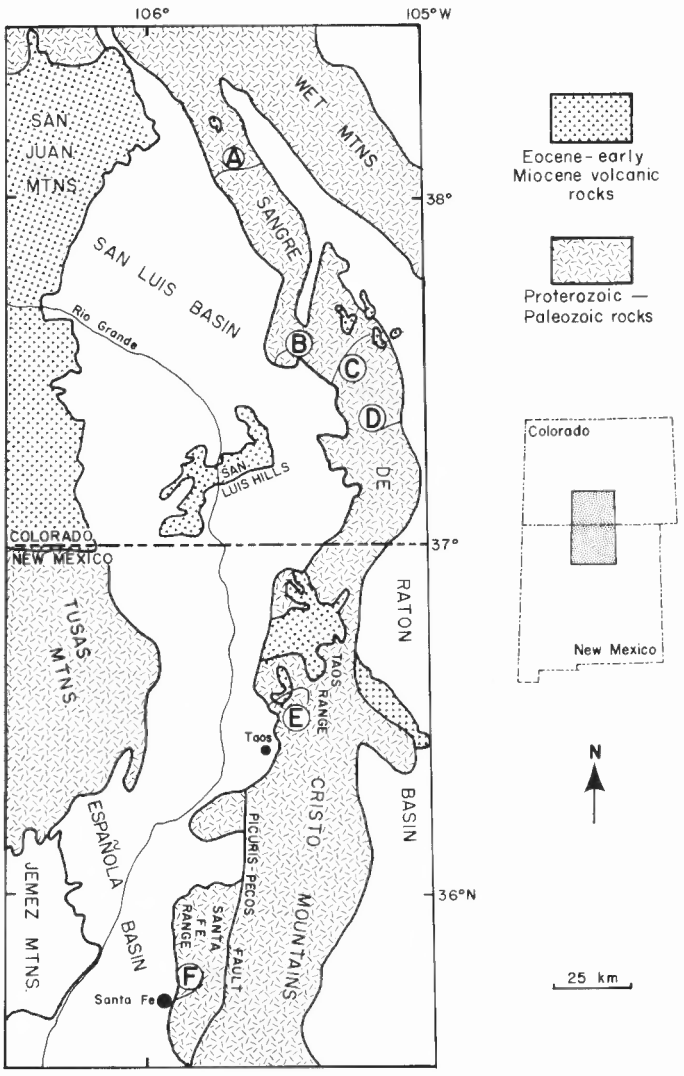


FIGURE 2. Location of FT dating traverses adjacent to the Rio Grande rift. A, northern Sangre de Cristo Mountains (Lindsey et al., 1986); B, Blanca Peak; C, La Veta Pass; D, Trinchera Peak; E, Taos Range–Wheeler Peak; F, Santa Fe Range.

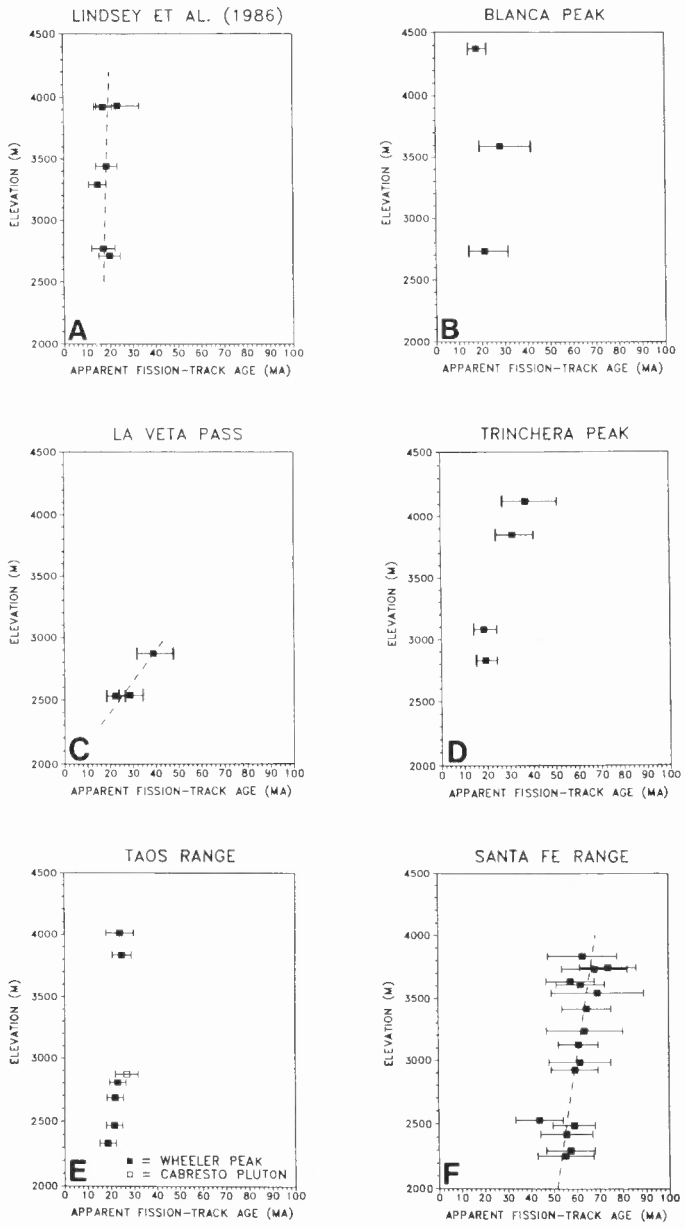


FIGURE 3. Age-versus-elevation plots for each area. A, Northern Sangre de Cristo Mountains (data from Lindsey et al., 1986). B, Blanca Peak. C, La Veta Pass. D, Trinchera Peak. E, Taos Range, Sangre de Cristo Mountains. F, Santa Fe Range, Sangre de Cristo Mountains.

of 15 kV and a beam current of 15 nA. Apatite (Durango) and scapolite (Smithsonian Std. R6600) were used to calibrate the fluorine and chlorine peaks, respectively. The dated grains were probed twice, once in the center and once on the rim, to identify zoning. The chlorine content of each grain is expressed as the number of Cl atoms per $Ca_{10}(PO_4)_6(F,OH,Cl)_2$ molecule. For reference, Durango apatite, which is considered a fluorapatite, has 0.12 Cl atoms/molecule.

Time-temperature estimates

Recently, the significance of the thermal history information contained in track-length distributions has been recognized, and the process of fission-track annealing in apatite has been empirically calibrated in the laboratory (Laslett et al., 1987; Duddy et al., 1988; Green, 1988; Green et al., 1989). Using the empirical laboratory results, Donelick (1988) has developed an inversion algorithm that utilizes the conventional age and track-length distribution of a sample to determine the time-temperature path recorded in apatite. The algorithm is based on the experimentally determined, track-length reduction equation of Laslett et al. (1987), the track length-density reduction curve of Green (1988) and the equivalent time concept of Duddy et al. (1988).

Three assumptions form the basis of this analysis. First, the chemical composition of the apatite should vary over a small range, and the apatite should have a composition near that of Durango apatite. The empirical annealing equation of Laslett et al. (1987) was calibrated using Durango apatite. Second, the shortest track is assumed to be the oldest track, which is a valid assumption for a sample with a simple cooling history, as discussed previously (see Fig. 1c–h). Samples with complex thermal histories cannot be evaluated with this model since a heating event will also form short tracks (see Fig. 1a, d). Finally, the empirical equation of Laslett et al. (1987) is assumed to describe the kinetics of the fission-track annealing process. The process of fission-track annealing is not completely understood, and alternative annealing equations have been proposed (K. C. Crowley, unpubl., 1989).

Consequently, given these three assumptions and the fact that the time-temperature paths determined from this method are non-unique, the derived thermal histories cannot be viewed as absolute cooling paths, but the results can be used to determine meaningful relative cooling rates. A major advantage of using this technique is that this is an

objective estimate that is free of any preconceived biases concerning the geologic history of the region under investigation (Donelick, 1988).

In this study, the algorithm of Donelick (1988) was used to estimate cooling curves for samples with more than 50 confined track-length measurements, with monocompositional apatite populations, and with ages passing the Chi-squared text.

The average rate of cooling in the temperature range of 120–60°C, which is the temperature range best constrained by track-length analysis, for each mountain block is presented in Table 1. Since the geothermal gradient has not remained constant during rift development, denudation rates cannot be calculated directly from these cooling rates. The thermal modeling required to determine denudation rates is beyond the scope of this paper; denudation rate calculations will be discussed elsewhere.

TABLE 1. Apatite-FT-age ranges and cooling rates between 120 and 60°C for Sangre de Cristo Mountains, Colorado and New Mexico.

Tectonic Event	Profile	AFTA range (Ma)	Cooling Rate (°C/Ma)
Early Laramide (late Cretaceous – Paleocene)	Santa Fe Range	44–74	1
Late Laramide (middle Eocene – late Eocene)	La Veta Pass (High elevation)	39	4
	Trinchera Peak (High elevation)	31–37	3
	Taos Range (Wheeler Peak)	34	4
Early Rift (middle Oligocene – middle Miocene)	Northern (Lindsey et al., 1986)	15–24	~4–5 *
	Blanca Peak	18–28	9
	La Veta Pass (Low elevation)	22–28	6
	Trinchera Peak (Low elevation)	19	5
	Taos Range (Low elevation)	23–25	6

* – estimated from age and elevation data using gradients of 30–35 °C/km

RESULTS

Each traverse shown in Figure 2 is considered in detail in the following sections. The new FT age data from the Sangre de Cristo Mountains of Colorado are summarized in Table 2, and the age-elevation data for each traverse are plotted in Figure 3. This figure shows that rocks now exposed in the eastern margin of the rift did not cool simultaneously due to uplift and erosion during the early phase of extension in the Rio Grande rift, but cooled in a complex, three-dimensional pattern.

Sangre de Cristo Mountains, Colorado

The Sangre de Cristo Mountains in Colorado are a long, narrow uplift composed primarily of Proterozoic metamorphic and igneous rocks and Paleozoic sedimentary rocks with minor Tertiary intrusives. Tweto (1979) notes that the Sangre de Cristo Mountains in this region are made up of two segments that join in the vicinity of Blanca Peak, where the range is cut by numerous faults.

The north-northwest-trending northern segment is bounded on both sides by Neogene faults. The Sangre de Cristo fault along the western side of this segment has been active during the Holocene (Knepper, 1976), whereas the Alvarado fault on the eastern side has had no Quaternary movement (Tweto, 1979).

The north-trending southern segment (Culebra Range) is bounded on the west by a complex zone of Neogene and Quaternary faults (Tweto, 1979). Some of the Quaternary faults have been active during the Holocene. Faults on the east side of the southern segment were active during the Laramide orogenic event (Cretaceous to Eocene) and were possibly active during the Neogene. No Quaternary movement has been identified along the eastern margin of the range.

Gries and Brister (1989) have determined the general Cenozoic history of the region through analysis of seismic and well data from the San Luis basin. Eocene sediments in the western part of the basin and along the west side of the Culebra Range indicate that portions of the San Luis basin were sites of deposition during the latter stages of the Laramide event. Beveling of the region occurred in the late Eocene.

TABLE 2. Apatite FT ages for Sangre de Cristo Mountains, Colorado.

SAMPLE NUMBER	LATITUDE LONGITUDE	ELEVATION (M)	LITHOLOGY	GRAINS COUNTED	FOSSIL TRACKS TRACKS/CM^2 (X 10^5)	FOSSIL TRACKS # TRACKS COUNTED	INDUCED TRACKS TRACKS/CM^2 (X 10^6)	INDUCED TRACKS # TRACKS COUNTED	NEUTRON FLUX (X 10^{15} NEUTRONS/CM^2)	AGE (STANDARD ERROR) (MA)	95% CONFIDENCE LIMITS (MA)	CHI-SQUARED PROBABILITY (%)	URANIUM CONTENT (PPM)
88SG06	37°17.34' 105°09.85'	4121	SANDSTONE	16	1.02	55	0.49	267	6.05	37.2 (5.9)	51.0 27.1	95.0	2.6
88SG07	37°17.87' 105°09.82'	3847	SANDSTONE	20	1.12	86	0.64	490	5.99	31.4 (4.1)	40.6 24.2	99.5	3.4
88SG08	37°19.10' 105°07.65'	3082	SILTSTONE	20	1.34	74	1.28	705	5.93	18.6 (2.5)	24.3 14.2	60.0	6.9
88SG09	37°19.92' 105°05.69'	2828	SILTSTONE	20	0.85	106	0.77	961	5.88	19.4 (2.3)	24.5 15.4	25.0	4.2
88SG10	37°36.82' 105°11.34'	2870	ARKOSE	20	2.67	163	1.19	728	5.82	38.9 (4.0)	47.7 31.6	90.0	6.6
88SG11	37°31.89' 105°17.69'	2536	SANDSTONE	20	2.50	220	1.51	1327	5.76	28.5 (2.6)	34.2 23.7	50.0	8.4
88SG12	37°29.67' 105°20.51'	2530	GNEISS	20	1.56	211	1.21	1634	5.70	22.0 (2.0)	26.4 18.3	25.0	6.8
88SG13	37°34.64' 105°29.11'	4373	METAGABBRO	20	1.00	117	0.94	1096	5.64	18.0 (2.0)	22.5 14.4	99.5	5.3
88SG14	37°34.12' 105°30.70'	3591	GNEISS	20	0.39	34	0.23	201	5.58	28.1 (5.4)	41.5 19.1	99.0	1.3
88SG16	37°33.06' 105°33.38'	2732	GRANITE	20	0.36	32	0.28	243	5.41	21.3 (4.2)	31.5 14.4	99.0	1.6

$\lambda_f = 7.03 \times 10^{-17}$/YR

Volcanic rocks, primarily from the San Juan volcanic field, then covered the beveled surface in the Oligocene. The San Luis basin formed as a half-graben tilted to the east, filling with Miocene-Pliocene Santa Fe Group derived from the rising Sangre de Cristo and San Juan Mountains. FT data from this area are of interest because little is known about details in the timing of the early phase of rift deformation in the two segments of the Sangre de Cristo Mountains.

Lindsey et al. (1986) used the distribution of low-grade metamorphic rocks, altered conodonts, and apatite FT ages from Pennsylvanian-Permian sedimentary rocks and Proterozoic gneissic rocks located in the northern segment of the Sangre de Cristo Mountains near Crestone (Fig. 2, profile A) to infer the thermal history of this segment of the range. Rocks in this part of the range were heated by burial beneath late Paleozoic and Mesozoic sedimentary rocks, by burial during Laramide thrusting and folding and locally by Oligocene intrusive activity. The heating events discussed by Lindsey et al. (1986) for the area around profile A on Figure 2 likely affected the Sangre de Cristo Mountains as a whole, although the relative importance of each of the heating mechanisms varies along the range. The area studied by Lindsey et al. (1986) subsequently cooled at approximately 19 Ma during early rift development (apatite FT ages of 15–24 Ma). Although no track-length analyses are presented by Lindsey et al. (1986), the uplift of this part of the range must have been rapid, because age is weakly correlated with elevation (Fig. 3a). The age and elevation data and reasonable estimates of geothermal gradient can be used to estimate that the rate of cooling is on the order of 4–5°C/Ma (Table 1).

The FT samples for this study were collected along three traverses between the profile of Lindsey et al. (1986) (Fig. 2a) and the profile from the Taos Range portion of the Sangre de Cristo Mountains (Kelley and Duncan, 1986; Fig. 2e). The three traverses are (from north to south) Blanca Peak, La Veta Pass and Trinchera Peak.

Blanca Peak

The apatite-FT ages on Proterozoic crystalline rocks exposed on Blanca Peak (Fig. 2b and Fig. 4, 88SG13, 14, 16) vary from 18 ± 4 Ma on the summit to 28 ± 10 and 21 ± 8 Ma at lower elevations

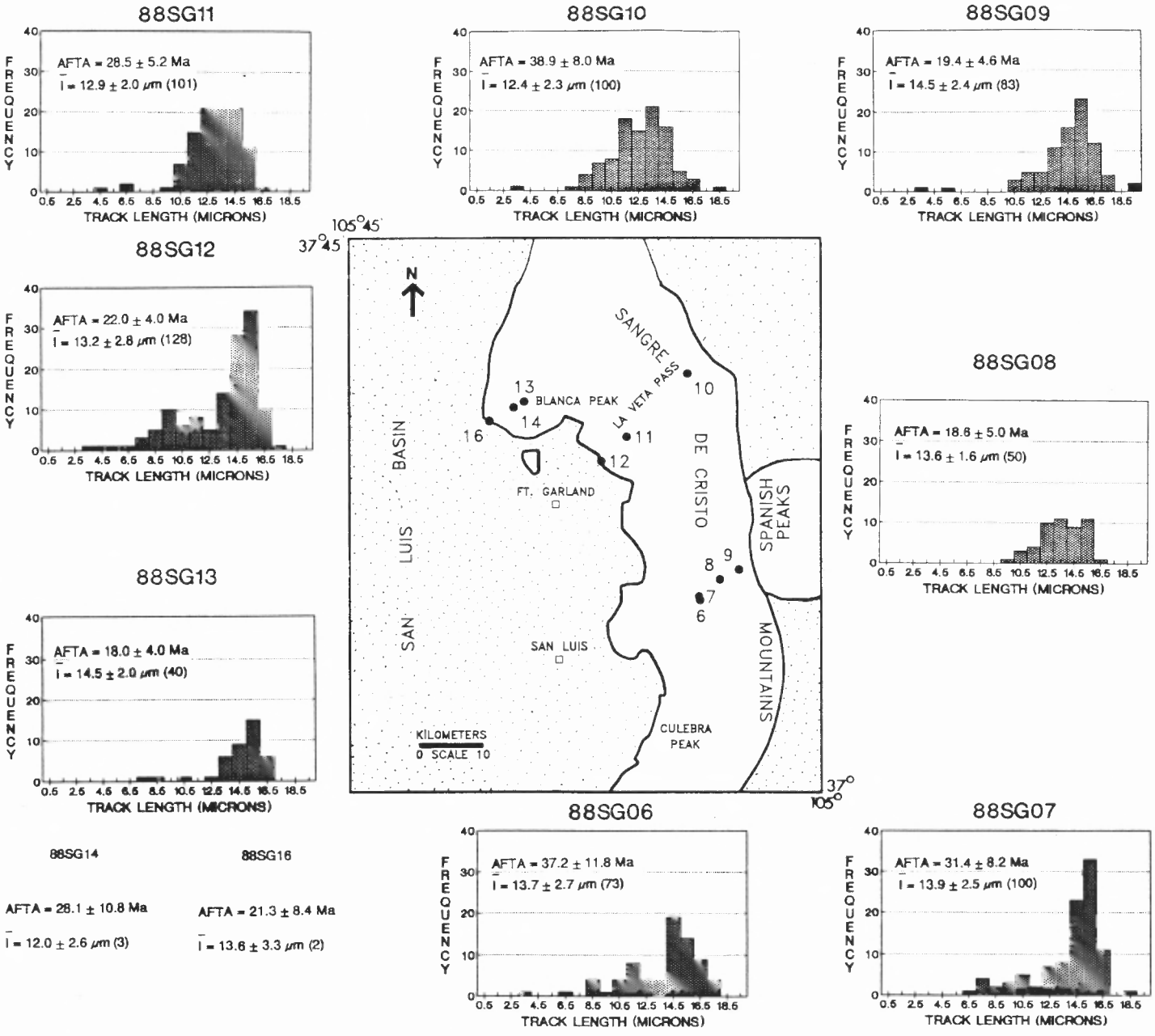


FIGURE 4. Sample localities, track-length histograms and apatite fission-track ages (AFTA) for the northern Sangre de Cristo Mountains, Colorado. The mean track length (Ī) and the number of confined tracks measured for each sample are also shown.

(Fig. 3b). The ages and track-length distributions for the low elevation samples are not well constrained due to low uranium concentrations in these apatites, which result in low track counts. The track-length data from the summit (Fig. 4) and the lack of correlation of age with elevation over such a large elevation change indicate that this portion of the Sangre de Cristo Mountains experienced rapid uplift (9°C/Ma; Table 1), similar to that observed by Lindsey et al. (1986) about 60 km to the north. This point is illustrated in Figure 5a (88SG13); this curve was derived from the FT age and length data for 88SG13 using the method of Donelick (1988).

Blanca Peak is a promontory projecting into the rift that is bounded on three sides by large normal faults. Tectonic unloading on three sides caused Blanca Peak to assume a roughly pyramidal shape. The broad base and the deficiency of mass at the apex has allowed Blanca Peak to rise isostatically at a rapid rate (Sales, 1978).

The age of the apatite from the metagabbro exposed at the summit is younger than the low-elevation samples from granitic rocks, which is opposite the expected trend. It should be pointed out that, if the error in the ages is considered, the reverse trend is not statistically significant. The age difference cannot be explained by differences in apatite chemistry. Based on microprobe analysis, all the apatite is fluorapatite; the chlorine content of the summit sample averages 0.11 Cl atoms/molecule and the granitic samples contain 0.02 Cl atoms/molecule. Complex faulting in the Blanca Peak area may be the cause of the observed age-elevation trend. This possibility is currently being investigated.

La Veta Pass

The samples from La Veta Pass (Fig. 2c and Fig. 4, 88SG10–12) yield FT ages of 39 ± 8 Ma for the Pennsylvanian-Permian Sangre de Cristo Formation at high elevation, 28 ± 5 Ma for the Pennsylvanian Minturn Formation at an intermediate elevation and 22 ± 4 Ma for a Proterozoic gneiss at low elevation (Fig. 3c). The mean track lengths for these samples are 12.4–12.9 μm with standard deviations of 2.0–3.0 μm. Apatite from all three samples at La Veta Pass is fluorapatite (0.01–0.06 Cl atoms/molecule). Modeling of the age and length data using the algorithm of Donelick (1988) indicates that this portion of the Sangre de Cristo Mountains cooled slowly (4°C/Ma; Table 1) until 20 Ma, when the range started to cool more rapidly (6°C/Ma; Table 1 and Fig. 5a). The samples at the top (88SG10) and bottom (88SG12) of La Veta Pass cooled at similar rates until about 20 Ma. At that time the cooling paths diverge, with the base cooling rapidly compared to the top. The geothermal gradient seems to have decreased around 20 Ma. This decline in gradient is probably related to the decrease in volcanic activity in southern Colorado (Steven, 1975; Lipman, 1981) during the mid-Miocene.

Trinchera Peak

Sandstones from the Pennsylvanian to Permian Sangre de Cristo and Minturn Formations exposed on the east side of the range in the vicinity of Trinchera Peak (Fig. 2d and Fig. 4, 88SG06–09) produced ages of

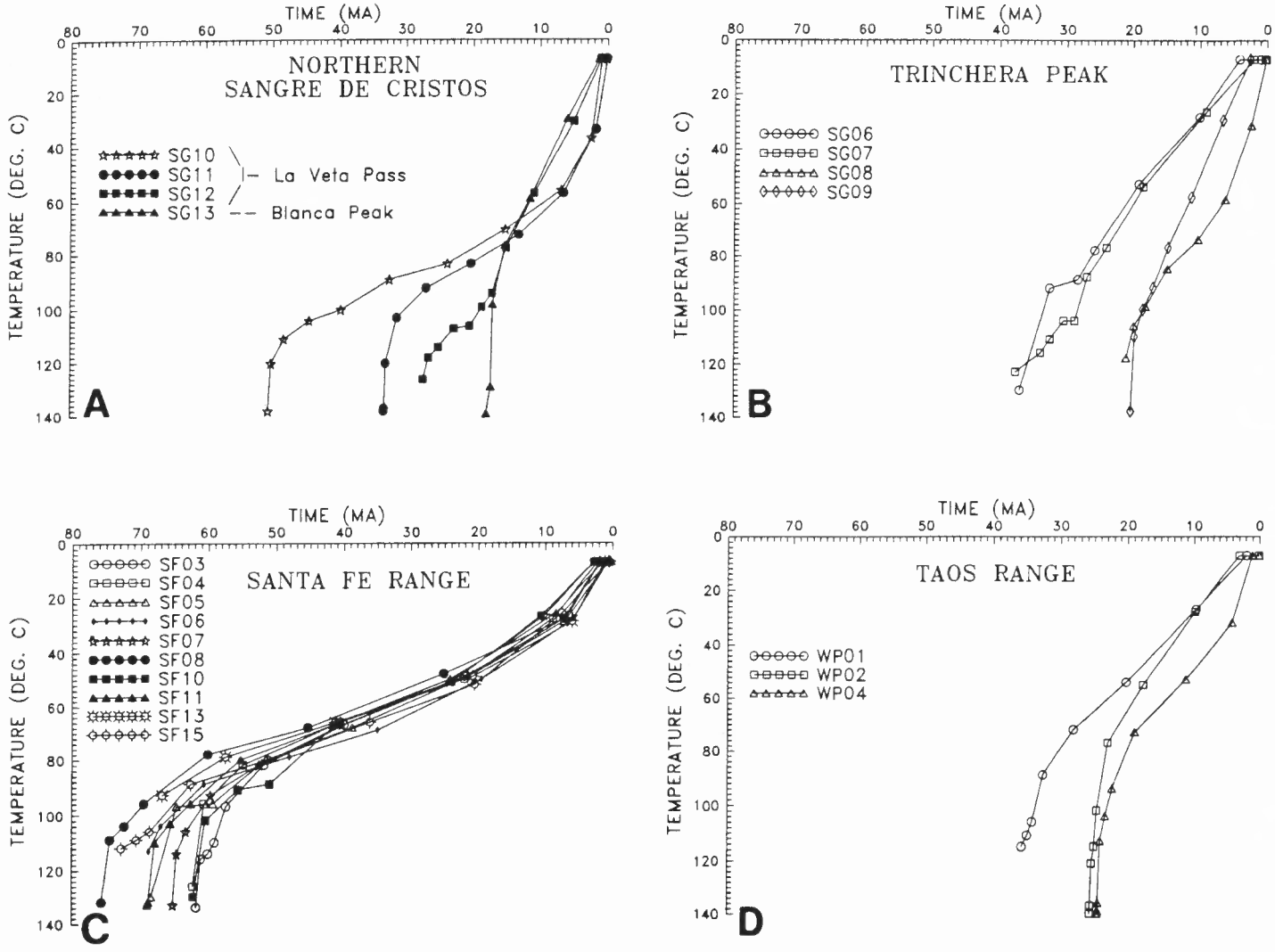


FIGURE 5. Estimated time-temperature curves (Donelick, 1988). A, Blanca Peak, La Veta Pass, northern Sangre de Cristo Mountains. B, Trinchera Peak, northern Sangre de Cristo Mountains. C, Santa Fe Range. D, Taos Range.

37 Ma at high elevations to 19 Ma at low elevations near the Spanish Peaks intrusive complex (Fig. 3d). The mean track lengths for the samples are 13.1–14.1 μm with standard deviations of 1.6–2.7 μm. Apatite from these sandstones is fluorapatite; the chlorine content of the apatite from these sandstones is remarkably uniform, ranging from 0.01 to 0.11 Cl atoms/molecule.

The highest elevation samples (88SG06 and 07, Fig. 5b) cooled slowly (3°C/Ma; Table 1) compared to the low-elevation samples (5°C/Ma; 88SG08 and 09). The data from the high-elevation samples probably record development of the late Eocene erosion surface, whereas data from the low-elevation samples reflect cooling following the Spanish Peak intrusive event (20–25 Ma; Smith, 1979).

Summary

The Sangre de Cristo Mountains north of La Veta Pass near Blanca Peak, Colorado, cooled rapidly during the late Oligocene to early Miocene. In contrast, the La Veta Pass and Trinchera Peak areas to the south record slow denudation in the Eocene, perhaps related to the development of the late Eocene erosion surface (Epis and Chapin, 1975), with cooling continuing into the early Miocene.

The northern Sangre de Cristo Mountains did not have high relief in the Oligocene. East-trending paleovalleys filled with volcanic rocks of western provenance that are preserved on the east side of the range at several localities indicate incision of drainages into the late Eocene surface with as much as 300 m of local topographic relief (Epis et al., 1976). The southern segment of the Sangre de Cristo Mountains may also have had low relief (Tweto, 1979). The FT data are consistent with this geologic evidence.

The work of Lipman (1981) and Steven (1975) indicate that volcanism in the San Juan and Latir volcanic fields, which are located to the west and south of the study area (Fig. 2), very likely affected the northern Sangre de Cristo Mountains of Colorado. Kearney (1983) mapped a sequence of lahars, tuffs and andesitic lava flows in the La Veta Pass area. One of the tuffs in the lower third of the volcanic section may correlate with the Ra Jadero Member of the Treasure Mountain Tuff in the San Juan Mountains (K/Ar age of 28.2–29.8 Ma; Lipman, 1975). The rest of the volcanic sequence is thought to be derived from relatively local sources. Consequently, the Miocene cooling recorded by the FT data is probably related to both denudation and relaxation of isotherms following the end of volcanism in southern Colorado.

Northern New Mexico

Kelley and Duncan (1986) determined apatite-FT ages for three mountain ranges in northern New Mexico, but track-length analyses were not done on all the samples. This section summarizes the track measurements for the Taos Range and Santa Fe Range samples from our previous study. Since we are now using a different track-length-measuring system, the previously published track-length samples were re-analyzed and revised.

Taos Range, Sangre de Cristo Mountains

The Taos Range (Fig. 2e) is composed of Proterozoic metamorphic rocks intruded by Cenozoic granites associated with the Questa caldera and Latir volcanic field (Lipman, 1981). Two of the samples (Fig. 6; 81WP05 and 81WP06) are from the 21 Ma Rio Hondo pluton, which is intruded by the 18 Ma Lucero stock (Lipman et al., 1986). One

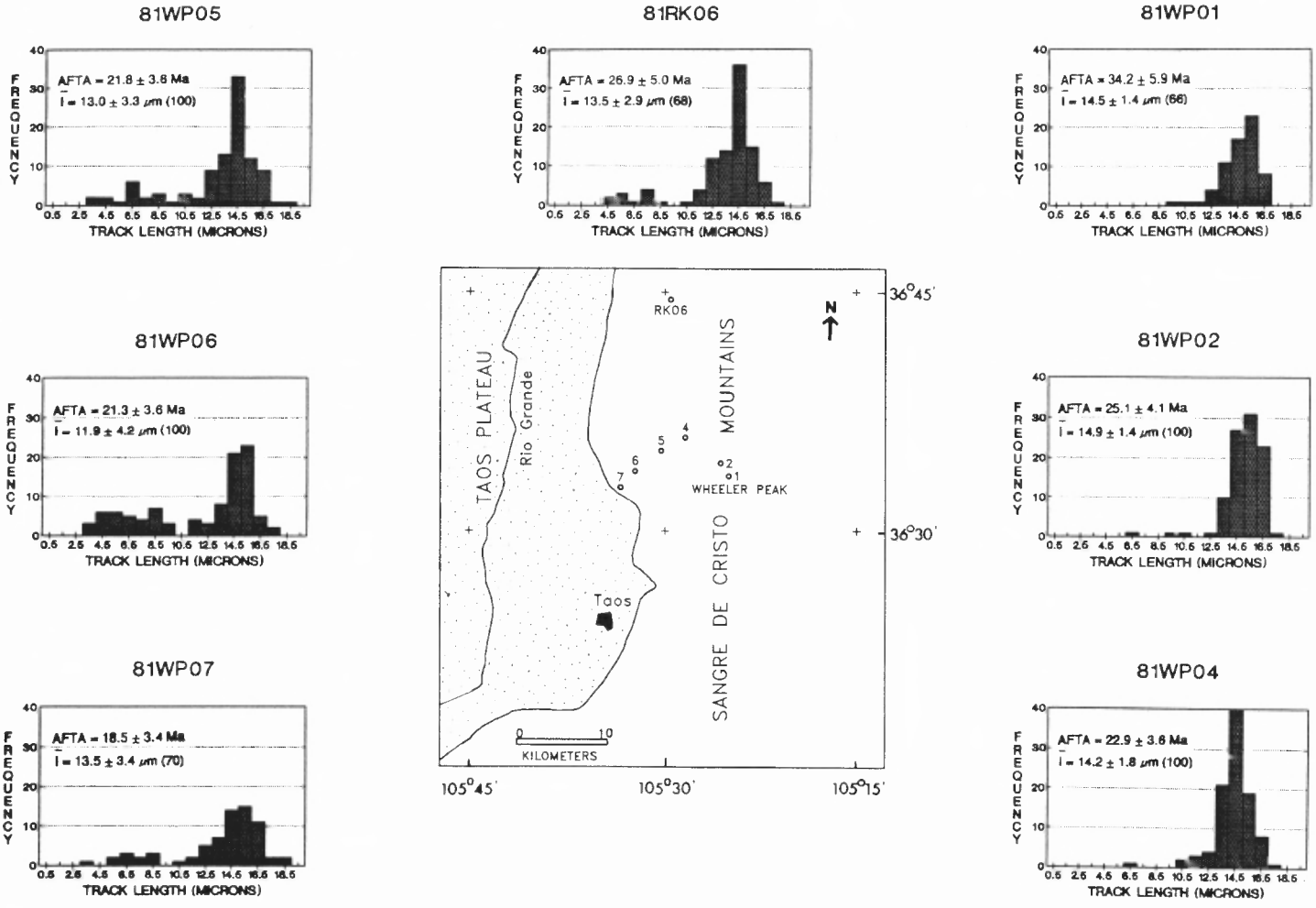


FIGURE 6. Sample localities, track-length histograms and apatite fission-track ages (AFTA) for the Taos Range, Sangre de Cristo Mountains, New Mexico. The mean track length and the number of confined tracks measured for each sample are also shown.

sample (81RK06) is from the 25 Ma Cabresto pluton north of Wheeler Peak. The remainder of the samples are from Proterozoic rocks in the vicinity of Wheeler Peak. Apatite-FT-age data as a function of elevation are shown in Figure 3e. No chemical analyses were obtained for these apatites.

Revised track-length data are shown in Figure 6. The three samples at high elevation from Proterozoic rocks (81WP01, 02, 04) have unimodal histograms that are characteristic of relatively simple cooling histories. The cooling of these samples is related to the combined effects of denudation and cooling following volcanism. The sample from the summit of Wheeler Peak cooled relatively slowly (4°C/Ma; Fig. 5d and Table 1) during denudation, whereas the lower elevation samples cooled more rapidly (6°C/Ma; Fig. 5d and Table 1) following cooling of intrusions in this area.

Track-length histograms for samples from the Cenozoic intrusions and the lowest Proterozoic sample (81WP05–07, 81RK06) have abundant short tracks (Fig. 6), which are indicative of a more complex thermal history. Since the model of Donelick (1988) is not applicable in this situation, simple forward modeling based on Green et al. (1989) was performed. A thermal event with temperatures on the order of 115°C at around 18 Ma, roughly corresponding to the time of emplacement of the Lucero pluton, approximately fits the observed age and track-length data. Further work in this area is needed.

Santa Fe Range, Sangre de Cristo Mountains

The Santa Fe Range (Fig. 2f) consists primarily of Proterozoic granitic and gneissic rocks (Embudo Granite) bounded on the east by the Picuris-Pecos fault and on the west by an ill-defined fault zone in the Española basin. The apatite-FT ages range from 44 to 74 Ma and show good correlation with elevation (Fig. 3f).

Apatite from the Embudo Granite is fluorapatite (0.0–0.01 Cl atoms/molecule). The mean track lengths (13.0–13.9 μm with standard deviations of 1.1–2.3 μm) and the general shape of the histograms (Fig. 7) are characteristic of slow cooling (1°C/Ma average over entire 120–60°C range; Table 1 and Fig. 5c).

The time-temperature paths in Figure 5c suggest moderate cooling (4°C/Ma) during uplift of the Santa Fe Range between 55–75 Ma during early Laramide tectonism, bringing the basement rocks to depths of approximately 3–3.5 km (temperatures of 80–90°C), assuming a geothermal gradient of 25°C/km. After 55 Ma the cooling rate declined significantly (1°C/Ma). The preservation of old FT ages in the Santa Fe Range imply that no significant denudation or deposition occurred in this block during late Laramide or early rift deformation.

The Santa Fe Range was probably the site of minor deposition during early rift development, forming the eastern portion of a broad, early Miocene Española basin. The basal part of the Tesuque Formation of the Santa Fe Group found adjacent to the Santa Fe Range was derived

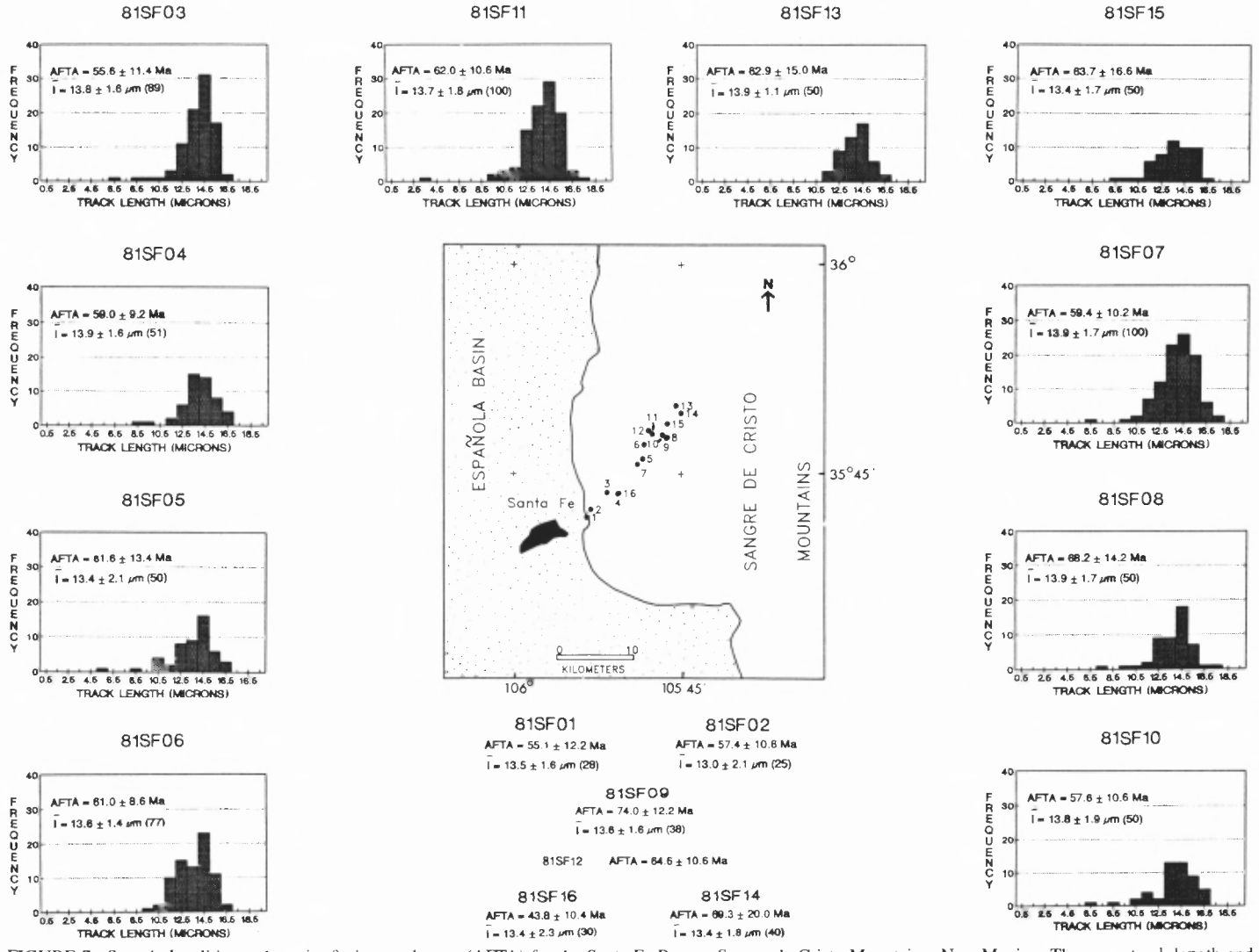


FIGURE 7. Sample localities and apatite fission-track ages (AFTA) for the Santa Fe Range, Sangre de Cristo Mountains, New Mexico. The mean track length and the number of confined tracks measured for each sample are also shown.

from the underlying Proterozoic rocks (Galusha and Blick, 1971), suggesting that at least part of the Santa Fe block was at the surface in the Miocene. Denney (1940) notes that the Santa Fe Group near Santa Fe does not contain many coarse-grained sediments, which indicates a source to the east of the modern range boundary. He proposes that the formation may have extended as far east as the modern summits of the Sangre de Cristo Mountains.

CONCLUSIONS

Clearly, the FT data show that each range within the Sangre de Cristo Mountains of Colorado and New Mexico bounding the eastern margin of the northern Rio Grande rift has a unique thermal history reflecting the effects of both denudation and volcanism. At least three major tectonic events are recorded by FT data from the Sangre de Cristo Mountains:

1. The Santa Fe Range cooled during early Laramide (late Cretaceous to Paleocene) uplift and erosion. Initially, denudation was moderate, causing cooling at rates of 3–4°C/Ma. Subsequently, no substantial denudation or deposition affected the area during the late Laramide (Eocene) or early rift deformation. The FT data and geologic evidence support the hypothesis that the Santa Fe Range may have underlain the eastern part of the Española basin during the early phase of rift development.

2. Remnants of areas that cooled during late Laramide deformation and during the development of the late Eocene erosion surface have been preserved at high elevations at La Veta Pass, Trinchera Peak and Wheeler Peak. Upwarp of isotherms during Oligocene–early Miocene volcanism apparently did not affect the FT ages in the levels of the crust now exposed along the crest of the Sangre de Cristo Mountains. Furthermore, these areas were not strongly uplifted during early rift development, allowing preservation of the older FT ages.

3. Many of the low elevation samples in the southern segment of the Sangre de Cristo Mountains (La Veta Pass, Trinchera Peak, Taos Range) cooled by a combination of relaxation of isotherms during the waning of Oligocene–early Miocene volcanism and denudation during early rift development. In contrast, the northern segment of the range has been strongly uplifted during early development of the rift. Rapid cooling at Blanca Peak is likely related to tectonic denudation along faults on three sides, which resulted in a rapid, isostatic response. The cooling rate derived from the FT data of Lindsey et al. (1986) is similar to that observed in the Sandia Mountains near Albuquerque, New Mexico (Kelley and Duncan, 1986; 6°C/Ma). The cooling rate from the Sandia and the northern Sangre de Cristo Mountains are perhaps more characteristic of denudation during early formation of the Rio Grande rift.

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Fishing party coming into Red River in 1898 over Red River Pass. The two gentlemen on the right are about to tie a hewn tree to the back of the wagon. The tree prevented the wagon from outrunning the horse team on the steep downslope into Red River. The wooden flume visible in the background is probably "The Big Ditch," which carried water from the headwaters of the Red River 41 miles to the placer mines east of E'town. Courtesy of Mrs. Winifred Hamilton.