Low Temperature Thermochronometry of the Avawatz Mountains, California: Implications for the Inception of the Eastern California Shear Zone

Erik Reinert

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This is to certify that I have examined this copy of a master's thesis by

Erik Reinert

and have found that it is complete and satisfactory in all respects and that any and all revisions required by the final examining committee have been made.

Committee Members:

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Darrel S. Cowan

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Richard J. Stewart

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John Stone

Date: 3/18/04

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Introduction

Thermochronometers are increasingly used to determine the rates and timing of exhumation in orogenic belts. A great deal of thermochronologic work has been done in the North American Cordillera addressing two problems: (1) When were rocks in various mountain belts exhumed? and, more recently, (2) How long-lived is the topography of these mountain belts? In addressing these problems, a consensus has arisen that most exhumation within the Basin and Range Province began in the mid-Miocene, and continues today at similar or reduced rates (e.g. Stockli et al., 2000; Reiners et al., 2000; Surpless et al., 2002; Armstrong, et al., 2003).

Thermochronometers with intermediate to high closure-temperatures such as argon-cooling ages and fission-track ages are useful tools when studying long-lived (greater than a few million years) tectonic exhumation where tens of kilometers of overburdening rocks have been removed. More youthful (latest Miocene and younger) range-bounding fault systems remain active within the Basin and Range and continue to produce young topography. However, youthful topography has often undergone insufficient exhumation to expose reset or partially reset ages in many thermochronometers. Consequently, quantitative treatment of recent (Pliocene and younger) bedrock uplift and exhumation is often overlooked in thermochronologic studies. Low-temperature thermochronometers, such as (U-Th)/He and apatite fission-tracks, must be used to study recent tectonic exhumation of rocks that previously resided within the upper 5-10 km of the crust.

Though much of the exhumation in the Cordillera of the western U.S. is due to extension since Miocene time, several notable exceptions exist, particularly within the

Basin and Range and bordering tectonic provinces in southern California (Fig. 1). The Transverse Ranges of southern California have undergone rapid post-Miocene uplift and exhumation due to transpression within the Big Bend of the San Andreas Fault (Fig.1) (Spotila et al., 1998; Blythe et al., 2000). Several transpressive structures are also active within the Eastern California Shear Zone, a region of distributed dextral shear east of the Sierra Nevada Block and within the Basin and Range Province (Figs. 1 and 2) (Glazner et al., 2002; Bartley et al., 1990; Miller et al., 2001; Dokka and Travis, 1990).

The Avawatz Mountains are one such transpressive mountain range, located at the eastern termination of the Garlock fault (Fig. 2). The Garlock is a major sinistral strike-slip fault that separates the highly extended Death Valley terrane to the north from the less extended Mojave Block to the south (Fig. 2). In the intra-continental transform model of Davis and Burchfiel (1973), total slip on the Garlock decreases from west to east and the fault terminates at a hypothetical zone of zero-displacement which projects east of the Avawatz. More recent work demonstrates that the Garlock fault terminates in a sharply southward bending thrust (Spencer, 1990a). The Garlock fault initiated in the mid Miocene (Burbank and Whistler, 1987; Monastero, et al. 1997; Smith et al., 2002). However, shortening in the Avawatz mountains appears to be significantly younger than the full history of the Garlock fault based on folded and tilted Miocene sediments within the range (Brady, 1984; Spencer, 1990a). This apparent disparity in ages leads to two opposing hypotheses: Either (1) the Avawatz Mountains are the logical termination of the Garlock Fault (and in turn behave as the

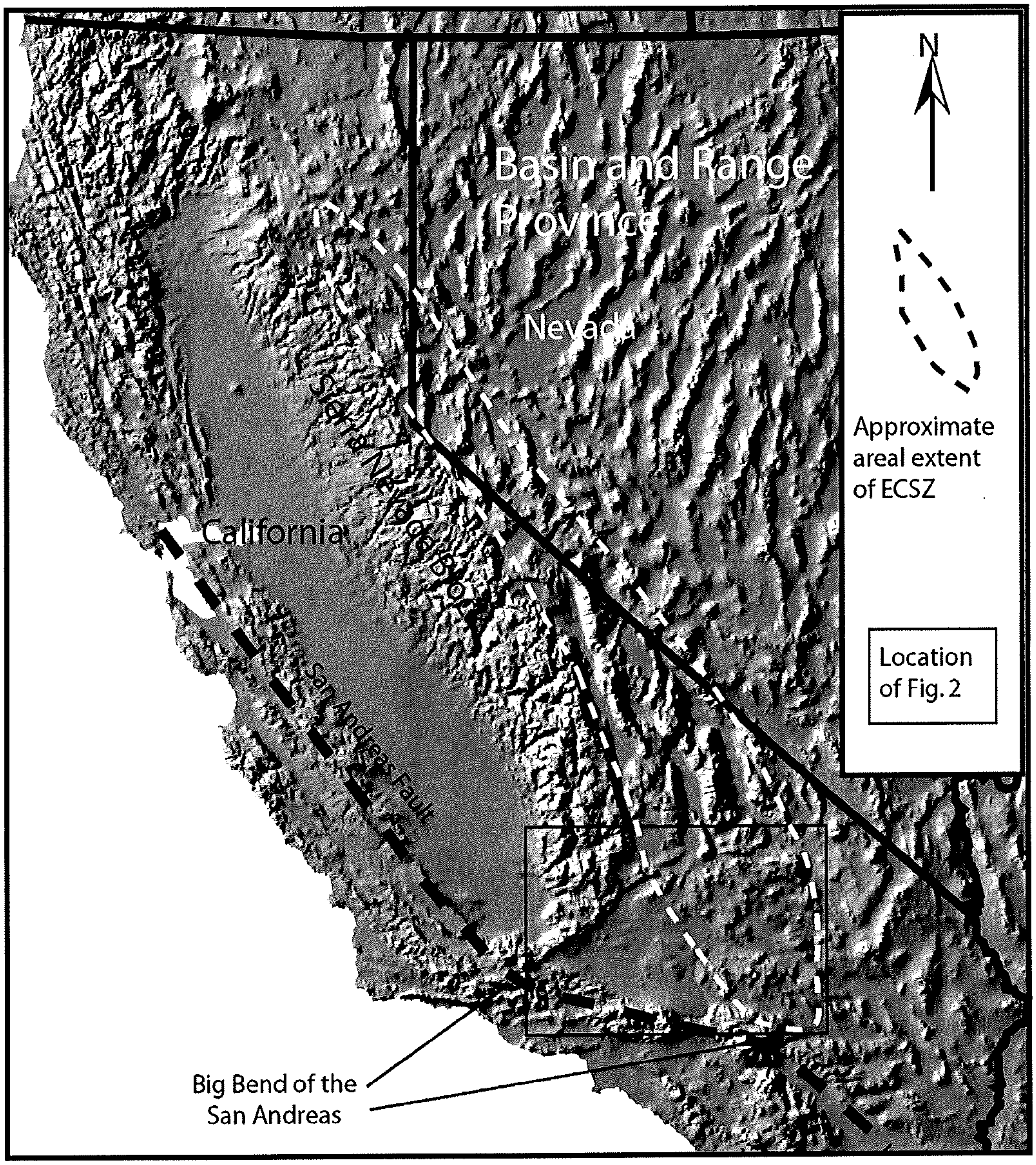


Figure 1: Location map. California and western Nevada. Location of Eastern California Shear zone (ECSZ) generalized from Miller et al. (2001).

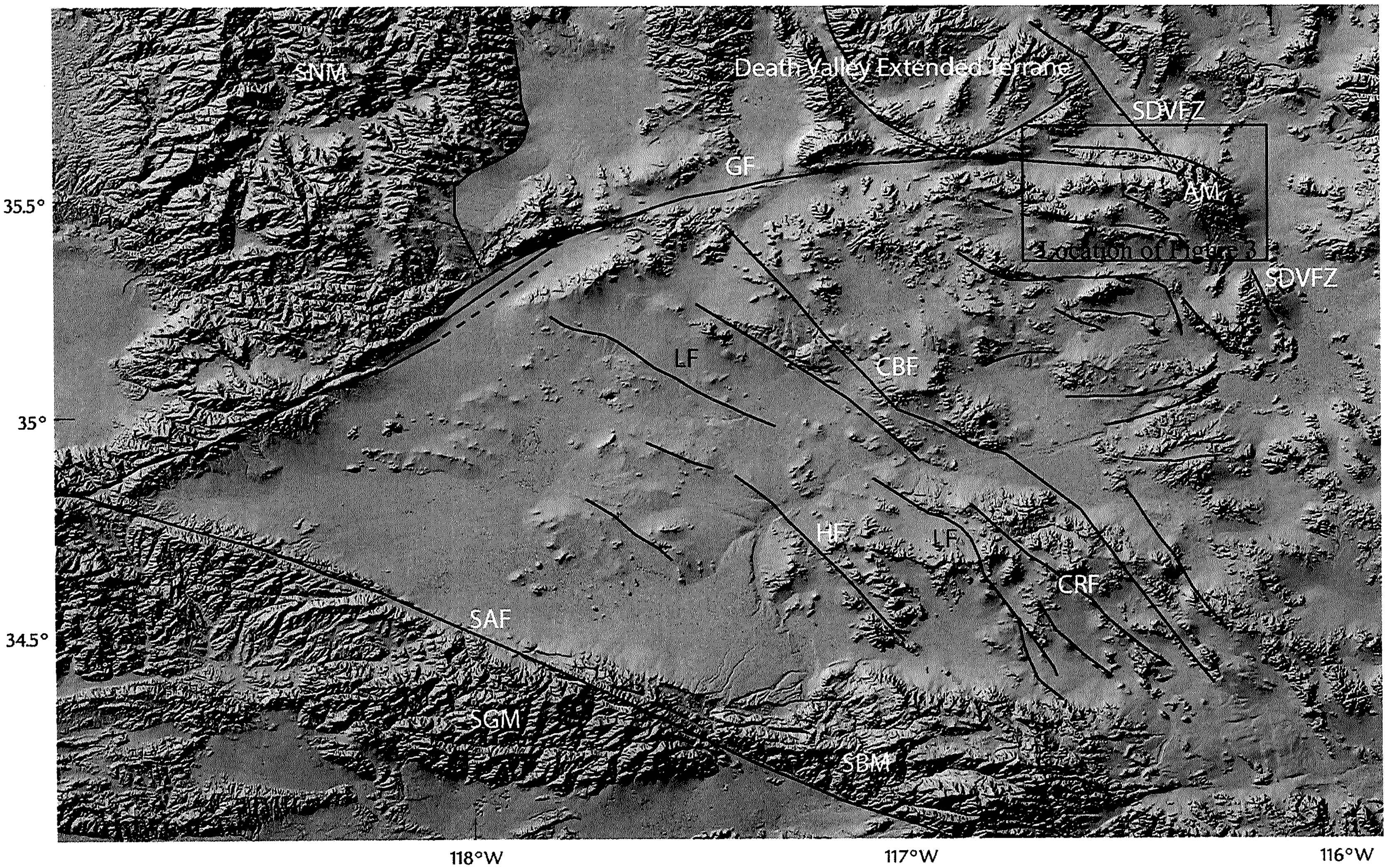
leading edge of a relatively rigid Mojave Block), or (2) thrust faulting in the Avawatz mountains is unrelated to long-term slip of the Garlock fault, and thrusting along the Avawatz range-front is caused by transpression within the Eastern California Shear Zone.

This paper addresses the Miocene to present cooling history of the Avawatz mountains using low-temperature thermochronometers [(U-Th)/He and apatite fission-tracks]. The purpose of this study is to better understand the kinematic history of the Garlock fault within the context of the Eastern California Shear Zone. This paper also demonstrates the ability of low-temperature thermochronometers to determine the exhumation history of small ranges (< 10 km wide) with modest amounts of bedrock uplift.

Tectonic Setting and Geologic Background

1. Location of the Avawatz mountains and range-bounding faults

The Avawatz mountains are located at the intersection of the dextral Southern Death Valley fault zone and the sinistral Garlock fault (Fig. 2). The northern range-bounding fault is the Mule Spring fault, a left-lateral splay of the Garlock fault which becomes increasingly thrust sense as it curves southward around the eastern flank of the range (Figs. 2 and 3). The eastern Avawatz mountains are bounded by the Old Mormon Spring fault, an east-vergent thrust fault that emplaces Mesozoic granitic rocks and Paleozoic to Precambrian sedimentary bedrock over Quaternary debris-flow fans (Spencer, 1990a and 1990b).


SNM
Death Valley Extended Terrane
SDVFZ
GF
AM
Location of Figure 3
SDVFZ
LF
CBF
HF
LF
CRF
SAF
SGM
SBM
35.5°
35°
34.5°
118°W
117°W
116°W

2. The Garlock fault and its tectonic significance

The Garlock fault separates the more extended Death Valley terrane to the north from the less extended Mojave Block to the south. Maximum offset on the fault is 64 km based on displacement of the Jurassic Independence dike swarm (Davis and Burchfiel, 1973). Clockwise increases in magnetic declination anomalies from the El Paso basin north of the central Garlock fault require initiation of slip by 11 Ma (Burbank and Whistler, 2002). Miocene volcanics and sedimentary rocks within the El Paso basin record the full 64 km of displacement on the Garlock and supply geologic evidence for slip initiation after 17 Ma (Monastero, et al., 1997). Slip-rate estimates of 3.1-3.8 mm/yr for the last 10.4 Ma, based on offset volcanic rocks in the Lava mountains extrapolated to the full 64 km offset, yield an inception of sinistral slip at 16.4 Ma (Smith et al., 2002). However Quaternary slip rates for the central Garlock fault are significantly faster than this estimate, ranging from 7mm/yr (Carter, 1994) to 5-7 mm/yr (McGill and Sieh, 1993). Initiation of the Garlock likely occurred due to rapid east-west extension between the Black mountains and the Sierra Nevada block during the Miocene (Davis and Burchfiel, 1973; Snow and Wernicke, 2000). Continued extension in Death Valley, Panamint Valley, and Owens Valley probably helps drive left-lateral slip on the Garlock fault today.

Davis and Burchfiel (1973) proposed the Garlock as an intra-continental transform fault based on the increasing magnitude of sinistral offset along the fault's trace from east to west. This interpretation predicts that the Garlock fault should terminate somewhere east of the present-day Avawatz mountains at a zone of projected zero-displacement. However, the Avawatz mountains truncate this hypothesized termination, and several workers have considered a thrust fault termination to be an acceptable alternative to the zero-displacement hypothesis (Spencer, 1990a; McGill, personal communication). In this interpretation the Mule Spring and Old Mormon Spring faults represent the northeastern leading edge of a relatively rigid Mojave Block.

Perhaps the most interesting feature of the Garlock fault for the purposes of this study is the broad oroclinal bend in the trace of the fault, which deviates from a northeast strike on its western end to an east-west strike on the eastern end of the fault (Fig. 3).

3. The Mojave Block

The Mojave block is a wedge-shaped tectonic province with characteristically subdued topography bounded by the Garlock fault to the north and the Big Bend of the San Andreas fault to the south (Figs. 1 and 2). The Cenozoic history of the Mojave Block includes several distinct tectonic events. The early Tertiary was a period of tectonic quiescence (Glazner et al., 2002) that allowed a widespread geomorphic surface to form within the Mojave Block (Dokka and Macaluso, 2001). Localized, large-magnitude extension began in the early Miocene and continued until 18 Ma in the central Mojave block (Glazner et al., 2002). Rhyolitic to basaltic volcanism began at the same time, continued well into the late Miocene, and ended with a few small-volume basalt flows at ~5 Ma (Glazner et al., 2002; Schermer et al., 1996).

Active northwest-striking right-lateral faults crosscut earlier tectonic features of the eastern Mojave desert in part of what is now known as the Eastern California Shear

Zone (ECSZ). The ECSZ was first named by Dokka and Travis (1990) who recognized the importance of these faults in accommodating missing motion on the San Andreas fault. Subsequent geodetic observations in eastern California now delimit the entire ECSZ as a zone of dextral strain that extends northwards through the Walker Lane to the Klamath mountains (Miller et al., 2001). This zone of deformation accommodates up to 15% of the relative motion between the Pacific and North America plates (Dokka and Travis, 1990). The ECSZ is easily recognizable in topographic maps as a belt of mountain ranges and intervening basins between the Sierra Nevada and the Basin and Range with northwest-striking physiographic and structural orientations (Fig. 1).

The strike-slip faults of the Mojave block can be divided into several discrete and recognizable domains (Fig. 2). The two largest and most important are:

(1) A domain of through-going northwest striking faults in the central Mojave block extends from the San Andreas fault to the Garlock fault. Though the ECSZ extends north of the Garlock fault, none of these northwest-striking faults cuts either the Garlock or the San Andreas. Instead, the faults end in zones of diffuse deformation (Dokka and Travis, 1990). This domain of faulting produced the 1999 Hector Mine earthquake and the 1992 Landers earthquake.

(2) A domain of east-striking oblique left-lateral faults in the northeastern Mojave block shows evidence of north directed reverse slip on some faults (Miller and Yount, 2002; Schermer et al., 1996). This domain of east-striking faults is immediately south of and strikes parallel to the broad oroclinal bend in the Garlock fault. Schermer et al. proposed a model for this system of east

striking faults whereby fault bounded blocks are rotated clockwise in response to left slip. Furthermore, they suggested that the ends of fault blocks were more affected by distributed ductile strain than the main portion of each fault block. Widely scattered magnetic rotations, fault curvatures, and in the case of the Avawatz mountains, uplift and shortening resulted from this relationship (see Figure 14, Schermer et al., 1996).

Controversy remains over the timing of strike-slip initiation in the Eastern California shear zone. Age estimates for the ECSZ range widely from 2-11 Ma (Dokka and Travis, 1990) to 5.6 Ma (Schermer et al., 1996). Yet, the importance of the ECSZ in accommodating plate boundary motions is well documented (Dokka and Travis, 1990; Miller et al., 2001). Consequently, tectonic events as far removed as the opening of the Gulf of California and the transition from extension to strike-slip motion in the Death Valley region and Walker Lane would greatly benefit from a more complete and precise understanding of ECSZ timing. Dokka and Travis estimated an inception of strike-slip motion at ~11 Ma for the ECSZ based on geologic mapping in this central domain of the Mojave Desert. Work in the northeastern sinistral domain of the Mojave block suggests that slip in this domain is significantly younger than the estimate of Dokka and Travis. Volcanic rocks between 17 Ma and 5.6 Ma within the northeastern Mojave desert have similar total displacements. This similarity in displacement amounts of all Miocene rocks in the region suggests that strike-slip motion in the ECSZ is late Miocene or younger (Schermer et al., 1996).

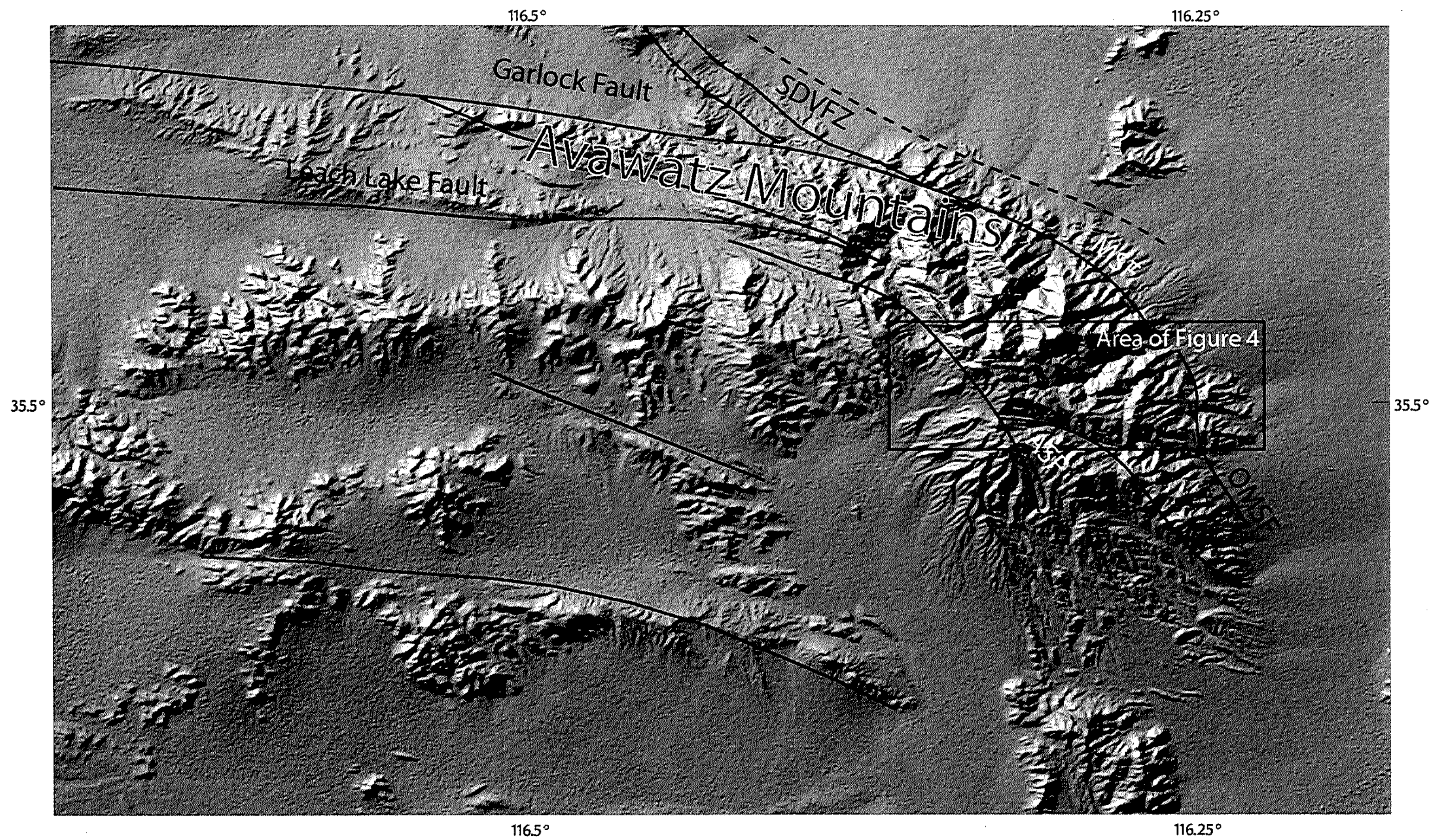
4. Southern Death Valley Fault

The Southern Death Valley fault (SDVF) is an active right-lateral fault that strikes northwest along the southwestern flank of the Black Mountains through southern Death Valley (Fig. 2). The SDVF borders the western front of the Black Mountains and intersects the Garlock fault along the northern flank of the Avawatz mountains in a zone of anastomosing reverse and strike-slip faults (Fig. 3). This anastomosing zone of faults narrows towards the eastern flank of the Avawatz mountains while becoming increasingly thrust-sense.

The SDVF is the easternmost fault in the Eastern California Shear zone (Miller et al., 2001). The interaction between the SDVF and the Garlock fault creates a region of compression that is responsible for shortening within the Avawatz mountains (Spencer, 1990a).

Geology of the Avawatz Mountains

The Avawatz Mountains are composed primarily of Mesozoic magmatic arc granitoids and, to a lesser extent, Precambrian – Paleozoic metasedimentary rocks (Spencer, 1990b). They are bounded on the north by the oblique Mule Spring fault and on the east by the Old Mormon Spring reverse fault (Figs. 3 and 4). The early Miocene Arrastre Spring fault in the western Avawatz mountains separates the primarily granitic bedrock of the Avawatz from early Miocene to Pliocene fluvial and alluvial deposits of the Avawatz Formation (Spencer, 1990a,b; Brady, 1984). Deposition of the Avawatz formation and normal faulting on the Arrastre Spring fault were coeval, and by late



116.5°
116.25°
35.5°
35.5°
116.5°
116.25°
Garlock Fault
SDVFZ
Avawatz Mountains
Leach Lake Fault
Area of Figure 4
OMSF

Miocene time the sediment source for the upper Avawatz Formation was somewhere to the southeast of the modern Avawatz mountains (Spencer, 1990a,b; Brady, 1984).

Methods

1. (U-Th)/He technique

The (U-Th)/He method of thermochronometry dates the time when apatite crystals have cooled through a temperature of ~70 °C (Wolf et al, 1996; Farley, 2000). The temperature when time starts to be recorded in the thermochronometer is the closure temperature. Below this closure temperature, apatite crystals begin to retain helium produced by the alpha decay of uranium and thorium, which occur as trace elements in the crystal lattice. He closure is not complete at 70 °C, but rather He diffusion gradually decreases within a temperature zone between ~40-80 °C, termed the helium partial retention zone (PRZ) (Stockli, et al., 2000, Ehlers and Farley, 2003).

The (U-Th)/He method potentially dates young rock-exhumation events because it represents a lower temperature system than any other currently developed thermochronometer. The Avawatz Mountains are an ideal location to apply this technique because recent and rapid vertical tectonic motions and tilting have probably occurred, and the bedrock of the range is primarily apatite-bearing quartz monzodiorite (Spencer, 1990a,b; Calzia and Rämö, 2000).

Dating a suite of rocks from a mountain block using a single thermochronometer at a range of elevations is a useful technique for studying tectonic exhumation. In addition, two or more thermochronometers with differing closure temperatures can be used from a single sample to provide more information on the cooling history of a range block. Advection of isotherms during rock uplift can complicate interpretation of cooling rates using this technique (Ehlers and Farley, 2003). A reasonable upper-limit on exhumation rates can be determined regardless of such complications, and the data may illustrate acceleration of cooling between the times that the first thermochronometer (e.g. apatite fission-tracks) and the second thermochronometer reach closure.

Apatite ages were obtained at the (U-Th)/He Chronometry Lab at Yale University in New Haven, CT and corrected for alpha ejection (Farley et al., 1996) by Professor Peter Reiners. Ages were determined for individual apatite crystals and repeated in triplicate for most samples in order to ensure that samples contained measurable helium concentrations and reproducible results.

2. Fission -track Dating

If recent cooling in the Avawatz mountains is associated with young thrust faults and occurred after a period of more quiescent tectonic behavior, the use of two thermochronometers in conjunction (in this case apatite fission-tracks and (U-Th)/He) would help illustrate the youthfulness of the range.

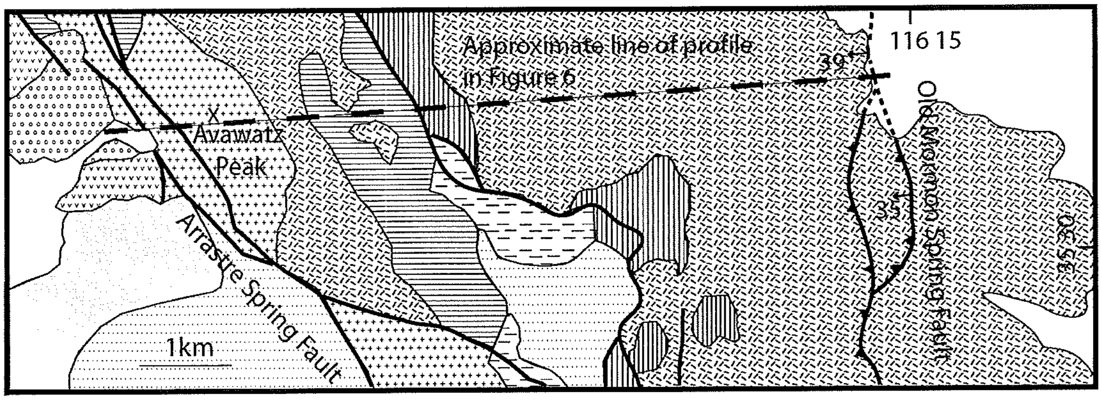
The apatite fission-track method of thermochronometry dates the time when apatite crystals have cooled below the temperature of ~110 °C (Green et al., 1989). Spontaneous fission of radioactive trace elements creates damage tracks in the crystal lattices of a variety of Uranium-bearing minerals. Fission-tracks in apatite anneal rapidly at temperatures higher than ~110 °C. As apatite cools through the closure temperature, the annealing rate slows. The partial annealing zone of apatite (PAZ), between 60 and 110 °C, is analogous to the helium partial retention zone.

Apatite fission-track dates were obtained at the fission-track laboratory facility at the University of Washington, under the supervision of Professor Richard Stewart. Apatite samples were mounted in epoxy, polished and etched with 0.5 M HNO_3 for 20 seconds according to Wagner and Van den Haute (1992). Samples were covered with mica detectors and sent off to the Oregon State Reactor Facility to be irradiated for 25 hours. Mica detectors were etched in 40% HF for 20 minutes (Wagner and Van den Haute, 1992).

Results

Average sample (U-Th)/He ages calculated from replicate single crystal analyses range from 4.0 ± 0.2 (2σ) Ma at 1010 m elevation (sample AV-5) to 7.2 ± 0.5 Ma at 810 m elevation (AV-11) (Fig. 5; Table 1). The oldest helium ages come from locations at both high elevations in the interior of the range and low elevations near active range-front of the Avawatz mountains (Figs. 5 and 6). Therefore, apatite helium ages show no age-elevation trend.

Apatite fission-track ages (Fig. 5; Table 2) range from 19.5 ± 5 Ma at 650 m elevation (AV-1) to 9.0 ± 2.5 Ma at 1010 m elevation (AV-5). The apatite fission-track data are remarkably similar to the helium data in that the lowest elevation sample is older than samples at higher elevations.



- Surficial Deposits (Quaternary)
- Avawatz Formation, sandstone and siltstone facies (Pliocene and Miocene)
- Avawatz Formation, conglomerate facies (Miocene)
- Sedimentary and volcanic rocks, undivided (Miocene)
- Metavolcanic rocks (Mesozoic)
- Avawatz Mountains Quartz Monzodiorite (Jurassic)
- Granites of Avawatz Peak (Jurassic or Triassic)
- Limestone and dolomite marble (Paleozoic)
- Quartzite, phyllite and marble (Cambrian and Upper Proterozoic)
- Quartzite, phyllite and marble (Upper Proterozoic)

Figure 4: Geologic Map of the central Avawatz mountains (from Spencer, 1990a).

Discussion

The circa 7 Ma He ages and circa 19 Ma fission-track age near the range front and the abrupt step towards younger ages at slightly higher elevations in both data sets (Fig. 5) indicate that the processes involved in producing the helium age-elevation distribution were also at work in producing the fission-track age-elevation distribution. Two of the old range-front samples (AV-1 and AV-11) are located in the hanging-wall of the Old Mormon Spring fault, whereas sample AV-2 is located in the footwall (Fig 6).

Figure 6 is a topographic profile of the Avawatz mountains drawn parallel to the sampling transect. Helium age isochrons at 4 Ma and 5 Ma are offset along a hypothesized fault located west of the active range-bounding fault. The 5 Ma He isochron is currently located at a higher structural level than the 7 Ma He isochron, which is depicted in the footwall of this hypothesized fault (Fig. 6). The helium age distributions in Figure 6 suggest recent reverse slip along this previously unmapped fault (see Figure 4) located within the plutonic bedrock of the Avawatz, where no offset markers exist. The extremely fractured nature of the Quartz Monzodiorite of the Avawatz mountains further supports the existence of this fault.

This offset of isochron markers within the bedrock of the Avawatz mountains is evidence for a recent faulting and cooling event. Furthermore the step towards older ages at low elevations near the range front in the initial thermochronologic results (Fig. 5) suggests that not all samples participated in this cooling event. Figure 7 is an interpreted plot of the thermochronologic data that excludes samples located in the footwall of the hypothesized fault in Figure 6. In this interpretation, an imaginary 7 Ma

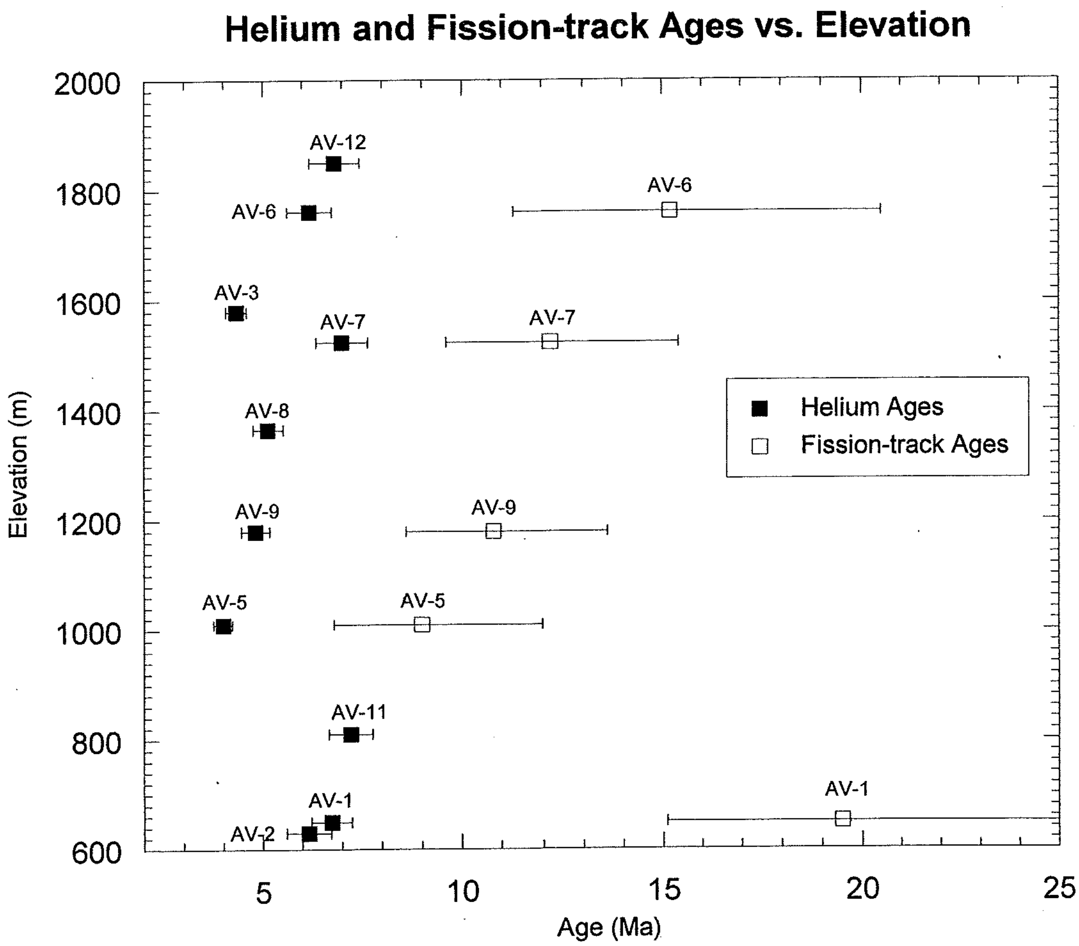


Figure 5: Apatite (U-Th)/He and fission-track ages vs. elevation from the Avawatz Mountains. Error-bars are 2-sigma estimates. 2-sigma estimates are calculated following the procedure of Farley et al. (2003) for the helium ages.

He isochron surface that projects above the current topography of the Avawatz mountains was once a continuous, nearly horizontal surface, that was offset by the hypothesized fault, tilted eastwards during faulting, and eroded away. The background or pre-orogenic age of the Avawatz mountains is circa 6.8 Ma based on the oldest He ages both at high and low elevations that previously resided at or near the same structural level.

Besides exclusion of the low-elevation samples from the interpreted data set (Fig. 7), I have also excluded the helium age of sample AV-7. In Figure 6, sample AV-7 lies anomalously close to the 5 Ma He isochron, yet the sample age is 7.0 ± 0.6 Ma. This age is based on two individual crystal analyses. However, a third analysis, rejected as irreproducible, has an age of 4.8 ± 0.3 Ma.

The timing and rate of the cooling event induced by offset along the hypothesized Avawatz bedrock fault are recorded in the remaining interpreted thermochronologic data (Fig. 7). A linear age-elevation fit to the interpreted fission-track data, indicates an exhumation rate between ~15 Ma and ~9 Ma of 0.13 mm/yr (Fig. 8). This exhumation rate is indicative of slow vertical passage of the sampling transect through a fission-track partial annealing zone (PAZ) and is thus considered an apparent exhumation rate. Note that the true exhumation rate of the Avawatz mountains could have been significantly slower (on the order of 50%) between 15 and 9 Ma if the data are corrected for heat advection and passage through a fission-track PAZ (Ehlers and Farley, 2002).

A linear age-elevation fit to all of the interpreted helium samples (Fig. 7), indicates an exhumation rate of 0.35 mm/yr between ~7 Ma and ~4 Ma (Fig. 8). The

Sample	UTM Easting, m	UTM Northing, m	Elevation, m	^{4}He, ncc	[U], ppm	[Th], ppm	Th/U	He	Mass, µg	F_t	Radius, µm	Age ($\pm 2\sigma$ error), Ma	Average Age ($\pm 2\sigma$ error), Ma
AV1	0567452	3930733	650										
Analysis a				0.41	110.9	147.3	1.33	90.92	4.53	0.77	60.5	6.74 (0.40)	6.75 (0.51)
Analysis b				0.41	154.1	190.4	1.24	129.37	3.14	0.71	42.8	7.62 (0.46)	
Analysis c				0.10	75.3	94.4	1.25	48.58	2.09	0.70	45.8	5.88 (0.35)	
AV2	0567790	3930392	630										
Analysis a				0.57	121.3	218.7	1.80	99.98	5.73	0.78	63.8	6.15 (0.37)	6.17 (0.57)
Analysis b				0.50	289.9	495.2	1.71	216.45	2.3	0.71	48.5	6.19 (0.37)	
AV3	0563134	3930346	1580	0.07	98.5	148.7	1.51	45.40	1.48	0.65	36.5	4.33 (0.26)	4.33 (0.26)
AV5	0564784	3930344	1010	0.02	10.6	5.8	0.55	4.43	5.28	0.77	57.3	4.00 (0.24)	4.00 (0.24)
AV6	0563392	3931647	1761										
Analysis a				0.14	41.2	28.2	0.69	24.99	5.57	0.77	55.3	5.65 (0.34)	6.19 (0.57)
Analysis b				1.12	159.5	198.9	1.25	134.23	8.33	0.80	68.5	6.73 (0.40)	
AV7	0564149	3931483	1524										
Analysis a				0.90	119.3	142.9	1.20	102.31	8.76	0.80	68.8	6.90 (0.41)	7.01 (0.64)
Analysis b				0.83	136.4	158.7	1.16	118.23	7.05	0.79	66	7.11 (0.43)	
AV8	0564729	3931574	1365										
Analysis a				0.25	139.5	141.1	1.01	78.09	3.23	0.73	47.5	5.16 (0.31)	5.14 (0.39)
Analysis b				0.25	138.9	179.3	1.29	81.43	3.04	0.72	47.5	5.15 (0.31)	
Analysis c				0.43	123.0	147.5	1.20	75.11	5.73	0.77	59.3	5.10 (0.31)	
AV9	0565414	3931577	1180										
Analysis a				0.04	25.9	49.6	1.92	15.06	2.92	0.74	57	4.49 (0.27)	4.82 (0.36)
Analysis b				0.15	33.1	74.8	2.26	25.85	5.64	0.76	55.5	5.54 (0.33)	
Analysis c				0.27	42.3	112.8	2.67	29.14	9.31	0.79	65	4.41 (0.26)	
AV11	0566792	3931720	810										
Analysis a				0.37	107.0	65.4	0.61	91.65	4.04	0.75	54.5	8.22 (0.49)	7.22 (0.54)
Analysis b				0.34	152.8	34.4	0.22	104.45	3.22	0.74	52.5	7.24 (0.43)	
Analysis c				0.24	109.2	58.3	0.53	68.74	3.55	0.75	52.3	6.22 (0.37)	
AV12	0560681	3930076	1850										
Analysis a				0.02	16.7	61.3	3.67	14.53	1.4	0.59	29.3	6.56 (0.39)	6.82 (0.63)
Analysis b				0.07	38.1	66.9	1.76	32.37	2.15	0.70	46.5	7.08 (0.42)	

helium data therefore represent a potential increase in exhumation rate in the last 7 million years. However, a recognizable break in slope occurs at ~4.8 Ma. A line fit to the data above this break in slope indicates an exhumation rate for the highest Avawatz samples of 0.11 mm/yr, similar to the apparent exhumation rate recorded by the fission-track data (Fig. 8). This exhumation rate is indicative of slow vertical passage of the sampling transect through a helium partial retention zone (PRZ) and is thus considered an apparent exhumation rate. Advection of isotherms and passage through the PRZ could again result in an overestimate in this rate on the order of 50% (Ehlers and Farley, 2002).

At ~4.8 Ma the exhumation rate recorded by the remaining helium data increases to 1.7 mm/yr (Fig. 8). Though this exhumation rate is again a potential overestimate due to advection of heat during vertical rock uplift, it is an order of magnitude faster than the apparent rate recorded by samples interpreted to be from a fossil PAZ and fossil PRZ. Sample AV-7 would fall along this exhumation rate line if the true helium age of the sample is 4.8 ± 0.3 Ma.

Based on the apparent exhumation rates recorded in the helium data and fission-track data, I propose the following model for the bedrock uplift and exhumation history of the Avawatz mountains:

1. Between ~15 Ma and ~5 Ma, the Avawatz mountains resided near the modern termination of the Garlock fault as a region of low relief topography, perhaps a relict of Early Miocene extension on the Arrastre Spring fault. Exhumation rates < 0.1 mm/yr were the result of slow erosional exhumation of this low relief topography. The Garlock fault was active by 11 Ma and did not

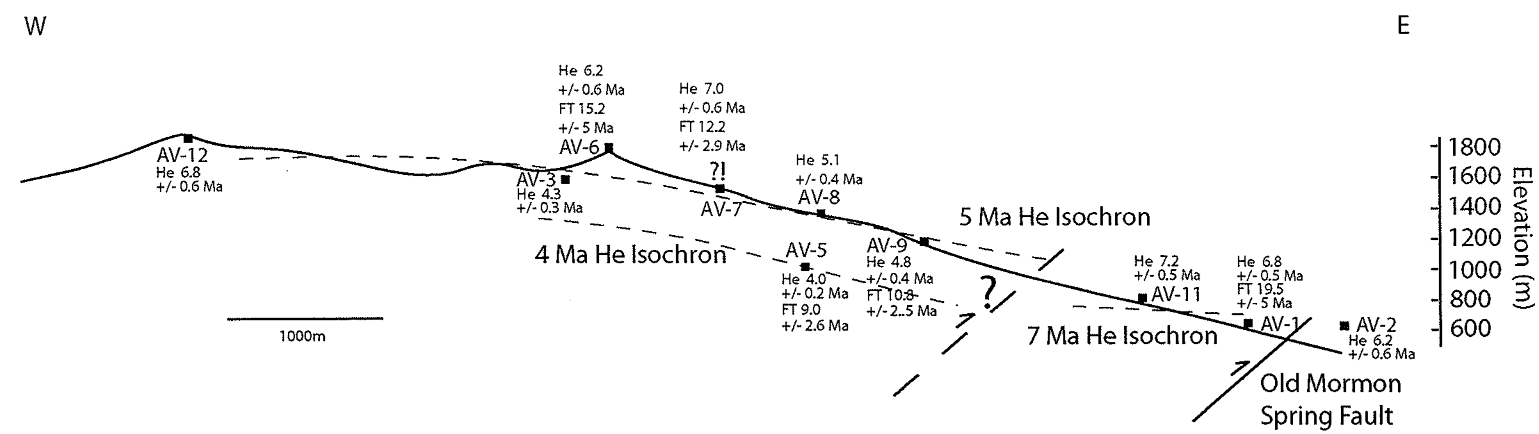


Figure 6: Avawatz Sample Profile: This topographic profile is taken parallel to the sampling traverse (see Figure 4 for location of the profile). Sample locations are projected onto this profile from either side of the profile line. No samples lie more than a kilometer north or south of the profile. Helium and fission-track ages are plotted next to each sample location. Note that sample AV-7 is anomalously located near the 5 Ma isochron, which suggests possible error in the age determination of this sample. He - Helium age; FT - fission-track age.

terminate in a thrust fault, but may have terminated in a zone of zero-displacement as hypothesized by Davis and Burchfiel (1973).

2. At ~7 Ma rocks currently located near the modern range front of the Avawatz mountains were located at or near the same structural level as rocks currently exposed at the highest elevations in the range. All of these rocks attained helium closure at this time during slow exhumation through a PRZ.

3. At ~4.8 Ma reverse slip began along a hypothesized fault located west of the currently active range-bounding fault within the quartz-monzodiorite bedrock. Slip on this fault offset previously horizontal He isochrons and tilted them towards the east and created the modern sample age distribution.

Slip on this hypothetical fault probably created the first significant topographic relief in the region of the Avawatz Mountains since early Miocene time. Relief production would have induced rapid erosion and rapid cooling near an ancient range front through landsliding, a process which is currently recorded in the debris-flow fans of the Avawatz mountains' east slope. Rocks within the range are intensely fractured and clay-altered, which probably encourages gravitational mass-wasting of the range-front to this day, and also supports the existence of the fault hypothesized east of the modern range front.

4. Shortening and range-block exhumation continued into the Quaternary and exposed a fossil PRZ, a fossil PAZ, and fully reset helium ages that record the cooling event that began at ~4.8 Ma. Modern range-front deformation appears to be localized on the range-bounding Old Mormon Spring fault. No abrupt offset in the 7 Ma isochron surface occurs across this fault. This lack of

Table 2 - Avawatz Fission-track Ages

Sample	Rock Type	UTM Easting, m	UTM Northing, m	Elevation, m	Number of Grains Dated	$\rho_s \times 10^5$ t/cm^2	$\rho_i \times 10^6$ t/cm^2	$\rho_d \times 10^6$ t/cm^2	Central Age, Ma (1 SE)	$P(\chi)^2$, %	Uranium Content (SE), ppm
AV-1	Avawatz Mountains Quartz Monzo-Diorite	0567452	3930733	650	10	7.79 (125)	3.92 (629)	2.93 (5465)	19.5 (-4.4 +5.7)	44.3	53 (5)
AV-5	Jurassic-Cretaceous (?) Granite	0564784	3930344	1010	16	0.57 (77)	0.615 (830)	2.89 (5465)	9.0 (-2.2 +3.0)	68.9	8 (1)
AV-6	Avawatz Mountains Quartz Monzo-Diorite	0563392	3931647	1761	6	6.31 (126)	4.42 (882)	2.87 (5465)	15.2 (-3.9 +5.3)	8.1	61 (4)
AV-7	Avawatz Mountains Quartz Monzo-Diorite	0564149	3931483	1524	18	4.77 (201)	3.89 (1640)	2.84 (5465)	12.2 (-2.6 +3.2)	10.4	55 (3)
AV-9	Avawatz Mountains Quartz Monzo-Diorite	0565414	3931577	1180	22	1.22 (198)	1.08 (1743)	2.82 (5465)	10.8 (-2.2 +2.8)	8.6	15 (1)

Table 2: Avawatz Fission-track Ages. Definitions are as follows: ρ_s, spontaneous track density; ρ_i, induced track density. Number in parenthesis is the number of tracks counted for ages and fluence calibration; ρ_d, track density in muscovite detector covering glass standard CN-1 (39 ppm); reported value determined from interpolation of values for detectors covering standards at the top and bottom of the reactor package (fluence gradient correction). SE, standard error. $P(\chi)^2$, chi-squared probability; zeta, 67.04 ± 5.40.

offset suggests that the Old Mormon Spring fault is Quaternary in age, and has accumulated little offset at present.

Conclusions

The model proposed above has significant importance for the regional tectonic history of the Eastern California Shear zone, the Garlock fault, and relative plate motions at the Pacific margin. Uplift and exhumation in the Avawatz mountains is not associated with the full history of slip on the Garlock fault, based on the post 5 Ma cooling event recorded in the Avawatz helium ages.

Initiation of the Eastern California Shear zone has been poorly dated by previous workers (Dokka and Travis, 1990; Schermer et al., 1996). Gan et al. (2003) estimated an inception of the ECSZ at 5.0 ± 0.4 Ma for the eastern part of the ECSZ and about 1.6 Ma later for the western part, on the basis of current strain rates and accumulated dextral strain across the Garlock fault recorded by the modern oroclinal bend in the fault trace. I present evidence from apatite (U-Th)/He and fission-track data that suggests recent, tectonically induced cooling of the Avawatz mountains began at ~4.8 Ma. These data suggest that inception of right lateral slip along the Southern Death Valley fault zone, the easternmost fault in the ECSZ, has created a barrier against sinistral slip at the tip of the Garlock fault. This fault interaction induced shortening and surface uplift.

Du and Aydin (1996) argued that restraint of strike-slip motion and transpression within Big Bend of the San Andreas fault may have transferred plate-margin motion further inland and created the ECSZ. Inception of the modern trace of

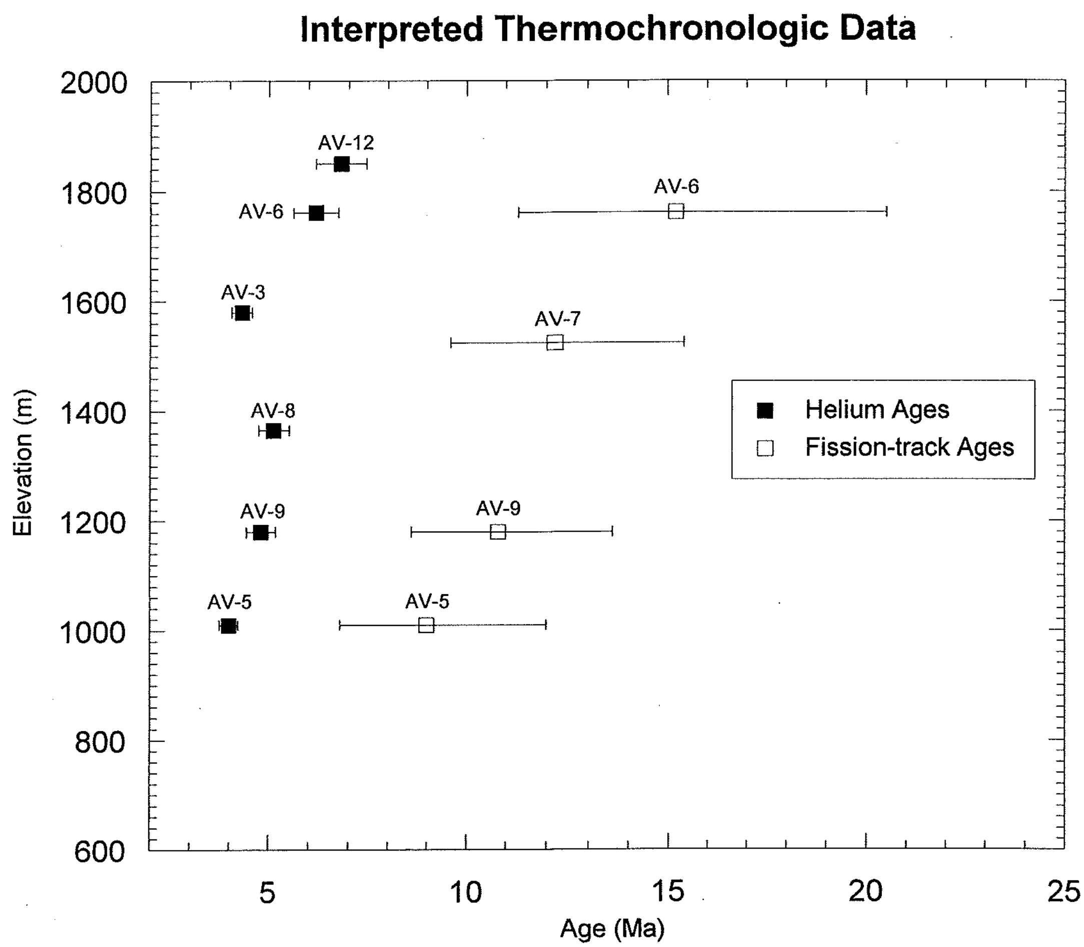


Figure 7: Interpreted Thermochronologic Data. Apatite (U-Th)/He and fission-track ages vs. elevation from the Avawatz Mountains. Samples AV-1, AV-2, AV-11, and AV-7 (Helium age only) have been removed from the data for interpretation (see text). Error-bars are 2-sigma estimates. 2-sigma estimates are calculated following the procedure of Farley et al. (2003) for the helium ages.

the San Andreas fault south of the Big Bend coincided with localization of the Pacific-North America plate margin in the Gulf of California (Page, 1990). Pacific-North America plate-margin localization, which occurred after ~6 Ma, is in accordance with a post 5 Ma inception of the ECSZ (Oskin et al., 2001). Thermochronologic data from the San Bernardino mountains and San Gabriel mountains along the Big Bend indicate that rapid, tectonically induced cooling began some time after ~7 Ma, and cooling rates accelerated in both ranges after ~3 Ma (Blythe et al. 2000; Spotila et al., 1998), again consistent with late-Miocene inception of transpression in the region.

Previous thermochronologic studies within the North American Cordillera have typically dealt with larger range blocks than the one presented in this study (e.g. Blythe et al., 2000; Spotila et al., 1998; Stockli et al.; House et al., 2001; Armstrong et al., 2003). However, the complex nature of plate-margin deformation in North America, potential relationships between young topography and changes in plate-margin kinematics, and the success of this study in determining the exhumation history of a small range with modest exhumation may encourage further studies of small (<10-15 km wide) range blocks.

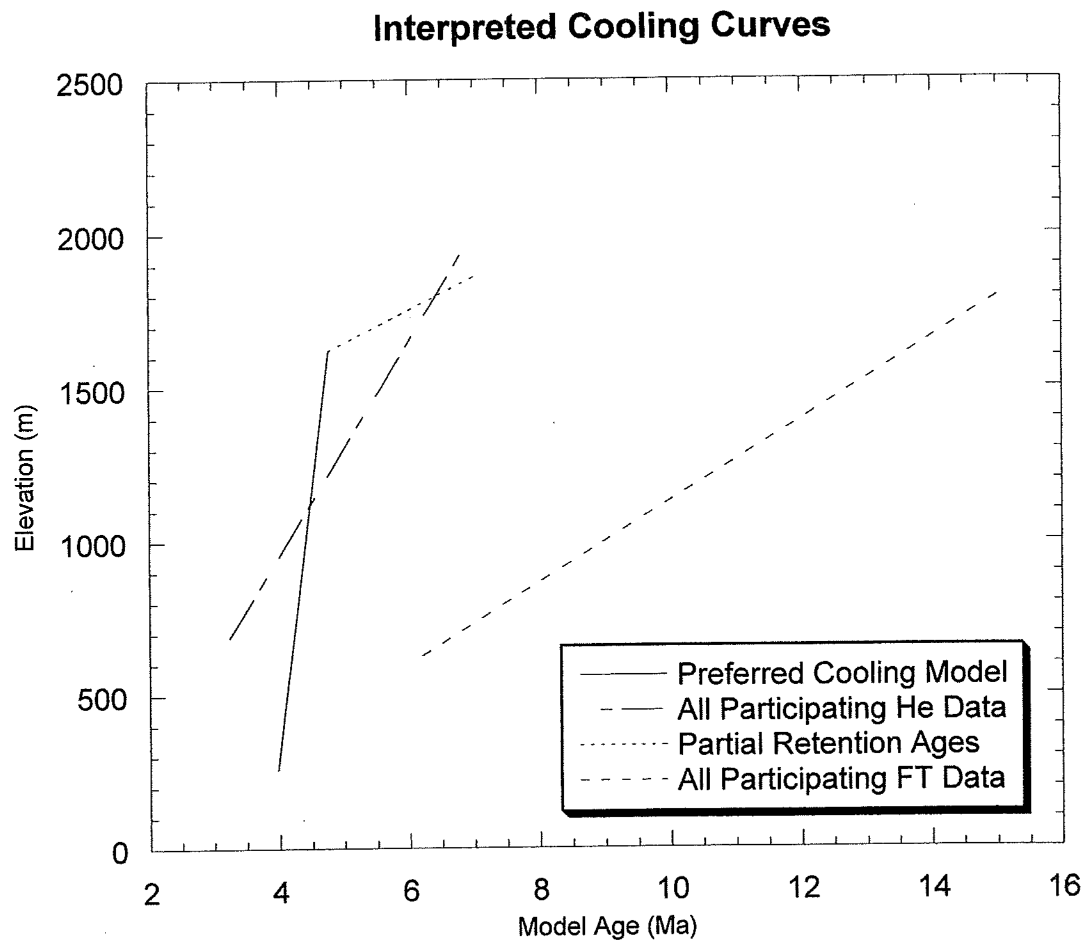


Figure 8: Interpreted Cooling Curves. Age-elevation linear fits for Avawatz thermochronologic data have the following parameters:
Preferred Cooling Model: slope = 1.7 mm/yr; intercept = -6514 m.
All Participating Helium Data: slope = 0.35 mm/yr; intercept = -440 m.
Partial Retention Ages: slope = 0.11 mm/yr; intercept = 1113 m.
All Participating FT Data: slope = 0.13 mm/yr; intercept = -191 m.
See text for explanation of interpretations.

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