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The Death Valley Turtlebacks Reinterpreted as Miocene-Pliocene Folds of a Major Detachment Surface[1]

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ABSTRACT

Determining the origin of extension parallel folds in metamorphic core complexes is fundamental to understanding the development of detachment faults. An excellent example of such a feature occurs in the Death Valley region of California where a major, undulatory, detachment fault is exposed along the well-known turtleback (antiformal) surfaces of the Black Mountains. In the hanging wall of this detachment fault are deformed strata of the Copper Canyon Formation. New age constraints indicate that the Copper Canyon Formation was deposited from ~6 to 3 Ma. The formation was folded during deposition into a SE-plunging syncline with an axial surface coplanar with that of a synform in the underlying detachment. This relation suggests the turtlebacks are a folded detachment surface formed during large-scale extension in an overall constrictional strain field. The present, more planar, Black Mountains frontal fault system may be the result of out-stepping of a normal fault system away from an older detachment fault that was deactivated by folding.

Introduction

Large-magnitude extension in the U.S. Cordillera has been accomplished principally along large-scale, low-angle normal faults called detachments. The footwall to these detachments commonly consists of metamorphic tectonites that have cooled rapidly from temperatures in the 300°C range and higher during the Cenozoic (e.g., Dokka et al. 1986; Holm and Dokka 1993; and many others). Although these temperatures are sufficient for development of ductile deformation features in quartzofeldspathic rocks, the age and tectonic significance of many of the footwall tectonites have been controversial. This is due, in part, to the fact that many contain an older Precambrian or Mesozoic metamorphic fabric that complicates their structural interpretation.

The Black Mountains of the Death Valley extended region in southeast California contain Precambrian metamorphic rocks exhumed via large-scale Tertiary extensional tectonism (figure 1). The Precambrian rocks are exposed as three NW-plunging topographic and structural antiforms whose overall shape resembles the carapace of a turtle (Curry 1938, 1954). The Death Valley "turtlebacks" consist of a thick L-S metamorphic tectonite (of predominantly Precambrian schist, gneiss, and marble) whose foliation is broadly parallel to an overlying undulatory detachment surface. The northwest orientation of the antiformal axes is subparallel to the present extension direction in the region (Burchfiel et al. 1987; Wernicke et al. 1988).

Adjacent to central Death Valley, the hanging wall consists of young, unmetamorphosed, and normal faulted sedimentary rocks (Drewes 1963; Otton 1977). The footwall rocks are little faulted, have been extensively intruded by midcrustal (10–13 km), Miocene age plutons (<12 Ma; Asmerom et al. 1990; Holm et al. 1992), and yield Miocene cooling ages that suggest rapid cooling associated with extensional unroofing (Holm et al. 1992; Holm and Dokka 1993). The Death Valley turtlebacks thus have first-order structural and morphological characteristics similar to *Cordilleran metamorphic core complexes* (Coney 1980), although some of the geologic features of the Black Mountains seem unique or are rarely seen in other core complexes (Otton 1982; Wright et al. 1991).

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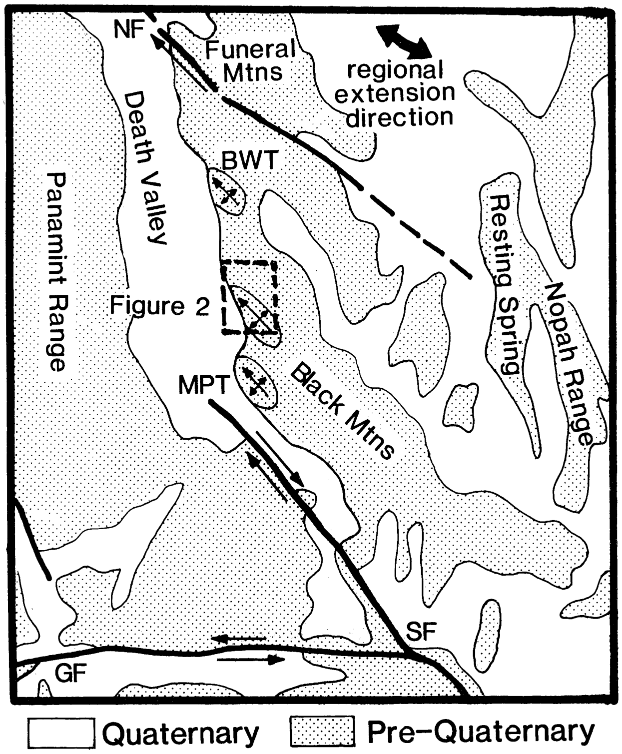

Figure 1. Index map of range blocks in the Death Valley region. GF, Garlock fault; NF, Northern Death Valley–Furnace Creek fault zone; SF, Southern Death Valley fault zone. Northwest plunging antiforms represent turtleback structures along the western flank of the Black Mountains. BWT, Badwater turtleback; MPT, Mormon Point turtleback.

The three-dimensional evolution and formation of the Death Valley turtlebacks and of *core complexes* in general has been an important question in the study of extensional tectonics. Wright et al. (1974) were the first to recognize the extensional origin of the Death Valley turtlebacks. They noticed the en-echelon pattern of these fold-like features, which they interpreted to pre-date Tertiary extension. Their interpretation was based largely on cross-cutting relations of the 11.6 Ma Willow Spring pluton (Asmerom et al. 1990), which was then thought to be of Mesozoic (or possibly older) age. Wright et al. (1974) concluded that the antiformal surfaces were colossal fault mullions resulting from extension localized along *pre-existing* undulatory and NW-plunging zones of weakness. In this paper we present new age data and structural evidence from deformed hanging wall strata of the Copper Canyon Formation that revives the idea of Hill and Troxel (1966) that the turtlebacks (antiforms) are Miocene and younger folds developed during large-scale extension in an overall constrictional strain field.

Geologic Setting

Extension during the last ~14 Ma in this region has resulted in the northwest tectonic transport of upper plate Mio-Pliocene and older strata (Holm and Wernicke 1990; Topping 1993). Reconstruction of Neogene extension suggests that the Panamint, Nopah, and Resting Springs ranges, now exposed across an area 150 km wide (figure 1), restore into a narrow crustal sliver <10 km wide adjacent to the relatively unextended Spring Mountains (Snow and Wernicke 1989; Wernicke et al. 1988). Juxtaposition of the Panamint and Nopah-Resting Springs Range blocks, first proposed by Stewart (1983) on the basis of isopach and facies trends of miogeoclinal stratigraphy, places the Panamint Range above the intervening Black Mountains prior to Miocene extension.

Denudation of the Black Mountains occurred during the mid- to late Miocene (10–6 Ma) as the Black Mountains footwall pulled out from underneath the relatively rigid, scoop-shaped hanging wall of the Panamint Range. On the eastern flank of the Black Mountains, volcanic rocks deposited over the interval 14–4 Ma become progressively less tilted and faulted with decreasing age (Wright and Troxel 1988). Strata ~8–9 Ma are locally intensely faulted and steeply rotated and overlain in angular unconformity by relatively undisturbed basalts and fanglomerates that are about 4–5 Ma (Wright et al. 1983, 1984). In addition, a southeast to northwest progression of cooling (from temperatures above 300°C to below 100°C) associated with unroofing of the crystalline core occurred at ~8.5–6.5 Ma (Holm et al. 1992; Holm and Dokka 1993).

The Copper Canyon Formation

Sedimentary rocks of the Copper Canyon Formation (Drewes 1963) exposed north of the Copper Canyon antiform (figures 2 and 3), overlie moderately to steeply tilted volcanic units with a marked angular unconformity. The formation is over 3 km thick, and dominated by coarse, thick-bedded to massive, red and brown conglomerate and sandstone, light green lacustrine deposits (dominantly siltstone and gypsum with minor limestone), and basalt flows. Interbedded with these units are several thin (<0.5–2 m thick) lithic, vitric, and felsic tuffs and landslide/megabreccia sheets. The stratigraphy and sedimentology of the formation has been described in detail by Drewes (1963), Otton (1977), and most recently by Scrivner (1984). The formation is overlain in mild angular unconfor-

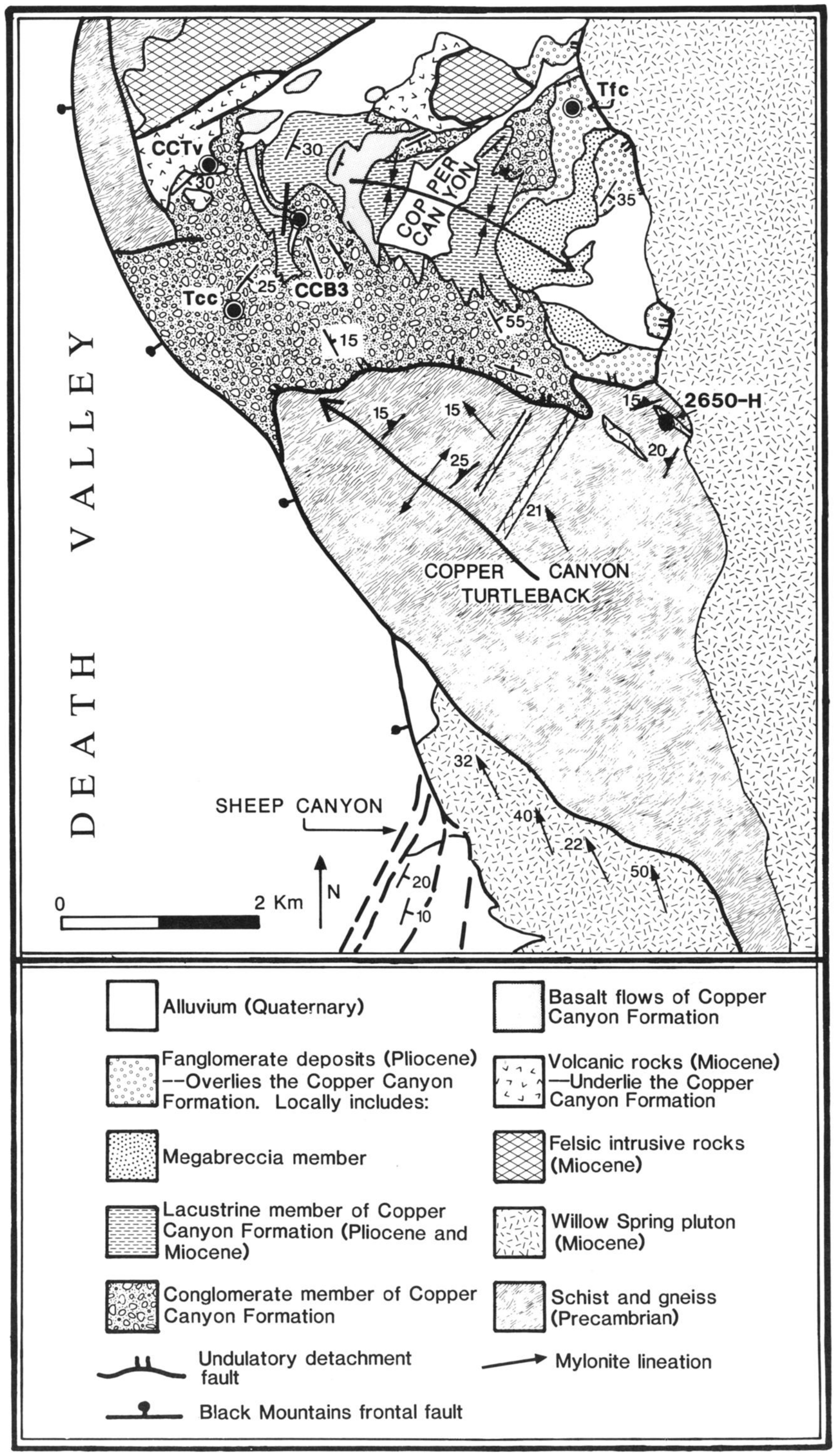

Figure 2. Geologic map of the Copper Canyon turtleback (antiform) and Copper Canyon Formation syncline (simplified after Drewes 1963 and Holm 1992). Sample localities are given for new age data obtained in this study. Sample 2650-H represents a footwall mylonite of the Willow Spring pluton (see Holm et al. 1992 for discussion).

mity (5°–10°) by a SE-dipping, gray and green coarse fanglomerate dominated by boulder-size subangular clasts of the Willow Spring pluton. This unit also contains a megabreccia sheet of the pluton and a single white tuff layer near its base (Drewes 1963).

The first isotopic age obtained from the Copper Canyon Formation was a K-Ar whole rock age of 4.9 Ma from a basalt flow low in the formation (reported by Otton 1977). In a more recent study, Scrivner (1984) reported an age of 7.5 ± 0.5 Ma by the same method on a basalt flow *above* the flow sampled by Otton. In addition, Scrivner and Bottjer (1986) reported a 9.4 ± 0.7 Ma zircon fission track

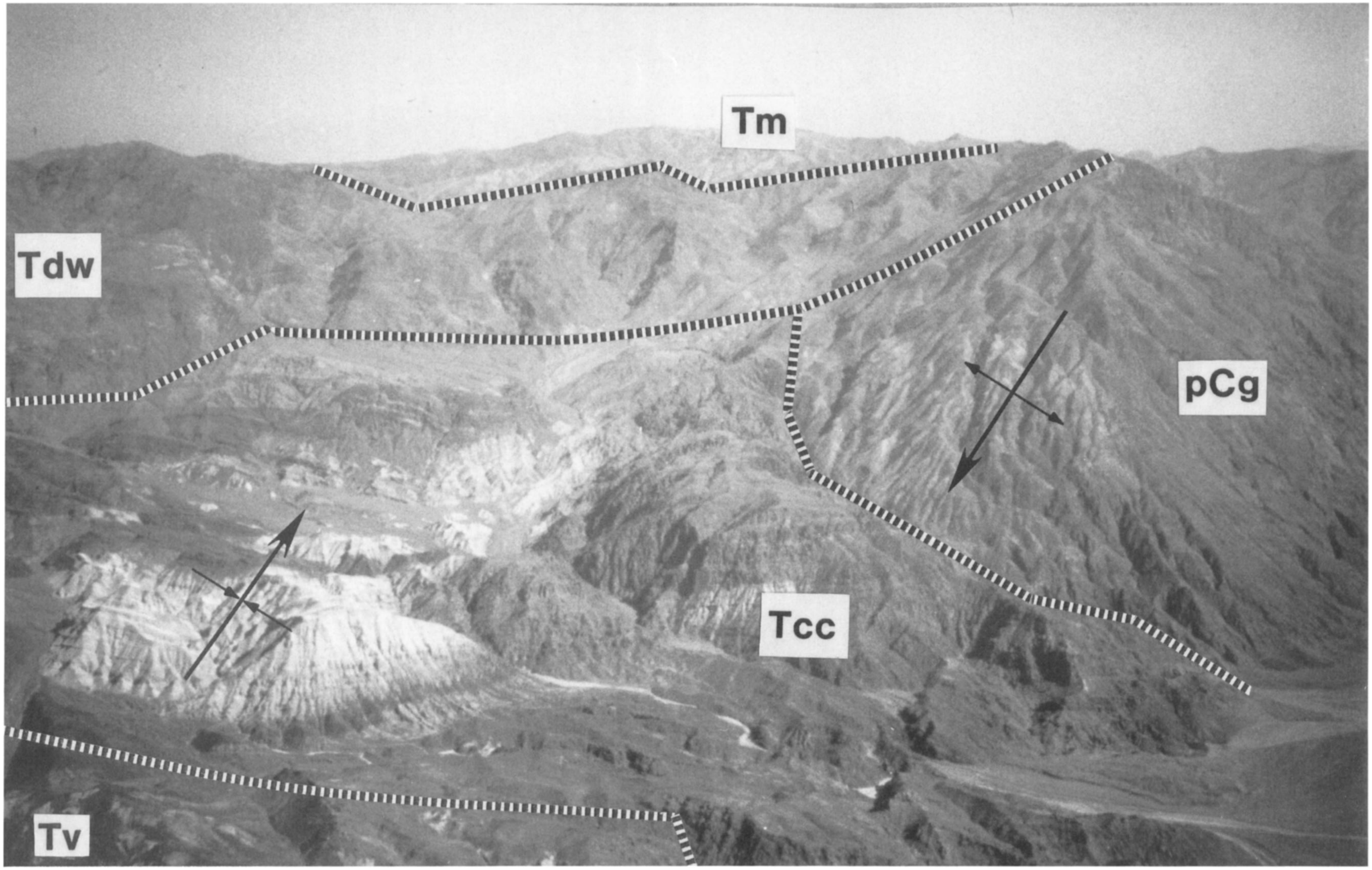

Figure 3. Southeast-facing photograph of the Black Mountains depicting coaxial synform hanging wall/antiform footwall pair (arrows denote plunge direction). Tcc, Copper Canyon Formation (late Miocene and Pliocene); Tv, volcanic rocks (Miocene, 6–7.5 Ma and older); Tm, granitic and monzonitic plutonic complex (Miocene, 8.7 Ma); Tdw, Willow Spring pluton (Miocene, 11.6 Ma); pCg, schist and gneiss (Precambrian); Not visible in the skyline and on the back side of the range are rhyolite intrusions and volcanic strata.

age from a vitric tuff bed in the upper portion of the formation. In this study, we have obtained new $^{40}Ar/^{39}Ar$ age data (using both the laser fusion and population methods) that clarify and constrain the time of deposition of the Copper Canyon Formation.

Mineral separation procedures, laboratory techniques, and data analysis by the population method follow that described by Holm et al. (1992). The laser fusion method was used to date one tuff unit in Tertiary volcanic rocks beneath the Copper Canyon Formation and two tuff layers within the Copper Canyon Formation. The samples were fused and analyzed using the GLM system at the U.S. Geological Survey in Menlo Park, California (Dalrymple 1989). Five to six separate fusions were done on each sample. Both simple and weighted means were calculated for the ages (and associated error) from the data for each fusion run, using the inverse variance as the weighting factor (table 1).

Table 1. Data Summary of Results of Ar/Ar Laser Fusion Analyses

Sample	Run	Age (Ma)	Std. Dev. (MA)	Summary of Mean Ages (Ma)
	1	3.111	.493	Simple mean = 3.07
	2	2.418	.554	Std Err Mean = .20
Tfc	3	3.438	.334	
	4	3.484	.271	Weighted mean = 3.25
	5	2.900	.452	Wtd Std Err = .17
	1	5.326	.461	Simple mean = 5.83
	2	6.128	.446	Std Err Mean = .18
Tcc	3	6.331	.368	
(coarse)	4	5.723	.305	Weighted mean = 5.88
	5	5.324	.546	Wtd Std Err = .16
	6	6.153	.412	
	1	6.005	.273	Simple mean = 5.54
	2	5.129	.392	Std Err Mean = .31
Tcc	3	5.772	.268	
(fine)	4	5.454	.258	Weighted mean = 5.57
	5	5.409	.258	Wtd Std Err = .12
	6	5.482	.377	
	1	6.048	.051	Simple mean = 6.05
	2	6.130	.053	Std Err Mean = .02
TVDV	3	5.980	.050	
	4	6.018	.048	Weighted mean = 6.05
	5	6.064	.051	Wtd Std Err = .02
	6	6.074	.050	

Biotite from a steeply dipping biotite-rich tuff unit (sample CCTv, figure 2) exposed directly beneath the unconformity at the base of the Copper Canyon Formation north of the mouth of Copper Canyon yielded a concordant $^{40}Ar/^{39}Ar$ plateau and intercept age of 7.5 ± 0.1 Ma (figure 4). Another felsic tuff unit from within the same stratigraphic package was sampled south of Dante's View (~3 km north of sample CCTv). Here the volcanic units are uncomformably overlain by a gently dipping 5.4 Ma vitrophyre (Fleck 1970). Biotite from this sample (TVDV) gave a laser-fusion age of 6.1 ± 0.1 Ma (table 1), slightly younger than the 6.3–6.5 Ma ages obtained for these same units by Fleck (1970) using the conventional K-Ar technique. These ages establish an upper bound for the onset of deposition of the Copper Canyon Formation.

Three age determinations were obtained on volcanic rocks within the Copper Canyon Formation and overlying fanglomerate. Coarse and fine biotite crystals from a 2 m thick, light-green lithic tuff (sample Tcc) exposed at the mouth of Copper Canyon yielded laser fusion ages of 5.9 ± 0.1 Ma and 5.6 ± 0.1 Ma, respectively and a combined mean age of 5.7 ± 0.2 Ma (table 1). A whole rock sample (CCB3) of a basalt flow located about 700 m above this lithic tuff gave a concordant $^{40}Ar/^{39}Ar$ plateau and intercept age of 4.9 ± 0.1 Ma (figure 4). The fanglomerates overlying the Copper Canyon Formation contain a discontinuous, 1 to 2 m thick, chalky-white tuff layer that contains minor amounts of biotite. A biotite separate from this layer (Tfc) yielded a laser fusion $^{40}Ar/^{39}Ar$ age of 3.1 ± 0.2 Ma (table 1). The ages of volcanic units from below and within the Copper Canyon basinal deposits (summarized in table 2) firmly establish a late Miocene to earliest Pliocene age of deposition for the Copper Canyon Formation and a middle Pliocene age for the overlying fanglomerates.

Clast types in the conglomerate member of the Copper Canyon Formation and in the overlying fanglomerate unit are dominated by Miocene intrusive and volcanic fragments (Drewes 1963; Otton 1977; Scrivner 1984; Holm and Lux 1991). The results of clast counts carried out at 16 sites within the formation are summarized in figure 5. Between 500 and 600 clasts were identified at each site, and the results projected to form a "compositional" section (with straight lines interpolated between sites). Clast composition from the lower to the upper part of the formation varies inversely with the structural succession of igneous units currently exposed in the range (see photograph of figure 3). Clasts of rock units exposed highest in the range (volcanic and hypabyssal intrusive rocks) are most abundant lower in the section, whereas clasts of deeper seated intrusive rocks (Willow Spring pluton and younger granitic rocks) occur in greater proportion higher in the section. The lower 500 m of the Copper Canyon Formation also contain abundant clasts of Precambrian schist and gneiss and lesser amounts of limestone and quartzite. Fanglomerates overlying the Copper Canyon For-

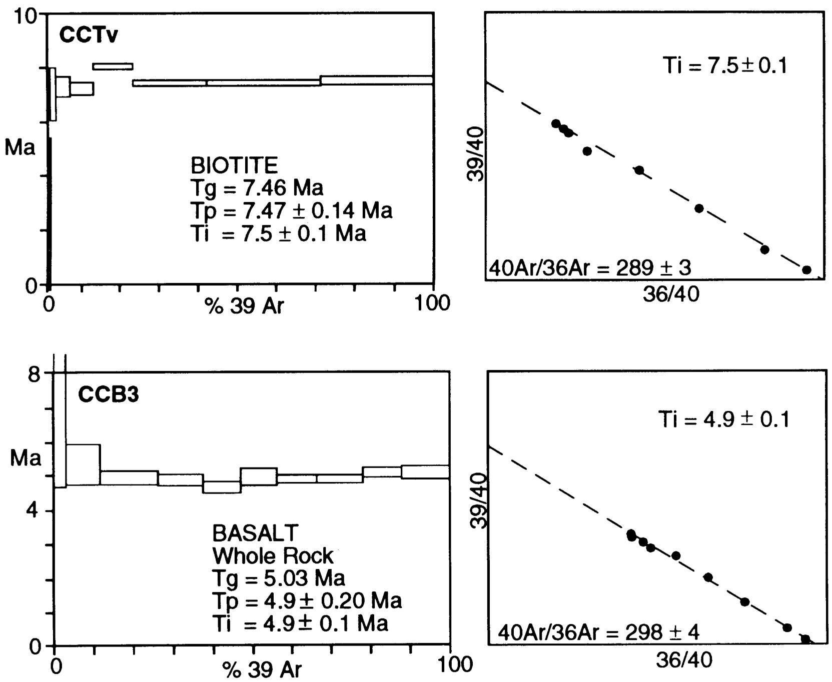

Figure 4. $^{40}Ar/^{39}Ar$ spectra and isotope correlation intercept diagram for a volcanic rock sample (CCTv) collected beneath the Copper Canyon Formation and for a basalt (CCB3) flow from within the Copper Canyon Formation. Tg, total gas age; Tp, plateau age; Ti, intercept age. See map of figure 1 for localities.

mation are composed of over 90% of granitic and diorite/gabbro clasts with only minor amounts of younger volcanics and older metamorphic clasts.

The amount of westward displacement of the hanging wall basin deposits described above is poorly constrained. The variation in clast composition suggests, however, that they are not greatly displaced from their original paleogeographical position considering that they consist entirely of rock types present nearby in the exposed footwall. The clast types in these deposits likely record late erosional stripping (post-6 Ma) of the central Black Mountains footwall rocks following tectonic denudation between 10 and 6 Ma (Holm et al. 1992). Clasts of the Precambrian basement rocks and silicic plutonic rocks at the base of the Copper Canyon Formation suggest they were exposed to erosion by ~6 Ma. The first appearance of Willow Spring pluton clasts suggests exposure occurred later, between 5.7 Ma and 4.9 Ma (Asmerom et al. 1990).

Evidence for Tertiary Folding

The Copper Canyon Formation and overlying fanglomerate are bounded on the south and east by a low-angle fault (the turtleback fault), and volcanics beneath the Copper Canyon Formation are bounded on the north by a moderately to steeply dipping fault (figure 2). The hanging wall rocks contain numerous normal faults of small displacement. Moderately to steeply west and northwest dipping larger normal faults are few in number. North of the Copper Canyon antiform, some of these faults are cut by the detachment fault, whereas others seem to sole into it; however, none of these faults are observed to crosscut the low-angle normal fault. As originally mapped over 30 years ago by Drewes (1963) and more recently by Otton (1977) and Holm (1992), the basinal strata were syndepositionally folded into a SE-plunging syncline with an axial surface roughly coplanar with the axial surface of a synform in the underly-

Table 2. Summary of Ages of Volcanic Rocks, Copper Canyon area, Death Valley, CA

Sample	Rock type	Locality	Mineral	Elevation (m)	Age ±2σ (Ma)
Tfc	Ash tuff	116°42.5′W, 36°09.2′N	biotite	677	3.1 ± .2
CCB3	Basalt flow	116°44.4′W, 36°08.6′N	whole rock	274	4.9 ± .1
Tcc	Lithic tuff	116°44.8′W, 36°08.1′N	biotite	131	5.7 ± .2
TVDV	Felsic tuff	116°42.8′W, 36°12.8′N	biotite	1562	6.1 ± .1
CCTv	Felsic tuff	116°44.8′W, 36°08.8′N	biotite	394	7.5 ± .1

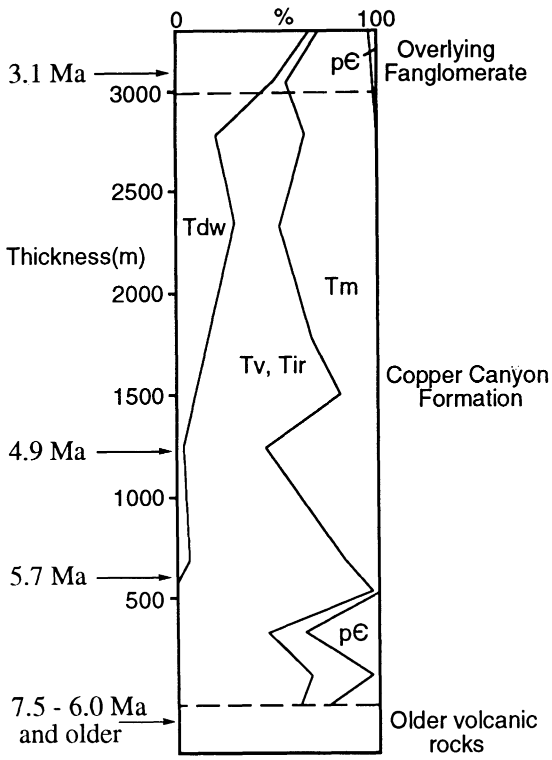

Figure 5. Compositional column of clast types in the Copper Canyon basinal sediments. Tv, volcanic units (Miocene); Tir, rhyolitic intrusive rocks (Miocene); Tm, granitic and monzonitic plutonic rocks (Miocene); Tdw, Willow Spring pluton (Miocene), pCg, gneiss, schist, quartzite, and marble (Precambrian).

ing detachment surface (figures 2 and 3). The thick sequence of 11 basalt flows in the middle of the formation (Otton 1977) are erosionally truncated on the limbs of the syncline and are overlain by less tightly folded strata of the upper Copper Canyon Formation and overlying fanglomerate.

Field evidence (Holm 1992) shows that the 11.6 Ma Willow Spring pluton does not cross-cut the antiformal structures but rather has a folded map view pattern that mimics the antiforms of the underlying layered Precambrian rocks (see figure 2 of Holm and Wernicke 1990, and Mancktelow and Pavlis 1994). Folding of the Willow Spring pluton is also indicated by the variation of magnetization direction of the pluton around the antiform structures (Holm et al. 1993). This suggests that most, if not all, of the folding recorded by the Death Valley turtlebacks is late Miocene to early Pliocene in age.

Tertiary folding in the Black Mountains is also supported by structural analysis of mylonitic tectonites in footwall rocks of the turtlebacks. Mapping reveals a mylonitic foliation and lineation in

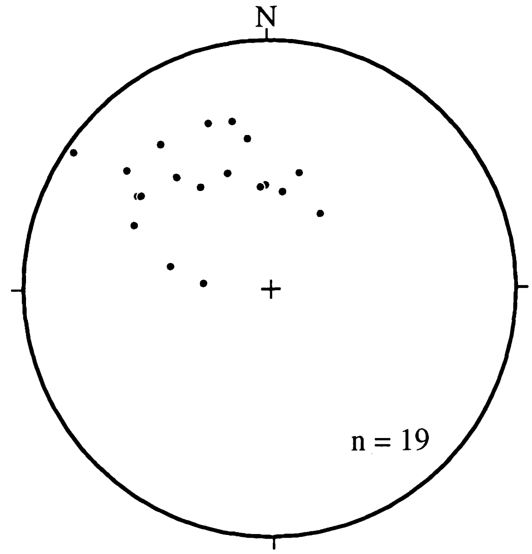

Figure 6. Stereogram showing orientations of lineations in ductilely deformed Willow Spring pluton at Sheep Canyon.

rocks of the Miocene Willow Spring pluton whose orientation is subparallel to the overlying, undulatory detachment fault. Further away from the fault, the ductile fabric within the pluton is dominantly an L-tectonite whose orientation is subparallel to the plunge of the fold axis of the turtlebacks (figures 2 and 6). An L-tectonite fabric is ordinarily taken to record constrictional finite strain. This suggests that, at least from 11.5 Ma to ~9 Ma (the time span during which much of the lineation was likely developed, Mancktelow and Pavlis 1994), the deformation of the Black Mountains crystalline core occurred, in part, in a constrictional strain field.

Discussion

Hill and Troxel (1966) were the first to suggest that the Death Valley turtlebacks were products of Tertiary folding. Subsequently their hypothesis was disregarded in favor of a Mesozoic or even Precambrian origin for antiform formation (Wright et al. 1974). We believe the field relations and age constraints described here are most consistent with a late Miocene and younger age of folding. We note that Tertiary folding is consistent with recent reconstructions of extension in this region that recognize a significant component of north-south shortening (Wernicke et al. 1988; Bartley et al. 1990; Glazner and Bartley 1991).

Coaxiality of folds in hanging wall sedimentary beds above warped detachment faults has been identified in other areas such as in the Chemehuevi Mountains of southeastern California (Miller and John 1988) and the Weepah Hills area of southwestern Nevada (Stewart and Diamond 1990). Coaxial folding of hanging wall strata has also been suggested for strata in the Whipple Mountains in southeastern California (Yin 1991; Yin and Dunn 1992), although the relationship there has probably been obscured by multiple generations of normal faulting and folding. Indeed, Yin (1991) has argued that because for most metamorphic core complexes the magnitude of warping (<20°) is much less than the magnitude of tilting of beds (40°–70°) due to rotation along normal faults in the upper plate, folding may be difficult to identify and, therefore, might actually be more common than is presently envisioned. It is likely that folding of both the Copper Canyon Formation adjacent to central Death Valley and the Miocene Esmeralda Formation in the Weepah Hills is well preserved because these packages are relatively little extended internally (Stewart and Diamond 1990). The observation of coaxiality of hanging wall folds, antiforms and synforms of foliations and sheetlike plutons, and undulations of detachment faults in the Black Mountains and elsewhere suggest folding of originally more planar surfaces.

Mancktelow and Pavlis (1994) describe extension parallel, mesoscopic folds in both the Copper Canyon and Mormon Point turtleback footwall rocks (figure 1) that occurred during high-grade metamorphism between 11.5 and 9 Ma; thus folding in the Black Mountains began prior to deposition of the Copper Canyon Formation. Planar, vertical ~7 Ma felsic dikes which intrude the Copper Canyon footwall rocks (figure 2) are oriented perpendicular to the antiform axis and therefore do not record the later folding. However, variably oriented mafic dikes of similar age exposed in the Badwater turtleback (figure 1) are apparently not folded (Miller 1992*a*, 1992*b*). This indicates that the folding of the Badwater turtleback rocks, which represent an allochthonous fault slice with a very different history from the two southern turtlebacks (Holm et al. 1992), was complete by 6–7 Ma.

The currently active range-front fault bordering the Black Mountains on the west is a steeply dipping surface with normal, down-to-the-west displacement (Geist and Brocher 1987). The geometry of this fault, which probably developed in the last 2–4 Ma, differs dramatically from the low-angle detachment fault responsible for unroofing of the Black Mountains prior to 4 Ma (Holm et al. 1992). The older detachment fault is highly corrugated apparently due to folding in an overall constrictional strain field. It seems possible that this large-scale folding associated with extension may have caused deactivation of the detachment surface and the formation of a younger, more planar fault system. The present Black Mountains frontal fault may represent this out-stepping of a normal-fault system away from a deactivated folded detachment.

The origin of the geometry of metamorphic core complexes has been an important problem in the study of detachment fault development. Detachment fault systems are three-dimensional features that require the study of both hanging wall and footwall structures. The relations described here strongly suggest that in the Death Valley region, extension parallel folds are a first-order feature formed as the result of shortening during extension. Recent field studies from other extensional terrains are providing a growing data base which suggests that this kinematic interpretation for detachment fault development may not be uncommon or unique to the Death Valley region (Bartley et al. 1990; Yin 1991; Dorsey and Roberts 1992; Oldow and Kohler 1994; Mancktelow and Pavlis 1994; Chauvet and Seranne 1994).

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