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2009, pp. 347-358. https://doi.org/10.56577/FFC-60.347

in:

Geology of the Chupadera Mesa, Lueth, Virgil; Lucas, Spencer G.; Chamberlin, Richard M.; [eds.], New Mexico Geological Society 60th Annual Fall Field Conference Guidebook, 438 p. https://doi.org/10.56577/FFC-60

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THERMAL HISTORY OF THE EASTERN SOCORRO BASIN, SOCORRO COUNTY, NEW MEXICO, BASED ON APATITE FISSION-TRACK THERMOCHRONOLOGY

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ABSTRACT—Apatite fission-track (AFT) analysis of clasts from the north-trending outcrop belt of the Eocene Baca Formation east of the Rio Grande near Socorro, New Mexico, reveals an intriguing north to south middle Cenozoic thermal pattern. Clasts from the northern end of the outcrop belt in Palo Duro Canyon yield AFT ages of 45 to 57 Ma, ages that are equivalent to or older than the stratigraphic age of the unit. The mean track lengths measured in these clasts are 13.7 to 13.8 µm. The AFT ages decrease to 30 to 33 Ma a short distance (4 km) south of Palo Duro Canyon. Further south along the outcrop belt, the AFT ages are 12 to 18 Ma and mean track lengths are long (13.8 to 14.0 µm) in exposures east and southeast of Socorro. AFT ages for Baca Formation increase eastward into the northern Jornada del Muerto, where the ages are 22 to 29 Ma and the mean track lengths are short (11 to 12 µm), indicative of partial resetting. To the south, outcrops of Baca Formation along U.S. Highway 380 east of the village of San Antonio yield 31 to 46 Ma AFT ages, similar to the ages found at the north end of the outcrop belt. The AFT ages decrease to 22 to 39 Ma at the southernmost exposure of the unit, which is located about five kilometers to the southwest of the highway outcrops. AFT ages from Proterozoic basement outcrops on the eastern margin of the Socorro basin also decrease from north to south toward Socorro. AFT ages >45 Ma for Abo and Proterozoic clasts in the Baca Formation provide constraints on the denudation history of the Laramide Sierra uplift. The partially reset Oligocene apparent AFT ages and associated reduced mean track lengths and totally reset Miocene AFT ages east of Socorro define a middle Cenozoic thermal anomaly on the eastern margin of the Socorro Basin that has a N-S extent of ~20 km.

Two thermal sources may have heated the Baca Formation to temperatures above 110°C during middle Cenozoic time. First, the eastern margin of the Socorro caldera lies ~10 km to the west of the outcrops with late Miocene cooling ages. Heat from the caldera, which had to be distributed convectively rather than conductively, reset or partially reset the fission-track clock at 32 Ma. Temperatures remained higher than 110°C until middle Miocene time as a consequence of continued volcanic activity in the Mogollon-Datil volcanic field to the southeast and burial of the area by at least 1 km of tuffs, lava flows, and volcaniclastic sediments. The area then cooled rapidly during uplift of the Loma de las Cañas starting ~18 Ma. Second, the outcrops with late Miocene cooling ages lie near the Socorro accommodation zone. A middle Miocene paleohydrothermal system with recharge in volcanic highlands southwest of Socorro, eastward flow through fractured rocks along the accommodation zone, and discharge in the eastern Socorro Basin may have locally increased the geothermal gradient. This hydrothermal regime was disrupted during late Miocene time by rift-related faulting and volcanism. The middle Cenozoic thermal anomaly preserved in apatite fission-track data from the Eocene Baca Formation in the eastern Socorro Basin likely formed as a result of elevated heat flow due to both volcanism and hydrothermal activity.

INTRODUCTION

The Eocene Baca Formation is a clastic unit that was deposited in basins in west-central and central New Mexico during Laramide orogenesis (Fig. 1). The Baca Formation in the Carthage-La Joya basin to the east of Socorro, New Mexico, (Fig. 1) was derived from the Laramide Sierra uplift, a highland that was later inverted during late Cenozoic extension and now is largely buried beneath the Rio Grande rift (Cather, 1983; Cather and Johnson, 1984), and from the Laramide Montosa uplift (Cather, 2009). The Baca Formation in the Carthage-La Joya basin was deposited during middle Eocene time; Bridgerian fossils are present in the lower part and ~40 Ma volcaniclastic rocks rest on the unit (Lucas and Williamson, 1993; Cather et al., 1987). In this study, we use apatite fission-track thermochronology to analyze the thermal history recorded in Proterozoic and Permian clasts from the Baca Formation. Most of the cooling histories derived from AFT analysis of Proterozoic basement rocks in the Socorro area are overprinted by Rio Grande rift tectonism (Kelley et al., 1992). We originally thought that clasts from the Baca Formation might provide some insights into the Laramide cooling history of the Sierra uplift.

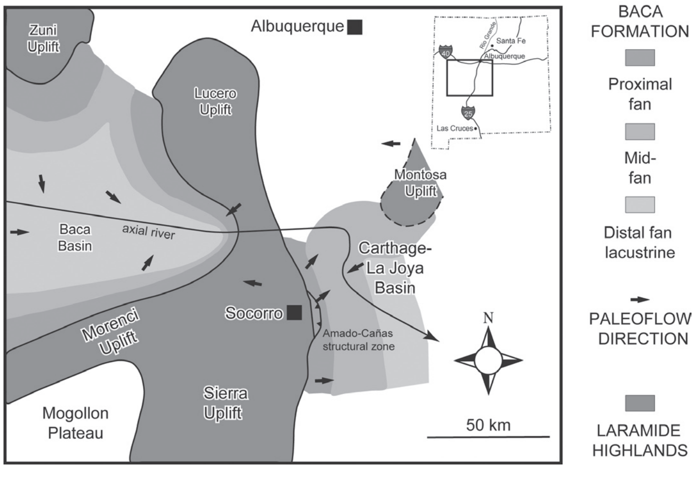

FIGURE 1. Map of the facies and paleocurrents preserved in Baca Formation and inferred locations of Laramide highlands in central and west-central New Mexico. Modified from Cather and Johnson (1984) and Cather (2009).

However, preliminary AFT results for clasts from an outcrop due east of Socorro yielded Miocene ages of 12 to 16 Ma rather than the expected Eocene or older AFT ages. Consequently, we undertook a more systematic study of the Baca outcrop belt east of Socorro, collecting samples along a north-south traverse of the belt. We discovered that the AFT ages are youngest just east of Socorro and that the AFT cooling ages increase north and south of Socorro.

OVERVIEW OF FISSION-TRACK THERMOCHRONOLOGY

Fission-track annealing in apatite is affected by temperature, the chemical composition of the apatite (tracks in chlorapatite completely anneal at higher temperatures (140°C) than those in fluorapatite (110°C); Green et al., 1986) and heating duration. Fission tracks in apatite are constantly being produced at a rate that is determined by the spontaneous fission decay rate constant for ^{238}U and are annealed at a rate controlled primarily by temperature. At temperatures above 110 to 140°C, the fission-track annealing rate is greater than the production rate, and no tracks accumulate in the mineral (i.e., the fission-track age is zero). As cooling proceeds, the apatite passes through a temperature range between about 60 to 140 °C known as the partial annealing zone (PAZ), where tracks are produced and partially annealed (shortened). Finally, at temperatures <60°C fission tracks that are produced are retained and annealing is relatively minor.

The fission-track age and lengths of confined tracks can be used to interpret the thermal history of a sample (Fig. 2). For example, a mineral that has cooled, then experienced mild reheating to temperatures within the PAZ, and then cooled again (Fig 2a) will have a "mixed" age that dates neither the heating nor the subsequent cooling event. Tracks in a mineral that has been subjected to a short, moderate temperature 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 the track length distribution is bimodal (Fig. 2b). In contrast, a sample with a simple cooling history (Fig. 2c) has a unimodal histogram. If the sample experienced slow cooling (1 to 4 °C/m.y.) so that it spent several millions of years passing through the PAZ, partial annealing shortens some tracks and the track-length distribution is skewed toward longer tracks (Fig. 2d; mean track length of 13 to 14 μm). If the sample cooled rapidly (5 to 10°C/m.y.) so that the sample spent very little time in the PAZ, the track-length distribution is symmetric and dominated by long tracks (Fig. 2f; mean of 14 to 15.5 μm). Finally, if a sample cooled very slowly so that it spent tens of millions of years in the PAZ (Fig. 2g), the track length histogram is broad and multimodal (Fig. 2h), and the mean track lengths are short (10 to 12 μm).

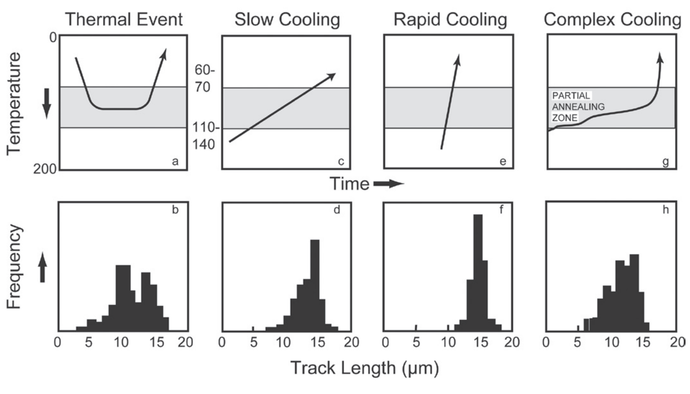

FIGURE 2. Representative thermal histories and associated track length distributions. See text for discussion.

GEOLOGIC SETTING OF SOCORRO AREA

Figure 3 is a simplified geologic map showing the location of features referred to in the following discussion. As mentioned in the introduction and illustrated in Figure 1, the Socorro area, like much of New Mexico, was affected by compressional tectonics during Laramide orogenesis. In the eastern Socorro basin, the eastern margin of the Sierra uplift may be represented by a north-south chain of small Proterozoic outcrops adjacent to a zone of highly folded Pennsylvanian Sandia Formation (Cather and Colpitts, 2004; Amado-Cañas structural zone, Figure 1). Here the Baca Formation rests unconformably on Pennsylvanian Madera Formation limestone, in contrast to areas north and south, where the Baca Formation lies on Triassic Chinle Group or Cretaceous Mesaverde Formation and Mancos Shale (Wilpolt and Wanek, 1951; Chamberlin, 1980; Cather et al., 2004; Cather and Colpitts, 2005). The Joyita Hills (Figure 3) were also high during early Cenozoic Laramide and late Paleozoic Ancestral Rockies deformation (Beck and Chapin, 1994).

A northeast-trending zone of basement weakness, the Morenci lineament, has influenced the location of volcanism in the Socorro region starting with the formation of the Socorro caldera 32 m.y. ago (Chapin et al., 1978). Several calderas in the Mogollon-Datil volcanic field southwest of Socorro, including the 32 Ma Socorro caldera, the 28.8 Ma Sawmill-Magdalena caldera, and the 27.3 Ma Mt. Worthington caldera developed along this lineament (Chapin, 1989). Northeast- to north-northeast-trending dikes in the southern Los Pinos Mountains (age undetermined) and on Chupadera Mesa southeast of the Los Pinos Mountains (30.2±2.0 Ma; Aldrich et al., 1986) lie on the projection of the Morenci lineament east of Socorro. When extension began in this portion of the Rio Grande rift at 29 Ma, the Morenci lineament seems to have acted as an accommodation zone, separating fault blocks dipping west to the north of the zone from those dipping east south of the boundary (Fig. 3). The Socorro accommodation zone has continued to "leak" magmas episodically through middle Miocene to present time (Chapin, 1989). Four silicic volcanic centers in the Magdalena Mountains and in the Socorro Mountains erupted along the Socorro accommodation zone 18.4 to 7.2 m.y. ago. The 4 Ma basalt flow of Sedillo Hill lies on the Socorro accommodation zone west of Socorro, and two 3.5 Ma basalt flows erupted on Chupadera Mesa near the projection of the Socorro accommodation zone east of the Rio Grande.

The Oligocene to late Miocene Popotosa Formation and the Pliocene to Pleistocene Sierra Ladrones Formation are basin-fill

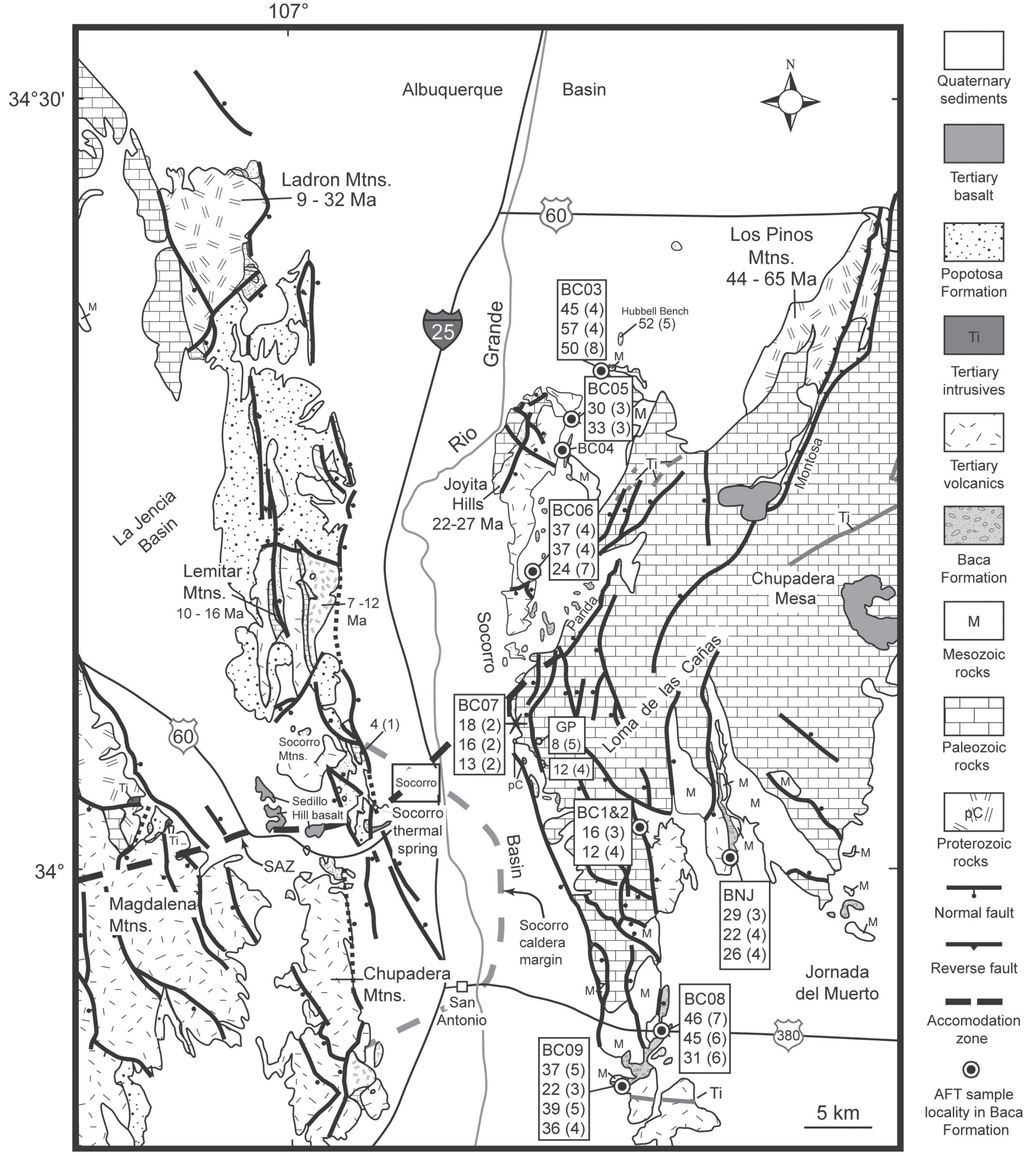

FIGURE 3. Simplified geologic map of the Socorro area. The Baca sample localities are depicted as circled dots. AFT ages (in Ma) and standard error in parenthesis are shown for Baca and selected Proterozoic (bold numbers) samples; general AFT age ranges (bold numbers) shown for most Proterozoic basement areas (Kelley et al., 1992, Wilks and Chapin, 1997, this study). GP = Gonzales prospect. A black dashed line represents the accommodation zone (SAZ) and a gray dashed line shows the estimated location of the margin of the Socorro caldera. The asterisk is the site of the altered Baca Formation discussed in the text.

sedimentary rocks that record the complex rift-related topographic and tectonic evolution of the Socorro area. The Popotosa Fomation filled early north-striking basins in the area now occupied by the modern Abbe Springs, La Jencia, and Socorro basins and the Socorro, Lemitar, and southern Magdalena Mountains (Chamberlin, 2004; Fig. 3). The western and southern margins of the basin are preserved in the Bear Mountains (just west of edge of Figure 3), the Magdalena Mountains, and the Chupadera Mountains, but the northern and eastern extent of the basin is poorly constrained. The lower Popotosa Formation is dominated by conglomerates and sandstones derived from fault blocks that disrupted volcanic strata derived from the Mogollon-Datil field to the south; most of the paleocurrent indicators suggest a northerly flow direction (Chamberlin, 1980, 1999). However, one facies within the lower Popotosa exposed in the Socorro Mountains (here > 9.5 Ma) has southwesterly paleocurrent indicators and is interpreted to represent a distal fan deposit from an uplift on the eastern margin of the Popotosa basin to the northeast of the Socorro Mountains (Chamberlin, 1980, 1999). This facies contains clasts of tuffs and intermediate lavas similar to those found in the Joyita Hills. The upper Popotosa Formation is composed of detritus shed from the surrounding highlands interfingered with thick playa deposits that developed in this closed basin.

One of the younger facies of the Upper Popotosa Formation preserved in the Socorro Mountains has westerly paleocurrents and is thought to be a distal fan deposit derived from the eastern margin of the basin since it contains sparse clasts of Permian Abo Formation (Chamberlin, 1980). Proximal Popotosa conglomerate correlative to this facies is exposed in the Mesa del Yeso quadrangle east of the Rio Grande (Cather et al., 2004). The clasts from this facies are dominated by tuffs and andesites, but this facies also contains trace amounts of red Permian Abo siltstone, fine-grained sandstone, biotite schist and granitic pebbles (possibly recycled Baca Formation); these bedrock lithologies are found to the east of the modern Rio Grande. This conglomeratic sandstone is interbedded with playa deposits that underlie 9.5 Ma rhyodacite and the unit overlies tuffs from the 7.4 Ma Grefco rhyolite dome (Chamberlin, 1980, 1999).

The northern part of the Magdalena Mountains block floored the southwestern margin of the Popotosa basin at ~20 Ma (Chamberlin and Osburn, 2006). Although extension and domino-style block faulting were occurring in the Lemitar, Socorro, Magdalena, and Chupadera Mountains throughout Oligocene to middle Miocene time, portions of these blocks were sites of localized deposition until late Miocene to Pliocene time, when high angle normal faulting disrupted the axis of the Popotosa basin. Sediments derived from the uplift of the Magdalena, Lemitar and Socorro blocks are found in the western piedmont facies of the Sierra Ladrones Formation.

METHODS

Sample Selection and Processing

Three to eight clasts were collected at each Baca Formation locality (Fig. 3). In most cases, Proterozoic granitic or metamorphic clasts were sampled; however, two outcrops at the northern end of the belt contained no Proterozoic clasts, so Permian Abo sandstone clasts were analyzed instead. In addition, three samples of Proterozoic granitic basement from the Hubbell Bench, the base of Socorro Peak, and from an outcrop south of the Gonzales prospect (GP, Figure 3) were analyzed to fill in gaps in the existing AFT data base (Kelley et al., 1992; Wilks and Chapin, 1997).

Apatite was separated from the samples using standard heavy liquid and magnetic separation techniques. Abo clasts from Palo Duro Canyon and most of the Proterozoic clasts yielded apatite; however, none of the Abo clasts from sample site BC4 (Fig. 3) contained apatite. Apatite grains were mounted in epoxy, polished to expose the grains, and etched for 25 seconds in a 5 M solution of nitric acid to reveal the fission tracks. The 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 using the zeta technique (Hurford and Green, 1983; Green, 1985) with Durango apatite age standards (accepted age 31.4 ± 0.5 Ma) and Corning standard glass CN-6. The ages were determined by counting both spontaneous tracks in the grain mounts and induced tracks in the muscovite detectors, as outlined by Naeser (1979) in his discussion of the external detector method.

The confined track length distributions in the apatite grain mounts were determined using a microscope fitted with a 100-x dry 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) in grains with prismatic faces were measured. The orientation of the tracks with respect to the c-axis was also measured.

Thermal History Modeling

Quantitative analysis of AFT data can be used to extract time-temperature information. 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; Crowley et al., 1991; Ketchum et al., 1999), but the process is not completely understood and several equations have been proposed to describe the annealing behavior of apatite (Laslett et al., 1987; Corrigan, 1991; 1993; Crowley et al., 1991; Ketchum et al., 1999). In this study, the AFTsolve program of Ketchum (2005), which includes all of the published annealing models, is used to estimate cooling curves for samples with more than 35 confined track-length measurements.

RESULTS AND MODELING

The AFT age and length data summarized in Figures 3 and 4 and Tables 1 and 2 suggest an interesting thermal history pattern along the north-trending outcrop belt of the Baca Formation. The AFT ages from the Baca Formation in the eastern Socorro basin decrease systematically from north to south toward the latitude of Socorro; then the ages increase toward the south and southeast,

TABLE 1. Apatite fission-track data for clasts in Baca Formation, eastern Socorro basin, New Mexico

Sample Number	Rock Type	Latitude Longitude	Elevation (m)	Number of Grains Dated	ρ_s x 10^5 t/cm^2	ρ_i x 10^6 t/cm^2	ρ_d x 10^5 t/cm^2	Central Age (Ma) (±1 S.E.)	$P(\chi)^2$ (%)	Uranium Content (ppm)	Mean Track Length (µm) (± 1 S.E.)
Palo Duro Canyon											
93BC03/1	Abo sandstone in	34°19.64'N	1570	20	2.46	3.05	1.021	45.3	99	31	13.8 (0.5)
	Baca Fm.	106°44.69'W			192	1190	(2134)	4			12
94BC03/2	Abo sandstone in	34°19.64'N	1570	20	3.14	3.26	1.073	56.8	99	32	13.7 (0.5)
	Baca Fm.	106°44.69'W			312	1619	(2065)	4.2			52
94BC03/3	Abo sandstone in	34°19.64'N	1570	10	2.13	2.55	1.074	49.5	99	25	N.D.
	Baca Fm.	106°44.69'W			54	322	(2065)	7.5			
East Joyita Hills											
93BC05/1	Proterozoic granite	34° 17.99'N	1529	20	0.95	1.81	1.024	29.6	99	18	13.3 (0.5)
	in Baca Fm.	106° 46.08'W			118	1123	(2134)	3.1			47
93BC05/2	Proterozoic granite	34° 17.99'N	1529	20	1.03	1.79	1.028	32.7	99	18	13.9 (0.5)
	in Baca Fm.	106° 46.08'W			128	1107	(2134)	3.4			51
94BC06/1	Proterozoic	34°11.40'N	1548	25	1.12	1.81	1.084	37	91	17	N.D.
	granitic gneiss	106°48.51'W			108	870	(2065)	4.1			
	in Baca Fm.										
94BC06/2	Proterozoic schist	34°11.40'N	1548	20	1.06	1.74	1.096	36.6	96	17	12.8 (0.9)
	in Baca Fm.	106°48.51'W			88	725	(2065)	4.4			23
94BC06/3	Proterozoic granite	34°11.40'N	1548	16	0.31	0.8	1.105	23.8	99	8	N.D.
	in Baca Fm.	106°48.51'W			14	179	(2065)	6.7			
Altered Baca outcrop											
94BC07/1	Proterozoic granite	34°05.65'N	1487	20	0.95	3.28	1.115	17.7	99	31	14.0 (0.5)
	in Baca Fm.	106°49.28'W			103	1787	(2065)	2			36
94BC07/2	Proterozoic granite	34°05.65'N	1487	20	1.11	4.36	1.131	15.9	88	40	13.7 (0.6)
	in Baca Fm.	106°49.28'W			105	2057	(2065)	1.7			48
94BC07/3	Tuff in	34°05.65'N	1493	20	0.4	1.92	1.137	13.1	99	18	13.8 (1.0)
	Spears Fm.	106°49.27'W			50	1196	(2065)	2			18
92BC01	Proterozoic granite	34°01.02'N	1686	20	0.32	1.36	1.260	16.1	99	11	12.9 (1.0)
	in Baca Fm.	106°42.87'W			43	927	(2052)	2.6			23
92BC02	Proterozoic granite	34°01.02'N	1686	20	0.06	0.33	1.250	12.2	99	3	N.D.
	in Baca Fm.	106°42.87'W			9	254	(2052)	4.1			
Jornada outcrop											
BNJ1	Proterozoic granite	34°01.0'N	1800	20	2.76	5.45	1.030	28.7	99	55	11.8 (0.5)
	in Baca Fm.	106°38.9' W			160	1581	(2134)	2.7			53
BNJ2	Proterozoic granite	34°01.0'N	1800	20	0.29	0.73	1.030	22.4	99	7	12.3 (1.0)
	in Baca Fm.	106°38.9' W			42	532	(2134)	3.7			17
BNJ3	Proterozoic granite	34°01.0'N	1800	20	0.24	0.54	1.035	25.6	99	6	12.0 (0.5)
	in Baca Fm.	106°38.9' W			39	434	(2134)	4.4			50
Highway 380											
94BC08/4	Proterozoic granite	33°53.14'N	1554	20	1	1.37	1.150	46.4	99	12	N.D.
	in Baca Fm.	106°42.11'W			53	361	(2065)	7			
94BC08/5	Proterozoic granite	33°53.14'N	1554	10	0.93	1.91	1.161	31.3	99	17	N.D.
	in Baca Fm.	106°42.11'W			29	296	(2065)	6.2			
94BC08/6	Proterozoic granite	33°53.14'N	1554	20	2	2.9	1.162	44.8	99	26	11.8 (0.8)
	in Baca Fm.	106°42.11'W			78	556	(2065)	5.7			32
94BC09/1	Abo siltstone	33°51.12'N	1560	20	1.23	2.16	1.172	36.8	99	19	13.5 (1.1)
	in Baca Fm.	106°44.41'W			63	552	(2065)	5.1			23
94BC09/2	Proterozoic granite	33°51.12'N	1560	20	0.42	1.24	1.183	21.8	70	11	10.7 (3.0)
	in Baca Fm.	106°44.41'W			48	717	(2065)	3.4			5
94BC09/3	Proterozoic granite	33°51.12'N	1560	20	0.7	1.16	1.193	39.3	82	10	12.0 (1.2)
	in Baca Fm.	106°44.41'W			87	726	(2065)	4.7			15
94BC09/4	Proterozoic granite	33°51.12'N	1560	20	0.78	1.42	1.193	36	99	12	13.8 (1.6)
	in Baca Fm.	106°44.41'W			80	729	(2065)	4.5			10

ρ_s - spontaneous track density; ρ_i - induced track density (reported induced track density is twice the measured density)

Number in parenthesis is the number of tracks counted for ages and fluence calibration or the number of tracks measured for lengths.

ρ_d - track density in muscovite detector covering CN-6 (1.05 ppm); Reported value determined from interpolation of values for detectors covering standards at the top and bottom of the reactor packages (fluence gradient correction)

S.E. = standard error; $P(\chi)^2$ = Chi-squared probability; N.D. = no data

λ_f = 1.551 X 10^{-10}yr^{-1}, g=0.5; zeta = 5516 ± 300 for apatite

Mean track lengths not corrected for length bias (Laslett and others, 1982)

away from Socorro (Fig. 4). Clasts of Abo sandstone from the northern end of the outcrop belt in Palo Duro Canyon yield AFT ages of 45 to 57 Ma, ages that are equivalent to or older than the stratigraphic age of the Eocene Baca Formation. These AFT ages indicate that Abo Formation resting on the Sierra uplift was heated to temperatures >110°C prior to Laramide deformation

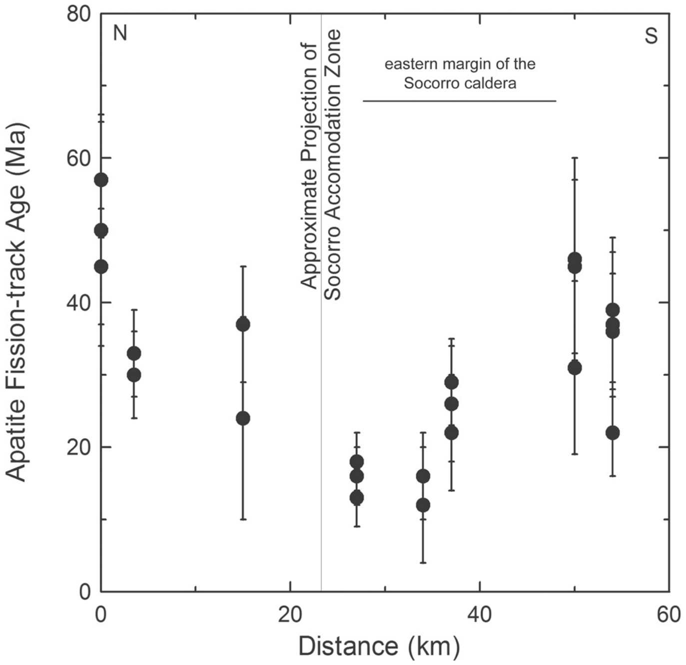

FIGURE 4. Plot of apatite fission-track age as a function of distance along the Baca Formation outcrop belt from north to south. Error bars are 2 standard error.

and that the uplift cooled slowly (2°C/m.y.), but steadily, during Laramide deformation. This style of Laramide cooling is similar to that observed in the Santa Fe Range portion of the Sangre de Cristo Mountains (Kelley et al., 1992). In contrast, Laramide cooling in the northern Front Range and in the Park Range of Colorado was relatively rapid (3 to 5°C/m.y.; Kelley and Chapin, 2004).

The AFT ages decrease to 30 to 33 Ma a short distance (4 km) south of Palo Duro Canyon, and are 24 to 37 Ma at the south end of the Joyita Hills, about 11 km further south. The next set of samples, located about 10 km ENE of Socorro, have much younger AFT cooling ages (12 to 18 Ma) with relatively long mean track lengths (13.7 to 14.0 μm). The AFT ages are also young (12 to 16 Ma) about 12 km to the southeast of Socorro. Moving further to the southeast away from Socorro, the AFT ages for the Baca Formation on the northern Jornada del Muerto are 22 to 29 Ma and the mean track lengths are relatively short (11 to 12 μm). To the south, outcrops of Baca Formation along Highway 380 east of the village of San Antonio yield 31 to 46 Ma AFT ages; the older ages are similar to the ages at the north end of the outcrop belt. At the southernmost exposure of the Baca Formation, about 5 km to the southwest of the Highway 380 outcrops, the AFT ages (22 to 37 Ma) and track lengths (10.8 to 13.8 μm) are comparable to the ages and lengths derived from samples at the south end of the Joyita Hills.

The general decrease in AFT age from north to south on the east side of the Rio Grande is also reflected in the data from Proterozoic outcrops. The AFT ages are 44 to 65 Ma in the Proterozoic exposures of the Los Pinos Mountains and on the Hubbell Bench (Fig. 3; Table 2). The ages decrease to 22 to 27 Ma in the Joyita Hills and to 8 ± 5 Ma for the highly fractured and mineralized Proterozoic outcrop at the Gonzales fluorite-barite deposit (Kelley et al., 1992; GP, Figure 3). A Proterozoic outcrop approximately 2 km south of the Gonzales deposit also has fluorite mineralization along a fault on the west side, but it is not as highly fractured as the area to the north; this granite yields an AFT age of 12.0 ± 4.1 Ma (Fig. 3; Table 2). A comparable trend is found in the Proterozoic rocks on the west side of the river (Fig. 3), although the outcrops on the west side of the basin have been strongly and variably affected by post-Pliocene uplift and erosion, volcanism, and potassium metasomatism (Chapin and Lindley, 1986).

Figure 5 illustrates the difference in cooling history recorded by the AFT age and length data from clasts at the north end of the outcrop belt (Palo Duro Canyon; e.g., 94BC03/2) and clasts just east of Socorro that have Miocene AFT ages (e.g., 94BC07/2). The thermal history of 94BC03/2 was derived using the following geologic constraints: 1.) the sample cooled during exhumation of the Sierra uplift during Laramide deformation; 2.) it was at the surface in Eocene time in order to be deposited in the Baca Formation; 3.) it was buried by about 1 km of ash-flow tuffs, lavas, and volcaniclastic sediments from the Mogollon-Datil volcanic field to the southwest and west of Socorro prior to Rio Grande rift faulting. This latter constraint is imposed because tuffs, lavas, and volcaniclastic rocks derived from the Mogollon-Datil volcanic field are preserved in the Joyita Hills just to the southwest of Palo Duro Canyon and in the northern Jornada del Muerto (Fig. 3). The thermal history for sample 94BC03/2 primarily reflects relatively slow cooling during Laramide deformation; this area has been little affected by Cenozoic burial and tectonism (Fig. 5).

Similar geologic constraints were applied to the modeling of the samples east of Socorro. In contrast to 94BC03/2, the Laramide history of 91BC07/2 is virtually unknown (Fig. 5). The AFT age and length data for this sample indicate that this area

Table 2. New apatite fission-track data for Proterozoic rocks, Socorro county, New Mexico

Locality	Sample Number	Rock Type	Latirude Longitude	Elevation (m)	Number of Grains Dated	ρ_s x 10^5 t/cm^2	ρ_i x 10^6 t/cm^2	ρ_d x 10^5 t/cm^2	Central Age (Ma) (±1 S.E.)	P(χ)^2 (%)	Uranium Content (ppm)	Mean Track Length (μm) (± 1 S.E.)
Hubbell	93HB02	Proterozoic	34°21.38' N	1591	20	2.19	2.44	1.050	51.6	99	24	13.0 (0.4)
Bench		granite	106°44.02'W			(188)	(1051)	(2134)	4.6			(47)
base of	95KMET148	Proterozoic	34°04.32'N	1620	20	0.07	0.95	0.964	3.9	95	10	N.D.
Socorro Peak		granite	106°56.76'W			(7)	(477)	(2065)	1.5			
south of	97GP03	Proterozoic	34°04.06'N	1536	20	0.08	0.51	1.306	12.0	86	4	N.D.
Gonzalez		qtz. monzonite	106°47.88'W			(9)	(270)	(2079)	4.1			
prospect												

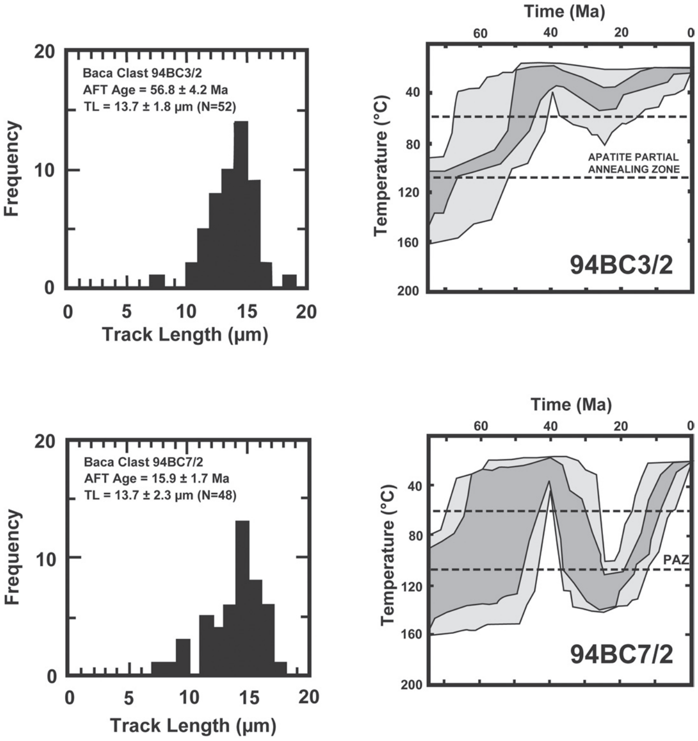

FIGURE 5. Representative track length distributions for clasts from Palo Duro Canyon (94BC3/2) and from the altered Baca outcrop east of Socorro (94BC7/2). Also illustrated are the time-temperature plots determined from the AFTsolve algorithm of Ketchum et al. (1999) that fit the AFT age and length data. The dark shading indicates the thermal histories that best fit the data, while the light shading corresponds to solutions providing acceptable fits (99% of possible solutions). The thermal histories are best constrained in the narrow bands and poorly constrained in the wide bands. The partial annealing zone (PAZ) for fluorapatite is shown for reference.

was heated to temperatures >110°C during Oligocene to early Miocene time. Although this area immediately east of Socorro was likely buried by about 1 km of ash-flow tuffs and volcaniclastic debris from nearby volcanic centers to the west, the AFT data require about 2.5 to 2.6 km of burial to heat the Baca Formation to temperatures >110°C, using a modern geothermal gradient of 38°C/km (Reiter et al., 1975). There is no compelling geological evidence that indicates that this part of the Loma de las Cañas (Fig. 3) was more deeply buried than areas to the north and south. Thus, the young ages are likely associated with locally elevated geothermal gradients during middle Cenozoic time.

DISCUSSION

Socorro Caldera

The eastern margin of the 32 Ma Socorro caldera lies ~10 km to the west of the outcrops with late Miocene cooling ages. A wide late Oligocene thermal aureole likely formed around this volcanic center, but was the heat from the magma chamber great enough to completely anneal fission tracks in the shallowly-buried clasts of the Baca Formation? We ran two simple end-member 2-D conductive thermal models (Blackwell et al., 1992) to examine the thermal affects of intrusion of an 800°C and a 1200°C 13 km thick magma body emplaced at a depth of 5 km in the crust. Maximum temperatures at 5 km and 10 km from the edge of the caldera at a depth of 1 km are 44 and 38 °C, respectively, for an 800°C chamber. These temperatures are 13 and 7 °C above background temperatures for this depth, assuming a pre-eruptive geothermal gradient of 31°C/km. Similarly, maximum temperatures at 5 km and 10 km from the edge of the caldera at a depth of 1 km are 53 and 40 °C, respectively, for an unrealistically hot 1200°C chamber. These temperatures are 22 and 9 °C above background temperatures for this depth, assuming a pre-eruptive gradient of 31°C/km. Clearly, the conductive temperatures are too low to have totally reset the fission-track ages. For this scenario to work, heat from the caldera must have been convectively distributed in order to totally reset or partially reset the fission-track samples located east of Socorro at 32 Ma. Temperatures associated with emplacement of the Socorro caldera magma chamber would have declined starting about 1 Ma after the eruption, but the AFT data indicate that temperatures remained higher than 110°C until middle Miocene time, some 14 m.y. after the emplacement of the magma chamber. Temperatures could have remained high as a consequence of continued, although more distant, volcanic activity in the Mogollon-Datil volcanic field to the southwest and burial of the area by at least 1 km of tuffs, lava flows, and volcaniclastic sediments. The modern outcrop pattern of preserved tuffs near the Loma de las Cañas uplift and the welding characteristics of the tuffs do not indicate that a greater thickness of ignimbrites accumulated immediately east of Socorro compared to areas to the north and south (Fig. 3). The area then cooled rapidly during uplift of the Loma de las Cañas starting ~18 Ma. Evidence for Miocene exhumation of crystal-poor tuffs from the Loma de las Cañas at 16 Ma is preserved in basal Popotosa Formation conglomerate on the Bosque del Apache wildlife refuge south of San Antonio (R. Chamberlin, personal communication, 2009).

Hydrothermal System

Another possible explanation for the AFT age pattern in the eastern Socorro basin is hydrothermal activity related to a plume of water discharging eastward from the high terrain of the Mogollon-Datil volcanic field southwest of Socorro (Fig. 6). Barroll and Reiter (1990) proposed a hydrothermal model to explain modern thermal regime in the Socorro area, including the presence of warm springs and anomalously high heat flow on the east side of the Socorro Mountains and very low heat flow in the La Jencia basin. Porous buried fanglomerates of the Upper Popotosa Formation form the bulk of the rift fill in the western La Jencia basin while Upper Popotosa playa claystones are dominate in the eastern part of the La Jencia basin. Barroll and Reiter (1990) suggest that the modern geothermal system is due to recharge in the Magdalena Mountains percolating down and flowing east through the fanglomerates until the water encounters the playa claystones. Water then moves downward into the porous tuffs beneath the playa claystones in the eastern La Jencia basin and through the tuff units that form the Socorro Mountains. On the east side of

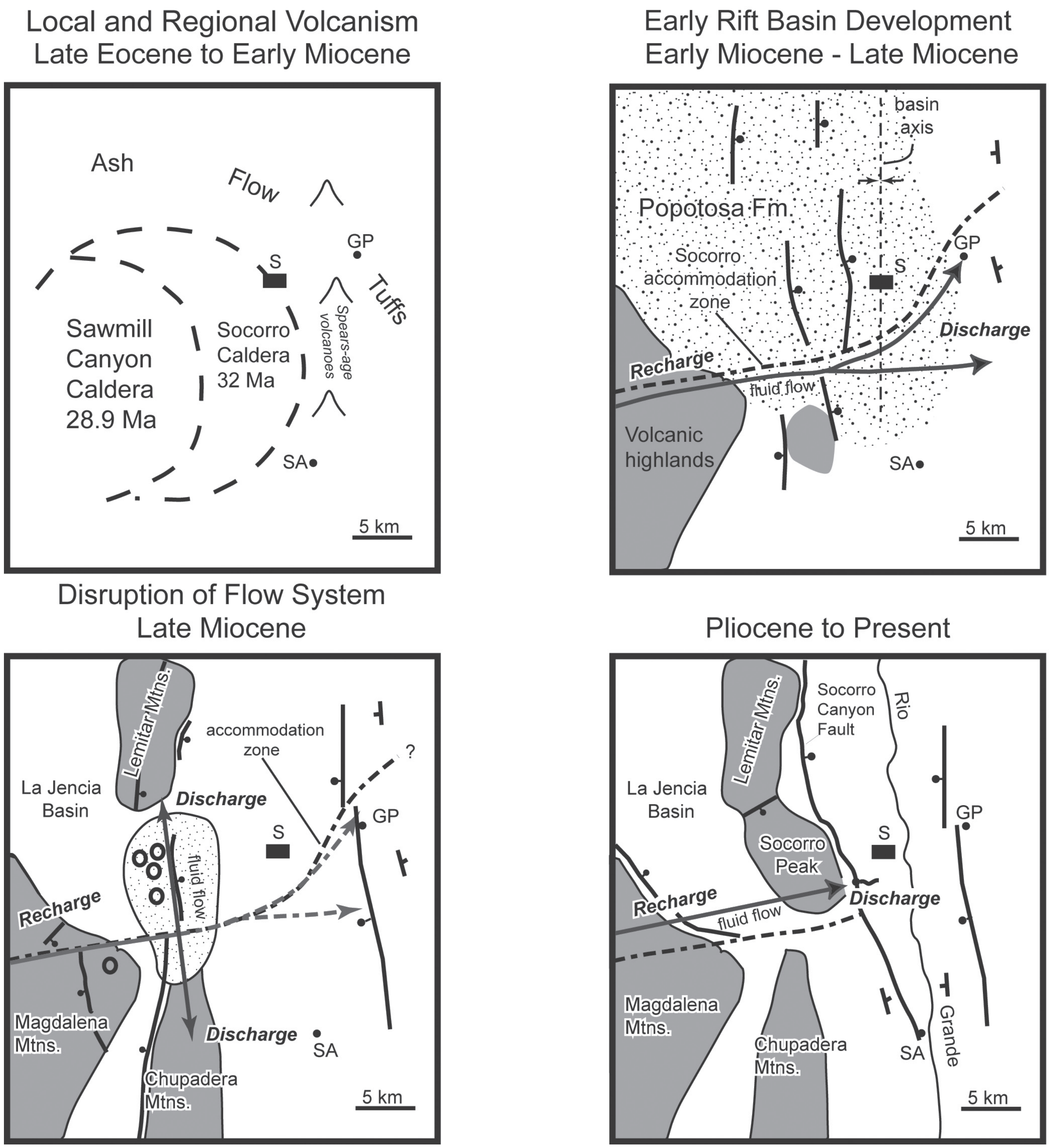

FIGURE 6. Summary of thermal events affecting the Socorro area. The present day locations of Socorro (S), San Antonio (SA), and the Gonzales prospect (GP) are shown for reference. (a) The area is buried by tuffs and volcaniclastic units related to explosive volcanism during late Eocene to early Miocene time. (b) By early to late Miocene, a hydrologic flow system develops, sourced in the highlands of the Mogollon-Datil volcanic field. Rio Grande rift faulting starts to define mountain and basin blocks and the accommodation zone is activated. Dip domains in rocks Oligocene and older are represented by strike-and-dip symbols. Water percolates through Cenozoic tuffs, Paleozoic sedimentary rocks, and a maximum of 2.8 km of Proterozoic basement in the vicinity of the accommodation zone and is discharged to the east of Socorro, resetting AFT ages, altering the Baca Formation, and causing mineralization around the Gonzales prospect. (c) Toward the end of Miocene time, rift-related faulting on the eastern margin of the Socorro basin disrupts the hydrological system and cooling begins on the eastern margin of the basin. Manganese mineralization occurs west of Socorro (Lueth et al., 2004). (d) Discharge is shifted westward to Socorro thermal spring by domino-style faulting in the Lemitar block and juxtaposition of aquitards (playa lake sediments) against aquifers as Socorro Peak is uplifted (Barroll and Reiter, 1990; Mailloux et al., 1999). The accommodation zone is truncated by the Socorro Canyon fault and a different set of dip domains in the Santa Fe Group is formed.

the range, tuffs are faulted against the playa units of the Popotosa Formation, so that the juxtaposition of aquitard against aquiclude forces the heated water to discharge on the east side of the mountain.

Mailloux et al. (1999) expanded on the ideas of Barroll and Reiter (1990) and developed a model that examines the late Cenozoic (17 Ma to present) paleohydrology of the Socorro area. Analogous to the model of Barroll and Reiter (1990), the recharge area is in volcanic highlands in the vicinity of the Magdalena Mountains to the west of Socorro (Fig. 6b-d). The water percolates down into Cenozoic tuffs, Paleozoic sedimentary rocks, and fractured Proterozoic basement and is heated by the background geothermal gradient. Using a background heat flow of 77 mW/m^2, Mailloux et al. (1999) found that 5 % of the total amount of water in the system has to circulate within the Proterozoic basement to maximum depths of 2.8 km below the Proterozoic/Paleozoic unconformity to attain temperatures that match the temperature of the water discharged at the modern Socorro thermal spring (32°C). The Socorro accommodation zone strikes east-northeast from the recharge area towards the discharge area. Highly fractured rock within the Socorro accommodation zone may have permitted deep circulation and influenced eastward movement of heated waters. Modeled paleogroundwater flow patterns during Cenozoic rifting predicted by Mailloux et al. (1999) reveal that groundwater discharge in the southern Socorro basin was focused on the eastern margin of the basin during the Miocene. The flow system was initially disrupted by rift-related faulting on the east side of the Socorro basin, allowing the eastern margin of the basin to cool during middle to late Miocene time. Discharge subsequently shifted at least 15 km westward to its present location at the base of Socorro Peak on the western margin of the basin during the Pliocene. The cause of the westward shift in groundwater discharge and associated elevated heat flow was the juxtaposition of thick confining units (playa lake deposits) against regionally extensive aquifers as the result of fault block rotation and the uplift of Socorro Peak starting 4 to 7 Ma (Fig. 6c). Fluids subsequently moved to the north and south, forming manganese deposits at ~6-7 Ma Ma (Lueth et al., 2004). Later, the Socorro accommodation zone was truncated by the Socorro Canyon fault, forming a different set of dip domains within the Santa Fe Group on either side of this N to NW trending structure (Fig. 6d).

Two independent lines of geological evidence, which are found in the outcrop from which the 94BC07 clasts were taken and in the Proterozoic outcrops in the vicinity of the Gonzales prospect, appear to support the existence of hydrothermal discharge to the east of the modern Rio Grande during the Miocene time from a source to the west. First, the outcrop containing the 94BC07 clasts is composed of typical red Baca Formation interspersed with bands and lenses that have been bleached white (star on Figure 3). Disseminated pyrite was observed in the altered Baca Formation. The bleached zones are not restricted to gravel lenses and layers, but commonly cut across bedding planes. Just north of this deposit in an unnamed drainage east of Arroyo de los Pinos south of Ojo de Amado, the Pennsylvanian Atrasado Formation of the Madera Group is shot through with NE-striking travertine veins that are up to a meter wide. Calcite veins cut the volcaniclastic Eocene Spears Formation nearby. A second outcrop of Baca Formation located between the 94BC06 and 94BC07 localities on the road to Gallinas well has a few thin (<6 cm) bleached zones. No other outcrops of Baca Formation examined during this study contained altered zones. Certainly, not all bleached zones in the Baca Formation are related to hydrothermal activity. Cather (1980) and Read et al. (2007) noted bleaching of the Baca Formation in the vicinity of mafic dikes and faults west of Socorro that are unrelated to the hydrothermal system proposed here. However, the close spatial coincidence of bleached Baca Formation, travertine deposits, and calcite veins cutting the Spears Formation appear to point to water flowing through this area sometime after the Eocene.

FIGURE 7. Fractured, altered quartz monzonite from east side of outcrop, Gonzales prospect. Note alteration and iron-staining parallel to fractures. Field book 18 cm high shown for scale.

Second, the fluorite-barite mineralization observed at the Gonzales prospect and at other Proterozoic outcrops in this area is concentrated along faults on the west side of the Proterozoic knobs, suggestive of a source from the west, with fluids moving up along the basin-bounding fault zone. Staining and alteration parallel to fractures in the highly fractured quartz monzonite on the east side of the outcrop at the Gonzales prospect is indicative of fluid flow through the crystalline rock (Fig. 7). Fluid inclusion paleotemperatures derived from the fluorite deposits are 135 to 184°C, hot enough to reset AFT ages. Oxygen and hydrogen isotope data derived from fluids within the inclusions are consistent with meteoric fluids exchanging with rocks at high temperature or with mixing of meteoric and magmatic water (Hill, 1994; Hill et al., 2000). The high uranium concentrations measured in the quartz monzonite outcrops at and near the Gonzales prospect (McLemore, 1983) may be related to the flow system.

The AFT data from the BC07, BC1&2, and GP localities provide powerful constraints on the timing of cooling following a time of elevated temperatures during pre-middle Miocene time, but the time of initiation of heating is less well-constrained to be post-Eocene. Other possible explanations for the N-S AFT age pattern in the Baca outcrops include: (1) leakage of magmas up along the projection of the Socorro accommodation zone; (2) general upward discharge of heated water along the projection of the Socorro accommodation zone from some other source than the Magdalena Mountains.

The Socorro accommodation zone has leaked magmas periodically since the Oligocene. However, although middle to late Miocene volcanism was common on the western margin of the Socorro basin (Chamberlin, 1980), only a few small dikes of undetermined age (Oligocene?) are exposed on the east side of the basin. Two basalt flows were erupted during the Pliocene on Chupadera Mesa 25 to 30 km away from the BC07 and GP localities (Fig. 3). The timing and exposed distribution of intrusive rocks on the eastern margin of the basin do not coincide with the time of cooling derived from the observed data nor with the the distribution of the unusually young AFT ages. The presence of an unexposed middle Miocene intrusive in the vicinity of the Gonzales prospect cannot be totally ruled out, but the gravity and magnetic data for Socorro County (Keller; 1983; Cordell, 1983) do not indicate large density anomalies in the near-subsurface in this area. The influence of 7.0 to 9.5 Ma silicic volcanism on the west side of the rift on the proposed hydrothermal system was not evaluated by Mailoux et al. (1999), but this volcanism, in combination with faulting, likely plugged up the east-directed plumbing system, resulting in north and south-directed fluid flow and 6 to 7 Ma manganese mineralization west of Socorro Peak (Fig. 6c; Lueth et al., 2004).

Reiter et al. (1986) noted a zone of elevated modern heat flow that roughly coincides with the Tijeras accommodation zone in the Albuquerque basin. These authors speculate that north-to-south fluid flow in the Rio Grande valley is involved in elevating the heat flow, but the data are not dense enough to resolve the origin of the water. In the modern system, water flowing southward through the Rio Grande rift-fill could encounter an accommodation zone and migrate upward. However, the ancestral Rio Grande did not flow through the Socorro area until about 4 to 5 Ma, and during middle Miocene time, the Popotosa basin was a internally-drained basin with its center near the site of the present-day Socorro and Lemitar Mountains (Chamberlin, 1980). Paleogeographic maps of the Popotosa basin and its margins indicate volcanic highlands in the Magdalena Mountains area and minor topographic highs along the eastern margin (Chamberlin, 1980). Topographically driven fluid flow was most likely west-to-east, with minor east-to-west flow; strong south-to-north or north-to-south flow was unlikely.

SUMMARY

AFT ages derived from clasts in the Eocene Baca Formation in the eastern Socorro basin decrease toward the Socorro accommodation zone, both from the north and from the south (Fig. 4). AFT ages in Proterozoic basement rocks on the east side of the basin also decrease from north to south toward the accommodation zone (Fig. 3). The AFT clast ages of 45 to 57 Ma at Palo Duro Canyon record slow cooling of the Laramide Sierra uplift. South of Palo Duro Canyon, the AFT ages in the Baca Formation are generally younger than the stratigraphic age (12 to 39 Ma). These partially reset to totally reset ages record heating due to (1) magma emplacement and caldera eruptions in the eastern Mogollon-Datil volcanic field during Oligocene time, (2) burial of the area by 40 to 24 Ma volcaniclastic sediments, ash-flow tuffs, and lava flows from the Mogollon-Datil volcanic field, and (3) hydrothermal alteration. The youngest totally reset 12 to 18 Ma Baca clast AFT ages and the ~9 Ma Gonzalez prospect AFT ages record cooling related to (1) uplift and erosion of the Loma de las Cañas block and (2) waning of hydrothermal activity. Mailloux et al. (1999) developed a hydrogeologic model of the early Popotosa rift basin that describes a possible geothermal system with a recharge area in the volcanic highlands southwest of Socorro and discharge east of Socorro. According to this model, water percolated into the fractured basement of the Socorro accommodation zone, where it was heated to temperatures >110°C, and was discharged along the eastern margin of the early Popotosa rift basin (Fig. 6b). The flow system was disrupted by Miocene faulting on the eastern margin of the Socorro basin and by late Miocene faulting and volcanism on the west side (Fig. 6c). Later uplift of Socorro Peak on the west side of the basin caused juxtaposition of sediments with contrasting hydrologic conductivity, so that warm water is now discharged at Socorro thermal springs (Fig. 6d). The hydrothermal model is appealing because it provides a ready source of heat to reset fission tracks during middle Miocene time and eliminates the need to keep the Baca Formation at elevated temperatures for 14 m.y., as required by a model that uses only a magmatic source of heat. Although the model is appealing, the model is in need of an update because important geologic constraints derived from detailed mapping (Chamberlin, 1999, 2001, 2004; Chamberlin et al. 2001, 2002, 2004, 2006), such as the deposition of Lower Popatosa Formation in north-striking valleys and the emplacement of late Miocene lava domes along the Socorro accommodation zone, need to be incorporated.

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