THERMAL AND BAROMETRIC CONSTRAINTS ON THE INTRUSIVE AND UNROOFING HISTORY OF THE BLACK MOUNTAINS: IMPLICATIONS FOR TIMING, INITIAL DIP, AND KINEMATICS OF DETACHMENT FAULTING IN THE DEATH VALLEY REGION, CALIFORNIA

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Abstract. Unroofing of the Black Mountains, Death Valley, California, has resulted in the exposure of 1.7 Ga crystalline basement, late Precambrian amphibolite facies metasedimentary rocks, and a Tertiary magmatic complex. The $^{40}Ar/^{39}Ar$ cooling ages, obtained from samples collected across the entire length of the range (>55 km), combined with geobarometric results from synextensional intrusions, provide time-depth constraints on the Miocene intrusive history and extensional unroofing of the Black Mountains. Data from the southeastern Black Mountains and adjacent Greenwater Range suggest unroofing from shallow depths between 9 and 10 Ma. To the northwest in the crystalline core of the range, biotite plateau ages from ~13 to 6.8 Ma from rocks making up the Death Valley turtlebacks indicate a midcrustal residence (with temperatures >300°C) prior to extensional unroofing. Biotite $^{40}Ar/^{39}Ar$ ages from both Precambrian basement and Tertiary plutons reveal a diachronous cooling pattern of decreasing ages toward the northwest, subparallel to the regional extension direction. Diachronous cooling was accompanied by dike intrusion which also decreases in age toward the northwest. The cooling age pattern and geobarometric constraints in crystalline rocks of the Black Mountains suggest denudation of 10-15 km along a northwest directed detachment system, consistent with regional reconstructions of Tertiary extension and with unroofing of a northwest deepening crustal section. Mica cooling ages that deviate from the northwest younging trend are consistent with northwestward transport of rocks initially at shallower crustal levels onto deeper levels along splays of the detachment. The well-known Amargosa chaos and perhaps the Badwater turtleback are examples of this "splaying" process.

Considering the current distance of the structurally deepest samples away from moderately to steeply east tilted Tertiary strata in the southeastern Black Mountains, these data indicate an average initial dip of the detachment system of the order of 20°, similar to that determined for detachment faults in west

central Arizona and southeastern California. Beginning with an initially listric geometry, a pattern of footwall unroofing accompanied by dike intrusion progresses northwestward. This pattern may be explained by a model where migration of footwall flexures occur below a scoop-shaped hanging wall block. One consequence of this model is that gently dipping ductile fabrics developed in the middle crust steepen in the upper crust during unloading. This process resolves the low initial dips obtained here with mapping which suggests transport of the upper plate on moderately to steeply dipping surfaces in the middle and upper crust.

INTRODUCTION

Determining the timing, pattern, and amount of unroofing during orogeny is fundamental to understanding processes of lithospheric deformation. In the Basin and Range province, geologic studies using fluid inclusions [Parry and Bruhn, 1987] and balanced and reconstructed cross sections [Bartley and Wernicke, 1984; Wernicke and Axen, 1988] indicate 10-15 km, and perhaps up to 20 km, of footwall unroofing for some mountain ranges. As these depths generally correspond to temperatures between 200°C and 500°C, $^{40}Ar/^{39}Ar$ thermochronologic analyses of minerals with closure temperatures in this range provide a test of the amount and timing of unroofing during Cenozoic extension [Foster et al., 1990; Richard et al., 1990]. With a regional distribution of ages, thermochronology can also be used to determine the areal pattern of cooling, and thus provide a powerful test of structural models of extension.

The Black Mountains of Death Valley, California (Figure 1) are centrally located in the Death Valley extended terrain between the Spring Mountains to the east and the Sierra Nevada to the west. Isotopic, field, and petrologic studies [Asmerom et al., 1990; Holm and Wernicke, 1990] show the Black Mountains to consist predominantly of a Miocene midcrustal magmatic system (intermediate-mafic to silicic) intruded into Proterozoic basement and lesser amounts of miogeoclinal strata metamorphosed to amphibolite facies [Otton, 1977]. Although $^{40}Ar/^{39}Ar$ thermochronologic studies in some surrounding ranges have proven to be problematical [e.g., DeWitt et al., 1988], preliminary results from the Black Mountains metamorphic core complex yielded well-behaved $^{40}Ar/^{39}Ar$ systematics in both Proterozoic basement rocks and Tertiary plutons [Holm et al., 1989; Asmerom et al., 1990; McKenna, 1990]. Thus the Black Mountains provide an excellent opportunity to study the thermal history of a range block unroofed during Tertiary extension. We present $^{40}Ar/^{39}Ar$ cooling age data and barometry on synextensional intrusions and crystalline basement rocks from 18 localities distributed throughout the Black Mountains. These thermochronologic and barometric results place important constraints on the time, amount, and style of intrusion and unroofing of footwall rocks exposed by crustal extension in the Death Valley region.

GEOLOGIC FRAMEWORK

Crustal extension in the Death Valley region has occurred principally between 15 Ma and the present. Reconstruction of Neogene extension in the region between the stable Spring Mountains block and the Sierra Nevada restores range blocks now scattered over an area 150 km wide into an area less than 10 km wide [Wernicke et al., 1988; Snow and Wernicke,
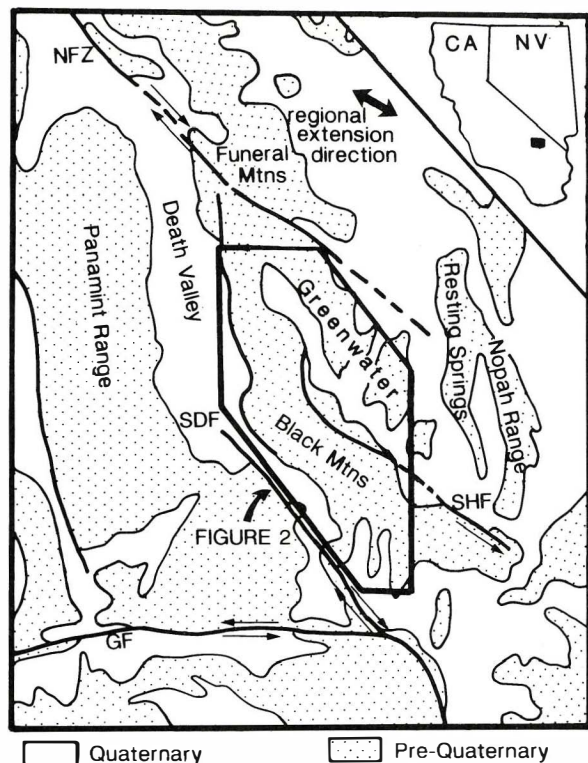
Fig. 1. Index map of the Death Valley region depicting ranges and major faults. Abbreviations are NFZ, Northern Death Valley-Furnace Creek Fault zone; SDF, Southern Death Valley fault; SHF, Sheephead fault; GF, Garlock fault.

1989]. According to these studies, regional westward migration of extension along down-to-the-west detachment faults resulted in the sequential detachment of crustal-scale slivers from a westward migrating hanging wall block [e.g., Asmerom et al., 1990]. Other studies in the region, however, advocate much less extension and favor the evolution of range blocks semi-independently of each other, each with separate deformational and thermal histories [e.g., Wright, 1989].

The Black Mountains lie on the east flank of Death Valley, California (Figure 1). Unroofing of footwall rocks on the western portion of the range has resulted in the exposure of a series of northwest plunging topographic and structural domes known as the Death Valley "turtlebacks" (Figure 2) [Curry, 1938; Wright et al., 1974a]. These features are composed predominantly of 1.7 Ga gneissic and schistose basement and a carapace of deformed and metamorphosed Eocambrian carbonate. In the core of the Black Mountains and largely surrounding the turtlebacks to the east is a batholith of gabbroic and dioritic composition. A recent isotopic study indicates that this intrusion (the Willow Spring Pluton) is mid-Miocene in age (11.6 ± 0.2 Ma [Asmerom et al., 1990]) and thus was emplaced during large-scale extensional tectonism in the region [Cemen et al., 1985]. Intruded into the pluton and Precambrian basement rocks is a silicic complex of granitic to monzonitic composition.

The Black Mountains core described above is structurally overlain along normal faults by the Amargosa chaos [Noble, 1941; Wright and Troxel, 1984], a highly extended mass of unmetamorphosed miogeoclinal strata of Eocambrian and Cambrian age and Tertiary volcanic and sedimentary rocks (Figure 2). The crystalline terrain was unroofed along these faults in late Miocene and younger time akin to other metamorphic core complexes in the Cordilleran orogen. Holm and Wernicke [1990] proposed that rocks of the Amargosa chaos have been translated 15–20 km northwestward from an original position in the southeastern Black Mountains (Figure 2). Accordingly, the chaos would represent a stranded portion of the hanging wall of an initially westerly dipping detachment fault along which the Black Mountains were denuded during late Miocene time. The predominantly shallow eastward dip of the fault currently exposed in the eastern Black Mountains would reflect eastward tilting of the range as the footwall was progressively denuded to the west. On the basis of the current configuration of the crustal section and on geobarometry of the Willow Spring Pluton, Holm and Wernicke [1990] suggested a paleodepth range of 10–30 km for the western portion of the Black Mountains prior to extension. This tectonic scenario for formation of the Black Mountains is consistent with previous reconstructions in the Death Valley region which suggest transport of the Panamint Mountains on the western side of Death Valley (Figure 1) off the top of the Black Mountains during Tertiary extension [Stewart, 1983; Snow and Wernicke, 1989]. In contrast to this scenario, Wright et al. [1987] interpret the Amargosa chaos as overlying a northwesterly moving lower plate with both top-to-the-east denudation of the eastern Black Mountains and top-to-the-west denudation of the western Black Mountains.

ANALYTICAL METHODS

In order to reveal the cooling age pattern across the Black Mountains, samples were collected from widely spaced localities throughout the range in both Tertiary plutonic rocks and Precambrian basement. Because of the extensive synextensional intrusions located in the central Black Mountains, more samples from different rock types were collected there in order to differentiate between cooling ages related to tectonic unroofing, to postmagmatic cooling, or to thermal resetting. Eighteen localities were sampled across an approximately 55 km northwest trending traverse along the length of the mountain range. From these samples, 30 age determinations were made on five different mineral systems and one whole rock separate (Table 1).

Minerals were separated using standard magnetic and heavy liquid separation techniques and hand picking. Sample preparation, irradiation, and analytical procedures for $^{40}Ar/^{39}Ar$ incremental release dating were described by Lux [1986]. Samples were irradiated in the University of Michigan reactor. Variations in neutron flux during irradiation were monitored with a biotite mineral standard (University of Maine laboratory standard, 247.6 Ma). Plateau ages were calculated from consecutive gas increments that together constitute >60% of the total gas released. Uncertainties are reported at the 2σ level and include the uncertainty in the flux measurement (J value). Analytical results for each sample are given in the Appendix[1].

Unaltered samples of the Smith Mountain Granite were studied petrographically to select those with the required phase assemblage for Al-in-hornblende geobarometry. The total Al

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[1] Appendix is available with entire manuscript on microfiche. Order from American Geophysical Union, N.W., Washington, D. C. 20009. Document T92-002;$2.50. Payment must accompany order.

116°47'
36°18'

N

Badwater
turtleback

0   5   10

km

X

Tg

Tdw

A'

Copper
Canyon
turtleback

X

Tg

Tg

Mormon
Point
turtleback

Gold
Valley

X

Tg

Smith
Mtn

X

Figure 3

Ashford
Canyon

Region
of Amargosa
Chaos

X

X

X

A

X

Unmetamorphosed Late Precambrian to
Tertiary sedimentary and volcanic
hangingwall rocks. Intact but steeply
east-tilted in southern Black Mountains

Tg   Granitic intrusive rocks

Footwall

Tdw   Willow Spring Diorite

X   1.7 Ga crystalline rocks including amphibolite
facies Late Precambrian carbonate rocks
surrounding the turtlebacks

SYMBOLS

▼ ▼ ▼ ▼ ▼   Basal unconformity, Tertiary
volcanic sequence

35°41'
116°20'

Black Mountains
detachment fault

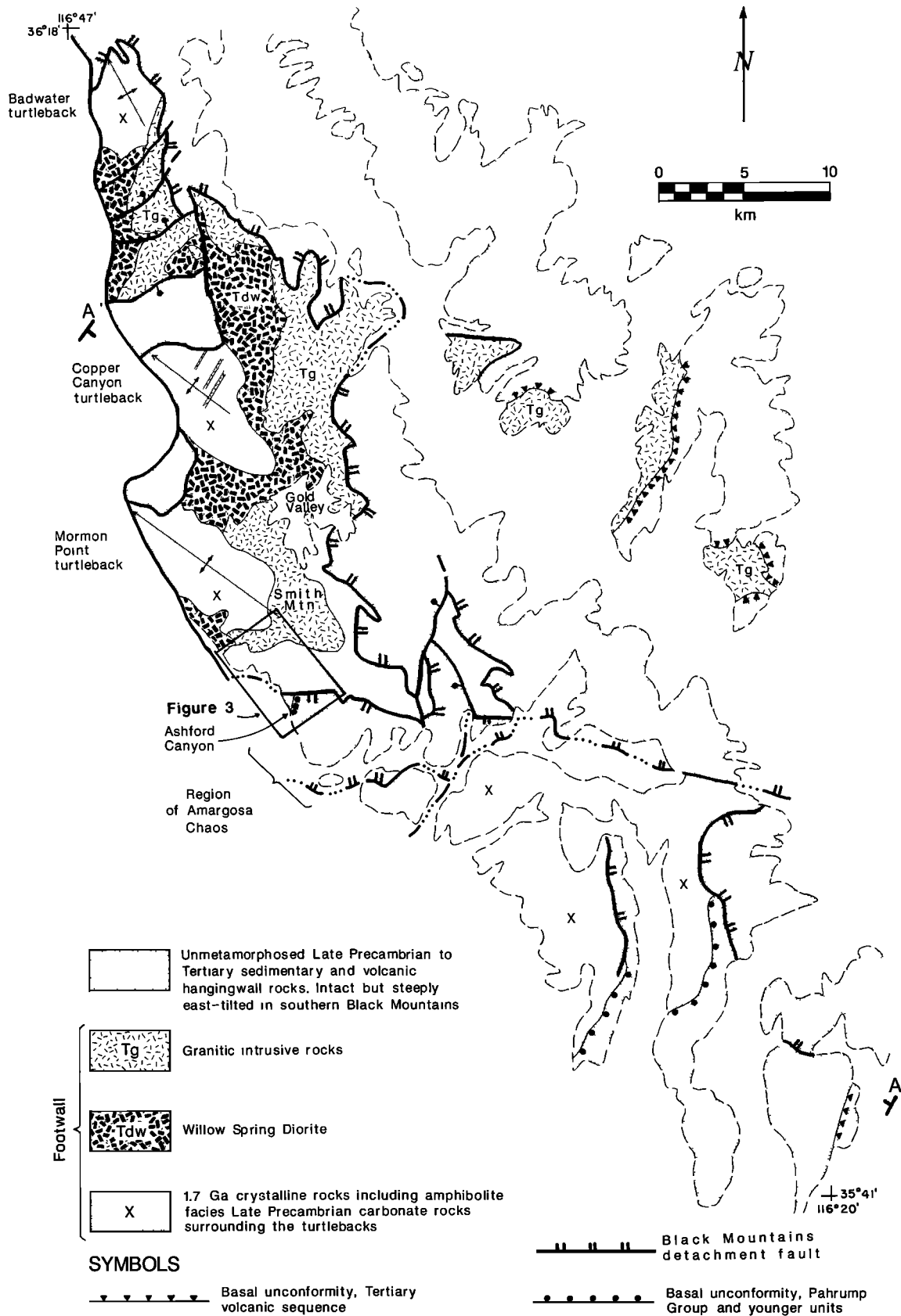● ● ● ● ●   Basal unconformity, Pahrump
Group and younger units

Fig. 2. Geologic map of the Black Mountains and Greenwater Range simplified after Streitz and Stinson [1974], Drewes [1963], Wright and Troxel [1984], Otton [1977] and Holm and Wernicke [1990].

Table 1. Summary of Black Mountains $^{40}Ar/^{39}Ar$ Data

Sample	Rock Type	Locality	Mineral	Elevation, m	Age*, Ma
		Southeastern Black Mountains			
IH1–BIO	pC basement	116°25.6' W, 35°52.5' N	biotite	1,119	234.3 ± 2.5 (tg)
RH–BIO	pC basement	116°30.0' W, 35°55.0' N	biotite	671	232.3 ± 5.9 (ti)
		Ashford Canyon			
AM–UNC–M	pC basement	116°39.6' W, 35°56.4' N	muscovite	195	1411.6 ± 10.7 (tg)
AM2a–M	pC basement	116°40.2' W, 35°57.5' N	muscovite	317	283.2 ± 4.1 (ti)
		Central Black Mountains Core			
TPG–SM	granite	116°40.0' W, 36°02.7' N	hornblende	988	8.7 ± 0.1 (ti)
			biotite		8.2 ± 0.1 (ti)
CCR–AR	gabbro-diorite	116°41.6' W, 36°06.1' N	hornblende	1,585	10.06 ± 0.39 (tp)
TPL–BIO	latite dike	116°40.5' W, 36°03.0' N	biotite	921	7.85 ± 0.18 (tp)
89–CC	pC basement	116°44.1' W, 36°06.6' N	hornblende	–60	>14.31 ± 0.81 (tg)
			biotite		6.63 ± 0.13 (tp)
988–25	gabbro-diorite	116°40.4' W, 36°03.1' N	hornblende	975	10.16 ± 0.20 (tp)
			biotite		8.39 ± 0.13 (tp)
89–MP	pC basement	116°45.1' W, 36°02.0' N	hornblende	61	9.94 ± 0.44 (tp)
			biotite		8.03 ± 0.14 (tp)
988–20	gabbro-diorite	116°40.4' W, 36°03.1' N	hornblende	975	10.42 ± 0.31 (tp)
			biotite		8.36 ± 0.17 (tp)
			plagioclase 1		6.70 ± 0.61 (tp)
			plagioclase 2		5.89 ± 0.51 (tp)
			orthoclase		7.20 ± 0.30 (ti)
CCTB–B	felsic dike	116°42.3' W, 36°07.1' N	biotite	1,067	6.90 ± 0.20 (ti)
TQM–HB	granite	116°37.6' W, 36°08.4' N	hornblende	1,670	8.69 ± 0.31 (tp)
DH–3780	gabbro-diorite (deformed)	116°40.4' W, 36°08.0' N	hornblende	1,152	8.05 ± 0.28 (tp)
			biotite		7.00 ± 0.10 (ti)
DH–2650	gabbro-diorite (deformed)	116°41.9' W, 36°07.5' N	hornblende	808	8.90 ± 0.60 (ti)
			biotite		6.66 ± 0.12 (tp)
		Northern Black Mountains			
90–38	diorite dike	116°45.0' W, 36°16.3' N	whole rock	750	6.31 ± 0.21 (tp)
BWT–B	pC basement	116°45.6' W, 36°17.1' N	biotite	265	13.23 ± 0.23 (tp)
DH–BWT–2	pC basement	116°45.0' W, 36°16.3' N	muscovite	732	24.00 ± 0.40 (ti)
			biotite		12.70 ± 0.20 (ti)
		Greenwater Range			
TOM–GW–B	granite	116°21.8' W, 35°59.9' N	biotite	902	9.76 ± 0.25 (tp)

* All tp (plateau age) and ti (intercept age) are concordant within error when both ages exist for individual samples; tg represents total gas age; pC is Precambrian.

content in rims of hornblende grains in these samples was obtained using a Cameca three-spectrometer CAMEBAX electron microprobe at Harvard University.

THERMOCHRONOLOGY RESULTS

Previous K-Ar isotopic studies of the Black Mountains concentrated on volcanic rocks which flank the eastern and northern sides of the crystalline terrane [Fleck, 1970]. However, Armstrong [1970] reported K-Ar ages from Tertiary intrusive rocks of 7.5 ± 0.3 Ma (biotite in diorite) and 6.3 ± 0.4 Ma (granite porphyry whole rock). The results of this study are discussed below with respect to the regional distribution of sample localities summarized in Table 1. Plate 1 is a summary diagram of the thermochronologic data presented in this paper. The ages are plotted on a map of the

Black Mountains which is the same as Figure 2 but without the geological patterns. No diffusion experiments to determine mineral closure temperatures were carried out in this study, and standard closure temperatures of 500° ± 25°C (hornblende), 350° ± 25°C (muscovite), and 300° ± 25°C (biotite) are assumed to interpret the data [McDougall and Harrison, 1988]. Interpretation of feldspar release spectra and closure temperature are discussed in the text.

Southeastern Black Mountains. Two ages were obtained from coarsely crystalline mica schists and quartz-feldspar gneisses from Precambrian basement in the southeastern Black Mountains. Biotite separates from samples IH1–BIO and RH–BIO yielded similar release spectra and total gas ages of 234.3 ± 2.5 Ma and 230.8 ± 6.1 Ma respectively. Neither sample yielded a plateau age, but both show a monotonic increase in age (from ~210 to 250 Ma) in progressively higher temperature

increments. Sample RH–BIO yielded an isotope correlation intercept age of 232.3 ± 5.9 Ma with a $^{40}Ar/^{36}Ar$ initial ratio of 304.5 ± 38.9. The similar, although somewhat disturbed, release spectra and total gas ages of these samples, as well as the concordant intercept age for one of the samples, lead us to conclude that this region of the Black Mountains has remained below 300°C since 230–235 Ma.

Ashford Canyon. Two Precambrian basement samples were collected from the vicinity of Ashford Canyon where late Precambrian Pahrump Group strata rest depositionally on basement (Figure 2). Sample AM–UNC–M is located ~30 m below the nonconformity (Figure 3). A muscovite separate from AM–UNC–M yielded a total gas age of 1411.6 ± 10.7 Ma and a release spectra in which five increments (with over 65% of the total gas) give ages between 1360 and 1400 Ma. We interpret this spectrum to indicate cooling below 350°C at about 1380 ± 20 Ma. A muscovite separate from sample AM2a–M (Figure 3) yielded a saddle-shaped spectrum with an age minimum of 279.3 ± 1.9 Ma. Saddle-shaped spectra are a typical sign of excess argon [McDougall and Harrison, 1988], and the $^{40}Ar/^{36}Ar$ initial ratio of 718.3 ± 47.2 for this sample confirms this. However, an intercept age of 283.2 ± 4.1 Ma indicates that the age minimum for this spectrum may be a meaningful cooling age. In addition, when a $^{40}Ar/^{36}Ar$ initial ratio of 718.3 is assumed, the release spectrum gives a total gas age of 284 Ma with over 90% of the gas (eight increments) falling between 280 and 300 Ma.
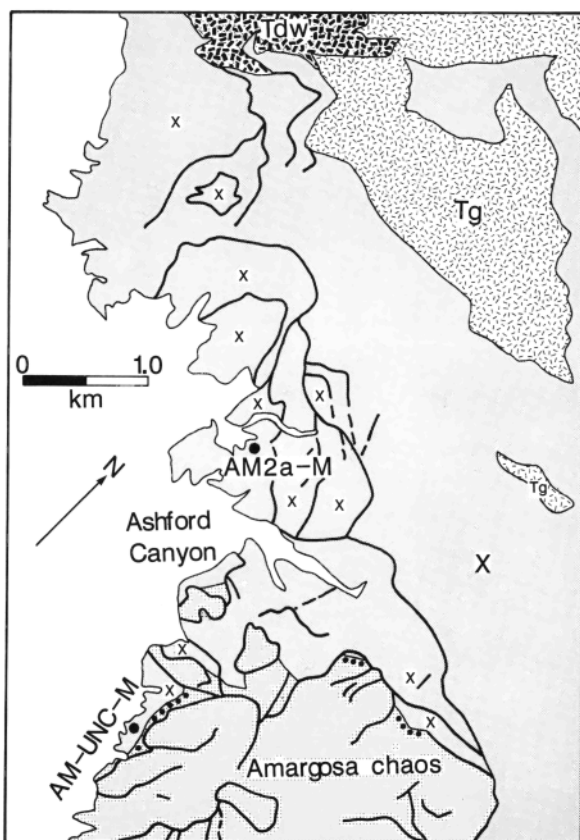

Fig. 3. Geologic map of Ashford Canyon region showing sample localities (simplified after Wright and Troxel [1984]). Patterned after Figure 2.

Central Black Mountains core. Eleven samples were collected from the central Black Mountains crystalline core (Table 1), the region occupied by the southern two turtlebacks (Mormon Point and Copper Canyon) and the adjacent Miocene intrusions (Figure 2). Two samples (988–20 and 988–25) of undeformed 11.6 Ma Willow Spring Pluton collected from the same outcrop near Willow Spring in Gold Valley (Figure 2) give hornblende plateau ages of 10.42 ± 0.31 Ma and 10.16 ± 0.20 Ma and concordant intercept ages of 10.3 ± 0.2 Ma and 10.2 ± 0.5 Ma. A hornblende separate from another undeformed sample (CCR–AR, collected ~6.4 km north of this locality) gives a plateau age of 10.06 ± 0.39 Ma and a concordant intercept age of 9.8 ± 0.2 Ma. Biotite separates from samples 988–20 and 988–25 give concordant total gas, intercept, and plateau ages of 8.36 ± 0.17 Ma and 8.39 ± 0.13 Ma respectively. We interpret these ages as indicating postcrystallization cooling below 500°C at 10.25 ± 0.15 Ma and below 300°C at 8.40 ± 0.15 Ma.

Release spectra were also obtained from plagioclase and orthoclase separates from sample 988–20. The Willow Spring Pluton contains only minor amounts of orthoclase and separation from plagioclase was fraught with difficulty owing to the presence of hydrated plagioclase grains. A separate consisting of ~50% orthoclase and ~50% plagioclase did not give a plateau but yielded an intercept age of 7.2 ± 0.3 Ma in agreement with its total gas age. While caution must be used in interpreting such data, it is worth noting that McKenna [1990] obtained an intercept age of 7.03 ± 0.04 Ma for an orthoclase separate from a nearby granite which intrudes the Willow Spring Pluton. Thus we tentatively interpret these data to indicate cooling below 200°–250°C (commonly determined closure temperature range from diffusion studies on K-feldspars [e.g., Hubbard and Harrison, 1989]) at 7.0–7.5 Ma.

Two splits of plagioclase from sample 988–20 yielded saddle-shaped spectra. The first split gives a plateau age of 5.89 ± 0.51 Ma for nine increments consisting of 76% of the gas and a concordant intercept age of 5.9 ± 0.4 Ma. The second split gives a plateau age of 6.70 ± 0.61 Ma for eight increments consisting of 70% of the gas and an intercept age of 6.4 ± 0.3 Ma. The disparate ages for two splits of the same separate as well as the saddle-shaped spectra lead to difficulties in interpreting these data. In addition, the lower discordant age from the orthoclase separate (in spite of a similar or possibly even higher closure temperature based on empirical evidence [McDougall and Harrison, 1988]) indicate to us no appropriate meaningful interpretation.

Intruded into the Willow Spring Pluton in the southern Gold Valley area (and underlying much of Smith Mountain, Figure 2) is a coarse grained granite which commonly exhibits Rapakivi texture and locally contains abundant coarse hornblende grains. A hornblende separate (TPG-SM) gives an intercept age of 8.7 ± 0.1 Ma and a near plateau for the last 10 increments (78% of the gas) of 8.5 ± 0.4 Ma with the oldest increment being 8.72 ± 0.15 Ma. Biotite from this sample gives an intercept age of 8.1 ± 0.1 Ma and a plateau age of 8.00 ± 0.21 Ma indicating that the granite cooled quite rapidly. Because the adjacent Willow Spring Pluton into which this granite intruded cooled below 500°C at 10.1–10.4 Ma, we interpret the 8.7 Ma hornblende age as representing the approximate time of crystallization of the intrusion.

A hornblende separate (TQM–HB) from a coarse-grained silicic pluton on the east side of the Black Mountains yielded a slightly saddle-shaped spectrum with a plateau age of 10.11 ±

0.73 Ma. However, the isotope correlation diagram, when regressed through the plateau points, gives an intercept age of 8.7 Ma and an initial $^{40}Ar/^{36}Ar$ ratio of 312.02 ± 5.12 indicating the presence of excess argon. When an initial $^{40}Ar/^{36}Ar$ ratio of 312 is assumed for the incremental release spectrum, the saddle shape disappears and the plateau age becomes 8.69 ± 0.31 Ma, concordant with the intercept age. This pluton, like the Smith Mountain Granite, intruded into the Willow Spring Pluton, and its hornblende age is similar to the hornblende age of the Smith Mountain Granite. We interpret this age as representing the time of crystallization of several silicic plutons in the Black Mountains.

Late-stage latite and rhyolite dikes with biotite and feldspar phenocrysts intrude both the Willow Spring Pluton and the Smith Mountain Granite in the vicinity of Gold Valley. These dikes exhibit an intense mylonitic foliation which commonly does not extend into undeformed country rock (Figure 4a). A coarse biotite separate from a dike sample (TPL–BIO) that intrudes the Willow Spring Pluton collected near Willow Spring (Table 1) yielded a plateau age of 7.85 ± 0.18 Ma and a concordant intercept age of 7.9 ± 0.1 Ma. These ages are only slightly younger than the biotite ages of the Smith Mountain Granite, the upper bound even overlapping in error with the plateau age although not with the intercept age. We interpret the dike age as the time of intrusion and crystallization into country rock with ambient temperatures between 200°C and 300°C as indicated by the K-feldspar and biotite ages obtained from the surrounding Willow Spring Pluton.

Precambrian basement samples were collected from the Mormon Point (sample 89–MP) and Copper Canyon turtlebacks (sample 89–CC; Figure 2). These rocks contain a coarsely recrystallized metamorphic fabric. Basement from the Mormon Point turtleback (sample 89–MP) gives a hornblende plateau age of 9.94 ± 0.44 Ma with a concordant intercept age of 9.9 ± 0.2 Ma similar to the hornblende ages in the Willow Spring Pluton. A concordant plateau and intercept biotite age from this sample indicates simple cooling below 300°C at 8.03 ± 0.14 Ma. Sample 89–CC shows a complicated hornblende spectrum with no intercept regression. The spectrum, however, appears very similar to partially reset spectra from other studies where the minimum age corresponds to a known later heating episode [Harrison and McDougall, 1980]. The minimum age for this spectrum (11.86 ± 1.57 Ma) corresponds with the age of intrusion of the Willow Spring Pluton, and therefore we interpret this spectrum to represent cooling below 500°C by at least 14 Ma with partial resetting at 11.6 Ma due to reheating by the gabbro-diorite batholith. Biotite from this sample yields a concordant intercept and plateau age indicating simple cooling below 300°C at 6.63 ± 0.13 Ma. The Copper Canyon turtleback data suggest that the basement rocks in this region

were below 500°C prior to intrusion of the Willow Spring Pluton. We interpret the Mormon Point hornblende age as having been completely thermally reset by the batholith at 11.6 Ma, followed by slow cooling to below 500°C at 10 Ma (note the similar hornblende ages from the Willow Spring Pluton).
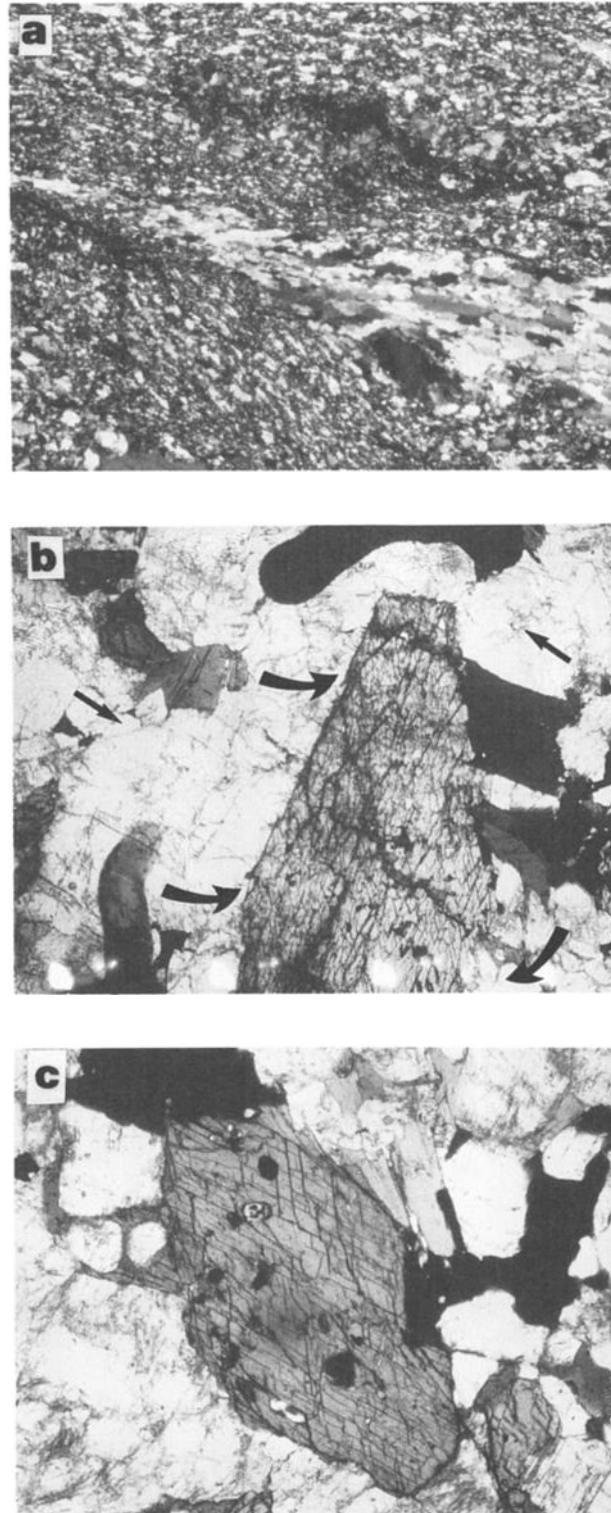

Fig. 4. (a) Photomicrograph of mylonitic texture common in porphyritic dikes in the central Black Mountains (sample TPL–BIO). Length is 2.0 mm across. (b) Photomicrograph of late leucocratic phase of the Willow Spring Pluton (sample 88–23) showing quartz in contact with hornblende (curved arrows). Straight arrows point to examples of K-feldspar grains and K-feldspar inclusions in plagioclase. Length is 0.5 mm across. (c) Photomicrograph of euhedral hornblende crystal from the Smith Mountain Granite (sample TPG–SM) in quartz-plagioclase-potassium feldspar-biotite rich matrix. Length is 0.5 mm across.

A ductilely deformed sample of the Willow Spring Pluton (sample DH-2650) obtained beneath the foliated Eocambrian carapace on the northeast side of the Copper Canyon turtleback (Figure 2) gives a hornblende plateau age of 8.77 ± 0.70 Ma with a concordant intercept age of 8.9 ± 0.6 Ma. Biotite from this sample yielded a plateau age of 6.66 ± 0.12 Ma and an intercept age of 6.8 ± 0.1 Ma. Another deformed gabbro-diorite sample (DH-3780) from a ductile shear zone ~3 km northwest of sample DH-2650 gives a hornblende plateau age of 8.05 ± 0.28 Ma and an intercept age of 8.3 ± 0.5 Ma. Biotite from this sample does not yield a plateau age but does give an intercept age of 7.0 ± 0.1 Ma. The hornblende ages from these samples are substantially younger than the hornblende ages derived from undeformed samples. The batholith intruded at 11.6 Ma into country rock with ambient temperatures below 500°C and cooled below 500°C at 10.1–10.4 Ma. Therefore we interpret these younger hornblende ages associated with ductilely deformed samples as indicating resetting during mylonitization with ambient temperatures between 300°C and 500°C. Davidson and Snee [1990] have demonstrated that under greenschist facies conditions (>300°C) hornblende can be reset during ductile shearing at ambient temperatures below the hornblende closure temperature. Mylonite fabrics are typically formed at temperatures above the closure temperature for diffusion in biotite. We therefore interpret the 6.7 and 7.0 Ma biotite ages from these samples as representing simple cooling following deformation.

The Copper Canyon turtleback is intruded by felsic dikes which are oriented perpendicular to the axis of the turtleback fold [Drewes, 1963]. Biotite in these dikes are often extensively altered to chlorite, and commonly exhibit deformation features such as strain shadows and kink bands. A biotite separate from one of these dikes was considered pure enough for age dating only after 2 days of hand-picking. Sample CCTB-B did not yield a plateau age but did give concordant intercept and total gas ages of 6.9 ± 0.2 Ma and 6.8 ± 0.2 Ma, respectively. These ages overlap with the biotite cooling ages obtained from the Precambrian basement and the Willow Spring Pluton in this region. The Copper Canyon turtleback dikes are volumetrically small and are considered unlikely to have completely thermally reset the surrounding country rock to above 300°C. We interpret the 6.9 ± 0.2 Ma intercept age as the time of intrusion of these dikes into rapidly cooling country rock similar to dike intrusion in the Gold Valley region ~1.0 m.y. earlier.

Northern Black Mountains. Samples BWT-B and DH-BWT-2 are mylonitized Precambrian basement from the Badwater turtleback in the northern Black Mountains. Sample BWT-B is located only a few meters below the brittle detachment surface, whereas sample DH-BWT-2 was collected from a deeply incised canyon in the lower plate (approximately 200 m below the brittle detachment surface). Micas from both localities are strained into mica-fish profiles typical of mylonitic textures. Muscovite from sample DH-BWT-2 shows a typical diffusion loss profile with an age minimum of 16.03 ± 1.90 Ma, four increments (representing 72% of the gas) with ages between 23.4 and 24.4 Ma, and an intercept age of 24.0 ± 0.4 Ma. Biotite from sample DH-BWT-2 is strongly discordant from the muscovite age giving a concordant intercept and plateau age of 12.63 ± 0.50 Ma. Biotite from sample BWT-B gives a slightly older plateau age of 13.23 ± 0.23 Ma and a concordant intercept age of 13.4 ± 0.1 Ma. We interpret these data as indicating that the Badwater turtleback

basement rocks cooled slowly through the 350°C isotherm at ~24 Ma with further cooling through 300°C at ~13 Ma.

Fine-grained dioritic dikes cut the basement foliation at a high angle and are synkinematic with late-stage brittle faulting [Miller, 1991]. A whole rock analysis of one of these dikes (sample 90–38) gives a plateau age and concordant intercept age that indicates crystallization at 6.3 ± 0.2 Ma. These data suggest that the basement rocks of the Badwater turtleback were within a few kilometers of the Earth's surface by at least 6.3 Ma.

Greenwater Range. The Greenwater Range lies just east of the Black Mountains (Figures 1 and 2) and consists of Tertiary silicic plutons overlain by 10–4 Ma variably faulted mafic to silicic volcanic rocks. In the southern Greenwater Range, 8–9 Ma Shoshone volcanics lie depositionally on feldspar porphyry granite [Figure 2; L. Wright and B. Troxel, personal communication]. A biotite separate from this granite (sample TQM-GW-B) gave concordant total gas, intercept, and plateau ages of 9.76 ± 0.25 Ma, consistent with rapid cooling from above 300°C at 9–10 Ma. This age is approximately 1 m.y. older than the age interpreted for major silicic plutonism in the central Black Mountains.

GEOBAROMETRY RESULTS

A lower bound on the depth estimate for crystallization of the Willow Spring Pluton at 9.5–12.5 km was determined by Holm and Wernicke [1990, Table 1] using the Al-in-hornblende geobarometer [Hammarstrom and Zen, 1986; Johnson and Rutherford, 1989] and assuming an overburden density of 2750 kg/m³. As observed by Holm and Wernicke [1990] and corroborated by Wright et al. [1991] the main portion of the batholith does not contain the appropriate assemblage required for this geobarometer. However, late leucocratic portions of which are intrusive into the main portion do contain the required assemblage. We concur with Wright et al. [1991] that their samples were inappropriate for using this geobarometer as they were unable to find any potassium feldspar and could not locate quartz in contact with hornblende. However, samples analyzed by Holm and Wernicke [1990] do contain potassium feldspar (as evidenced from optical, microprobe, and chemical staining analyses) as well as quartz in contact with hornblende (Figure 4b). In addition, successful analyses and similar results using this geobarometer on these rocks have been reported by Meurer and Pavlis [1991].

Dated samples of the Smith Mountain Granite (TPG-SM) also contain the proper mineral assemblage necessary for application of the Al-in-hornblende geobarometer. The results of microprobe analyses of coarse euhedral hornblendes (Figure 4c) from three doubly polished sections of the granite are given in Table 2. Total Al content from rim analyses of hornblende indicates a pressure of 2.76 ± 0.5 kbar (using the modified equation of Johnson and Rutherford [1989, p. 838]) or a depth estimate of 10.0 ± 1.8 km using an average overburden density of 2750 kg/m³. The total Al content obtained here is substantially greater than that recently reported for the Smith Mountain Granite by Wright et al. [1991]. A possible explanation for this discrepancy might be that different phases of the granite were sampled. Considering that intrusion occurred simultaneously with unroofing, it seems quite possible that various phases might record different depths of emplacement.

TABLE 2. Cation Proportions From Rim Analyses of Hornblende in Smith Mountain Granite

	Cation								
Sample	Si	Al	Fe	Mg	Ca	Na	K	Ti	Mn
90-SMG-4	6.85	1.46	2.04	2.65	1.94	0.27	0.15	0.10	0.06
	6.82	1.45	1.82	2.82	1.92	0.31	0.17	0.16	0.06
	6.76	1.45	2.05	2.69	1.90	0.34	0.17	0.15	0.07
90-SMG-1	6.75	1.49	2.01	2.70	1.89	0.36	0.18	0.16	0.07
	6.71	1.51	2.04	2.71	1.94	0.33	0.19	0.15	0.07
	6.78	1.47	2.04	2.63	1.87	0.39	0.18	0.16	0.07
	6.81	1.41	1.99	2.74	1.93	0.28	0.17	0.14	0.07
	6.77	1.52	1.93	2.69	1.93	0.32	0.18	0.14	0.07
	6.78	1.49	2.01	2.72	1.89	0.29	0.18	0.14	0.06
	6.78	1.50	2.06	2.65	1.88	0.35	0.17	0.13	0.07
	6.78	1.44	1.93	2.77	1.92	0.34	0.17	0.16	0.07
91-SMG-3	6.74	1.53	2.06	2.63	1.92	0.27	0.18	0.14	0.07
	6.77	1.53	2.05	2.61	1.92	0.30	0.16	0.13	0.07
	6.99	1.23	1.92	2.83	1.98	0.24	0.13	0.09	0.07
	6.96	1.29	1.84	2.91	1.87	0.26	0.14	0.12	0.06
	6.74	1.51	2.03	2.66	1.93	0.34	0.17	0.15	0.07
	6.75	1.52	2.00	2.68	1.90	0.34	0.18	0.14	0.07
90-SMG-3	6.78	1.50	1.97	2.68	1.87	0.35	0.18	0.16	0.07
	6.83	1.37	1.90	2.85	1.93	0.28	0.16	0.15	0.06
	6.80	1.49	1.81	2.83	1.88	0.34	0.18	0.15	0.06

Proportions are per 23 oxygens.

DISCUSSION

Timing, Depth, and Deformation of Miocene Intrusions

Intrusions in the Black Mountains are entirely Tertiary in age, the oldest being the Willow Spring Pluton dated at 11.6 ± 0.2 Ma [Asmerom et al., 1990]. Previous mapping distinguished at least three major silicic intrusive bodies younger than the pluton based on compositional differences and dike relations [Drewes, 1963; Otton, 1977].

Willow Spring Pluton. The minimum hornblende age of ~14.3 Ma for a thermally reset Precambrian basement sample (89-CC) in the central Black Mountains indicates ambient temperatures below 500°C prior to intrusion of Tertiary plutons. This establishes an upper bound for the depth of intrusion of the Willow Spring Pluton at ~16.7–20 km assuming typical Basin and Range geothermal gradients after Lachenbruch and Sass [1978] of 25–30°C/km prior to intrusion. Considering elevated geothermal gradients during Miocene time would make the upper bound for intrusion depth even less. The 8.4–6.7 Ma biotite ages from the pluton (samples 988-20, 988-25, DH-2650, and DH-3780) are too young to be attributed to simple postemplacement conductive cooling of an 11.6 Ma intrusion. We therefore interpret the biotite ages as representing cooling associated with extensional unroofing. This interpretation implies that the pluton intruded into country rock with ambient temperatures above 300°C. Again, assuming 25–30°C/km geothermal gradients, we obtain a lower bound for intrusion emplacement depth of 10–12 km. This lower bound is consistent with geobarometric results on a late crystallization phase of the pluton. Allowing for some uplift between crystallization of the main and late leucocratic phases of the pluton, considering it crystallized and cooled

during regional extensional tectonism and unroofing in the Death Valley region [Cemen et al., 1985; Holm and Dokka, 1991], we consider an intrusion depth for the main phase of the pluton of 10–15 km most likely.

The Death Valley turtlebacks contain a thick, well-developed mylonitic foliation in basement rocks that is subparallel to the overlying carbonate carapace and brittle detachment surface. Involvement of foliated and lineated Willow Spring Pluton in these footwall mylonites (sample DH-2650) indicates that at least some of the foliation formed during Miocene extension [Holm and Wernicke, 1989; Holm and Lux, 1991]. Mylonitic deformation appears to have begun prior to intrusion of the Smith Mountain Granite complex as suggested by the ~8.9 Ma hornblende age from deformed gabbro-diorite (sample DH-2650), consistent with the observation that the Willow Spring Pluton is more ductilely deformed than the younger granitic complex [Holm and Wernicke, 1990].

Smith Mountain Granite complex. The 8.7 Ma hornblende ages obtained from granitic plutons in the central Black Mountains (samples TQM–HB and TPG–SM) signify a major silicic intrusive event coeval with extensive volcanism in the Greenwater range. The Smith Mountain Granite and coeval plutons in the central Black Mountains intruded into country rock with an ambient temperature above 300°C as indicated by the 8.4 Ma biotite ages obtained from the Willow Spring Pluton country rock into which it intruded. We interpret the 8.2 Ma biotite age obtained from the Smith Mountain Granite as indicating continued postemplacement cooling after the country rock had cooled through 300°C. The $^{40}Ar/^{39}Ar$ cooling age data and geobarometry on the Smith Mountain Granite, taken together, are consistent with a depth range for crystallization of 8.2–11.8 km.
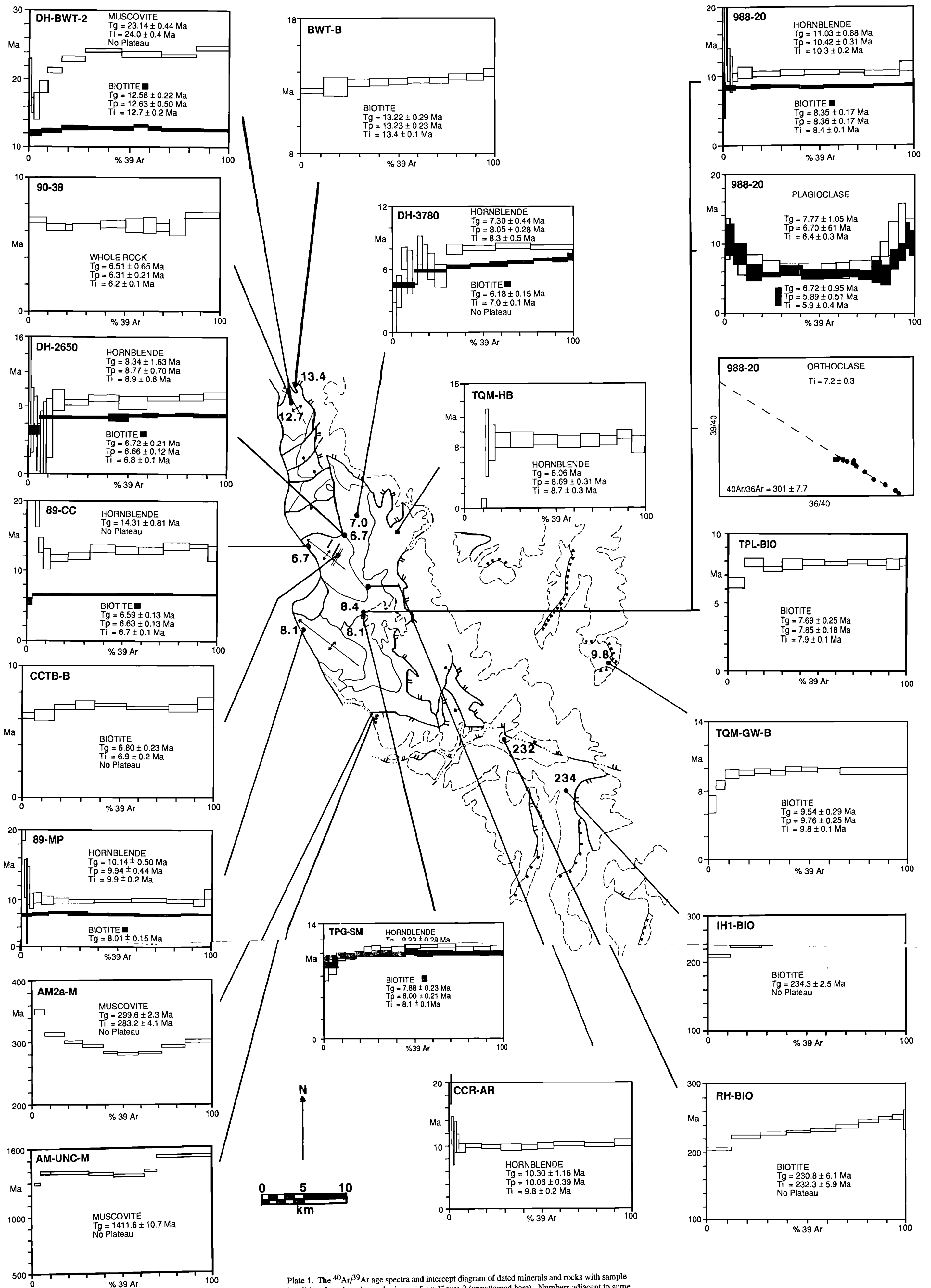
DH-BWT-2
MUSCOVITE
Tg = 23.14 ± 0.44 Ma
Ti = 24.0 ± 0.4 Ma
No Plateau

BIOTITE ■
Tg = 12.58 ± 0.22 Ma
Tp = 12.63 ± 0.50 Ma
Ti = 12.7 ± 0.2 Ma

BWT-B
BIOTITE
Tg = 13.22 ± 0.29 Ma
Tp = 13.23 ± 0.23 Ma
Ti = 13.4 ± 0.1 Ma

988-20
HORNBLENDE
Tg = 11.03 ± 0.88 Ma
Tp = 10.42 ± 0.31 Ma
Ti = 10.3 ± 0.2 Ma

BIOTITE ■
Tg = 8.35 ± 0.17 Ma
Tp = 8.36 ± 0.17 Ma
Ti = 8.4 ± 0.1 Ma

90-38
WHOLE ROCK
Tg = 6.51 ± 0.65 Ma
Tp = 6.31 ± 0.21 Ma
Ti = 6.2 ± 0.1 Ma

DH-3780
HORNBLENDE
Tg = 7.30 ± 0.44 Ma
Tp = 8.05 ± 0.28 Ma
Ti = 8.3 ± 0.5 Ma

BIOTITE ■
Tg = 6.18 ± 0.15 Ma
Ti = 7.0 ± 0.1 Ma
No Plateau

988-20
PLAGIOCLASE
Tg = 7.77 ± 1.05 Ma
Tp = 6.70 ± 61 Ma
Ti = 6.4 ± 0.3 Ma

Tg = 6.72 ± 0.95 Ma
Tp = 5.89 ± 0.51 Ma
Ti = 5.9 ± 0.4 Ma

DH-2650
HORNBLENDE
Tg = 8.34 ± 1.63 Ma
Tp = 8.77 ± 0.70 Ma
Ti = 8.9 ± 0.6 Ma

BIOTITE ■
Tg = 6.72 ± 0.21 Ma
Tp = 6.66 ± 0.12 Ma
Ti = 6.8 ± 0.1 Ma

TQM-HB
HORNBLENDE
Tg = 6.06 Ma
Tp = 8.69 ± 0.31 Ma
Ti = 8.7 ± 0.3 Ma

988-20
ORTHOCLASE
Ti = 7.2 ± 0.3

40Ar/36Ar = 301 ± 7.7

89-CC
HORNBLENDE
Tg = 14.31 ± 0.81 Ma
No Plateau

BIOTITE ■
Tg = 6.59 ± 0.13 Ma
Tp = 6.63 ± 0.13 Ma
Ti = 6.7 ± 0.1 Ma

TPL-BIO
BIOTITE
Tg = 7.69 ± 0.25 Ma
Tg = 7.85 ± 0.18 Ma
Ti = 7.9 ± 0.1 Ma

CCTB-B
BIOTITE
Tg = 6.80 ± 0.23 Ma
Ti = 6.9 ± 0.2 Ma
No Plateau

TQM-GW-B
BIOTITE
Tg = 9.54 ± 0.29 Ma
Tp = 9.76 ± 0.25 Ma
Ti = 9.8 ± 0.1 Ma

89-MP
HORNBLENDE
Tg = 10.14 ± 0.50 Ma
Tp = 9.94 ± 0.44 Ma
Ti = 9.9 ± 0.2 Ma

BIOTITE ■
Tg = 8.01 ± 0.15 Ma

IH1-BIO
BIOTITE
Tg = 234.3 ± 2.5 Ma
No Plateau

AM2a-M
MUSCOVITE
Tg = 299.6 ± 2.3 Ma
Ti = 283.2 ± 4.1 Ma
No Plateau

TPG-SM
HORNBLENDE
Tg = 9.22 ± 0.28 Ma

BIOTITE ■
Tg = 7.88 ± 0.23 Ma
Tp = 8.00 ± 0.21 Ma
Ti = 8.1 ± 0.1 Ma

RH-BIO
BIOTITE
Tg = 230.8 ± 6.1 Ma
Ti = 232.3 ± 5.9 Ma
No Plateau

AM-UNC-M
MUSCOVITE
Tg = 1411.6 ± 10.7 Ma
No Plateau

N

CCR-AR
HORNBLENDE
Tg = 10.30 ± 1.16 Ma
Tp = 10.06 ± 0.39 Ma
Ti = 9.8 ± 0.2 Ma

0   5   10
km

Plate 1. The ^{40}Ar/^{39}Ar age spectra and intercept diagram of dated minerals and rocks with sample localities plotted on the geologic map from Figure 2 (unpatterned here). Numbers adjacent to some localities are ages (in millions of years) plotted for ease of viewing the overall cooling age pattern for biotite.

Greenwater plutons. Granitic plutons in the adjacent Greenwater range (Figure 1) are depositionally overlain by 8–9 Ma Shoshone volcanics and yield a biotite plateau age of 9.76 ± 0.25 Ma, substantially older than both the hornblende and biotite ages from the Smith Mountain Granite complex. Because field relations indicate that all silicic intrusions in the Black Mountains are younger than the Willow Spring Pluton [Drewes, 1963], we infer that the Greenwater plutons represent crystallization of a granitic body intermediate in age between the Willow Spring Pluton and the Smith Mountain Granite complex. Although no basement rocks are exposed in the vicinity of this pluton, we note that it appears to be located in the same structural position or depth beneath the late Precambrian nonconformity and overlying Miocene volcanic rocks as the basement rocks in the southeastern Black Mountains. It seems likely therefore that this pluton intruded at shallow levels into country rock colder than 300°C and that the 9.76 Ma biotite age represents a near crystallization age. The nearly concordant age of the overlying Shoshone volcanics indicates unroofing and exposure prior to 9 Ma, soon after crystallization.

Mylonitic dikes. Numerous porphyritic latite and rhyolite dikes in the central Black Mountains commonly exhibit a mylonitic foliation which is usually (although not always) absent in the country rock adjacent to these dikes. A 7.85 Ma biotite age obtained from a dike near Willow Spring in Gold Valley indicates crystallization of these dikes within 1.0 m.y. after crystallization of the Smith Mountain Granite complex. The dike nature and the porphyritic texture of these late-stage intrusions indicate colder ambient temperatures and therefore likely a shallower depth of intrusion than the older plutonic complex. At Gold Valley, these dikes intruded into country rock undergoing rapid cooling rates of 35°–100°C/m.y. based on the age and closure temperature differences between biotite and K-feldspar. We interpret dike intrusion as fracture infilling of crust brittlely deforming during rapid unroofing. Because the temperature of the dikes would be substantially higher than the surrounding country rock immediately after emplacement, these dikes deformed ductilely in an overall brittle regime, thus having a mylonitic foliation imparted to them which is largely nonexistent in the adjacent country rock.

Thermochronologic data from Tertiary plutons, combined with geobarometric data, provide time-depth constraints on the Miocene intrusive history of the Black Mountains crystalline terrain. At 11.6 Ma, the Willow Spring Pluton intruded at a depth range of 10–15 km into country rock with an ambient temperature below 500°C. At ~8.7 Ma the Smith Mountain Granite complex intruded at a depth of 8.2–11.8 km into country rock with temperatures above 300°C. These time and depth constraints indicate only minor to moderate amounts of unroofing (0–6.8 km) at average rates of 0–2.2 mm/yr between 11.6 Ma and 8.7 Ma. Clasts of both the Smith Mountain Granite complex and the Willow Spring Pluton in the Copper Canyon Formation to the north [Holm and Lux, 1991] indicate exposure of these rocks prior to 5 Ma. Thus data from the Gold Valley area indicate an increase of unroofing rates to greater than 2.3–3.2 mm/yr after 8.7 Ma.

Translation of the Amargosa Chaos

Holm and Wernicke [1990] observed that the crystalline rocks in the central Black Mountains lie well away from Tertiary unconformities of pre-10 Ma strata which lie

exclusively on unmetamorphosed strata of Paleozoic, Eocambrian, or late Precambrian age, suggesting significant preextensional depths. One exception is the area occupied by the Amargosa chaos at the vicinity of Ashford Canyon south of the Mormon Point turtleback (Figure 2). Here late Precambrian Pahrump Group strata and overlying Tertiary strata are deposited on basement which cooled below 350°C at approximately 1380 Ma (sample AM–UNC–M). These rocks lie only 5–6 km south of exposures of the Willow Spring Pluton and the regionally metamorphosed Noonday Dolomite on the Mormon Point turtleback (Figure 3). This area occupies the southern boundary of the Nopah Upland (Figure 5), described as a region of crystalline rock uplifted in the late Precambrian (pre-Noonday time) and flanked to the south by Pahrump Group strata [Wright et al., 1974b]. At Ashford Canyon and elsewhere, unmetamorphosed Pahrump Group strata lie only 2–3 km below the Tertiary unconformity, implying shallow depths at the onset of extension. Wright and Troxel [1984] have argued that the relative positions of
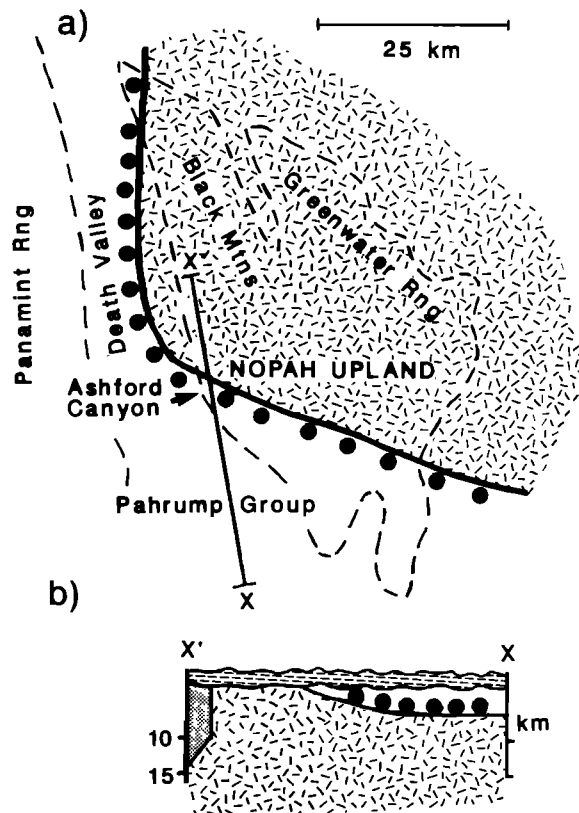

Fig. 5. (a) Paleogeologic map of the Death Valley region, representing time that immediately preceeded deposition of the Noonday Dolomite [after Wright et al., 1974b]. Filled circles represent basal nonconformity of Pahrump Group strata. (b) Cross section X–X' just prior to Tertiary volcanism showing the shallow depth required for the Nopah Upland assuming stratigraphic depth equals structural depth. Dashed lines represent late Precambrian strata. Shaded region depicts the "missing" depth differential (7–13 km) considering that the 11.6 Ma Willow Spring Pluton intruded at a depth of 10–15 km. See text for discussion.

basement rocks and various Pahrump Group sections in this area have remained intact since Precambrian time. If it is assumed that stratigraphic depth equals structural depth, the paleogeography according to Wright et al. [1974b] would require the Precambrian basement rocks making up the Mormon Point and Copper Canyon turtleback to lie only a few kilometers below the surface at the onset of extension (Figure 5). However, the $^{40}Ar/^{39}Ar$ data and geobarometry on Miocene intrusions presented here indicate a midcrustal depth (10–15 km) for these rocks during Miocene time.

It seems unlikely that Miocene intrusive rocks beneath the Precambrian nonconformity at Ashford Canyon could have a differential depth of 7–13 km over a distance of only 5–6 km between their exposure along the Mormon Point turtleback and Ashford Canyon (Figure 3). Holm and Wernicke [1990] attributed the proximity of the unmetamorphosed and regionally metamorphosed Pahrump Group strata to translation of the unmetamorphosed rocks northwestward away from an original position in the southeastern Black Mountains. Translation occurred along a detachment zone underlying the highly faulted Amargosa chaos, the detachment zone having locally cut into basement rocks beneath the nonconformity, thus juxtaposing allochthonous basement (and the overlying nonconformity) onto intact basement in the vicinity of Ashford Canyon (Figure 3). We emphasize that this detachment fault would be difficult to map where basement was faulted onto basement. However, the ~283 Ma muscovite age minimum of sample AM2a–M approaches ages obtained from the basement in the southeastern Black Mountains (samples RH–BIO and IH1–BIO) suggesting equivalence. In addition, this sample, collected nearer to the inferred fault than sample AM–UNC–M, shows a disturbed spectra with excess ^{40}Ar, a characteristic common in faulted and sheared rocks. We conclude that the thermochronologic data presented here, when taken in conjuction with depth determinations for Miocene intrusions, are best explained by restoration of the Amargosa chaos (and the late Precambrian nonconformity exposed at Ashford Canyon) 15–20 km southeastward to equivalent rocks in the southeastern Black Mountains.

Cooling Age Pattern

Samples from the southeastern and central Black Mountains show a pattern of cooling with biotite ages younging toward the northwest (Plate 1). Biotite total gas ages of 230–235 Ma from Precambrian basement in the southern Black Mountains (samples RH–BIO and IH1–BIO) suggest temperatures below 300°C well before the onset of extension in this region. Shallow depths for these rocks prior to Tertiary unroofing would be expected given their proximity to unmetamorphosed late Precambrian-Cambrian and Tertiary sedimentary rocks which depositionally overlie basement in the southeastern Black Mountains. Taking 300°C as the maximum temperature of these samples prior to Tertiary unroofing and considering a low geothermal gradient, we obtain a depth maximum of 12 km prior to extension. Thermochronology and field relations in the adjacent Greenwater Range indicate unroofing of ~10 Ma shallow level granites between 9 and 10 Ma while the western Black Mountain rocks remained deeper than 10 km.

In the central Black Mountains, biotite ages within the Willow Spring Pluton show a younging towards the northwest with samples collected from Gold Valley cooling through 300°C ~1.5 m.y. before samples collected at and northeast of

the Copper Canyon turtleback. This cooling age pattern is visible in samples from both the pluton and the Precambrian basement rocks suggesting that the pluton thermally equilibrated with the country rock at temperatures above the closure temperature for biotite. We interpret the northwest younging of biotite cooling ages to reflect progressive tectonic unroofing of the Copper Canyon and Mormon Point turtlebacks toward the northwest from midcrustal depths (temperatures above 300°C), consistent with the overall regional extension direction and with regional west directed tectonic denudation suggested by Wright et al. [1984]. Progressive unroofing was accompanied by footwall dike intrusion which also decrease in age toward the northwest.

Mica cooling ages from the northern Black Mountains (the Badwater turtleback) are substantially older than micas from both the Copper Canyon and Morman Point turtlebacks in the central Black Mountains. The dissimilar cooling ages suggest that rocks making up the Badwater turtleback lay at a shallower level in the crust prior to intrusion of the Willow Spring Pluton and the onset of unroofing than were the rocks of the Copper Canyon and Mormon Point turtlebacks. Therefore the Copper Canyon and Mormon Point turtlebacks would represent the deepest exposed level of the Black Mountains crust unroofed during Tertiary extension; this is in contradiction to the westward deepening crustal section hypothesis presented by Holm and Wernicke [1990]. A possible explanation for the older mica ages which would resolve this contradiction considers the Badwater turtleback as allochthonous with respect to the southern two turtlebacks, having been translated northwestward in the direction of overall regional extension similar to the Amargosa chaos described above. Restoration of the Badwater turtleback southeastward to a location either above or southeast of the Copper Canyon turtleback would account for the correct positioning of older mica ages and would also explain the formation and concentration of high-temperature ductile deformation fabrics around the Copper Canyon turtleback 4–5 m.y. after the Badwater turtleback cooled below 300°C. Alternatively, the northwest dipping detachment fault may have ramped up to a shallower level in the crust toward the northeast in the vicinity of the Badwater turtleback. As dike intrusion seems to have accompanied unroofing and cooling in the Gold Valley and Copper Canyon turtleback regions at 7.9 Ma and 6.8 Ma, respectively, the younger dikes located on the Badwater turtleback (6.3 Ma) may reflect the later unroofing of that area albeit from shallower depths (<300°C).

Cooling Age versus Elevation

Hornblende ages from undeformed Willow Spring Pluton samples suggest uniform cooling of the intrusion below 500°C at 10.1–10.4 Ma, approximately 1.0 to 1.5 m.y. after crystallization. Similar hornblende cooling ages from undeformed samples of the pluton were obtained by McKenna [1990]. There is no discernable age difference between samples collected over an elevation difference of ~1.5 km (Figure 6). This is perhaps not surprising considering that the pluton intruded into country rock with temperatures below 500°C at its base. Intrusion of the pluton would have created a temporary unstable geotherm with an inverted isotherm at its base. While it is certainly possible that some cooling might be attributed to denudation, we feel that at these high temperatures cooling was probably dominated by conductive cooling of the pluton as it thermally equilibrated with the country rock. Rapid
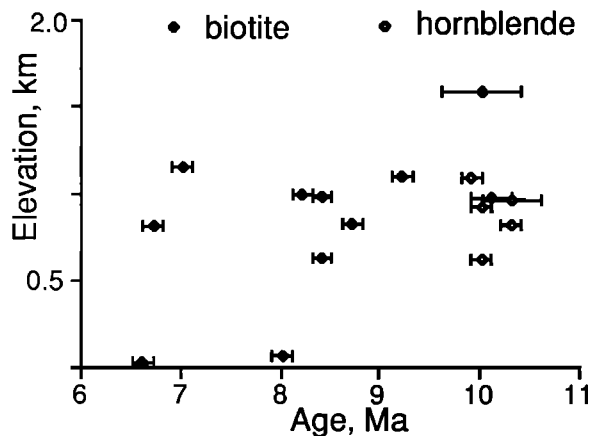
Fig. 6. Cooling age versus elevation data from the central Black Mountains. Data points are from this study and from McKenna [1990]. Hornblende ages are from the Willow Spring Pluton only. Biotite ages are from the pluton and from Precambrian basement.

equilibration of a steep or inverted geotherm cooling through 500°C would likely mask any competing effect of cooling associated with vertical denudation and therefore no difference in hornblende cooling ages with elevation would be expected [cf. Wright et al., 1991; McKenna and Snee, 1991].

We have also plotted biotite cooling ages (from both Precambrian and gabbro-diorite samples from the central Black Mountains) versus sample elevation using data from this study and from that of McKenna [1990]. At first sight there appears to be considerable scatter in the biotite data with respect to elevation (Figure 6). However, cooling ages obtained from specific regions (8–9 Ma ages from the Gold Valley/Mormon Point area, and 6.7–7.0 Ma ages from the Copper Canyon region) appear to show a steep positive correlation with elevation. A possible interpretation is that the steep slopes represent locally a vertical component of motion (present day coordinates) of the 300°C isotherm. If the motion were approximately vertical and related to unroofing, the age versus elevation data from this study suggests unroofing rates of ~2.5–4.0 km/m.y. We emphasize, however, that caution must be used when interpreting such data in the Black Mountains especially considering the recent evidence for Miocene and younger folding of the pluton [Holm and Lux, 1990; Pavlis, 1991].

Initial Dip and Kinematics of Detachment Faulting

A principal focus of interest in continental extension concerns the initial geometry and angle of dip of major detachment zones [Buck, 1988; Wernicke and Axen, 1988; King and Ellis, 1990; Miller, 1991; Holm, 1991]. The thermochronologic and geobarometric constraints presented here suggest limits on the average initial dip of the Black Mountains detachment. The data presented above indicate that the deepest portions of the Black Mountains (the region adjacent to and occupying the northern portion of the Copper Canyon turtleback) were at a maximum depth of 15 km prior to the onset of unroofing. Projected onto a cross section subparallel to the regional extension direction these rocks currently lie ~45 km away from the tilted nonconformity in the southeastern Black Mountains. The current width of exposed

footwall relative to changes in structural depth across strike allow an estimate of the average initial dip when variables such as amount of internal extension and amount of overburden are considered. For instance, a thick section of overburden will give a lower estimate for the initial dip of the detachment beneath the nonconformity. Also, internal extension of the range block would cause the current width of exposed footwall to be greater than it initially was and thus make the dip estimate lower. Assuming only 1–2 km of overburden above the nonconformity and a liberal estimate of 50% internal extension of the range block, we obtain a maximum average initial dip angle of ~30°. Considering 3–5 km of overburden and less internal disruption (10–20%) gives initial average angles of ~15°–20°. By using this and other techniques, similar average initial dips have also been determined for detachment faults in west central Arizona and southeastern California [Dokka and Baksi, 1988; Miller and John, 1988; Foster et al., 1990; Richard et al., 1990].

Recent mapping of the Badwater turtleback suggests that transport of the upper plate occurred on moderately to steeply dipping surfaces in the middle and upper crust, favoring only moderate amounts of extension in the Death Valley region [Miller, 1991]. In addition, the Black Mountains have been cited as an example of large footwall uplift beneath a planar high-angle normal fault, again requiring only moderate to minor horizontal extension [King and Ellis, 1990]. These conclusions conflict with regional interpretations that suggest large amounts of extension in the region [Snow and Wernicke, 1989; Stewart, 1983; Wernicke et al., 1988] and with the low average initial dip of the detachment obtained here. The conflicting results of the above studies may be resolved in part by considering the initial geometry of the detachment and its evolution during extension. It seems apparent that near the preextensional surface in the southeastern Black Mountains the detachment initially dipped moderately to steeply, as indicated by the moderately to steeply east tilted Tertiary strata and steep fault-bed angles. Considering initial dips in the upper 5–10 km of 40°–90°, the average initial dip below that depth would be of the order of 6°–13° (Figure 7a). These considerations imply an initially listric geometry similar to that commonly observed on reflection seismograms of normal faults in the Basin and Range and elsewhere [Smith and Bruhn, 1984].

As extension and unloading of the footwall occurs, isostatic forces cause the footwall to flex and uplift; this results in the migration of a monoclinal flexure through the footwall in the direction of transport [Hamilton, 1988; Buck, 1988; Wernicke and Axen, 1988]. This would be reflected in a diachronous rapid cooling pattern, a result of unroofing occurring progressively across the range. The differential cooling represented in the $^{40}Ar/^{39}Ar$ data, as well as the accompanying footwall dike intrusion in the Black Mountains, may reflect this process. Another consequence would be that gently dipping to subhorizontal ductile fabrics developed in the middle crust (where the average initial angle was very low) during extension would steepen in the brittle upper crust during unloading (Figure 7b). As unroofing continued and the steepened fabrics were brought nearer the surface, they would be tilted once again to lower angles as the flexure continued to migrate through the upper crust. Therefore the high-angle orientation would not be the original orientation as argued by Miller [1991]; rather it is the result of an earlier steepening as the rocks were unroofed from an originally low-angle orientation in the midcrust (Figure 7).
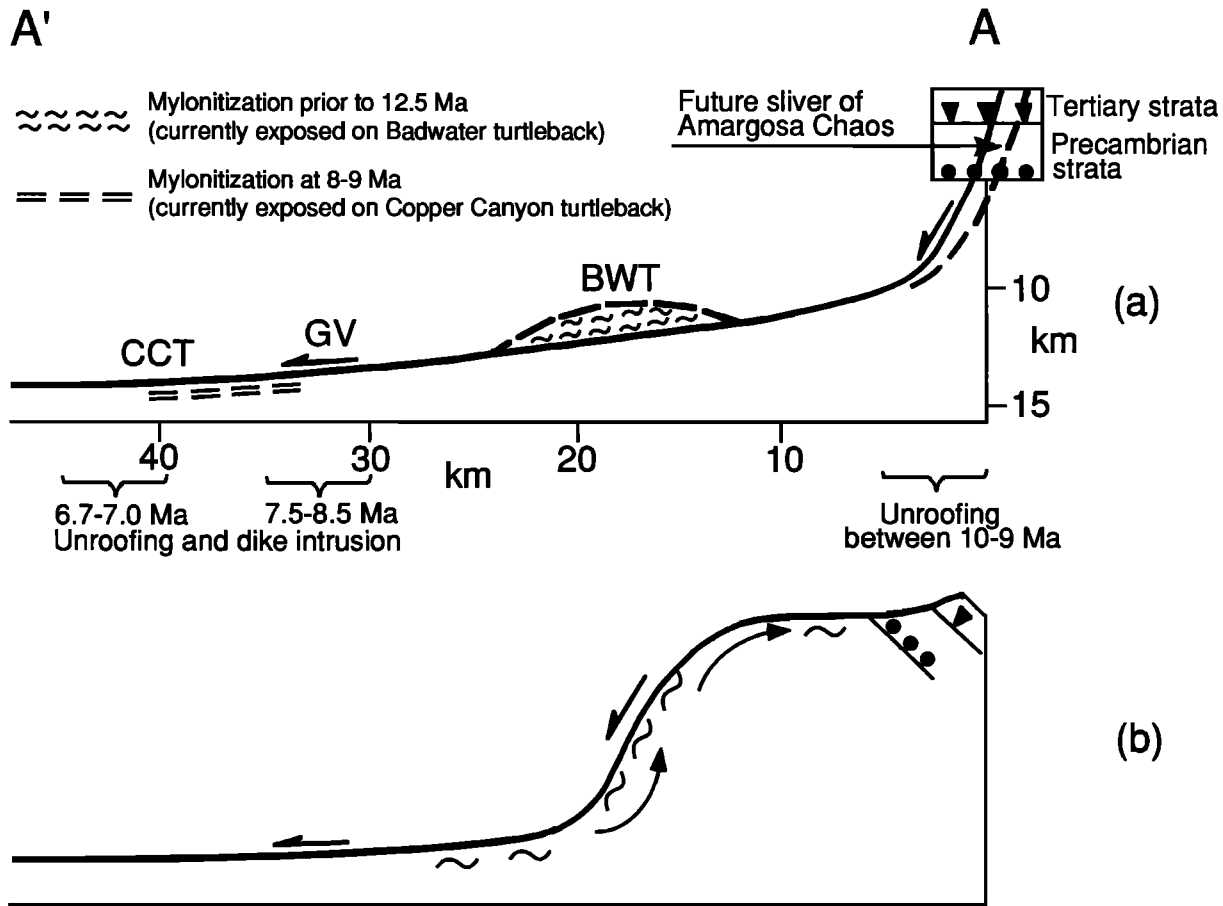
Fig. 7. (a) Schematic cross section (along A–A' of Figure 2) showing likely average initial dip and geometry of detachment fault responsible for unroofing of the Black Mountains and reconstructed position of Badwater turtleback rocks (BWT) prior to unroofing. GV is Gold Valley region; CCT is Copper Canyon turtleback rocks. Depth estimates are obtained from geobarometry and from thermochronology. (b) Diagrammatic representation of preferred model for unroofing of the Black Mountains [after Hamilton, 1988; Buck, 1988; and Wernicke and Axen, 1988]. See text for discussion.

CONCLUSIONS

We have used ^{40}Ar/^{39}Ar age spectrum data, combined with geobarometry, to constrain the intrusion and unroofing history of the Black Mountains. Data from the Gold Valley region of the central Black Mountains indicate intrusion of the 11.6 Ma Willow Spring Pluton into country rock with temperatures below 500°C and at depths of 10–15 km. A granitic complex dated at 8.7 Ma intruded into country rock above 300°C at 8.2–11.8 km depths. Intrusion of fine-grained porphyritic latite dikes indicate shallow crustal levels by 7.9 Ma. These cooling depth data suggest slow to moderate unroofing rates (0–2.2 mm/yr) between 11.6 and 8.7 Ma and more rapid rates (>2.3–3.2 mm/yr) after 8.7 Ma for the Gold Valley region.

The southeastern Black Mountains were at shallow crustal levels (<300°C) well before the onset of Tertiary extension with basement biotite cooling ages of 230–235 Ma. Thermochronology and field relations indicate that ~10 Ma shallow level granitic plutons in the southern Greenwater Range were unroofed shortly after crystallization (by ~9 Ma).

In the central Black Mountains biotite cooling ages in rocks of both the Precambrian basement and surrounding Miocene plutons young to the northwest indicating diachronous unroofing between 8.5 and 6.7 Ma. Diachronous unroofing was accompanied by dike intrusions which also decrease in age toward the northwest. Biotite ages from 13 Ma to as young as 6.7 Ma from the turtlebacks indicate a midcrustal origin prior to extensional unroofing. Preextensional depths of the order of 10–15 km and the northwest younging cooling age pattern are consistent with palinspastic reconstructions of Tertiary extension which require ~80 km of west directed horizontal transport of the Panamint Mountains off the top of the Black Mountains [Stewart, 1983; Snow and Wernicke, 1989].

The cooling age pattern and depth estimates obtained here from across the Black Mountains indicate northwestward detachment with an average initial dip on the order of 20°. Starting with an initially listric geometry, progressive migration of a footwall flexure in the direction of transport (expressed by the diachronous cooling age pattern) accomodates the observations of moderately to steeply dipping Tertiary strata

in the southeastern Black Mountains [Holm and Wernicke, 1990], and field relations suggesting an earlier high-angle detachment orientation [Miller, 1991], with the low average initial dips obtained here. Mica ages discordant from the overall northwest younging trend (ages from the Amargosa chaos and Badwater turtleback) are explained by northwestward transport of initially shallower crustal levels onto deeper levels along splays of the major detachment zone.

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