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The Black Mountains turtlebacks: Rosetta stones of Death Valley tectonics

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Abstract

The Black Mountains turtlebacks expose mid-crustal rock along the western front of the Black Mountains. As such, they provide keys to understanding the Tertiary structural evolution of Death Valley, and because of the outstanding rock exposure, they also provide valuable natural laboratories for observing structural processes. There are three turtlebacks: the Badwater turtleback in the north, the Copper Canyon turtleback, and the Mormon Point turtleback in the south. Although important differences exist among them, each turtleback displays a doubly plunging antiformal core of metamorphic and igneous rock and a brittle fault contact to the northwest that is structurally overlain by Miocene–Pleistocene volcanic and/or sedimentary rock.

The turtleback cores contain mylonitic rocks that record an early period of top-southeastward directed shear followed by top-northwestward directed shear. The earlier formed mylonites are cut by, and locally appear concurrent with, 55–61 Ma pegmatite. We interpret these fabrics as related to large-scale, basement-involved thrust faults at the turtlebacks, now preserved as areally-extensive, metamorphosed, basement over younger-cover contacts.

The younger, and far more pervasive, mylonites record late Tertiary extensional unroofing of the turtleback footwalls from mid-crustal depths. Available geochronology suggests that they cooled through 300 °C at different times: 13 Ma at Badwater; 6 Ma at Copper Canyon; 8 Ma at Mormon Point. At Mormon Point and Copper Canyon turtlebacks these dates record cooling of the metamorphic assemblages from beneath the floor of an ~11 Ma Tertiary plutonic complex. Collectively these relationships suggest that the turtlebacks record initiation of ductile extension before ~14 Ma followed by injection of a large plutonic complex along the ductile shear zone. Ductile deformation continued during extensional uplift until the rocks cooled below temperatures for crystal plastic deformation by 6–8 Ma. Subsequent low-angle brittle fault slip led to final exposure of the igneous and metamorphic complex.

The turtleback shear zones can constrain models for crustal extension from map-view as well as cross-sectional perspectives. In map view, the presence of basement-involved thrust faults in the turtlebacks suggest the Black Mountains were a basement

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high prior to late Tertiary extension. In cross-section, the turtleback geometries and histories are most compatible with models that call on multiple faults rather than a single detachment to drive post-11 Ma extension.

Keywords: turtlebacks; Death Valley; extension; ductile shear zones; basin; range

1. Introduction

The three Black Mountains turtlebacks have long been considered important but enigmatic features of Death Valley geology. They were named "turtlebacks" by Curry (1938) because their convex-upwards morphologies resemble turtleshells. In terms of bedrock geology, however, the turtlebacks stand out because they offer the only exposures of crystalline basement rock along the Black Mountains front (Curry, 1938, 1954; Fig. 1). They are probably the single most important features in deciphering Death Valley's complex tectonic story.

Each of the turtlebacks displays the essential features of Cordilleran Metamorphic Core Complexes (Davis, 1980; Lister and Davis, 1989): a ductilely deformed metamorphic core, an overlying body of highly faulted upper crustal rock, and at their northwest margins, a brittle extensional fault zone between them. Additionally, mylonitic rocks of the core reflect a sense-of-shear that is similar to, but older than, the fault zone. Post- to syn-mylonitization folding about axes subparallel to shear zone transport produced up to 4 km of structural relief both at high angles and parallel to transport. Thus, each turtleback individually represents a "core complex" that occupies an area of only about 6 km^2, but collectively, the turtlebacks represent different parts of a large-scale extensional system. This complex 3D geometry provides outstanding opportunities to observe both shallow- and moderately deep-level processes of shear zone evolution.

The Death Valley region is an especially fertile area for testing models for crustal extension. There, tectonic interpretations generally fall into one of two categories (Fig. 2). One category, the "Rolling Hinge" model (Stewart, 1983; Hamilton, 1988; Wernicke et al., 1988; Snow and Wernicke, 2000), calls for ~80 km of horizontal translation and unroofing of the Black Mountains on a detachment fault of regional extent. Because the Black Mountains contain ~11 Ma plutons, this faulting must postdate 11 Ma. This model views strike-slip faults, such as the en echelon Furnace Creek and Sheephead faults, as upper crustal edges of the detachment system. The other category calls for extension by slip on numerous, distinct fault zones (Wright and Troxel, 1984; Wright et al., 1991; Serpa and Pavlis, 1996; Miller and Prave, 2002). This category, the "Pull-Apart" model, calls on the strike-slip faults to penetrate deeply into the crust and drive extension between their terminations, similar to the model proposed by Burchfiel and Stewart (1966) for modern Death Valley. Both interpretations rely heavily on findings from the turtlebacks because they each describe the turtlebacks as the principal shear zones. In the Rolling Hinge model, the turtlebacks are different exposures of the same detachment fault; in the Pull-Apart model, the turtlebacks define three of the largest, and distinct, faults.

Both tectonic interpretations also rely on differing views of the original configuration of the Mesozoic fold-thrust belt. The Rolling Hinge model requires an originally narrow thrust belt in which the Panamint and Chicago Pass thrusts, now separated by about 80 km, were originally the same structure. Detachment faulting during late Tertiary extension cut this fault and displaced the two parts to their present locations (Figs. 1 and 2A). By contrast, the Pull-Apart model requires an originally wider thrust belt in which the Panamint and Chicago Pass thrusts originated as separate features (Fig. 2B).

The turtlebacks are here described as "Rosetta Stones" because they provide keys to decipher both the original fold-thrust belt geometry as well as the geometry and mechanisms of late Tertiary extension. Their locations at the western edge of the Black Mountains place them in the middle of the fold and thrust belt. Most recently, Miller and Friedman (1999) and Miller (2003) have found evidence in their footwalls for mid-crustal, pre-55 Ma, basement-involved thrust faulting. The addition of the Black Mountains to the fold-thrust belt helps constrain its original

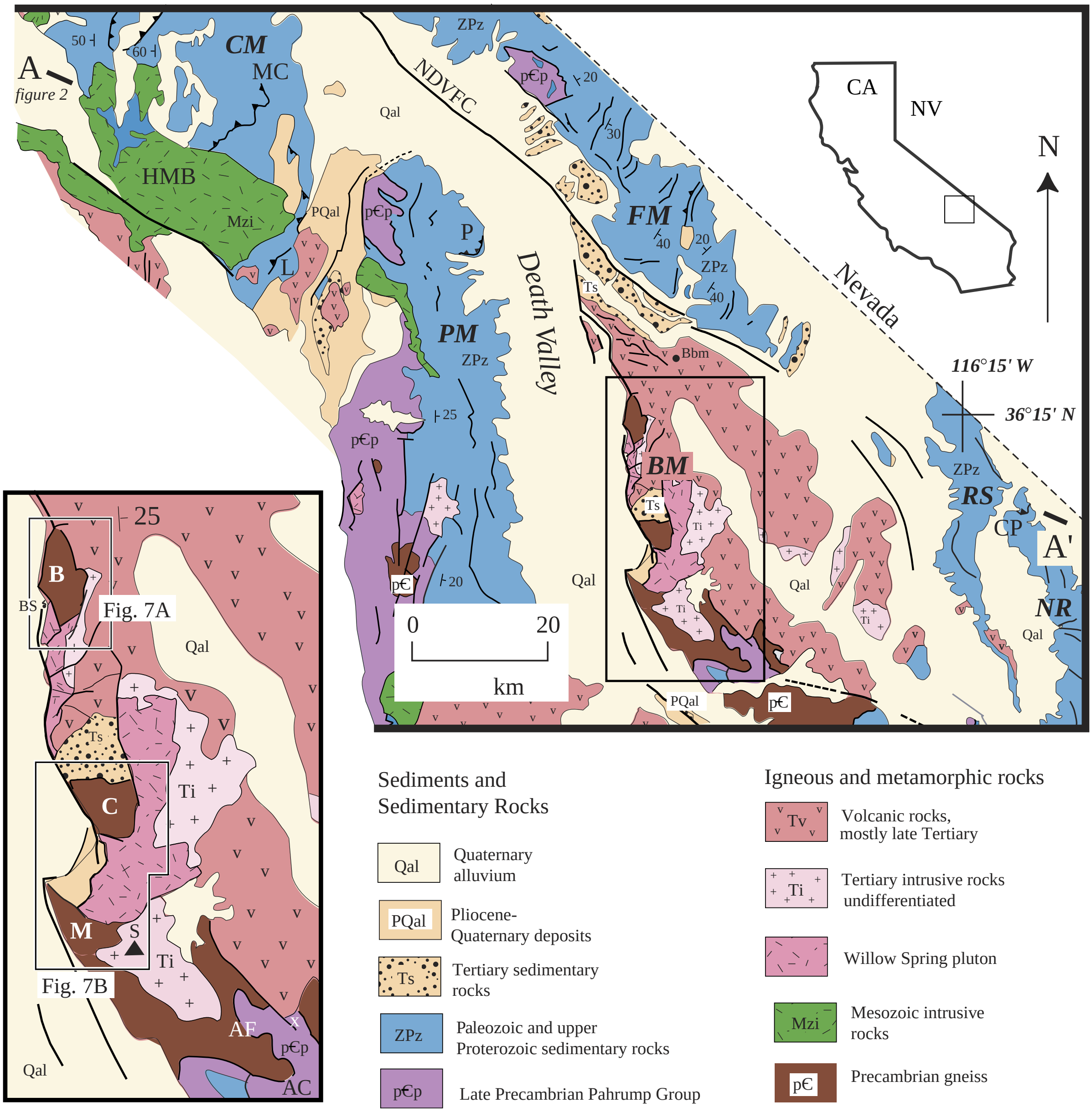


Fig. 1. Map of the central Death Valley region; inset shows close-up view of Black Mountains. Abbreviations: AC—Amargosa Chaos; AF—Amargosa Fault; B—Badwater turtleback; Bbm—Billie Borate Mine; BM—Black Mountains; BS—Badwater Spring; C—Copper Canyon turtleback; CM—Cottonwood Mountains; CP—Chicago Pass thrust; FM—Funeral Mountains; HMB—Hunter Mountain batholith; L—Lemoigne thrust; M—Mormon Point turtleback; MC—Marble Canyon thrust; NR—Nopah Range; P—Panamint thrust; PM—Panamint Mountains; RS—Resting Spring Range; S—Smith Mountain.

geometry to one that favors the Pull-Apart model and severely limits the Rolling Hinge model.

The turtlebacks therefore offer world-class field laboratories to study the processes of structural geology and tectonics—the former through their superb exposures of mid- and upper-crustal fault zones and associated fault rocks and structures, and the latter through the insights they can give to models of crustal

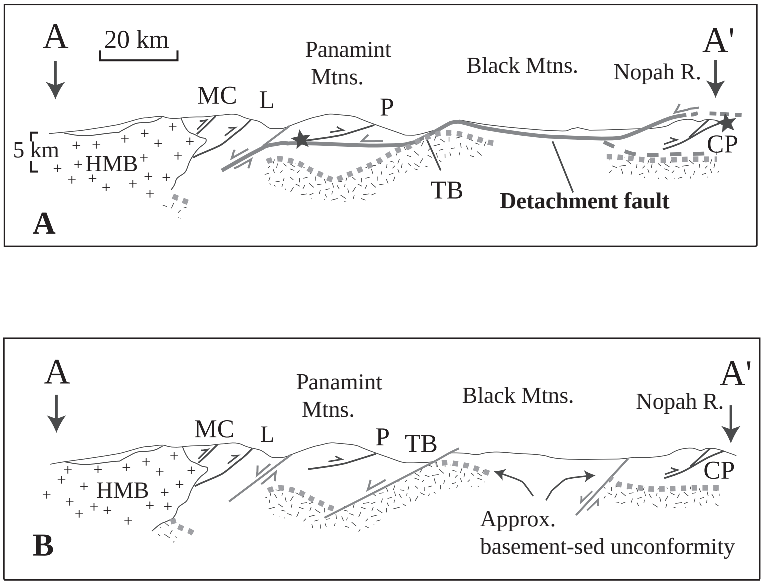


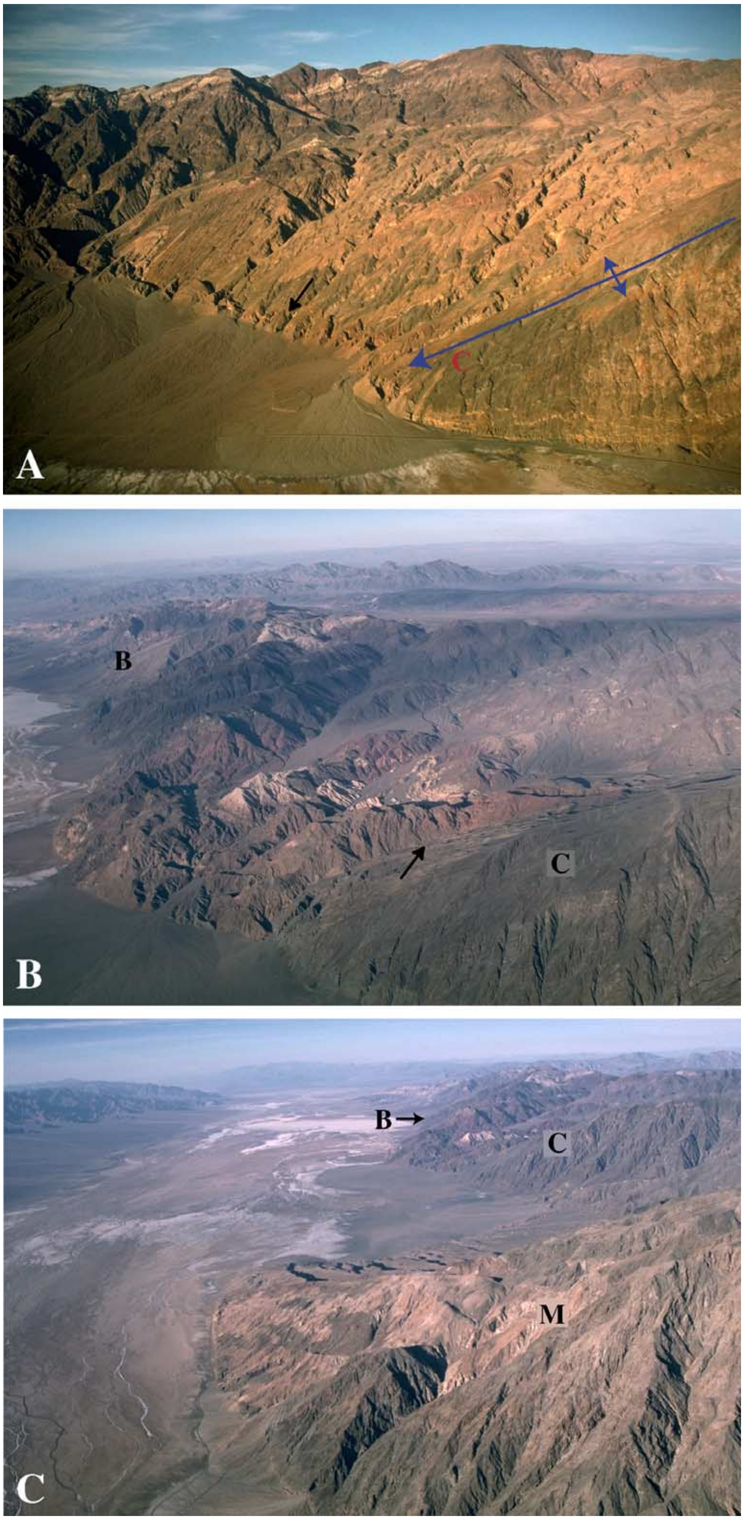
Fig. 2. Schematic cross-sections from A to A′ of Fig. 1 that compare interpretations of present-day structure of Death Valley region. Abbreviations: CP—Chicago Pass thrust; HMB—Hunter Mountain batholith; L—Legmoigne thrust; MC—Marble Canyon thrust; P—Panamint thrust; TB—Turtlebacks. BMT and TB are both projected into line of section. A: Present-day structure as interpreted in context of the Rolling Hinge model by Wernicke et al. (1988) and Snow and Wernicke (2000). Note that extensional turtleback faults (TB) are part of a regional detachment. Stars mark correlative structures offset by the detachment. Dashed line beneath Nopah range indicates that part of the detachment system underlies the Nopah Range as well. B: Present-day structure as interpreted in context of Pull-Apart model. Note that extensional turtleback faults are deep-seated faults.

extension. This paper reviews contributions made by researchers on the turtlebacks and concludes with our preferred interpretation of the turtlebacks as being long-lived shear zones that probably reactivated basement-involved thrust faults.

2. Research on the turtlebacks

Curry (1938) first described the crystalline cores of the turtlebacks, their fault zones, and their distinctive antiformal geometries. From north to south, Curry (1938, 1954) described three turtlebacks in the Black Mountains, the Badwater, Copper Canyon, and Mormon Point turtlebacks (Figs. 1 and 3A,B,C). He and Noble (1941) both noted the geometrical similarities between the turtlebacks and the Amargosa fault near Virgin Spring, in the southern Black Mountains, and suggested their common origin as a regional thrust fault. Drewes (1959) argued that the fault zones were Pliocene or Pleistocene gravity-driven features, imposed on the turtlebacks long after thrust faulting and folding. His map of the central and southern Black Mountains (Drewes, 1963) gave the first detailed look of the complicated structure and hanging wall stratigraphy of the Mormon Point and Copper Canyon turtlebacks. Wright et al. (1974) first recognized that the turtleback fault zones were rooted normal faults that played an important role in Death Valley's late Cenozoic extensional story.

Fig. 3. Photographs of the Black Mountains turtlebacks. In each, view is to north. Abbreviations: B—Badwater turtleback; C—Copper Canyon turtleback; M—Mormon Point turtleback. A: View of Badwater turtleback. Fold symbol and letter "c" corresponds to fold axes as depicted on Fig. 7A. Arrow marks location of Fault #2 of the Badwater turtleback fault system. B: Copper Canyon turtleback. Footwall is green; Hanging wall is red and tan. Arrow marks location of Copper Canyon turtleback fault. C: Mormon Point turtleback. Tan color marks footwall marble; greenish rock marks basement gneiss.


C
A
B
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Otton (1976, 1977) mapped the Mormon Point and Copper Canyon turtlebacks at 1:24,000 and described most of the relations that are key to interpretations today.

A common theme of this early research is the importance of pre-Cenozoic deformation in shaping the turtlebacks. Wright et al. (1974) and Otton (1976), for example, recognized the relevance of the turtlebacks to crustal extension, but called on Mesozoic shortening to form their antiformal geometries. However, with the recognition of the extensional nature of metamorphic core complexes and their associated ductilely deformed rocks elsewhere (e.g. Davis et al., 1982, 1986; Miller et al., 1983) as well as the recognition that the Willow Spring pluton in the Black Mountains was only 11 Ma (Asmerom et al., 1990), most later workers emphasized the extensional features in the turtlebacks (e.g. Miller in Wright et al., 1991; Pavlis in Wright et al., 1991; Miller, 1992a,b; Holm et al., 1992). By the mid-1990s, most workers accepted that Tertiary extension, not Mesozoic shortening, was the primary cause of the turtleback geometries (Mancktelow and Pavlis, 1994; Holm et al., 1994a,b).

Otton (1976), however, mapped older-over-younger contacts at the Mormon Point and Copper Canyon turtlebacks, which Holm (1992) interpreted as minor thrust faults related to the Mesozoic contraction. Using U–Pb dating of zircons, Miller and Friedman (1999) found pegmatite at the Badwater turtleback that locally cross-cut mylonitic fabrics to be 55 Ma; they interpreted the older fabrics as related to the Mesozoic Sevier Orogeny. Miller (2003) later reported more structural data to propose that a significant basement thrust existed at the Badwater turtleback in addition to the thrust faults at the Mormon Point and Copper Canyon turtlebacks, and concluded that the thrusts were probably early Tertiary in age. This paper further develops that argument to show the relevance of these structures to the pre-extension geometry of the fold-thrust belt.

Several recent studies of the turtleback fault zones and their hanging walls have clarified important aspects of the northern Black Mountains stratigraphy, turtleback fault geometries and timing of slip. Miller (1991) and Keener et al. (1993) found evidence for successive generations of turtleback fault zones, and interpreted that they were cut by present-day faults in front of the range. This interpretation is questioned by Hayman et al. (2003). Pavlis et al. (1993) and Burchfiel et al. (1995) interpreted the kinematic framework of the embayed mountain front at Mormon Point. Greene (1997) mapped stratigraphy and structures of the hanging wall of the Badwater turtleback north of Natural Bridge canyon. Knott (1998) documented Pleistocene slip on the Badwater and Mormon Point turtlebacks and described fault segmentation along the length of the Black Mountains front. Nemser (2001) and Hayman et al. (2003) modeled faulting in the upper plates of the Badwater and Mormon Point turtlebacks. Most recently, Dee et al. (2004) found evidence for two stages of ductile deformation at the Mormon Point turtleback, the most significant of which predated 9.5 Ma.

3. Features of the turtlebacks

The lower plate, brittle fault zone, and upper plate define the three principal components of each turtleback (Figs. 3 and 4). As suggested by studies of metamorphic core complexes elsewhere (e.g. Lister and Davis, 1989) and documented by Miller (1992a,b), Holm (1992), Pavlis et al. (1993), Keener et al. (1993), Nemser (2001), and Hayman et al. (2003), brittle deformation of the hanging walls fit into the same extensional kinematic picture as that of the fault zones, which in turn have approximately the same sense of shear as the footwall mylonites. Each component also exhibits to varying degrees the antiformal geometries characteristic of the turtlebacks. The footwalls, however, include Proterozoic and both Neogene and Paleogene intrusive rock and so have geologic histories that predate Neogene extension. Here, each component of the turtlebacks, as well as their antiformal shapes, will be reviewed separately.

3.1. Turtleback footwalls

Each turtleback footwall consists of quartz-feldspar gneiss and marble with minor amounts of pelitic schist. They are intruded by a host of igneous rocks that date from the early to late Tertiary. Most footwall rocks, except for the youngest intrusions, exhibit a range of tectonite fabrics. Consequently, the igneous

Fig. 4. Photograph of three principal elements of the turtlebacks as seen at Badwater turtleback. Note listric normal fault in hanging wall directly above geologist.

rocks have been critical in sorting out episodes of deformation.

3.1.1. Footwall stratigraphy

The gneiss, with a U–Pb zircon age of 1.7 Ga (Wasserburg et al., 1959; DeWitt et al., 1984), belongs to the regional crystalline basement complex of the Mojave Province (Condie, 1992). The marble and schist are metasedimentary assemblages that are arguably derived from the overlying miogeoclinal section. Most workers have traditionally assigned these metasedimentary rocks to the Noonday Dolomite and Johnnie Formations (Wright et al., 1974, 1991; Otton, 1976; Holm, 1992). Most still assign part of the section to the Noonday Dolomite, but some now question the interpretation of the associated, non-dolomitic rock. In the lowest exposed levels of the Badwater turtleback, the exposed section of pelitic rock contains about 50 m of feldspathic quartz mylonite, suggestive of an arkosic protolith (Fig. 5A). This observation, plus the relative abundance of calcite marble with silty laminae, led Miller (1992a,b) to suggest that the clastic rocks were Crystal Spring Formation, possibly overlain by Noonday Dolomite. At Mormon Point, Holm (1992) described diamictite-like gneiss structurally beneath the Noonday(?) marble that he argued was Kingston Peak Formation. We dispute this interpretation, noting that the "clasts" are actually deformed granitic sills.

Intrusive rocks of the footwalls consist of early Tertiary pegmatite and a variety of mafic to felsic late Tertiary plutons and dikes. Based on U–Pb zircon ages, the pegmatite is 55 ± 3 Ma at the Badwater turtleback (Miller and Friedman, 1999), and 61 Ma at the Copper Canyon turtleback (R. Friedman, 2000, personal communication). The pegmatite consists almost entirely of feldspar and quartz, with minor muscovite and/or biotite and few accessory minerals. It is most voluminous at the Badwater turtleback, where it constitutes approximately 30% of the footwall, but becomes less voluminous southward, where it constitutes less than 10% of either the Copper Canyon or Mormon Point turtlebacks. Typically, the pegmatite forms lens-shaped bodies from 1 m to about 10 m in width that are concordant to foliation in adjacent rock, but it locally forms dikes. Miller and Friedman (1999) interpreted the lens-shaped bodies as boudins and the dikes as parts of locally preserved "rafts" within ductilely deformed, late Tertiary extensional shear zones. Lee (2003) used geochemistry to argue that the pegmatites were derived directly from their metamorphic host rocks.

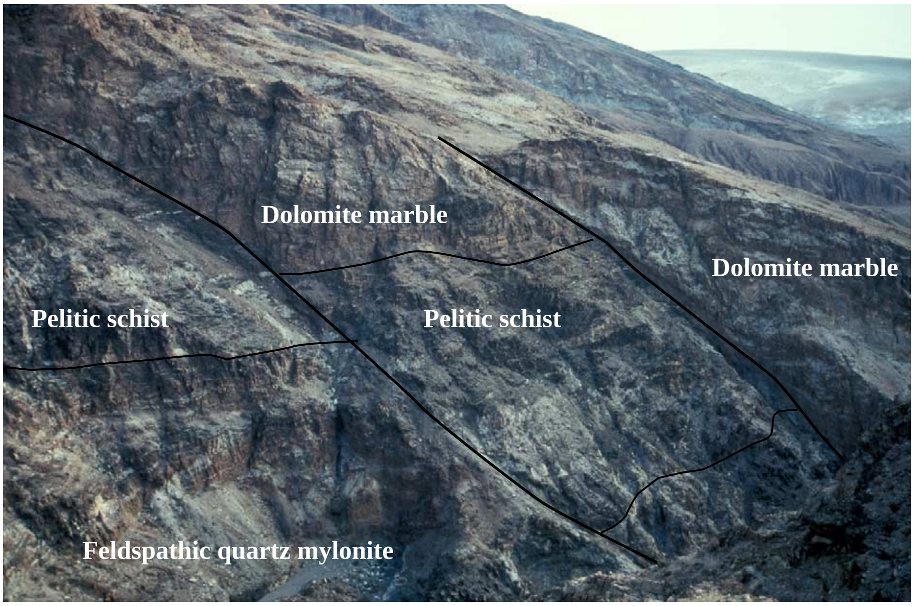


Fig. 5. Photograph of south wall of deep canyon in Badwater turtleback and stratigraphy of metasedimentary rock.

The late Tertiary intrusions consist of the Willow Spring pluton, Smith Mountain Granite and associated felsic bodies, and latite and diabase dikes. These rocks are described in detail by Holm et al. (1994a,b), Wright et al. (1991), Otton (1976) and Drewes (1963). The Willow Spring pluton and the Smith Mountain Granite are a comagmatic Late Miocene mafic (hornblende gabbro to quartz diorite) and felsic (biotite rapikivi granite) assemblage respectively that show magma mingling textures along a mutually intrusive contact (Meurer, 1992; Pavlis in Holm et al., 1994a,b). In addition to this field evidence, geochronological data from the plutonic complex are broadly supportive of this conclusion with two U–Pb zircon dates from the Willow Spring pluton of 11.6 ± 0.2 Ma by Asmerom et al., 1990 and 10.93 ± 0.75 Ma by DeWitt (reported in Wright et al., 1991). These ages are only slightly older than a 10.8 Ma Ar/Ar cooling date on orthoclase from the structurally highest exposed level of the Smith Mountain Granite (Pavlis in Holm et al., 1994a,b) and a U–Pb zircon age of 10.44 ± 0.22 Ma (Miller et al., 2004).

An important feature of the Late Miocene intrusive complex is that the intrusives form a sill-like body intruded along the structural top of each turtleback (Pavlis in Holm et al., 1994a,b; Pavlis, 1996). This sill is itself stratified with the mafic Willow Springs assemblage structurally beneath the felsic Smith Mountain granite. This geometry is undoubtedly not coincidental given the evidence that the Smith Mountain and Willow Springs assemblages are phases of the same plutonic body and so probably reflects density stratification within the original magma chamber of the sill. This geometry also led to dramatic thermal manifestations in the Copper Canyon and Mormon Point turtlebacks as the hot plutonic sheet above them cooled (Pavlis, 1996). Effects included: (1) partial to complete destruction of older fabrics by recrystallization; (2) growth of new mineral assemblages suggestive of low-P, upper amphibolite facies conditions (olivine in marble and muscovite breakdown to form K-spar+ sillimanite in pelites); and (3) cooling to biotite closure temperatures at 6–8 Ma (Holm and Dokka, 1993; Pavlis and Snee, unpublished data), which is 3–5 m.y. after plutonism, but consistent with the slower cooling of rocks below a large intrusive sheet (e.g. Pavlis, 1996).

3.1.2. Footwall fabrics

Footwall rocks that pre-date the Smith Mountain granite exhibit tectonite fabrics at all exposed structural levels in the turtlebacks. These fabrics fall into two categories: those that involve, and those that are cut by, the pegmatite. Those that involve the pegmatite dominate the footwalls. They show top-to-the-NW sense-of-shear, consistent with late Tertiary extension (Fig. 6A). This shear sense determination is unambiguous, as it is based on numerous outcrop and microscopic criteria, including shear bands, asymmetric porphyroclasts and mica fish, and preferred grain-shape orientations (e.g. Miller, 1992a,b; Holm, 1992).

A late Tertiary age for these fabrics is further indicated by three other structural and geochronologic findings. First, the fabrics affect the base of the 11.6 Ma Willow Spring pluton (Holm, 1992; Pavlis in Wright et al., 1991; Pavlis, 1996). Second, Holm et al. (1992) obtained Ar–Ar biotite ages of 13 Ma, 6 Ma, and 8 Ma for the Badwater, Copper Canyon and Mormon Point turtlebacks, respectively, to indicate when each turtleback cooled through ~300 °C. As 300 °C is the approximate temperature required for crystal-plasticity in quartz (Mitra, 1978; Passchier and Trouw, 1996), these ages help define when mylonitization ceased in gneissic rocks of each footwall; calcite-dominated marbles, which require temperatures of about 250 °C (Schmid, 1982), could continue to deform ductilely. Third, Miller (1992a,b) noted a continuous evolution of the mylonite zone at the Badwater turtleback across the ductile–brittle transition into brittle normal faulting with a clear connection to Tertiary extension. Miller (1999a,b) then applied the findings by Holm et al. (1992) to suggest that most of the deformation at the Badwater turtleback was between about 16–13 Ma.

At the Mormon Point turtleback, Miller and Friedman (2003) obtained a U–Pb zircon age of 9.53 ± 0.04 Ma from silicic dikes that cut most of the shear zone. Dee et al. (2004) found that these dikes were deflected into the shear zone and internally deformed at the highest structural levels. Based on an approximate 45° angle of deflection, they argued for a post 9.5 Ma angular shear strain of only about one. Pre-9.5 Ma shear strains, however, were likely much greater.

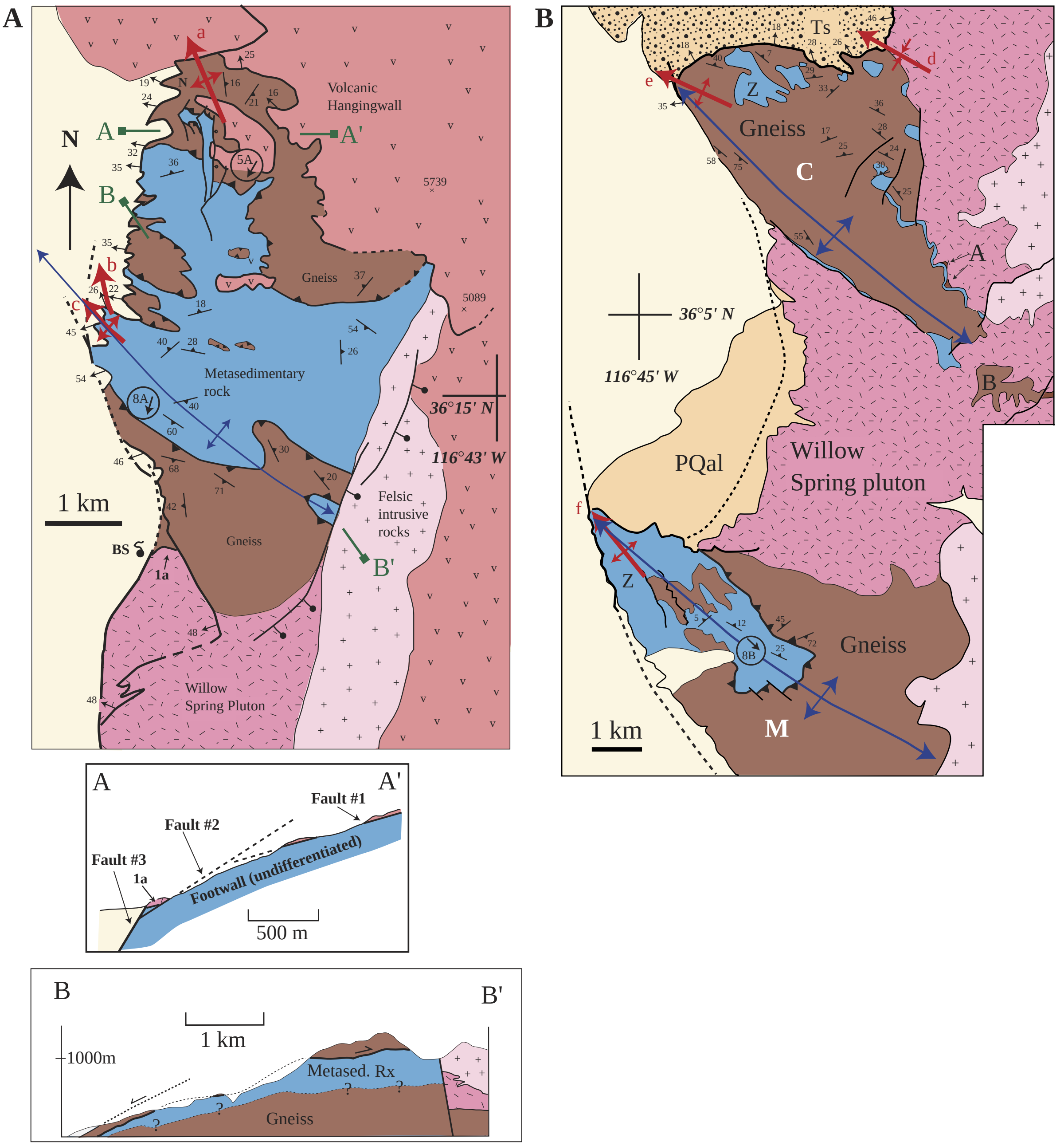
In contrast, early fabrics that are cut by the pegmatite appear as locally preserved "rafts" within the late Tertiary zone. Foliations and lineations of these rocks are parallel to those of the late Tertiary fabrics and so can be identified only where pegmatite is present. They typically show a top-to-the-east sense of shear (Holm, 1992; Turner and Miller, 1999; Miller, 2003) to suggest a pre-late Cenozoic shortening origin. Miller (2003) suggested they were at least partly coeval with intrusion of the pegmatite to make them of early Tertiary age. We argue later in this paper that the

Fig. 6. Large asymmetric pegmatite clast, deformed with top-northwest (right) shear sense at the Badwater turtleback. Plane of photograph is parallel to stretching lineations.

parallelism of both sets of fabrics suggests the turtle-back shear zones are in fact reactivated thrust faults.

3.1.3. Metamorphism

Each turtleback footwall experienced amphibolite- to upper amphibolite facies metamorphism prior to unroofing by late Tertiary extension. This grade is evident by the presence of crystal-plastically strained feldspar, indicative of temperatures greater than about 450 °C (Tullis and Yund, 1980; Pryer, 1993), as well as the metamorphic mineral assemblages in pelitic and carbonate rocks. At the Badwater Turtle-



back, kyanite-bearing schists, in association with garnet, rutile, ilmenite, and quartz (GRAIL) yielded a pressure of 700 ± 100 MPa for an approximate depth of 20 km and temperature between 500 °C and 675 °C (Whitney et al., 1993). At Mormon Point, Pavlis (1996) described k-spar and sillimanite-bearing schists to indicate much higher temperature second-sillimanite conditions. These high grade fabrics at Mormon Point are closely associated with the Miocene plutonic assemblage, which suggests that they formed during the Late Miocene (Pavlis, 1996). Furthermore, amphibolite samples collected from both the Copper Canyon and Mormon Point turtlebacks contain embayed garnets overgrown by a rim of plagioclase, a texture that suggests a higher pressure garnet amphibolite assemblage was overprinted by a lower pressure, hornblende-plagioclase assemblage.

To date no samples have been collected at either Mormon Point or Copper Canyon that contain low-variance mineral assemblages useful for thermobarometry. However, hornblende geobarometry of the Willow Spring pluton (Holm and Dokka, 1993) and Smith Mountain Granite (Meurer, 1992) indicates pressures no greater than 300 MPa in the Copper Canyon and Mormon Point turtlebacks during the Late Miocene. These pressures correspond to intrusion depths of 10–11 km in the turtleback footwalls (Holm and Wernicke, 1990; Holm and Dokka, 1993). Furthermore, Meurer (1992) found that intrusion depths increased northward in the Willow Spring pluton, consistent with exhumation along an initially more steeply dipping fault.

3.1.4. Footwall folds

Each turtleback footwall is the structural culmination of a northwest–southeast trending, doubly plunging antiform. These folds are second-generation (F2) structures relative to the main metamorphic foliation (S1) in the footwalls, and are composite features representing different styles of overprinting at different positions within large-scale ductile shear zones. The age of the S1 foliation is unclear, but undoubtedly includes Mesozoic and/or early Tertiary metamorphism. However, it was clearly re-used and transposed by S2 during the early stages of the extensional deformation.

Because the turtleback folds are largely defined by this foliation, they must have formed during or after the extension. At Badwater, Miller (1999a,b) applied a slip-line analysis (Hansen, 1971) to asymmetric minor folds on the northeast limb to suggest that they formed within a ductile shear zone during top-to-N 63°W transport. Each turtleback antiform is locally subparallel to the overlying brittle fault zone, the "turtleback faults" discussed in the following section. It is this feature that gives rise to the geomorphic expression (Fig. 3) first described by Curry (1938) and later attributed to extensional fault-reactivations of the foliation by Wright et al. (1974). This generalization, however, is an oversimplification when each turtleback is examined in detail.

Specifically, the principal footwall folds vary considerably from one turtleback to another. At the Badwater turtleback, the hingeline is poorly defined, but the northeastern "limb" displays abundant outcrop-scale non-cylindrical folds of the basement gneiss with metasedimentary rock. These folds typically trend northwest and range from upright to recumbent. Mormon Point exhibits a high degree of non-cylindrical folding of both the principal antiform and subparallel minor folds. The axial surface of the principal antiform is nonplanar, as it ranges from nearly upright at the southeast end of the turtleback to gently inclined

Fig. 7. Maps and cross-sections of Black Mountains turtlebacks. Dark blue fold symbols indicate approximate location of footwall antiformal hinge, whereas red fold symbols indicate locations of apparent fold hinges in fault surface. Locations of photographs in Figs. 5A and 8A,B are shown in circles with arrows that designate view direction. A: Map and cross sections of Badwater turtleback. Abbreviations: BS—Badwater Spring; N—Natural Bridge Canyon. Badwater Turtleback normal fault shown as line separating gneiss and metasedimentary rock from Quaternary alluvium, "volcanic hanging wall," or Willow Spring Pluton. Badwater Turtleback thrust fault shown by heavy line with teeth that separates metasedimentary rock from structurally overlying basement gneiss. As bottom of metasedimentary rock is not exposed, its contact is queried in cross section B-B′. Dip-slip separation on high-angle normal fault on east side of cross-section B-B′ is only approximate. Composite cross-section A-A′ shows geometry of brittle fault system projected into line A-A′ of map. Fault 1a on map corresponds to fault 1a on cross-section. C: Map of Copper Canyon (C) and Mormon Point (M) turtlebacks, modified from Otton (1976) and Holm (1992). Exposures of basement gneiss above Noonday Dolomite (Z) exist at location A. Large enclave of gneiss that structurally overlies dolomite is at location B. Exposed thrust fault at Mormon Point is marked by heavy line with teeth.

towards the northwest. By contrast, the Copper Canyon turtleback only locally displays complex infolding of basement and metasedimentary rock, and overall exhibits a macroscopic upright to steeply inclined geometry with a gentle northeast limb and a steep southwest limb.

To varying degrees, the footwall folds of each turtleback also display doubly-plunging geometries (e.g. Miller, 1992b; Mancktelow and Pavlis, 1994; Pavlis in Holm et al., 1994a,b). As a result, the relationship between the folds and structurally overlying faults varies across each turtleback. To the southeast, fold hinges plunge southeastward beneath the structurally overlying Miocene plutonic complex and/or Precambrian basement (Fig. 7A,B). As reported by Mancktelow and Pavlis (1994), this contact is itself deformed, with ductile fabrics in the floor of the plutons that are parallel to the those in the turtleback footwalls. Northwestward, fold hinges become horizontal and then plunge moderately northwestward, typically steeper than the structurally overlying brittle fault. The structurally overlying brittle faults, in turn, display less structural relief than the folds. Therefore, at both Copper Canyon and Mormon Point, the brittle faults cut across structural section on both limbs of the antiforms to expose the structurally overlying Miocene plutonic complex in the core of the synclinoria between them (Fig. 7B). At the Badwater turtleback, the structurally deepest part of the turtleback is exposed near its center.

This general form of the turtleback anticlinoria suggested to Mancktelow and Pavlis (1994) and Pavlis (1996) that the folds formed as part of a continuous deformational sequence related to distributed transtensional shear, after intrusion of the plutonic complex. In this scenario, the transtension created localized shortening that buckled low- to moderate-angle extensional shear zones (S2), superimposed on the turtleback main-phase foliation (S1). This buckling generated large-scale structural relief in the shear zones, which ultimately were transected by brittle faults. Serpa and Pavlis (1996) extended this concept to the broader regional scale. They noted that the F2 folds in the turtleback footwalls trend more northerly than younger folds and so probably reflect greater amounts of finite clockwise vertical axis rotation. Similarly, Miller (1999a,b) found that lineations in mylonitic gneiss trended more northerly than those in calcite marble at the Badwater turtleback. As the gneiss reflected earlier, higher temperatures than the marble, these data may also reflect clockwise rotation during transtension.

3.1.5. Basement thrust faults

Each turtleback exhibits areally extensive non-planar contacts where basement gneiss overlies younger, metasedimentary rock. Miller (2003) interpreted these contacts as SE-directed, basement-involved thrust faults that were re-deformed during late Tertiary extension. At the Badwater turtleback, several hundred meters to approximately 1 km of gneiss overlies the carbonate at its northern and southern edges respectively (Figs. 7A and 8A). Near the center of the Badwater turtleback, thin bodies of gneiss structurally overlie, and are infolded with, carbonate rock. As the exposed trace of the gneiss-over-carbonate contact is approximately 4.5 km long in the direction of transport, Miller (2003) concluded that the thrust fault had at least that much displacement. At the Copper Canyon turtleback, small bodies of gneiss structurally overlie carbonate rock at the contact with the Willow Spring pluton, and as an enclave within the pluton (Fig. 7B; Otton, 1976; Holm, 1992). At Mormon Point, ~300 m of gneiss structurally overlies the metasedimentary rock northwest of Smith Mountain (Figs. 7B and 8B; Otton, 1976; Holm, 1992).

Miller (2003) further noted exposures of pre- and syn-pegmatite mylonitic rocks that display top-to-the-east and -southeast fabrics. These exposures, although relatively rare, are most abundant at deep structural levels within each turtleback. As the pegmatite is early Tertiary in age (Miller and Friedman, 1999) and some of the mylonitic fabrics appeared to be concurrent with its intrusion, Miller (2003) argued that both mylonitization and basement thrusting were probably early Tertiary.

Except for the presence of cross-cutting pegmatite and the sense-of-shear, the early mylonitic foliation is indistinguishable from the late Tertiary, extension-related foliation. Both sets of foliations are concordant and both display similarly oriented stretching lineations. In some localities where both foliatons are preserved together, the later foliation appears to merge with the older one (Fig. 9). We therefore sug-

Fig. 8. Photographs of exposed older-over-younger contacts at Badwater and Mormon Point turtlebacks. Photograph locations are shown as "8A" and "48B" in Fig. 7A and B, respectively. A: At south side of Badwater turtleback; view toward south. B: On Mormon Point turtleback; view toward east.

gest that the extensional turtleback shear zones originated as basement thrust faults, possibly as late as early Tertiary, but were reactivated and almost completely transposed during late Tertiary extension.

3.2. Turtleback hanging walls

The delineation of the "hanging wall" of each turtleback is somewhat subjective, as the footwalls

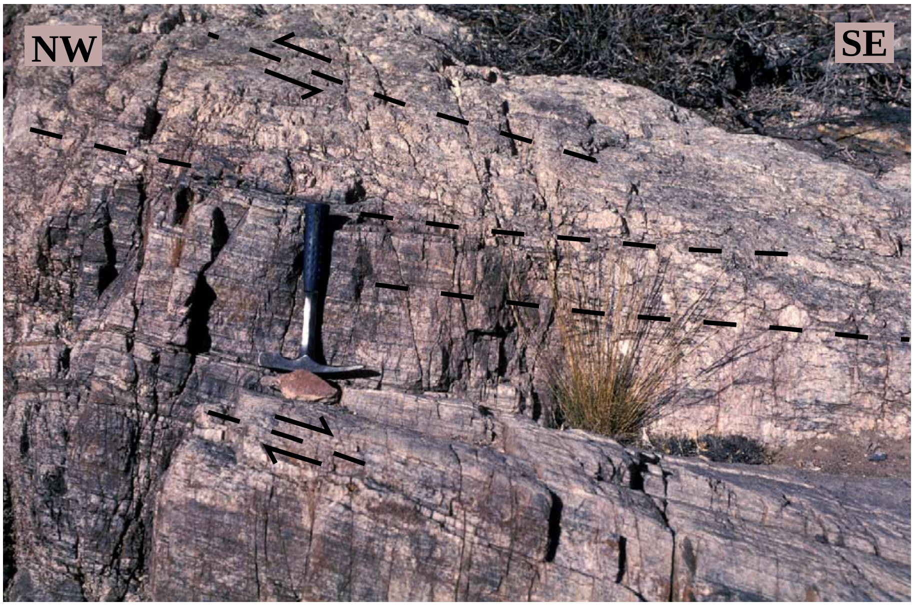


Fig. 9. Photograph of concordant foliation in pegmatite and previously deformed gneiss. Note that pegmatite clearly cuts across foliation in the gneiss on the left edge of the photograph and immediately behind the clump of grass. The gneiss also exhibits a much greater intensity of foliation, but that the foliation continues into the pegmatite. Kinematic indicators from the gneiss yield top-southeastward shear directions; those from the pegmatite yield top-northwestward shear directions.

of each turtleback plunge northwestward and may continue for some distance beneath Death Valley. They also plunge southeastward beneath the Miocene plutonic complex. The Panamint Range could therefore be considered as part of the hanging wall of either turtleback, whereas the Badwater turtleback could be considered as part of the Copper Canyon turtleback's hanging wall. Alternatively, when viewed to the south, the turtleback hanging walls consist entirely of plutonic rock and structurally overlying Proterozoic basement. This discussion is therefore limited to the *immediate* hanging walls: rocks that directly overlie the visible portions of the brittle turtleback fault zones.

Numerous studies of the immediate hanging walls of each turtleback have clarified the ages and types of rock present, as well as aspects of the structural geology of each one. In general, each turtleback has a hanging wall that consists almost entirely of Miocene to Pleistocene sedimentary and/or volcanic rock. However, significant differences exist between each one. Similarly, the structures within each hanging wall reflect aspects of late Tertiary extension, but vary considerably in specific details.

Rocks of the Badwater turtleback hanging wall consist of the Miocene to Pliocene Artist Drive Formation, Greenwater Volcanics (Greene, 1997), megabreccia deposits of these same rocks, and Pleistocene fanglomerate deposits. The volcanic flows and interbedded sedimentary rocks lie in the hanging wall immediately north of the turtleback, whereas the megabreccia and fanglomerate deposits lie in the hanging wall immediately west and above the central part of the turtleback. To the south, brecciated rock of the Willow Spring Pluton lies in the hanging wall.

Miller (1999b) interpreted the megabreccia deposits as having originated in landslides, and suggested that the brittle turtleback fault surface acted as a gravitational sliding surface in its later history. Fanglomerate deposits along the west side of the Badwater Turtleback that stratigraphically overlie the megabreccia deposits provide evidence for Pleistocene unroofing of the Badwater turtleback (Cichanski, 1990). Deposits of 0.67 Ma Lava Creek B tephra, as reported by Knott et al. (2001a,b) and Hayman et al. (2003), establishes their Pleistocene age, while an increase in the proportion of metamorphic clasts upwards documents exposure of the footwall to erosion.

Hanging wall rocks of the Copper Canyon turtleback consist, in upwards succession, of Late Miocene Willow Springs diorite, Tertiary volcanic rocks and Copper Canyon Formation, and fanglomerate and megabreccia deposits (Drewes, 1963). The Copper Canyon Formation dominates the hanging wall. It consists of approximately 3000 m of alluvial fan deposits, in fault contact with the turtleback, that grade laterally (northward) into playa and freshwater lake deposits, and basalt flows. Holm et al. (1994a,b), using Ar/Ar, obtained an age of ~6 Ma to ~3 Ma for its deposition. The Copper Canyon Formation is significant because it records local basin development in a transtensional setting, presumably an early phase of the formation of modern Death Valley (Ellis and Trexler, 1991). Its fine-grained deposits also display abundant well-preserved Neogene mammal and bird tracks (Curry, 1938; Scrivner and Bottjer, 1986).

At the Mormon Point turtleback, hanging wall rocks consist of two distinct assemblages (Otton, 1977; Knott et al., 2001a,b): a Pleistocene section and older Pliocene (?) section. The older Pliocene (?) rocks dip much more steeply than the Pleistocene rocks and are limited to a prism of rock bounded by the turtleback fault and the Willow Wash fault, a major hanging-wall fault above the turtleback fault. Pleistocene rocks occur locally as nearly flat lying deposits atop an angular unconformity on the older rocks but are primarily exposed as variably tilted, faulted and exhumed rocks in the hanging wall of the Willow Wash fault. Burchfiel et al. (1995) made a detailed structural/stratigraphic map of the area in which they defined 11 separate units, marked by rapid facies changes and much interfingering. They argued that the sediments were deposited along the margin of modern Death Valley and later uplifted as the range-bounding normal fault stepped out into the playa. Knott et al. (2001a,b) and Hayman et al. (2003) reported the presence of the 0.76 Ma Bishop Ash and 0.67 Ma Lava Creek B Ash within the younger deposits providing the first clear evidence of a Pleistocene depositional age.

Structures in the turtleback hanging walls consist predominantly of high-angle brittle faults that terminate downward at the turtleback detachments in both listric and planar geometries (Fig. 4). This relation is visible in the many small canyons that cut into the footwalls of the Badwater and Mormon Point turtlebacks and in the cliffs of Copper Canyon Formation immediately north of the Copper Canyon turtleback. Knott et al. (1997) argued that the multiple strandlines at Mormon Point actually consisted only of one strandline that had been offset by multiple normal faults. Hayman et al. (2003) found that, at Badwater and Mormon Point, these faults defined a conjugate set with an approximately vertical maximum compressive stress. They estimated that these faults accounted for approximately 600 m of Pleistocene and younger horizontal extension at Mormon Point. This interpretation contrasts with Keener et al. (1993) who inferred that the Mormon Point turtleback fault was not active and was cut by a high-angle fault at depth.

Each turtleback also displays some degree of folding in its hanging wall. The most intensely folded hanging wall exists at Copper Canyon, where Drewes (1963) mapped a series of southeast-plunging asymmetric folds over an area of approximately 10 km^2. The most prominent anticline has a mapped length of more than 3 km and verges north-northeastward. At Mormon Point, Hayman et al. (2003) reported a roll-over anticline adjacent to the detachment fault. Immediately north of Badwater, several kilometer-scale folds are visible in the Artist Drive Formation.

3.3. Turtleback fault zones

The turtleback fault zones are the discrete brittle surfaces that separate the ductilely deformed mid-crustal rock of the footwalls from the upper crustal rock of the hanging walls. Superb exposures of these fault zones exist along the west front of each turtleback (Fig. 3A,B,C). In general, the turtleback faults dip westward or northwestward at shallow angles ($<35°$), show evidence for a latest episode of predominantly normal slip, and display a wide variety of cataclastic fault rocks. Moreover, they each appear to have been active as recently as the late Pleistocene (Knott, 1999; Hayman et al., 2003). Outstanding questions persist regarding their specific geometries and their relations to the rest of the Black Mountains frontal fault zone.

3.3.1. Fault geometries and relation to frontal fault zone

The classic interpretation of the turtleback fault geometries holds that they are antiformal and broadly coincident with the antiforms in the footwalls (Curry, 1954; Wright et al., 1974; Otton, 1976; Holm and Dokka, 1993). The turtlebacks do display geometries suggestive of both antiforms and synforms, the hinges of which are shown on Fig. 7A,B, but it is not yet clear if these features actually represent single, curved fault surfaces. Instead, several of the larger "folds" are probably the poorly exposed intersections of two or more differently oriented, subplanar fault surfaces. Miller (1991) argued this case at Badwater (hinge a on Fig. 7A), as did Pavlis et al. (1993) for Mormon Point (hinge f on Fig. 7B). Additionally, the apparent folds at Copper Canyon (hinges d and e on Fig. 7B) remain ambiguous, as they could be interpreted as either intersecting faults or kink-like folds in a single fault. Two minor folds at Badwater (hinges b and c on Fig. 7A) do appear to reflect true undulations in the fault, as the fault trace is continuous across the fold hinges. The antiformal hinge (hinge c) coincides with the antiformal hinge of the footwall.

The turtleback fault geometries are also important to understanding the structural evolution of the fault systems, as well as their genetic relation to the Black Mountains frontal fault zone. At Badwater, the turtleback fault consists of at least three distinct fault surfaces, which decrease in age but increase in dip towards the west. Fig. 7A shows these surfaces as faults #1, #2, #3. Miller (1991) attributed these relations to progressive rotation and abandonment of fault surfaces through time, with fault #3, the range-bounding fault, cutting fault #2. While the Miocene–Pliocene volcanic rocks of the hanging wall dip 20–30° eastward to support this interpretation, Knott (1998) and Hayman et al. (2003) noted that the Pleistocene material of the hanging wall has not rotated. Therefore, significant rotation of the turtleback fault and footwall must have taken place prior to deposition of the Pleistocene material, possibly before initiation of slip on fault #2.

At Mormon Point, a gravity and magnetic study by Keener et al. (1993) suggested a similar geometry to Badwater in that the principal turtleback fault appeared to be cut by a later, range-bounding fault. Hayman et al. (2003), however, argued an alternative geometry, where the exposed detachment fault (fault #2 at Badwater) is the active, controlling structure, and the present, high-angle, range-frontal fault terminates downward at the detachment. To support their interpretation, they noted that, at Mormon Point, the hanging wall has been extended by approximately 600 m by minor normal faults that terminate downward onto the detachment. We note, however, that 600 m of slip is only about one third of the total likely slip predicted across the Black Mountains frontal faults during the time interval considered by Hayman et al. (2003). Geodetic data and Quaternary offsets in northern Death Valley (Williams et al., 1999) indicate the Death Valley fault system should be extending the region ~2.9 km/m.y.; i.e. since deposition of the Bishop Ash (~600 ka) approximately 1.8 km of horizontal motion should have occurred across the frontal faults. Therefore, more slip has presumably accumulated across buried faults, including the frontal faults, than the exposed fault array at Mormon Point. Alternatively, the cumulative slip on hanging wall faults reflects only a portion of the slip on the main detachment fault (D. Cowan, personal communication, 2003).

We consider the relation between the turtleback faults and the frontal fault zone of the Black Mountains to be an open question. Hayman et al. (2003) document features that require the turtleback faults to be recently active. This activity makes it difficult to envision the turtleback faults as cut by the frontal fault zones, unless there is cycling back and forth between gravitationally driven slip on the turtleback faults and rooted slip on the frontal fault zones as suggested by Miller (1999b) for Badwater. Miller (1992a,b, 1999a,b) also showed that fault 2 of the Badwater turtleback fault system coincides with the Black Mountains range front about 2 km south of Badwater, and cuts structurally upwards into volcanic rocks immediately north of Natural Bridge Canyon (Fig. 7A). In this way, the fault appears to be more of an abandoned range front fault than a true detachment. The Badwater turtleback detachment, if there is one, is most likely fault #1 on Fig. 7A.

3.3.2. Kinematics and fault rocks

As inferred from slickenline orientations, the most recent episode of slip on the turtleback faults has been normal (Pavlis et al., 1993; Miller, 1999b; Hayman et al., 2003). However, the faults likely had an earlier history of right-lateral oblique motion, consistent with the slip direction on the rest of the Black Mountains fault zone (Struthers, 1990; Brogan et al., 1991; Slemmons and Brogan, 1999). The most recent, normal slip therefore appears to be a departure from a more long-standing norm.

At Badwater, evidence for earlier oblique motion comes from the fault geometry, folded fault rocks, slickenlines, and high-angle faults in the footwall (Miller, 1999b). Hinge c in Figs. 3A and 7A, marks a true fold in the fault plane that plunges about N 60°W. Miller (1999b) argued that for the hanging wall to remain intact, slip had to parallel the hinge. Additionally, a Hansen slip line analysis of mesoscopic folds in the fault zone yielded a northwest-directed, oblique vector, and slickenlines on crystalline rocks south of hinge C indicated oblique motion. Miller (1999b) suggested that because these slickenlines were on crystalline rock, they were more durable and therefore reflected an earlier episode of slip than the dip-parallel ones that are preserved solely on the underside of the relatively soft hanging wall. Finally, the footwall is cut by numerous, demonstrably oblique high-angle faults.

At Mormon Point and Copper Canyon, Pavlis et al. (1993) used large-scale fault geometry and the distribution of fault rocks to infer oblique motion. There, calcite-rich implosion breccias exist within right-stepping planar sections of the turtleback faults. These breccias form through episodes of sudden dilatancy (Sibson, 1986), which would most likely occur through seismic right-lateral oblique motions on the fault zone. Additionally, Pavlis et al. (1993) and Keener et al. (1993) documented oblique slip in several localities along southwest dipping segments of both the Mormon Point and Copper Canyon turtleback fault based on complex slickenline arrays in fault-rocks below the fault surface. As at Badwater, the footwalls in both Mormon Point and Copper Canyon turtleback are cut by more steeply dipping, oblique-slip faults that do not appear to cut into the hanging walls (Pavlis et al., 1993).

Besides the implosion breccias near Mormon Point, each turtleback fault displays spectacular exposures of fault gouge, foliated and non-foliated cataclasite, and microbreccia. These fault rocks have been the subject of several studies, including those of fault behavior (Miller, 1996), kinematics (Cladouhos, 1999a,b), and fault rock evolution (Hayman, 2002). Fault rocks are best developed below the discrete sliding surface of the turtleback fault. They typically show a downward structural progression from clay-rich gouge into foliated cataclasite and then into a variable damage zone of cataclasis and hydrothermal alteration that extends up to several tens of meters into the footwall. Cowan et al. (1997, 2003) showed that these zones correlated with decreasing shear strains away from the fault zone. Miller (1996) documented mesoscopically ductile flow in the fault gouge, and Cowan and Miller (1999) showed that episodes of ductile flow in gouge appear to alternate with episodes of discrete sliding. Alternating localized and non-localized events conflict with other studies of fault rock development that argue for continuous localization of slip on developing fault zones (e.g. Chester and Logan, 1986; Logan et al., 1992).

3.3.3. Estimates of slip

Because the brittle turtleback faults separate such disparate rock types, slip estimates tend to be based on indirect evidence. Several observations, however, suggest that the amount of slip for each brittle fault is limited to only a few kilometers at most. To a first approximation, the most relevant feature is the Willow Springs pluton, as visible portions of it exist in the hanging walls and footwalls of the both the Badwater and Copper Canyon turtlebacks (Figs. 1 and 7A).

At the Badwater turtleback, a small fault-bounded exposure of mylonitic basement rock exists in the hanging wall of Fault #2 near Badwater spring (Fig. 7A). Based on this exposure, Miller (1991) inferred approximately 2 km of slip on Fault #2. As indirect support of this estimate, we note that north of Natural Bridge canyon, Fault #2 cuts upwards into the volcanic hanging wall, with rocks of the Artist Drive Formation in both its hanging wall and footwall (Fig. 7A). At Mormon Point, Knott et al. (2001a,b) estimated 438 m of Pleistocene heave on the turtleback fault based on an offset bed of Bishop Ash.

4. Discussion and conclusions

Among the structural features of Death Valley, the turtlebacks contain some of the most critical information relevant to testing models of crustal extension. In particular, models are constrained by two types of information from within the turtlebacks: (1) observations of the turtleback shear zones themselves, and (2) implications of the basement-involved thrust faults of the turtlebacks for the pre-extensional geometry of the fold-thrust belt in Death Valley. This information has implications that extend far beyond Death Valley, as the region is frequently cited as a type example for continental extensional tectonics.

Tectonic models for the Death Valley region include both regional map-view reconstructions that attempt to constrain the regional strains (e.g. Serpa and Pavlis, 1996; Snow and Wernicke, 2000) and models of the extensional process in cross-sectional views (e.g. Holm et al., 1992; Miller, 1999a). Although these approaches provide important illustrations of the extensional process, they are limited to two dimensions. In fact, the turtlebacks are complex three-dimensional entities that formed over ~14 m.y. of extensional overprinting on an older Mesozoic framework. We submit that many of the controversies regarding the Death Valley region in general, and the turtleback systems in particular, stem largely from the inability to communicate observations of these multiple dimensions. Even the coauthors of this paper are not in complete agreement on several details, but our approach here is to clarify our view of the four-dimensional history. Following previous presentations, we consider the problem in the context of two-dimensional map and cross-sectional views, but we acknowledge that these views are oversimplifications of the geometric evolution.

4.1. Map-view reconstructions of regional deformation

Several tectonic models for the Death Valley region emphasize large-scale, map-view reconstructions based on the correlation of regional structures and stratigraphic assemblages within the Death Valley region. These controversies were initiated by the correlation of the Panamint thrust in the northern Panamint Mountains with the Chicago Pass thrust system in the Nopah and Resting Spring ranges (Wernicke et al., 1988). Other workers, however, have challenged this correlation on different lines of evidence (e.g. Wright et al., 1991; Serpa and Pavlis, 1996; Miller and Prave, 2002). The resolution of this question is critical because extensional magnitudes vary radically in different versions of these reconstructions.

As described by Miller (2003), the presence of basement-involved thrust faults in the turtlebacks help define the pre-extension configuration of the fold-thrust belt in Death Valley, and therefore provide keys to interpreting the crustal extension. As argued below, their presence suggests that the Black Mountains were a structural high prior to Tertiary extension. It further suggests that restoration of the Cottonwood Mountains above the Black Mountains is unlikely, yet this configuration is required if the Panamint and Chicago Pass thrusts were the same thrust displaced by a master detachment system.

Evidence for a pre-extensional structural high in the Black Mountains is supported by the general absence of Paleozoic sedimentary rocks and the deep stratigraphic level of the pre-Tertiary unconformity in the Black Mountains. In the Amargosa Chaos, ~12 Ma sedimentary and volcanic rocks lie depositionally on late Proterozoic to early Cambrian sedimentary rocks (location “x” on Fig. 1 inset; Wright and Troxel, 1984; Topping, 1993). At the Billie Mine in the northern Black Mountains, ~14 Ma sedimentary rocks of the early Furnace Creek basin depositionally overlie early Cambrian rock (Fig. 1; Cemen et al., 1985; Wright et al., 1999; Miller and Prave, 2002). These contacts contrast markedly with the northern Panamint Mountains where late Paleozoic rocks lie directly beneath the Tertiary unconformity. It is therefore likely that the thrust systems now exposed in the turtlebacks produced significant structural relief above what is now the Black Mountains and that the late Paleozoic cover was largely stripped from the Black Mountains prior to Tertiary extension. Correlation of the Panamint thrust with the Chicago Pass thrust across this structural high is suspect because structural relief created by the thrust structures would disturb the simple thrust belt geometries required by the correlation. The correlation also places Late Paleozoic rocks and thrust belt structures of the Cottonwood Mountains structurally above and east of the turtleback basement thrusts. This restoration conflicts with the observed rocks below the Tertiary unconformity or anywhere within the Black Mountains.

An alternative explanation, that the exposed Black Mountains cover rocks are entirely allochthonous and so can not reliably indicate a basement high, is unlikely. In this scenario, the cover rocks should contain slices that sample all parts of the hanging wall assemblage, including late Paleozoic rocks (Fig. 10). Furthermore, those rocks should be preserved beneath the Tertiary unconformity. In fact, the youngest Paleozoic sedimentary rocks recognized in the Black Mountains are lower Paleozoic.

Moreover, the thrust structures among the ranges are not age correlative. In the Cottonwood Mountains, thrust structures are Permian to Triassic in age (Snow et al., 1991), which is much older than the apparent late Mesozoic–early Cenozoic age for the Black Mountains thrust faults. Finally, the Paleozoic rock of the Cottonwood Mountains is intruded by the Jurassic Hunter Mountain batholith while the Proterozoic and early Paleozoic rock of the Panamint Mountains are intruded by the Cretaceous Harrisburg Pluton (Fig. 1). If either of these ranges originated above the Black Mountains, then the plutons must have intruded through them. However, no equivalent Mesozoic intrusive rock have been recognized in the Black Mountains (Fig. 10C).

4.2. Cross-sectional views of the turtlebacks

In cross-sectional view, the principal controversy surrounding the turtlebacks centers on the theme of a master detachment system with a rolling hinge (e.g. Holm et al., 1992) vs. models that call on a polygenetic origin for the turtlebacks (e.g. Wright et al., 1991; Mancktelow and Pavlis, 1994; Serpa and Pavlis, 1996; Pavlis, 1996). A related controversy concerns the inferred connection, in space and time,

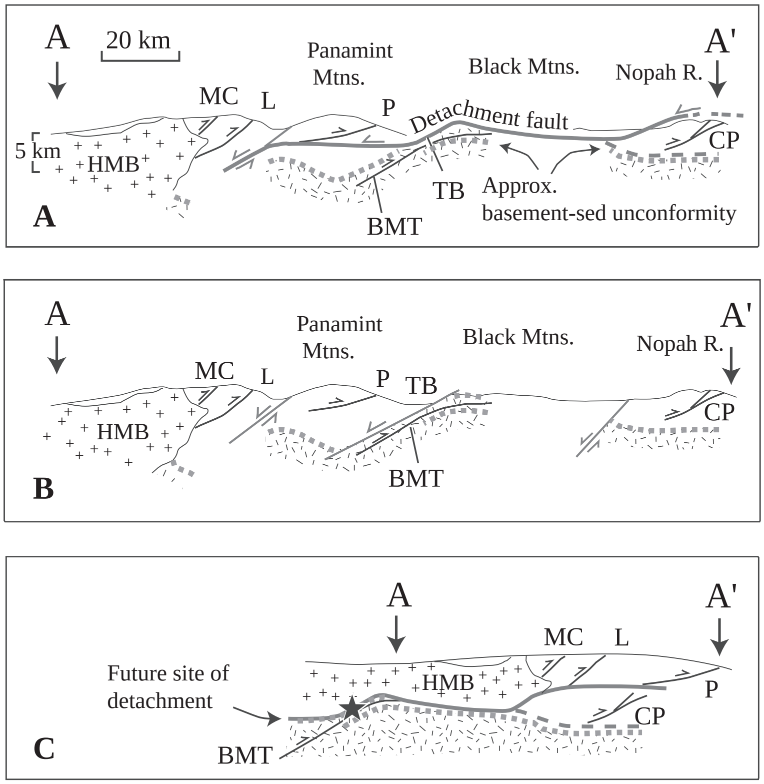


Fig. 10. Schematic cross-sections from A to A′ on Fig. 1 that account for presence of basement thrust faults (BMT) in the Black Mountains. A: depiction of present-day structure according to Rolling Hinge Model. B. Depiction of present-day structure according to Pull-Apart Model. C: Correlation of Chicago Pass and Panamint thrusts requires transport over basement high in Black Mountains and also places Hunter Mountain Batholith on top basement rock of the Black Mountains.

between the turtleback systems and structurally higher-level structures in the Black Mountains. These structures include those in the Amargosa Chaos area to the south (Wright and Troxel, 1984; Topping, 1993; Topping in Holm et al., 1994a,b) and low-angle normal fault systems that frame the Black Mountains to the east. The structural relationships between the Badwater and the other turtlebacks also represent an important detail because the Badwater turtleback is geochronologically distinct and lies in the hanging wall of the Copper Canyon turtleback.

Existing Ar–Ar geochronology for the turtlebacks can be interpreted to satisfy both models. Holm et al. (1992) found that, from south to north, the Mormon Point, Copper Canyon, and Badwater turtlebacks cooled through 300 °C at about 8 Ma, 6 Ma and 13 Ma, respectively. They interpreted the cooling ages at Mormon Point and Copper Canyon as evidence of the hinge rolling northwestward from Mormon Point to Copper Canyon and the much older age at Badwater as an earlier, deep-seated event. We agree that the old age at Badwater reflects an earlier event, but the 8 Ma and 6 Ma ages at Mormon Point and Copper Canyon do not require a rolling hinge. Instead, they probably reflect diachronous cooling related to two simultaneously operating processes: (1) cooling from the emplacement of the ~11 Ma Black Mountains plutonic suite and (2) unroofing of the turtlebacks by extension, presumably at different times. In this context we suggest that two features of the turtlebacks are particularly relevant: the geometries of the turtleback folds, and the location of much of the Badwater turtleback beyond the northern terminus of the Willow Springs pluton (Fig. 7A).

The latter feature suggests that intrusion of the Willow Spring pluton dominated the cooling history of the southern turtlebacks (Holm and Dokka, 1993; Pavlis, 1996), but likely had little effect on the Badwater turtleback. As a result, the older cooling ages in the Badwater turtleback reflect a minimum age for the initial ductile deformation related to extension in the

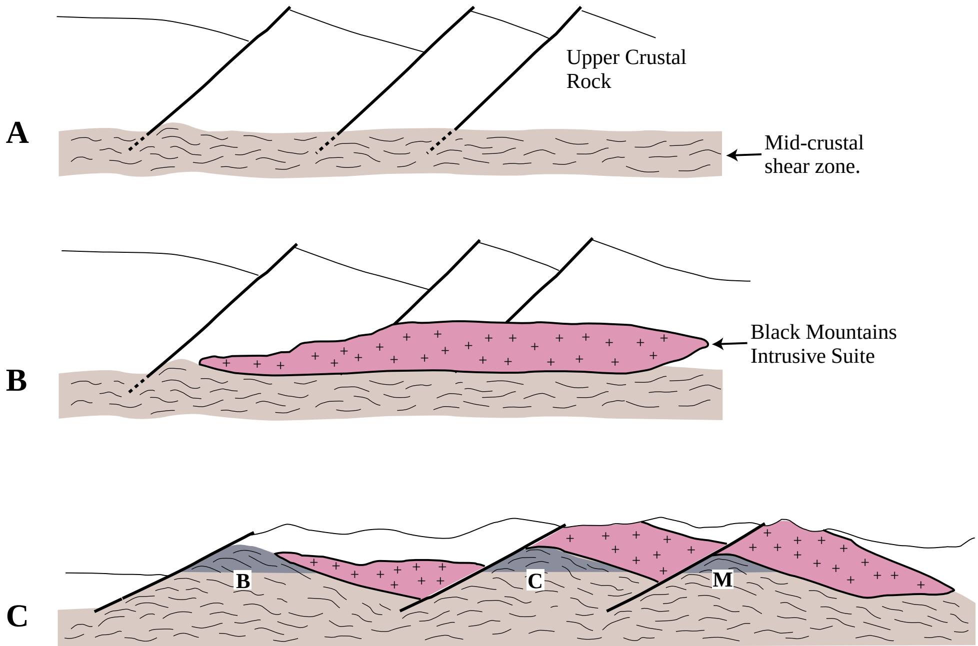


Fig. 11. Schematic cross-sections to illustrate principal extensional events at the turtlebacks. A: Prior to ~11 Ma, upper crustal faults terminated at mid-crustal shear zone. B: Intrusion of Black Mountains intrusive suite at ~11 Ma. These sill-like plutons intruded along the top of the shear zone and recrystallized fabrics at Copper Canyon and Mormon Point turtlebacks, but had little effect at Badwater Turtleback. C: Continued extensional faulting and ductile shear exhumed the intrusive suite and underlying mid-crustal shear zone. Dark-shaded areas represent approximate present-day exposure of metamorphic portion of each turtleback footwall.

region. This early history was also present in the other turtlebacks, but was largely obliterated at ~11 Ma when the Black Mountains intrusive suite was emplaced above them, completely recrystallizing pre-existing microstructures and resetting all low-T geochronometers. This conclusion is consistent with onset of volcanism and incipient extensional basin development prior to ~14 Ma (Wright et al., 1999). For example, Miller and Prave (2002) found that activity on the pre-13 Ma Badwater Turtleback fault likely influenced sedimentation in the early Furnace Creek Basin.

Similarly, the variability of fold geometries of the turtlebacks, especially between the highly non-cylindrical Mormon Point turtleback and the nearly upright Copper Canyon turtleback, are difficult to reconcile with the concept of a single, master rolling hinge. Moreover, their doubly plunging geometries are also inconsistent, because a migrating hinge should leave behind a single low-angle shear zone.

Our conceptual view of the turtleback evolution is that they all share a common, early history as parts of a mid-crustal shear zone at ~12–16 Ma that at least in part reactivated a pre-existing basement thrust fault (Fig. 11A). This shear zone locally reached upwards to connect with supracrustal fault zones as described by Miller (1992a,b, 1999a,b) at the Badwater turtleback. When the Black Mountains intrusive suite was emplaced at ~11 Ma, however, it cut across many of these faults and recrystallized fabrics in the subjacent ductile shear zone (Fig. 11B). Consequently, the thermally unmodified older shear zone is only preserved at the Badwater turtleback. At the Mormon Point and Copper Canyon turtlebacks, the older shear zone is now represented only by the thermally overprinted tectonite fabrics of the southeastward plunging segments of the turtleback antiforms. Continued crustal extension caused the exhumation of the intrusive suite and eventual formation of the brittle turtleback faults, shown in Fig. 11C as dismembering the intrusive suite. This view of the turtlebacks, in which much of the ductile deformation occurred before emplacement of the Miocene intrusives, and most brittle deformation occurred after their emplacement, differs significantly from the rolling hinge model which requires that most of the brittle and ductile deformation post-dated intrusion.

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