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5. Detachment Faulting in the Death Valley Region, California and Nevada

By Warren B. Hamilton, 1988

CONTENTS

Abstract

Detachment faults of Oligocene to Holocene age are widely exposed in the Death Valley region, where crustal extension is interpreted to have amounted to at least 100 percent and is continuing at a high rate. Upper-crust fault blocks of both preextensional and synextensional materials, rotated to consistent eastward dips, and the west-dipping normal faults that separate and dismember them, all end downward at undulating detachment faults in the Panamint, Black, and Funeral Mountains, Bare Mountain, and the Bullfrog Hills. Beneath the detachment faults are rocks that were in the middle crust before extension, and thick ductile shear zones were developed during early, deep slip on the structures. The detachment faults may represent great normal faults that initially dipped westward but that have been rotated and raised as tectonic denudation unroofed them progressively westward. The huge upper-plate blocks of the Grapevine and southern Funeral Mountains were stranded atop raised and flattened sectors of the faults, whereas the upper-plate blocks of the Panamint and Cottonwood Mountains continue to slip away. Synextensional basin-fill materials compose half the width of upper plates at the detachments; panels of pre-Tertiary rocks were not in contact with one another above detachments except during early stages of extension. Although very late slip on near-surface domiform detachment faults is down dip into widening basins, earlier slip was regionally westward and northwestward, independent of present directions of dip of the detachment surfaces.

In the southern Great Basin, extension farthest west has taken place during Pliocene and Quaternary time, that farthest east took place mostly in the middle Miocene; and a broad medial tract was extended during late Oligocene and early Miocene time, with a westward younging of termination of major extension—middle Miocene in the Nevada Test Site, late Miocene in the Bullfrog Hills, Pliocene in the Funeral Mountains, and still active in Death Valley. The imbricate middle Miocene faulting of Yucca Mountain represents the headwall position of the Bare Mountain-Bullfrog Hills-Funeral Mountains detachment system when the part of the original fault to the east had risen so that further slip there was precluded but when the part to the west still dipped westward.

Middle Tertiary extension was approximately westward, relative to the continental interior, and this produced north-trending fault blocks. Late Neogene extension has been northwestward, and the old blocks, with their inherited trends, are being carried obliquely apart. The present east limit of major deformation is along the east side of Death Valley and is marked by northwest-trending right-slip faults in the north and south and by oblique-slip north-trending normal faults between them.

INTRODUCTION

The width of the Basin and Range province has been about doubled by crustal extension during middle and late Cenozoic time. The sort of structures on which this deformation has been accomplished are exposed particularly well in the Death Valley region (fig. 5.1), where rapid extension is continuing. This chapter describes and interprets the extensional structures of that region and, to a lesser extent, surrounding regions. Many of these interpretations are controversial. For a regional synthesis with conclusions broadly incompatible with those presented here, see Carr (1984).

Yucca Mountain, in the southwest part of the Nevada Test Site and the northeast corner of the Death Valley region (see fig. 5.2), is being considered as a repository for radioactive waste. An understanding of the late Cenozoic structure of the region is needed for evaluation of the deep geometry of the site and of the possible ground motions and disruptions that might accompany earthquakes. Neogene structures are exposed within the test site only at upper crustal levels. They are largely middle Miocene in age and consist mostly of normal faults, with steep to moderate dips, between gently rotated blocks. Moderate extension of the upper crust is required by this geometry, but far more extension took place in early Miocene and late Oligocene time. Extensional structures of the sort that originated within the middle crust and that are likely to lie deep beneath Yucca Mountain are exposed widely in the Death Valley region.

Exposures are excellent in Death Valley and vicinity, where altitudes are near sea level, but mediocre closer to the test site, where altitudes are typically near 1,000 m. Compare the many photographs, presented in this chapter, of detachment faults exposed superbly at low altitudes with the two photographs (figs. 5.3*B*, 5.4*C*) of detachment faults exposed poorly at altitudes of about 1,000 m. Exposures are still poorer in much of the test site itself and throughout most of the Great Basin. Because structures of the type displayed so well in Death Valley are likely to be present much more

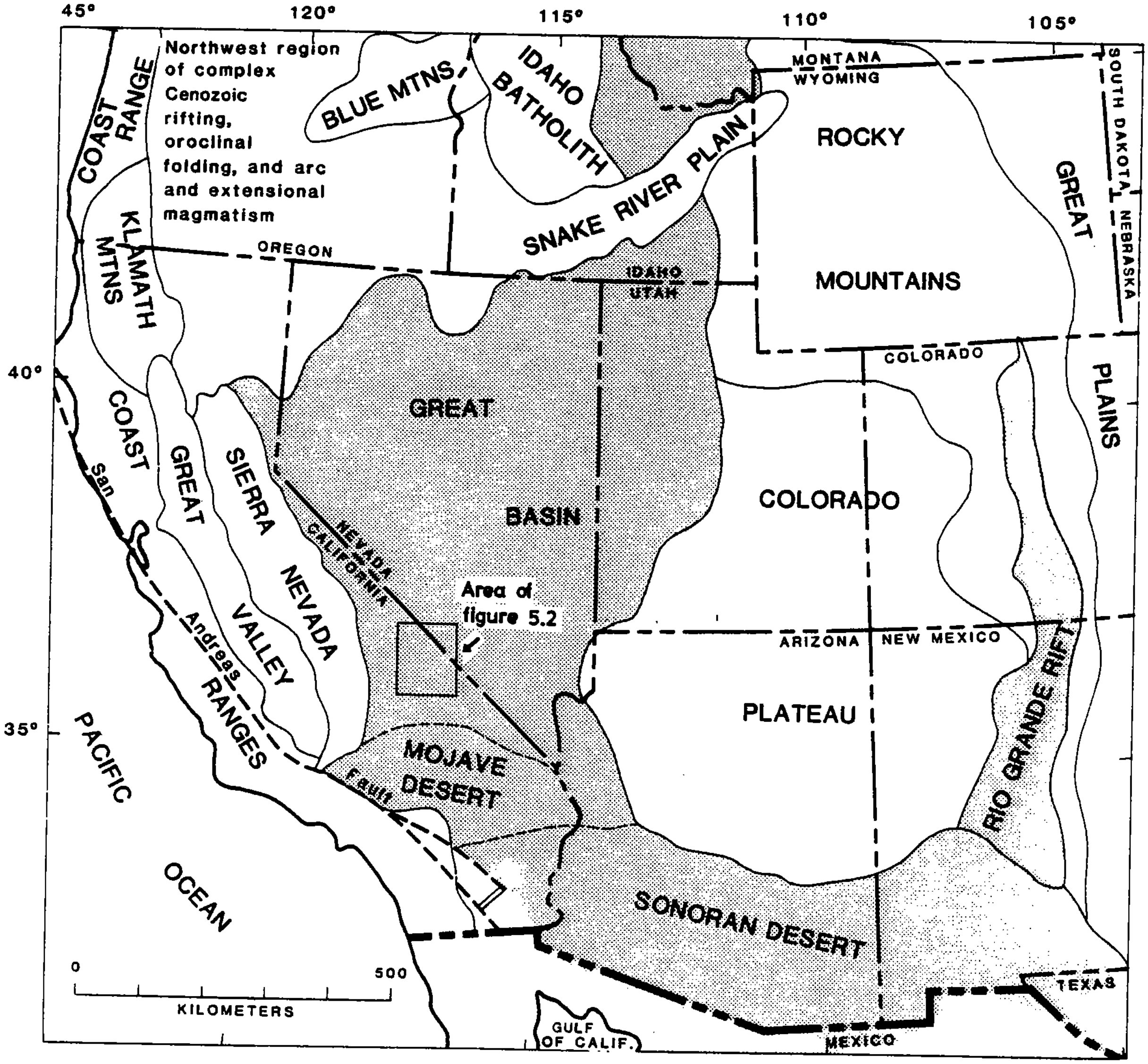


Figure 5.1. Physiographic provinces of the Western United States. Basin and Range province (shaded) of middle and late Cenozoic extensional faulting consists of the Great Basin and the Mojave and Sonoran Deserts. Regions of similar deformation in the Rio Grande Rift and north of the Snake River Plain are also shaded.

widely in the Great Basin than has been generally recognized, I have included many photographs of them as possible guides to relations that might be sought elsewhere.

Studies in many parts of the Basin and Range province, including the Death Valley region, have demonstrated that severe extension incorporates detachment faulting. A detachment fault is a major undulating or gently dipping extensional fault that attenuates a crustal section. The term has been used in this context by G.A. Davis (Davis and others, 1980) and many others. The terms "denudation fault" (Armstrong, 1972) and "decollement" (Miller and others, 1983, as used in an extensional context only) are synonyms of detachment fault. The origin of these structures is much debated.

Early geologists in the Death Valley region were at the forefront of interpretations of extensional geology. Emmons (1907) and Emmons and Garrey (1910) mapped a detachment fault and recognized the extensional nature of normal faulting half of a century ahead of most Basin and Range geologists. The so-called chaos and turtleback features described by Curry (1954), Noble (1941), and others from Death Valley can now be placed in the framework of great extensional deformation. Hunt and Mabey (1966) were first to recognize a complete domiform detachment fault, the Tucki Mountain fault in the Panamint Mountains, as being of extensional origin. Hamilton and Myers (1966) discussed the region and reached the then-outrageous conclusion that Cenozoic extension had doubled the width of the Great Basin. Stewart (1983) recognized that the great upper-plate block of the Panamint Mountains had moved completely over the Black Mountains lower plate. Much of the mapping of the last several decades in the Black and Funeral Mountains has been done by L.A. Wright and B.W. Troxel (Wright and Troxel, 1973, 1984; Wright and others, 1974), who have emphasized extensional explanations but have interpreted exposed structures largely in terms of imbricate normal faulting related to deeply hidden detachment faults. Work underway by B.C. Burchfiel, B.P. Wernicke, and others is focused on exposed detachment faults.

My work in the Death Valley region consists of widespread reconnaissance, which provides a basis for interpretation of mapping published by other geologists. I brought to the region biases developed in the course of my work in southeastern California and my contacts with many other geologists working with detachment faults in that region; among those to whom I am indebted for comprehension of these structures are G.A. Davis, G.H. Davis, K.A. Howard, Barbara John, and S.J. Reynolds. I developed from geologic-map and seismic-reflection data the interpretation (Hamilton, 1982, 1987) that the middle crust is extended primarily by the sliding apart of lenses separated by zones of ductile shear, that the upper crust is broken into rotated blocks in response to the widening of the composite top of these separating lenses, and that most detachment faults are the tops of these lenses. A contrary model was developed by B.P. Wernicke (1985), who argued that master normal faults cut through the entire crust at gentle to moderate angles, that isostatic rise carries these faults toward the surface as they are denuded tectonically, and that detachment faults are primarily exposures of such master normal faults. Although in my 1987 paper I continued to argue for the broad applicability of the crustal-lens model, in this paper I instead accept much of Wernicke's model as applicable to upper-crustal deformation; I retain the crustal-lens model for much middle-crustal deformation. An extensive fieldtrip with Wernicke in early 1987 convinced me of the validity of much of his interpretation. I return to the subject of crustal mechanics in this paper after describing the structural geology. All photographs here are my own, and their lengthy captions are intended to augment the brief generalizations in the text.

The southwestern part of the Great Basin, which includes the Death Valley region, is the most actively extending part of the Basin and Range province. Within the area shown in figure 5.2, or near it to the west and northwest, are the highest steep scarps, the most severe deformation of Quaternary materials, the deepest topographic closures of structural depressions, and the youngest exposed detachment faults. Indeed, some gently dipping detachment faults exposed at the surface are still active. Nonresistant Neogene upper-plate materials are widely preserved above the detachments, and late Quaternary valley fill hides much less structure than in less active regions. Also shown in figure 5.2 are detachment faults that are exposed in the Panamint, Funeral, and Black Mountains, Bare Mountain, and the Bullfrog Hills. The Argus and Greenwater Ranges and the Cottonwood and Grapevine Mountains display only upper-plate materials but must be underlain by detachment faults at shallow depth.

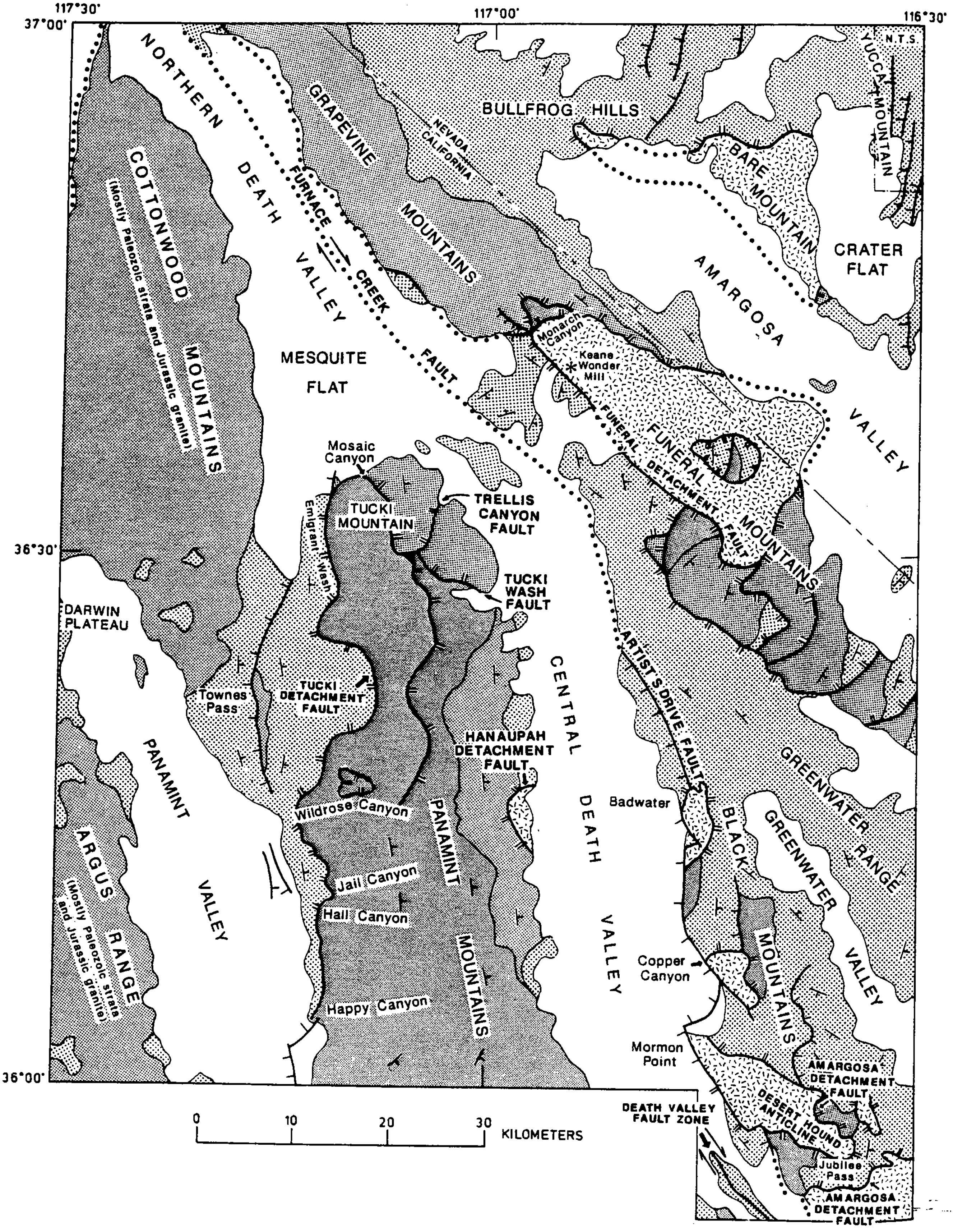
The following discussion proceeds in a general way from east to west within the Death Valley region, and thus from areas in which there is little active faulting to areas of great young activity.

BARE MOUNTAIN, BULLFROG HILLS, FUNERAL MOUNTAINS, AND YUCCA MOUNTAIN

The farthest northeast exposed detachment fault of the Death Valley region is that of Bare Mountain and the Bullfrog Hills, which is now inactive. This Bare Mountain detachment fault projects eastward beneath Yucca Mountain. The detachment faults exposed in Bare Mountain, the Bullfrog Hills, and the Funeral Mountains appear to be domiform exposures of a single fault surface that initially dipped west-northwestward and was denuded as the Grapevine Mountains upper-plate block slid down it.

Bare Mountain Detachment Fault

The lower plate of the Bare Mountain detachment fault, which consists of variably metamorphosed Late Proterozoic and Cambrian strata, has been much extended internally by normal faults that now mostly dip gently (Cornwall and


117°30'
117°00'
116°30'
37°00'
36°30'
36°00'
N.T.S.
YUCCA MOUNTAIN
BULLFROG HILLS
NEVADA
CALIFORNIA
BARE MOUNTAIN
CRATER FLAT
NORTHERN DEATH VALLEY
GRAPEVINE MOUNTAINS
FURNACE CREEK FAULT
AMARGOSA VALLEY
COTTONWOOD MOUNTAINS
(Mostly Paleozoic strata and Jurassic granite)
MESQUITE FLAT
Monarch Canyon
Keane Wonder Mill
FUNERAL DETACHMENT FAULT
FUNERAL MOUNTAINS
Mosaic Canyon
TUCKI MOUNTAIN
TRELLIS CANYON FAULT
Emigrant Wash
TUCKI WASH FAULT
DARWIN PLATEAU
Townes Pass
TUCKI DETACHMENT FAULT
HANAUPAH DETACHMENT FAULT
CENTRAL DEATH VALLEY
ARTIST'S DRIVE FAULT
GREENWATER RANGE
PANAMINT VALLEY
Wildrose Canyon
PANAMINT MOUNTAINS
Badwater
BLACK MOUNTAINS
GREENWATER VALLEY
ARGUS RANGE
(Mostly Paleozoic strata and Jurassic granite)
Jail Canyon
Hall Canyon
Copper Canyon
Happy Canyon
Mormon Point
AMARGOSA DETACHMENT FAULT
DESERT HOUND ANTICLINE
DEATH VALLEY FAULT ZONE
Jubilee Pass
AMARGOSA DETACHMENT FAULT
0
10
20
30
KILOMETERS

Kleinhampl, 1961, who regarded the Neogene faults as thrust faults; Cornwall, 1972; Monsen, 1982; M.D. Carr and S.A. Monsen, oral commun., 1985, 1986). Metamorphism of the lower-plate rocks increases gradually from lowest greenschist facies in the far south (slaty pelites, nonmarbleized carbonates: my observations) to lower amphibolite facies in the northwest (staurolite + garnet, epidote + hornblende: Monsen, 1982; T.D. Hoisch, oral commun., 1987).

Upper-plate rocks have been stripped from most of the Bare Mountain lower plate but are preserved in the south and north. At the south end of Bare Mountain, nonmetamorphosed Cambrian strata are truncated downward against the gently plunging detachment fault (fig. 5.3*A*). Middle Miocene ashflows, about 11 m.y. old, and slide megabreccia lie upon the southern upper-plate Cambrian rocks and are but gently tilted (Swadley and Carr, 1987). Around the north end of Bare Mountain, upper middle Miocene volcanic rocks, older than about 11.2 m.y., dip downward to truncations against the detachment fault (fig. 5.3*B*), whereas lower upper Miocene volcanic and sedimentary rocks about 10.5 m.y. old and younger lie unconformably across both the fault and the deformed upper-plate volcanic rocks and are merely tilted (Florian Maldonado and P.P. Orkild, oral commun., 1985, 1987; compare Carr, 1984). Breccia of unmetamorphosed Cambrian and Late Proterozoic rocks locally intervene between upper and lower plates (fig. 5.3*B*) and attest to the earlier passage across the lower plate of an upper plate of Paleozoic strata, presumably that of the present Grapevine Mountains. The time of inception of faulting is not defined by local data, but in the Grapevine Mountains (discussed below), which likely slid westward from above Bare Mountain, extension probably was underway in late Oligocene time. The faulting about 11 m.y. ago represents only the last slip on the detachment fault, which thus had a history that predates also the faulting of Yucca Mountain.

EXPLANATION

☐ Quaternary materials

UPPER-PLATE ROCKS

░ Tertiary, sedimentary and volcanic rocks, Oligocene through Pliocene

▒ Paleozoic, includes Mesozoic granitic rocks

▓ Precambrian, Middle Proterozoic plutonic rocks and Late Proterozoic sedimentary and metasedimentary rocks

LOWER-PLATE ROCKS

▨ Metamorphic and plutonic rocks, of diverse ages, below lowest exposed faults

Faults, dotted where concealed

⇌ Strike-slip, arrows indicate relative movement

┴┴┴ Normal, hachured on downthrown side

╨╨╨ Detachment faults and normal faults rotated to gentle dips, hachures on upper plate

┴ Strike and dip of inclined strata

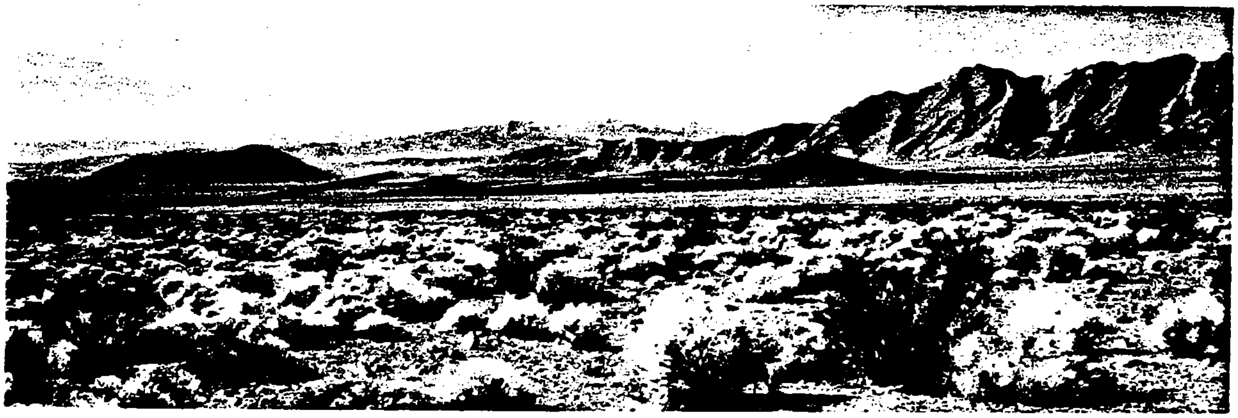
Figure 5.2. Tectonic and generalized geologic map of Death Valley region, California and Nevada. Most normal faults are omitted. Adapted mostly from published maps cited in text. See figure 5.1 for location.

Although Bare Mountain is deeply eroded, its crest and lateral ridges define a symmetrical domiform surface which plunges northward and southward to approximately become the exposed detachment fault, and hence likely has been but little eroded beneath the detachment fault elsewhere. This surface dips under upper Quaternary alluvium on both the east (fig. 5.3*A*, *C*) and west sides of the range, where there are no exposures of upper-plate rocks. A steep range-front fault was inferred by Carr (1984), Cornwall (1972), and Cornwall and Kleinhampl (1961) to bound the east side of Bare Mountain. M.C. Reheis (chapter 8) found evidence for local disruption of alluvium at the foot of the range and inferred that steep faulting has broken the front within Holocene time.

The absence of range-front scarps in either bedrock or surficial materials (fig. 5.3*A*, *C*) is strong evidence against the presence of a young range-front fault at the east base of Bare Mountain. The surface defined by the crests of the lateral ridges projects smoothly beneath the alluvium of Crater Flat with a dip of about 30°. The continuation of that surface beneath the alluvium with about that inclination is demonstrated by detailed gravity traverses across the range front (Snyder and Carr, 1982). No gravity gradient is present as would be if a steep fault was at the foot of the bedrock exposures. Farther east under Crater Flat, a steeper subsurface contact at considerable depth can be fitted to ambiguous gravity models but is not required. Carr (1984), Carr and others (1986), and Snyder and Carr (1982, 1984) inferred two Miocene calderas to lie beneath Crater Flat, but facies and distribution of Miocene ignimbrites require no ignimbrite sources in this area, and the gravity analysis by Snyder and Carr is in my view merely a visual aid in support of permissive rationales for such calderas.

Bullfrog Hills Detachment Fault

The detachment fault of the Bullfrog Hills, west of northern Bare Mountain, has an upper plate of Miocene volcanic and sedimentary rocks, as young as 7.5 m.y. old, which dip moderately to steeply eastward and northeastward



A

B

C

to a truncation against the poorly exposed fault, which defines a gentle north-plunging dome (Florian Maldonado, written commun., 1985; Cornwall and Kleinhampl, 1964; Emmons and Garrey, 1910). Faulting continued later here than in Bare and Yucca Mountains nearby to the east but is now inactive or nearly so.

The Bullfrog lower plate consists of Late Proterozoic strata metamorphosed at amphibolite facies, including staurolite-kyanite assemblages (T.D. Hoisch, oral commun., 1987), Jurassic(?) pegmatite, and variably mylonitized undated gneiss. Between the upper and lower plates is a sheet of slightly metamorphosed and much disrupted Paleozoic strata, analogous to the carapaces seen on many other detachment faults in the region and formed presumably as a friction breccia beneath the Grapevine Mountains block as it slid over the Bullfrog lower plate.

Funeral Mountains Detachment Fault

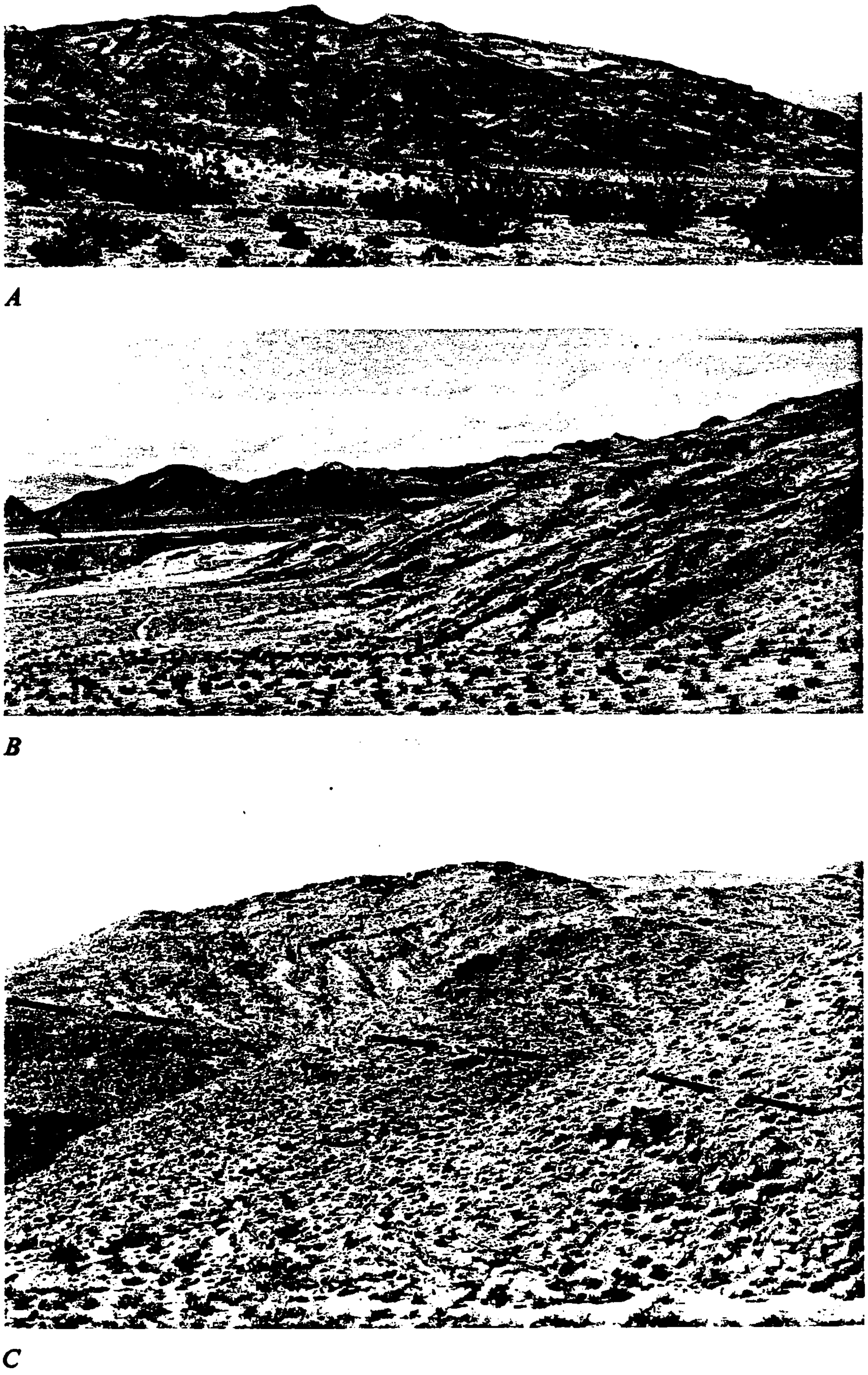
What I regard as a continuous domiform Funeral Mountains detachment fault with an elliptical trace was mapped as many separate faults of diverse types by Giaramita (1984, who recognized its continuity around the north end of the complex), Hunt and Mabey (1966), McAllister (1971), Swadley and Carr (1987), and L.A. Wright and B.W. Troxel (written commun., 1986, unpublished map; see also Labotka, 1980, and Labotka and Albee, in press). The lower plate has a domiform upper surface both where the upper plate is preserved and where it has been stripped away (fig. 5.4).

Lower-plate rocks are metamorphosed clastic strata, and subordinate carbonate rocks, that are at least mostly Late Proterozoic but may include basal Cambrian in the far southeast. These rocks were metamorphosed to lower greenschist to upper amphibolite facies, probably during Jurassic time (Labotka and Albee, in press). At the southeast end of the exposed complex, where the detachment-fault trace lies along the south side of upper Echo Canyon, Proterozoic lower-plate clastic rocks are metamorphosed at low grade and are now quartzite and glossy slate and phyllite; the sparse clastic rocks in the directly overlying upper-plate Paleozoic section, which consists mostly of carbonates, are nonmetamorphosed sandstone and argillite that lack secondary mica (my observations; also, T.D. Hoisch, oral commun., 1987). Metamorphic grade increases northwestward in the lower plate to upper amphibolite in the far northwest (Labotka, 1980; Labotka and Albee, in press), and the high-grade rocks are intruded by abundant sheets of pegmatite and muscovite granite. Kyanite is present in middle- and high-grade rocks, locally with sillimanite at highest grade; these high-grade rocks formed at a depth of about 20 km and a temperature near 700 °C (Giaramita, 1984; Labotka, 1980; Labotka and Albee, in press). At least the high-grade metamorphism must have involved introduction of magmatic heat (Labotka and Albee, in press). Whether the low-grade rocks of the southeast part of the lower plate formed at lesser depth, as I infer, than the high-grade northwestern rocks, or at a comparable depth but much lower temperature, has not been proved.

Foliation and layering are subparallel in the transposed middle- and high-grade rocks of the lower plate, whereas cleavage cuts bedding in the low-grade rocks. Orientation of layering is quite variable, but dominant dips are eastward at gentle to moderate angles (Wright and Troxel, unpublished map).

The central and northwest parts of the lower plate bear a retrograde greenschist-facies carapace, 10 to 150 m thick, within which foliation and transposed lithologic layers are parallel to the detachment fault that bounds the carapace. Continuity of the carapace on ridge crests shows that the gently domiform topography defined by those crests (fig. 5.4*A*, *B*) is eroded very little beneath the detachment fault. The carapace displays isoclinal ductile and semiductile folding that verges in the same direction, top to the west (fig. 5.5*A*, *B*), as the slip of upper-plate rocks and opposite to fold vergence in nonretrograded amphibolite-facies lower-plate rocks beneath the carapace (fig. 5.6), where I have studied carapace and core in Monarch Canyon and along the western range front. The carapace apparently was developed during the early, deep-seated stage of Tertiary extension. Giaramita (1984) also recognized this west-verging folding and shearing, and its significance, of retrograded high lower-plate rocks at the north end of the lower plate. The carapace in many places has a veneer a few meters thick of mylonitized carbonate rocks, smeared out as a lubricating ductile layer (fig. 5.5*B*, *C*). I saw no carapace at the south end of the lower plate, although as I did not see actual exposures of the fault there, a thin carapace could be present.

Figure 5.3. Bare Mountain detachment fault. The last important slip on this fault occurred about 11 m.y. ago. *A*, View southwest to south end of Bare Mountain. Detachment fault (line on left; the right skyline is eroded little beneath the fault) separates Middle or Upper Cambrian limestone and dolomite (dark hill on left) from low-grade-metamorphic Late Proterozoic clastic rocks (rest of range to right). Upper plate slipped obliquely toward the right distance. *B*, View east along detachment fault (heavy dashes) at north end of Bare Mountain. Lower plate (foreground and right) is of metamorphosed Lower Cambrian and Late Proterozoic rocks. Upper plate is of east-dipping ashflows and tuffs of upper middle Miocene Timber Mountain Tuff. A tectonic lens of unmetamorphosed but severely brecciated Middle or Upper Cambrian carbonate rocks intervenes in the middle distance (below light dashes). Upper plate moved relatively west (left). *C*, View north-northwest along east side of central Bare Mountain, which consists of low-grade-metamorphic Lower Cambrian and Late Proterozoic carbonate and clastic rocks. The lateral ridgecrests have been little eroded beneath the detachment fault bounding these lower-plate rocks. Detailed gravity surveys show the bedrock surface to continue with gentle inclination beneath the alluvium. The lack of range-front scarps in either bedrock step indicate that there has been little if any Quaternary faulting here. (See also part *A*.)


A
B
C

Upper-plate rocks, rotated mostly to dip steeply to moderately northeastward in the north and eastward and southeastward elsewhere, and sharply truncated downward against the detachment fault, are nonmetamorphosed Late Proterozoic and Paleozoic sedimentary rocks and upper Oligocene and lower, middle, and lower upper Miocene sedimentary and volcanic rocks (figs. 5.4*B*, *C*, 5.5*C*). Upper-plate Late Proterozoic and Paleozoic rocks stand mostly as the high, rugged Grapevine and southern Funeral Mountains, whereas Tertiary units, which dominate the upper plate atop the intervening northern and central Funeral Mountains, have mostly been eroded to low ground flanking the dome and are broadly covered by undeformed Quaternary materials. Upper-plate rocks moved relatively westward above all parts of the lower-plate dome, including its east flank and the large klippe on its crest. Upper-plate pre-Tertiary strata are nonmetamorphosed in both the Grapevine and southern Funeral Mountains and show no apparent northwest increase in grade parallel to that of the lower plate. A lens, crescentic in plan, of coherent low-grade metasedimentary rocks intervenes between the main lower plate of high-grade rocks and the upper plate of nonmetamorphosed strata at the north end of the Funeral Mountains. Slide megabreccia layers are intercalated in lower Miocene strata at the west base of the Funeral Mountains (fig. 5.5*C*), so upper-plate faulting probably was underway by early Miocene time; a late Oligocene age of inception is deduced below from evidence in the Grapevine Mountains.

The complex upper plate in the southeastern Funeral Mountains consists of panels of Paleozoic strata overlain, with broad concordance, by uppermost Oligocene and lower and middle Miocene strata (Cemen and others, 1985), rotated to general eastward and southeastward dips between west- and northwest-dipping normal faults (McAllister, 1970, 1971) which mostly have gentle dips and are not known to cut the detachment beneath. This composite of domino panels is in turn broken by a range-front fault, trending southeastward, southwest of which are steeply to moderately dipping early Pliocene strata which overlie the upper Miocene strata of the northern Black Mountains (Cemen and others, 1985; Hunt and Mabey, 1966; McAllister, 1970, 1973). The Pliocene strata are tightly to openly folded about doubly plunging northwest-trending axes (McAllister, 1970, 1973). It appears that extension at the south end of the Funeral Mountains continued through at least early Pliocene time and was followed by modest northeast-southwest shortening, and that the area has been internally stable during at least late Quaternary time. I infer from the complex configuration of the range-front fault that it was rotated to a gentle dip, then broadly folded.

Figure 5.4. Domiform detachment fault of the Funeral Mountains. The last slip on this fault occurred during Pliocene time. *A*, View southeastward into the northern Funeral Mountains. The domiform crest is essentially the stripped detachment fault. Sense of slip of upper plate was westward across the dome, from distant left to near right. *B*, View northwestward along the west side of the Funeral Mountains, from Keane Wonder Mill. Mylonitic carapace (layering, right) was developed concordantly below detachment fault by shearing and retrogression of Late Proterozoic middle-grade metasedimentary rocks. Arrow indicates dip of upper-plate middle Tertiary redbeds in low bluff beneath late Quaternary pediment. Upper plate moved relatively leftward. White mass in left middle distance is a Holocene travertine terrace, which here covers the fault trace. Upper-plate Grapevine Mountains in left distance. *C*, View west along domiform detachment fault (lines), northern Funeral Mountains. Unmetamorphosed latest Proterozoic upper-plate clastic strata are truncated downward against lower-plate amphibolite-facies much older Late Proterozoic strata. Head of Monarch Canyon.

The upper plate in the Grapevine Mountains consists of complexly deformed but nonmetamorphosed latest Proterozoic to Pennsylvanian sedimentary rocks overlain on the northeast by a thick northeast-dipping section of upper Oligocene and Miocene sedimentary and volcanic rocks (Reynolds, 1969, 1976). Sedimentary breccias are intercalated in the Oligocene section, and I assume that these were shed from nearby fault scarps and hence that extension was underway in late Oligocene time. Subhorizontal faults, topographically high in the range, mostly place younger Cambrian rocks on older ones and at least in part display top-to-the-west slip; beneath these faults are large recumbent folds with southwest vergence. Both faults and folds may be products of middle Tertiary extension, the faults having been normal faults that dipped moderately westward before northeastward tilting of the range. Reynolds (1969) mapped many patches of middle Tertiary strata and sedimentary breccia, which, where attitudes are shown, mostly dip moderately downward to subhorizontal contacts, atop high ridges of Cambrian rocks; I infer these contacts to be segments of a rotated range-front fault.

The Grapevine Mountains face Death Valley on the southwest with a high but much-eroded scarp, and the range is cut by deep canyons. This old frontal normal fault trends southeastward into the Funeral Mountains detachment fault but does not cut it—the range-front fault is restricted to the upper plate.

The domiform gravity high of the Funeral Mountains lower plate plunges gently under the Grapevine Mountains upper plate in the northwest and the southern Funeral Mountains upper plate in the southeast (Chapman and others, 1977; Mabey, 1963). Apparently those great upper-plate blocks are perched atop the dome.

Continuity of Faulting between Bare Mountain, Bullfrog Hills, and the Funeral Mountains

Temperature of metamorphism increased northwestward in the Bare Mountain lower plate, from perhaps 350 °C to 500 °C, and the Bullfrog Hills lower plate records a yet higher temperature and a depth of metamorphism of perhaps 20 km. There appears to be a northwestward increase of depth of exposure in the Bare Mountain and Bullfrog Hills lower plates. The Bare Mountain and Bullfrog Hills detachment faults dip gently toward one another beneath tectonically overlying Miocene volcanic rocks, so likely either both domiform detachment faults expose parts of a single fault surface or else the Bullfrog Hills lower plate represents a deeper crustal lens that emerged from beneath the Bare Mountain one.

This northwestward increase in probable depth of metamorphism parallels that in the continuously exposed lower plate of the Funeral Mountains, where also metapelites increase in grade from slate and phyllite in the southeast to kyanite-staurolite schist in the northwest. Biotite, garnet, and kyanite isograds can be projected from the Funeral Mountains northward and north-northeastward across Amargosa Valley to Bare Mountain and the Bullfrog Hills.

A broad, shallow gravity low lies in Amargosa Valley, between the exposures of the Bare Mountain and Funeral

Figure 5.5. Retrograde carapace produced on Funeral Mountains lower plate concordantly beneath detachment fault. Transposition was in same west-directed sense as was slip of overlying upper plate, and represents early deep-seated shearing on the fault system that evolved into the shallow, brittle detachment fault. *A*, Carapace in north wall of Monarch Canyon. Detachment fault projects just above skyline; entire wall, 120 m high, is in carapace of rocks transposed parallel to fault. Sense of overturning of ductile folds (most conspicuous in sheared white Jurassic? pegmatites) is top-to-the-left (west). Host rocks are Late Proterozoic mica and hornblende schists and, most abundant high on the wall, carbonates. *B*, Mylonitized marble veneer (layered rocks, upper left half of view) atop carapace. Brittle detachment fault is just above the exposure, which is 6 m high. Dark marble layer near top is deformed in a west-verging isocline; thick marble beneath it is boudinaged; gouge lies beneath boudinaged quartz vein that forms base of layered sequence. Rock at lower right is phyllonitic augen schist. View north, 1 km northwest of Keane Wonder mill. *C*, Detachment fault, 3 km northwest of Keane Wonder mill, looking north. Smooth rock surface (right center) sloping gently left is the stripped lower plate of the detachment, which has a veneer 1 m or so thick of mylonitized marble (light color). Lower Miocene redbeds, tuff, and breccia (left center) dip steeply east to truncation against fault, which is in part marked by dashes.

Mountains detachment faults (Chapman and others, 1977; Mabey, 1963; Snyder and Carr, 1982). I infer that lower-plate rocks are present at shallow depth throughout this area, that upper-plate rocks consist largely or entirely of low-density Cenozoic materials, and that overlying postdetachment Pliocene and Quaternary deposits are thin. Indeed, probable lower-plate rocks make small outcrops near the center of the valley (Swadley and Carr, 1987).

The detachment faults of the Funeral Mountains, Bullfrog Hills, and Bare Mountain may represent upwarps of a continuous fault surface that initially cut west-northwestward down into the crust, from a depth of 10 km or less in present southeastern exposures to 20 km or more in northwestern ones, over a present distance of about 30 km. A depth change from 10 km to 20 km corresponds to an initial westward dip of about 20°. Gently dipping normal faults have been mapped within the lower plates of Bare Mountain by Cornwall and Kleinhampl (1961), Monsen (1982), and Monsen and M.D. Carr (written commun., 1986, 1987), and of the Funeral Mountains by L.A. Wright and B.W. Troxel (written commun., 1986), indicating that these lower plates were themselves extended; hence, the initial dip of the master fault that is now seen as the detachment was probably steeper than this 20°.

Slip of Late Proterozoic and Paleozoic rocks on this master fault was relatively small in the southeast, for in both Bare Mountain and the Funeral Mountains nonmetamorphosed strata are placed on slightly metamorphosed strata, but large in the northwest, where the nonmetamorphosed rocks of the Grapevine Mountains overlie deep-seated crystalline rocks of the Funeral Mountains and, presumably, the subsurface western projection of the Bullfrog Hills lower plate. The intervening tract of lower-plate rocks was denuded tectonically as the Grapevine block slid across it, and synextensional Tertiary sedimentary and volcanic rocks now form the upper plate in the gap.

Such an explanation accords with the model of B.P. Wernicke, with the addition to his proposed mechanism of extension within the lower plate as well as of the upper plate and with uplift of the lower plate being progressive by sectors. A great normal fault initially dipped westward, more steeply than 20° by an angle not yet well constrained, to a depth of at least 20 km. The upper-plate rocks initially above the shallow end of this fault were fragmented into great and

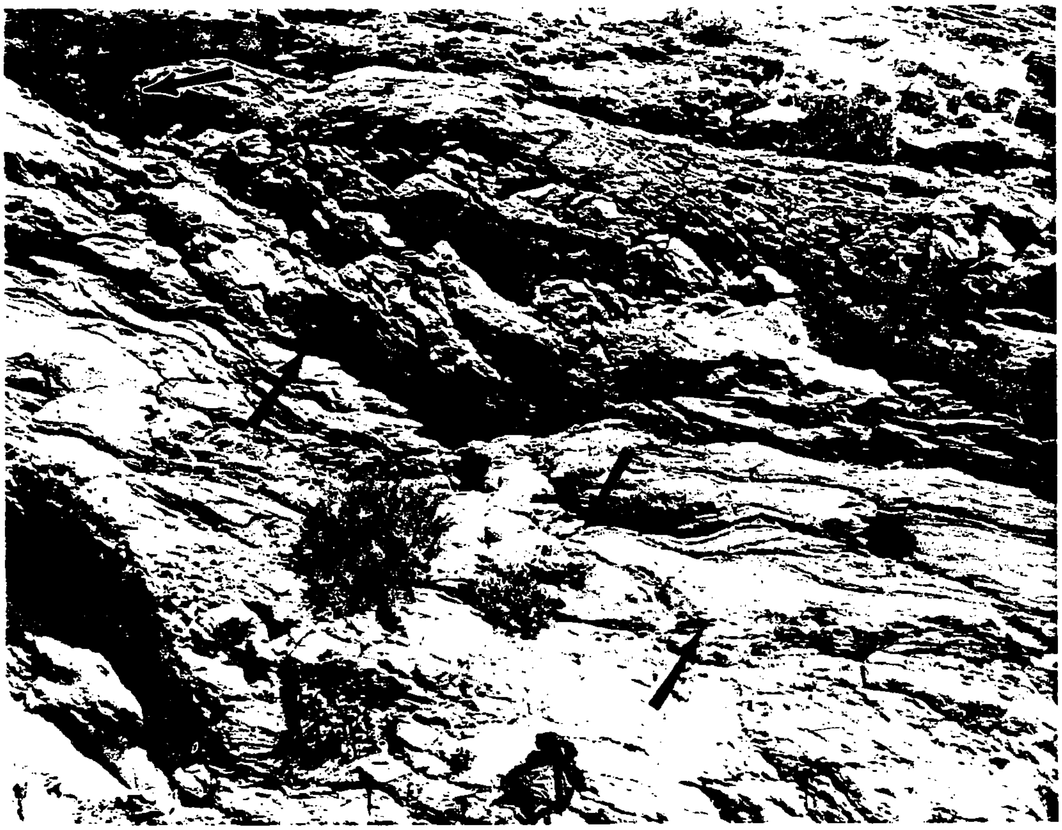


Figure 5.6. Lower-amphibolite facies Late Proterozoic metacarbonate rocks, below carapace in canyon 1 km east of Keane Wonder mill. S-folds (arrows to hinges) indicate shear of top-up-to-east (left) sense—this Jurassic (?) synmetamorphic shearing had sense opposite to that in Neogene carapace (figs. 5.5*A*, *B*). Exposure 4 m high.

small blocks, from the size of ranges such as the Grapevine Mountains downward. The denuded part of the lower plate rose isostatically, eastern upper-plate blocks were stranded atop the flattened sector of the fault while western blocks continued to move, and the age of last slip decreased westward as the hingeline between dipping and flattened fault migrated in that direction.

Biotite and muscovite K-Ar ages of pre-Tertiary lower-plate crystalline rocks of the Funeral Mountains, Bullfrog Hills, and northern Bare Mountain scatter from 10 to 50 m.y. old, but most are between 10 and 22 m.y. (M.D. Carr, written commun., 1985; Giaramita, 1984; McKee, 1983; Stern and others, 1966). These ages of cooling presumably record Miocene uplift, by tectonic denudation, from midcrustal depths at which ambient temperatures were above those permitting full retention of argon in the micas.

Imbricate Faulting of Yucca Mountain

Middle Miocene volcanic rocks, broken and rotated by subparallel west-dipping imbricate normal faults, form a nearly continuous ring from Yucca Mountain westward and southward to the north and south ends of exposure of the Bare Mountain detachment fault. That fault dips gently eastward beneath Crater Flat (fig. 5.3*A*, *C*) and hence projects beneath Yucca Mountain, and volcanic rocks correlative with those of Yucca Mountain are rotated down and truncated against the detachment. The extensional deformation of Yucca Mountain likely is a product of slip on the Bare Mountain detachment fault. Yucca Mountain faulting is much more severe in rocks 12.5 to 13.5 m.y. old than in those less than 11.5 m.y. old, and was largely completed by 10 m.y. ago (Carr, 1984; Maldonado, 1985; Scott and Bonk, 1984). Dips of Yucca Mountain faults increase, and dips in its strata decrease, away from the exposures of the Bare Mountain detachment fault (Scott, 1986). Late middle Miocene rocks farther east in the Nevada Test Site display much less deformation than do the correlative rocks of Yucca Mountain. There has been little normal faulting since the early late Miocene, and presumably any underlying detachment faults also are inactive or almost so.

Scott and Whitney (1987) deduced from these relations that the west-dipping imbricate faults of Yucca Mountain represent a headwall complex by which slip on the Bare Mountain detachment fault reached the surface, and they argued that the fault does not continue farther east at depth. I agree with their analysis insofar as it applies to the last small bit of detachment faulting, that which postdated 12.5 m.y. ago. The explanation is not applicable to the earlier very different configuration and vastly greater slip on the fault.

I see Yucca Mountain faulting as having occurred above the ~11-m.y.-old hingeline between flattened and dipping master fault. By that time, the tectonically denuded fault surface had risen in the east to an undulating surface on which there was little if any continuing slip, whereas in the west, it still dipped moderately westward so that slip was continuing. This earliest late Miocene hingeline lay far to the west of successively older hingelines and associated headwall complexes, which in turn lay far to the west of the initial positions of their preextension upper- and lower-plate complexes. The upper-plate Grapevine Mountains block had by late Miocene time already gone by—most of the detachment slip predated the Yucca Mountain episode.

BLACK MOUNTAINS

The central Black Mountains display detachment faults, or undulating exposures of a single fault, the lower plates of which consist entirely of plutonic rocks, and the upper plates of which consist variously of Middle Proterozoic and younger plutonic rocks, Late Proterozoic sedimentary rocks, and Miocene to Quaternary sedimentary and volcanic rocks (fig. 5.2). Early stages of extension, recorded by ductile structures, were presumably of middle Tertiary age; late-stage extension, dated by local involvement of upper-plate Neogene strata, was underway by early late Miocene time. Faults in the present medial and eastern Black Mountains are now largely inactive, and may have become so progressively with time from east to west. Along the west side of the range, west-dipping sectors of detachment faults are still active, and perched, active range-front faults in the upper plates end downward against those active detachment faults. These conclusions are based partly on maps and descriptions by Curry (1954), Drewes (1959, 1963), Hunt and Mabey (1966), Noble (1941), Otton (1977), Wright and others (1974), and Wright and Troxel (1984), and partly on my own field reconnaissance.

Amargosa Detachment Fault and Amargosa Chaos

Noble (1941) recognized, in the low Jubilee Pass area between the central and southern Black Mountains, an undulating fault that separates plutonic rocks beneath from a variety of Proterozoic, Cambrian, and Neogene materials above. The fault surface defines a series of antiforms, dipping and plunging gently, over an area about 15 km wide across the strike. Noble recognized the consistent westward transport of rocks above the fault relative to those below. He emphasized that a thick crustal section had been cut out across the fault, which he nevertheless assumed to represent Tertiary compressive overthrusting and named the "Amargosa thrust fault." I here refer to the fault as the Amargosa detachment fault. Noble described widespread megabreccia in the upper plate and deduced that it formed by disruption of a thin overriding sheet. He classified the breccia, on the basis of its constituent rock types, into Virgin Springs, Jubilee, and Calico phases of the "Amargosa chaos."

Much of Noble's area was mapped in detail by Wright and Troxel (1984), and I have toured the area both with Troxel and alone. The interpretations by Wright and Troxel have evolved since their map went to press; my statements in this section represent a mixture of their published interpretations, their subsequent interpretations as I understood them from discussions in 1985 with Troxel and in 1986 with Wright, and my own interpretations. Noble applied his terms very inconsistently, but his "Calico phase of the Amargosa chaos" typically is a coherent upper Miocene formation of volcanic and tuffaceous rocks which include thick marblecake megabreccia apparently formed by intrusion and extrusion of magmas into wet bentonitic mud. Noble's "Jubilee phase" typically is a coherent lower upper Miocene redbed formation that contains intercalated slide megabreccia of mixed plutonic rocks and Late Proterozoic and Tertiary sedimentary rocks. Much of Noble's "Virgin Springs phase" is a discontinuous friction breccia of severely disrupted and attenuated Late Proterozoic sedimentary rocks, as much as 100 m thick, at the base of the upper plate (fig. 5.7*A*, *B*), rubbed off a transiting upper plate of Late Proterozoic sedimentary rocks; Noble lumped the large block of coherent Late Proterozoic strata north of Jubilee Pass with this "chaos." The detachment-fault domes are discontinuously outlined by carapaces of these friction breccias derived from overriding Late Proterozoic rocks, and the carapaces dip both eastward and westward beneath structurally overlying Neogene rocks. This widespread friction carpet of Proterozoic strata between upper-plate Neogene rocks and lower-plate plutonic rocks demonstrates that the parts of the lower plate now overlain tectonically by Tertiary materials have been denuded tectonically by the westward slip of Proterozoic rocks, and hence that the slip recorded by the truncations of Tertiary strata is but a small fraction of the total slip of upper-plate rocks above the faults.

Wright and Troxel (1984) did not make this interpretation and instead inferred the west flanks of the domes to be relatively minor west-dipping normal faults rotated to gentle dips, and the east flanks to be truncated against unexposed west-dipping faults; the map relations to me preclude this interpretation, and I see, as did Noble, an undulating underlying fault. Upper-plate units dip generally eastward to their truncations downward against that fault. Upper-plate rocks are broken by numerous west-dipping normal faults, but as far as I am aware these have not been proven to penetrate the lower plate.

As the various detachment antiforms are separated by upper-plate materials, it is possible that they represent the tops of crustal lenses that are separated by gently dipping shear zones, and that there has been great extension within the lower plate as well as within the upper plate.

The western antiform of the detachment surface in the Jubilee Pass area rises and broadens northwestward to include the plutonic rocks of the high central Black Mountains (fig. 5.2; Desert Hound anticline of Noble, 1941; Wright and Troxel, 1984). On the west, Late Proterozoic sedimentary rocks, locally with the Middle Proterozoic plutonic basement rocks on which they were deposited preserved beneath them, form a large east-tilted block that is truncated downward against the detachment fault. Beneath the detachment are plutonic rocks, which include Jurassic granitic and gneissic rocks (I base this correlation on the lithologic similarity of the distinctive but undated megacrystic granodiorite and quartz monzonite here with dated Jurassic granitic rocks of the Mojave Desert and regions to the south), likely also Middle Proterozoic plutonic rocks, and possibly Tertiary granite. A major perched range-front fault bounds the upper-plate Proterozoic rocks against east-dipping Neogene strata and megabreccia in the low ground at the west foot of the range. This fault is limited to the upper plate—the fault trends northward into the detachment fault, which there dips gently westward, and ends against it. The west front of the central Black Mountains nearby to the northwest is the detachment surface from which tectonically overlying Neogene strata have been largely stripped. The detachment fault is exposed discontinuously along the foot of the range where upper-plate Pliocene redbeds and basalt are preserved in the low ground. The lower plate here consists of Jurassic granitic rocks; the juxtaposed upper-plate redbeds contain no clasts of this rock type but instead were derived from upper-plate Late Proterozoic rocks similar to those against which the redbeds are faulted by the perched range-front fault to the south, so the redbeds which now form the hanging wall of the detachment fault originated as the hanging wall of an upper-plate normal fault and were rotated downward against the detachment as extension progressed. Along much of this sector, upper-plate rocks are wholly buried beneath upper Quaternary Death Valley alluvium that laps onto the stripped footwall.

The Amargosa detachment fault along the east side of the Desert Hound antiform was mapped northward to lat 36° N. by Noble (1941) and Wright and Troxel (1984), and was traced about 2 km farther north, as the "Amargosa thrust fault," by Drewes (1963). It is not clear from Drewes' reconnaissance map whether the detachment fault continues northward as the structural top of all plutonic rocks or descends into the undivided crystalline rocks; I infer the latter. Drewes schematically mapped breccia, near the contact between plutonic rocks and overlying Tertiary volcanic and sedimentary rocks, of Late Proterozoic or Cambrian formations which he regarded as coherent Paleozoic rocks shuffled with Neogene strata by networks of Neogene thrust and normal faults. I have not seen these complexes but deduce from Drewes' descriptions that the breccia might be a friction carpet atop lower-plate plutonic rocks (in which case they mark a detachment fault structurally high above the Mormon Point turtleback detachment fault at the west foot of the range), or that, more likely, they are slide breccias intercalated stratigraphically in Neogene formations (in which case the subjacent plutonic rocks may be the basement rocks for these formations and be in the upper plate of the Amargosa detachment fault). If the first alternative is correct, then the turtleback faults, discussed next, are the tops

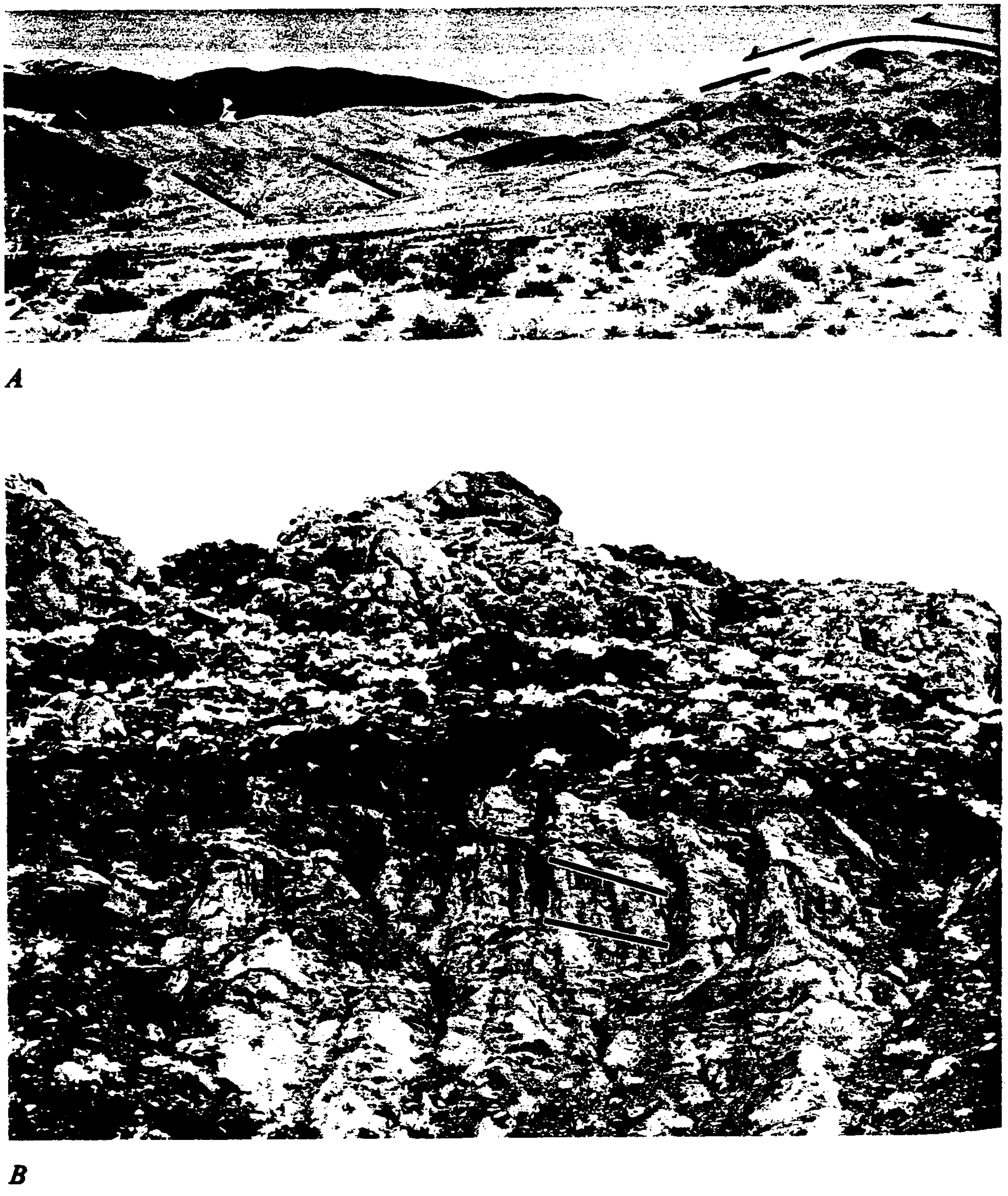


Figure 5.7. Amargosa detachment fault, Jubilee Pass area, Black Mountains. *A*, Unconsolidated upper Pliocene or lower Pleistocene fanglomerate (light colored, left, bedding parallel to lines) dips eastward to truncation against the gentle west flank of a dome in the Amargosa detachment fault. Domiform, lower-plate hill of plutonic rocks (right; Rhodes anticline of Noble, 1941) is little eroded beneath projected detachment fault (lines, arrows). A friction breccia of Late Proterozoic rocks, like that in part *B*, is preserved between fanglomerate and lower plate around base of dome. View northwest from about 4 km east-northeast of Jubilee Pass. *B*, Disruption along Amargosa detachment fault. Gouge (between lines near center) separates upper and lower plates. Exposed part of lower plate consists of crushed and altered Middle Proterozoic gneiss. Exposed part of upper plate is a friction breccia (part of "Virgin Springs phase of Amargosa chaos" of Noble, 1941) of greatly attenuated Late Proterozoic dolomite (light, top), diabase (dark, center), and other sedimentary rocks (directly above gouge). Exposure about 30 m high, 3 km east-northeast of Jubilee Pass. Upper Neogene strata (not in view) dip downward to a truncation against this breccia, as in part *A*.

of tectonic lenses deeper than the Amargosa detachment fault. The second alternative appears more likely, however, as the turtleback faults that emerge from beneath these structurally high plutonic rocks bear carapaces of mylonitized Late Proterozoic strata, from which I infer that the turtlebacks represent the same structural level as the Amargosa detachment fault. The denudation of the structurally high plutonic rocks presumably was due to Tertiary extension in any case.

The lower plate of the Amargosa detachment fault is continuously exposed north to the Mormon Point turtleback along the west base of the Black Mountains, and I have arbitrarily connected the east flanks of Mormon Point and Desert Hound anticline structures on figure 5.2.

Around the southern part of the central Black Mountains, middle and upper Miocene volcanic and sedimentary rocks generally dip more steeply than do Pliocene ones (Wright and Troxel, 1984), but all are truncated by the same undulating Amargosa detachment fault. In the western part of this terrane, Pleistocene strata also are rotated, although to gentler dips, in the same general eastward direction (Wright and Troxel, 1984). The abundance of slide megabreccia in late Miocene sections attests to the presence of upper-plate scarps at that time. In the northern Black Mountains, steep-dipping Pliocene strata lie semiconcordantly above upper Miocene ones (Cemen and others, 1985; Hunt and Mabey, 1966). Faulting is still very active at the west foot of the northern Black Mountains.

The southern Black Mountains, south of the area shown in figure 5.2, consist mostly of plutonic rocks, and these, as I read the map of the north edge of them by Wright and Troxel (1984; I have not been in this area), lie entirely beneath the Amargosa detachment fault. The rest of the southern Black Mountains is covered by the 1:250,000 map compiled by Jennings and others (1962) from reconnaissance maps, mostly still unpublished. The compilation map shows the plutonic rocks to be faulted against—overlain structurally by, at least in part—Late Proterozoic, Cambrian(?), and Tertiary strata on the east and south. I infer that the plutonic rocks, about 15 km by 20 km in exposed dimensions, lie beneath the Amargosa detachment fault, whether that fault is a continuous single surface or the composite top of separate crustal lenses.

Turtleback Detachment Faults

Three stripped domiform detachment faults along the west base of the central Black Mountains were aptly termed "turtlebacks" by Curry (1954), who assumed them to be anticlinal folds in a thrust fault. They were studied further by Drewes (1959, 1963), Otton (1977), and Wright and others (1974). Drewes regarded the faults as ancient shear zones along which small surficial blocks are now sliding into Death Valley. Wright and his associates inferred the turtlebacks to be giant mullions on a normal fault which had undergone large late Miocene to Quaternary slip and had evolved from deep and ductile to shallow and brittle.

The turtlebacks are marked on figure 5.2 by the fault closures at Badwater and at Copper Canyon and by the northwest end, at Mormon Point, of the large southern fault dome. The west flank of each of these turtleback detachments is presently active—large active normal faults in the upper plates end downward against them (figs. 5.8, 5.9). The hanging wall of each normal fault becomes the hanging wall also of the detachment fault, down which it is now sliding. Late Quaternary slip of the normal-fault footwall blocks on the detachment faults has not yet been demonstrated.

The turtleback domes plunge 15° to 25° northwestward. Flank dips are asymmetric, gentle to the northeast but moderate to the southwest. Concordant mylonitic carapaces fade out downward in the footwall plutonic rocks. Mylonitized Late Proterozoic dolomite and other metasedimentary rocks veneer the Badwater carapace (Curry, 1954) and the northeast flank of the Copper Canyon one (Otton, 1977; figs. 5.9, 5.10). This veneer represents a smear of rocks not otherwise present locally either above or below those turtlebacks, unless they form part of the Mormon Point lower plate (Otton, 1977). Mullions and mylonitic lineations trend dominantly northwestward along the turtlebacks. Although critical for interpretation of the turtlebacks, it is not clear from published descriptions whether the ductile-slip features of the steep southwest flanks of the turtlebacks correspond to those of the gentle northeast flanks—that is, whether or not the contrasted flanks had similar histories before late Quaternary time. Variable brittle brecciation occurs beneath the faults (fig. 5.10) and postdates the ductile deformation. Gouge zones along the faults vary greatly in thickness, as do friction breccias at the bases of the overriding plates. The slip direction of upper-plate rocks is shown by mylonitic lineations and other structures to have been northwestward during the ductile phase, oblique to the northerly trend of the range, relative to lower-plate rocks.

Upper-Plate Normal Faults

Normal faults break the rocks above the turtleback detachment faults but end at the detachments.

The Artist's Drive fault of the northern Black Mountains has an imposing west-facing scarp developed from upper Miocene volcanic and tuffaceous rocks (figs. 5.8*A*). The steep, young part of the scarp is as high as 500 m, and along much of its base is a late Holocene scarp, 5 to 10 m high, on which northwest-plunging mullions and slickensides indicate oblique slip. Erosion of the 500-m scarp from the fault dip of 50° or so to the present rugged angle-of-repose slope of 35° has occurred primarily by landsliding, and late Quaternary slide megabreccias form a hilly apron along the fault.

The abundance of similar megabreccias in Tertiary sections rotated to steep dips and truncated against detachment faults, throughout the Death Valley region as in many other parts of the Basin and Range province, is to me one of many indications that high normal-fault scarps were formed at the

Figure 5.8. Overlapping eastward views showing large range-front fault of northern Black Mountains truncated downward against Badwater turtleback detachment fault. *A*, Artist's Drive range-front fault (marked by arrows) is a major Quaternary structure with late Holocene slip. High-standing footwall is of upper Neogene volcanic and tuffaceous rocks. Hanging wall (low varicolored hills) includes both downdropped upper Neogene rocks and Quaternary slide megabreccias from the scarp. *B*, Artist's Drive fault (between left and center arrows; see part *A*) is truncated against detachment at center arrow. Turtleback surface is stripped dome in center of view. Erosion has caused retreat of the perched scarp (right arrow). As the extensional Artist's Drive fault has Holocene slip, at least the hanging wall of that fault has slipped on the detachment fault in Holocene time. Footwall of Artist's Drive fault is of strongly rotated upper Neogene strata, so it too has had much late Neogene slip on the detachment.

surface while major detachment faulting went on at greater depth.

The Artist's Drive fault, the steeply tilted rocks of its footwall, and the slide breccias of its hanging wall are all truncated sharply against the gently dipping Badwater turtleback fault (fig. 5.8*B*), as Curry (1954) recognized. The extensional Artist's Drive normal fault has had Holocene slip and affects only the upper plate of the detachment system, so the detachment fault beneath the hanging wall of the normal fault must also have had Holocene slip. The footwall Miocene rocks are rotated downward to a sharp truncation against the turtleback, so there must be much young slip beneath the footwall of the normal fault also, although that part of the detachment fault is not known to be presently active. The certainly active part of the gently dipping fault is that which dips westward into the widening Death Valley.

Along strike to the south, another major young normal fault in the upper plate is truncated southward and downward against the Copper Canyon turtleback. Here, the footwall of the normal fault comprises plutonic rocks, and the hanging wall, upper Neogene sedimentary and volcanic rocks rotated to moderate eastward dips; footwall and hanging-wall rocks and the intervening fault end against the smooth detachment fault (fig. 5.9). Drewes (1959, 1963) and Otton (1977) both mapped the abrupt truncation of the normal fault against the turtleback and recognized that hanging-wall slip shifted from the normal fault to the turtleback. The turtleback, with its mylonitic carapace and metasedimentary-mylonitic veneer, continues eastward beneath the footwall of the normal fault, and presumably that part of the detachment is now inactive.

Similar relations hold at the north side of the Mormon Point turtleback. A gently dipping, concave-upward fault bounds a block of Pliocene(?) and Quaternary strata, rotated to eastward dips, against the turtleback surface in the south, but against plutonic rocks structurally above the turtleback in the north.

The hanging-wall blocks north of the Mormon Point and Copper Canyon turtlebacks are themselves bounded against the alluvium of Death Valley by active normal faults (fig. 5.9). Latest Pleistocene and Holocene alluvial fan surfaces are broken by small normal faults close to the range front as defined by these upper-plate faults and by the turtlebacks themselves. These steep faults presumably are refracted upward through unconsolidated or poorly consolidated materials from faults that dip more gently at shallow depth. Analogous coseismic structures from the 1959 Hebgen Lake earthquake in Montana were described by Myers and Hamilton (1964).

The southwest side of each of the three turtlebacks is a stripped fault surface that dips markedly more steeply than the northeast side. The alluvial fill of Death Valley is being

Figure 5.8. Continued.

actively offset along these steeper faults, for scraps of alluvium cling to the faces high above the present alluvial surfaces. It is not yet clear whether the steep southwest flanks of the turtlebacks share the ductile-slip histories of the gentle northeast flanks or represent younger faults cutting older, gentler structures in some places and merging with them in others.

Continuity of Faulting in Black Mountains

The detachment faults of the central Black Mountains are exposed as a number of separate plunging domes, no contacts between which are known to be exposed, over a terrane about 15 km wide and having a proved extent, in a north-northwest direction, of 45 km; the southern Black Mountains terrane, if indeed consisting of subdetachment rocks as discussed above, adds 20 km more to the length. Are the detachment antiforms structural highs in a single fault surface that is continuous between them, or are at least some of the antiforms the tops of lenses which originated at various structural levels?

Lower-plate rocks consist of granite, migmatite, gneiss, and augen gneiss, so all these rocks may have been in the middle crust when extension began. The meager data available provide an inadequate basis for evaluating the possibility that there is a systematic variation in depth of exposure of these rocks beneath the detachment fault, or faults, in some direction. The presence of carapaces of mylonitic rocks on the turtlebacks in the northwest but of breccias on the domes in the Jubilee Pass area perhaps indicates that early slip on the former was at a greater depth than that on the latter, but the possible contrast has been too little studied for confident analysis.

The upper plate of the central Black Mountains, above the turtleback detachment faults, consists of plutonic rocks overlain directly by upper Miocene strata. Presumably the plutonic rocks were exposed at the surface by tectonic denudation after the Panamint Mountains block had passed across this region, and the lower plate of that structure was broken in turn by structurally lower faults.

Relation between Detachment Faults of the Black and Funeral Mountains

The thick section of upper Miocene and Pliocene sedimentary and volcanic rocks that on the west side of the Black Mountains is truncated downward against the turtleback detachment faults dips steeply to moderately northeastward off the northeast side of the range to a truncation against the inactive range-front fault of the southeastern Funeral Mountains. This frontal fault likely is limited to the upper plate of a detachment system. The axis of the gravity low that presumably marks the deepest part of the base of the Neogene strata lies only a few kilometers from the trace of the range-front fault (Chapman and others, 1977; Mabey, 1963). The shallowness of this gravity low precludes the presence of more than 1 or 2 km of the low-density strata, so the Neogene section projects downdip to a shallow truncation against gently dipping faults atop dense rocks. A northwest-trending gravity high in an area of upper Neogene strata of the northeastern Black Mountains, midway between the Badwater turtleback and the gravity low in front of the Funeral Mountains, may mark a hidden turtleback in the underlying detachment system.

Possibly Black Mountains and Funeral Mountains detachment faults may be continuous beneath the upper-plate strata that intervene at the surface, and the gravity low in this case should define the deepest part of the flexed fault. Alternatively, the frontal fault of the Funeral Mountains may break the Black Mountains detachment fault beneath the basin axis. The structure in any case represents but a minor late stage in the extension in this area, for, as discussed subsequently, the Panamint Mountains upper-plate block likely was torn from the Funeral Mountains and transported across the Black Mountains detachment system and rifted across Death Valley.

PANAMINT MOUNTAINS

The Panamint Mountains mostly comprise a great east-tilted block that is allochthonous above a major detachment fault, exposed around Hanaupah and Death Valley Canyons at the east foot of the range, which I here term the Hanaupah detachment fault. The upper-plate block is complicated by many normal faults rotated and deformed with the block. Most of these faults are relatively minor, with slips on the order of a kilometer or so each, but aggregate slip on the large faults of the structurally high Tucki detachment-fault system is probably several tens of kilometers. The imbricate Hanaupah and Tucki detachments both cut out thick crustal sections.

Hanaupah Detachment Fault

The Hanaupah detachment fault is exposed at the east base of the range and there dips about 15° westward. It was mapped and described by Hunt and Mabey (1966), who recognized it as an extensional structure although they referred to it as the "Amargosa thrust fault." The lower plate consists of augen gneiss in which mylonitization increases upward toward the detachment fault. The protolith is undated but presumably is either Middle Proterozoic or Jurassic. The K-Ar ages of biotite in two samples of gneiss are 11 and 14 m.y. (Stern and others, 1966). The gneiss is intruded by very abundant silicic and intermediate Tertiary dikes which, although undeformed, display much static argillic alteration. Dikes dip about 70° westward where I examined them north of Hanaupah Canyon, and they appear to have a similar steep westward dip in a photograph in Hunt and Mabey (1966, fig. 97), although they (p. 137) referred to the dikes in one locality as "nearly vertical."

Upper-plate rocks, as truncated against lower-plate mylonitic gneiss along the exposed part of the Hanaupah detachment fault, are east-dipping upper Miocene volcanic rocks intercalated with slide breccias, and, unconformably beneath them and dipping more steeply eastward, nonmetamorphosed Ordovician and older strata (Cemen and others, 1985; Hunt and Mabey, 1966). These Phanerozoic

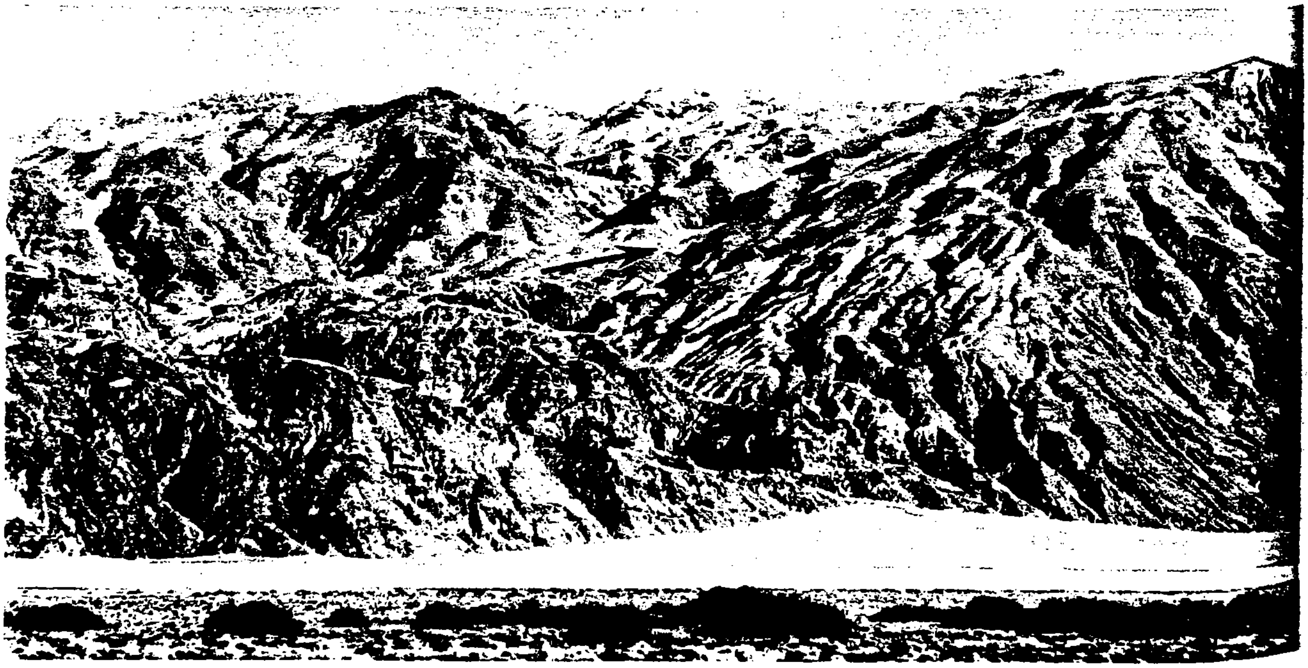


Figure 5.9. View east at upper-plate normal fault truncated downward against Copper Canyon turtleback detachment fault (smooth face right of arrow; has mylonitic veneer of light meta-carbonates). Active normal fault (along dots on left, arrow on right) has footwall (above) of plutonic rocks and hanging wall (below) of upper Neogene volcanic rocks. Fault is truncated against detachment fault at point of arrow. Neogene rocks are sliding down detachment fault and are rotated back into it. Detachment swings into steeper range-front fault on right; upper-plate Neogene rocks are broken by range-front fault on left.

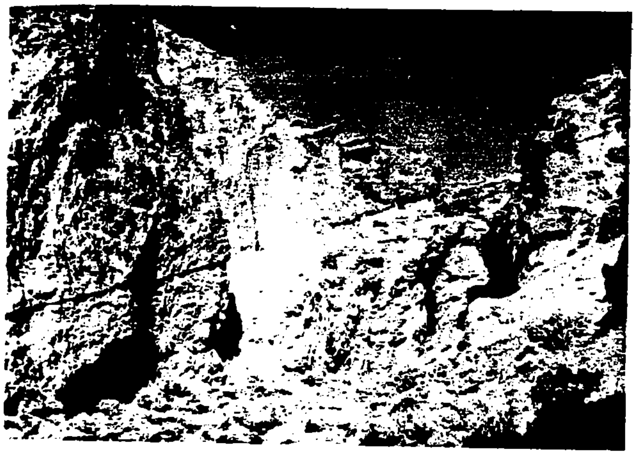


Figure 5.10. Mormon Point turtleback detachment fault as the range-front fault of the central Black Mountains. Fault dips 20° west (obliquely toward left front). Upper plate is of Quaternary fanglomerate, which dips gently back to truncation against fault. Lower-plate friction breccia of Late Proterozoic metadolomite is broken into phacoids whose long axes lie in strike direction.

rocks are the structural top of the main, east-tilted allochthonous Panamint block. Upper- and lower-plate rocks are brittly intersheared along the fault, and a thick breccia of upper-plate rocks lies atop part of it (Hunt and Mabey, 1966). The detachment fault is now inactive.

I infer that lower-plate mylonitization took place during early, ductile deep-seated slip on the detachment fault, in or before middle Miocene time, and that the lower plate was still at a temperature of perhaps 200 °C when the postmylonitization dikes were intruded into it after middle Miocene time. Late, brittle slip was at least largely younger than the dikes. Eastward tilting of the lower plate by about 20° after emplacement of the dikes likely is indicated by the present attitude of the dikes, so the lower plate is itself allochthonous above some deeper structure, and the detachment fault likely dipped about 35° westward when the dikes were intruded into the lower plate.

Tucki Detachment-Fault System

Detachment faults form a domiform complex, here referred to as the Tucki detachment-fault system, in the northern Panamint Mountains, recognized as of extensional origin by Hunt and Mabey (1966). These structures lie within the upper plate of the Hanaupah detachment fault. The lowest fault of the Tucki system defines a dome, outlined by a mylonitic carapace beneath the late brittle fault, which has flank dips of 15° to 30°, a broad crest, and a plunge of about 20° northward (figs. 5.11, 5.12; Hunt and Mabey, 1966; Wernicke and others, 1986; my observations). Although domiform, the fault cuts structurally downward westward in the lower plate, which consists of Late Proterozoic strata, metamorphosed to greenschist and amphibolite facies, and Mesozoic muscovite granite. The mylonitic carapace comprises rocks retrograded to lower greenschist facies and severely transposed parallel to the domiform fault that caps the carapace, is a few tens of meters to perhaps 100 m thick, and is developed discordantly across the higher grade rocks beneath (fig. 5.12*B–D*). Above the carapace and detachment fault is a zone of gouge and incoherent breccia 3 to 50 m thick (fig. 5.12*B*).

Upper-plate units mostly dip steeply to moderately eastward and are truncated against the detachment fault. Upper-plate rocks low on the west side of the dome are Pliocene fluvial strata, slide megabreccia, and basalt (Hall, 1971; J.E. Conrad and E.H. McKee, written communs., 1985; Hunt and Mabey, 1966; Larsen, 1979; Wernicke and others, 1986; my observations), faulted directly against the lower plate (fig. 5.12*E*).

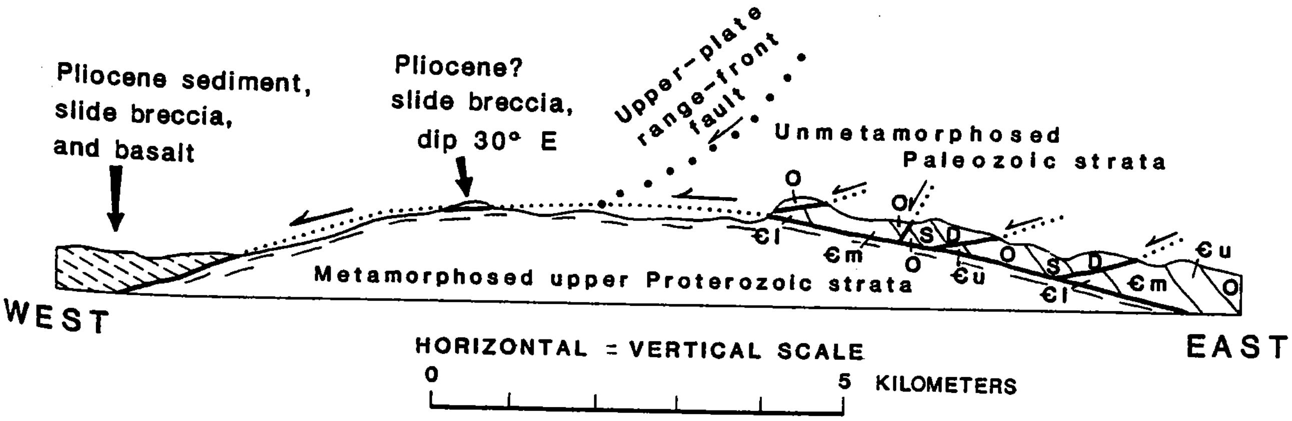
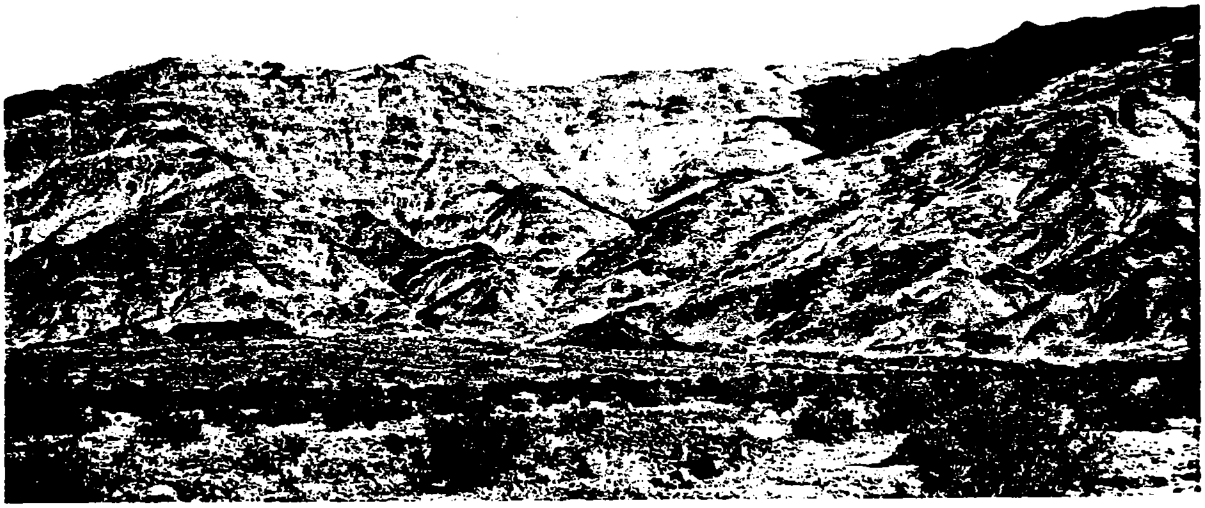


Figure 5.11. Section across Tucki Mountain domiform detachment fault, near north end of Panamint Mountains. Sense of slip of upper plate is westward on both flanks of the dome. Paleozoic strata: Єl, Єm, and Єu, Lower, Middle, and Upper Cambrian; O, Ordovician; S, Silurian; D, Devonian. Adapted from Hunt and Mabey (1966, fig. 86).

A



B

Figure 5.12. Domiform Tucki detachment fault at the north end of the Panamint Mountains. *A*, View south-southwestward across Death Valley to Panamint Mountains, from crest of northern Funeral Mountains. Valley floor lies below sea level; Telescope Peak (left skyline) rises to almost 3400 m. Entire Panamint block is allochthonous above the Hanaupah detachment fault, exposed along base of range on left. Broad dome of Tucki Mountain (right) is little-eroded lower plate of Tucki detachment fault. Crests of foreground ridges are little eroded beneath Funeral Mountains detachment fault; low hills projecting through fans beyond are of upper-plate middle Tertiary strata that mostly dip east toward detachment. *B*, View south to Mosaic Canyon and east flank of dome. Smooth slope on right, marked by lines, is stripped detachment surface; mylonitic carapace 50 m or so thick produces layers on top of lower plate of Late Proterozoic metasedimentary rocks. Upper plate (upper left) is of unmetamorphosed Paleozoic carbonate rocks. Sense of slip of upper plate was westward (upward and right). A zone of gouge and breccia (between lines left of mouth of canyon) separates plates. Top of lower plate swings along rangefront on right but upper plate has slid, or been eroded, away. *C*, Boudinaged and mylonitized Late Proterozoic metadolomite in retrograded carapace beneath Tucki detachment fault. Face is about 10 m high; top is about 20 m below the detachment fault; view eastward. Mosaic Canyon, near mouth. *D*, Metadolomite carapace at top of lower plate. Left skyline is the stripped detachment fault, from which has been eroded south-dipping Pliocene or Pleistocene fanglomerate. Microbrecciated metadolomite (above lines) has been transposed discordantly across variably disrupted metaclastic rocks; both are Late Proterozoic. View eastward, about 3 km west of Mosaic Canyon. *E*, West flank of dome. Smooth bedrock slope is stripped detachment, dipping gently west, on Late Proterozoic metasedimentary rocks and Mesozoic muscovite granite. Unconsolidated upper Pliocene or lower Pleistocene alluvium dips (lines) east to truncation against detachment. Emigrant Wash.

On the crest and east flank of the dome, two large normal faults (Trellis Canyon and Tucki Wash faults of Wernicke and others, 1986; fig. 5.2) and several lesser ones, each with top-to-the-west slip but now rotated to gentle dips to either west or east, form an imbricate array and merge with the basal fault (Hunt and Mabey, 1966; Wernicke and others, 1986). In the west part of this complex, where the aggregate slip on all of the faults is represented by the basal fault at Mosaic Canyon, nonmetamorphosed Cambrian strata are placed on metamorphosed Late Proterozoic lower-plate rocks (fig. 5.12*B*), and at least 10 km of crustal section is missing; but in the east, beyond the inflection away from the fault of the structurally higher imbricate faults, the basal fault (Harrisburg fault of Wernicke and others) merely places less metamorphosed Late Proterozoic strata on slightly older and more metamorphosed strata. Lower Cambrian formations lie 15 km farther west at the top of the imbricate stack than at the base. This distance is the minimum aggregate offset across the imbricate faults. The stratigraphically highest rocks in the east-dipping panels above the imbricate faults are present at the east foot of the northern Panamints, where strata of probable middle Miocene age overlie Devonian strata, both dipping steeply eastward, and are in hidden contact with steeply dipping unconsolidated boulder deposits presumed to be of late Pliocene or early Quaternary age (Wernicke and others, 1986; B.P. Wernicke, oral commun., 1987).

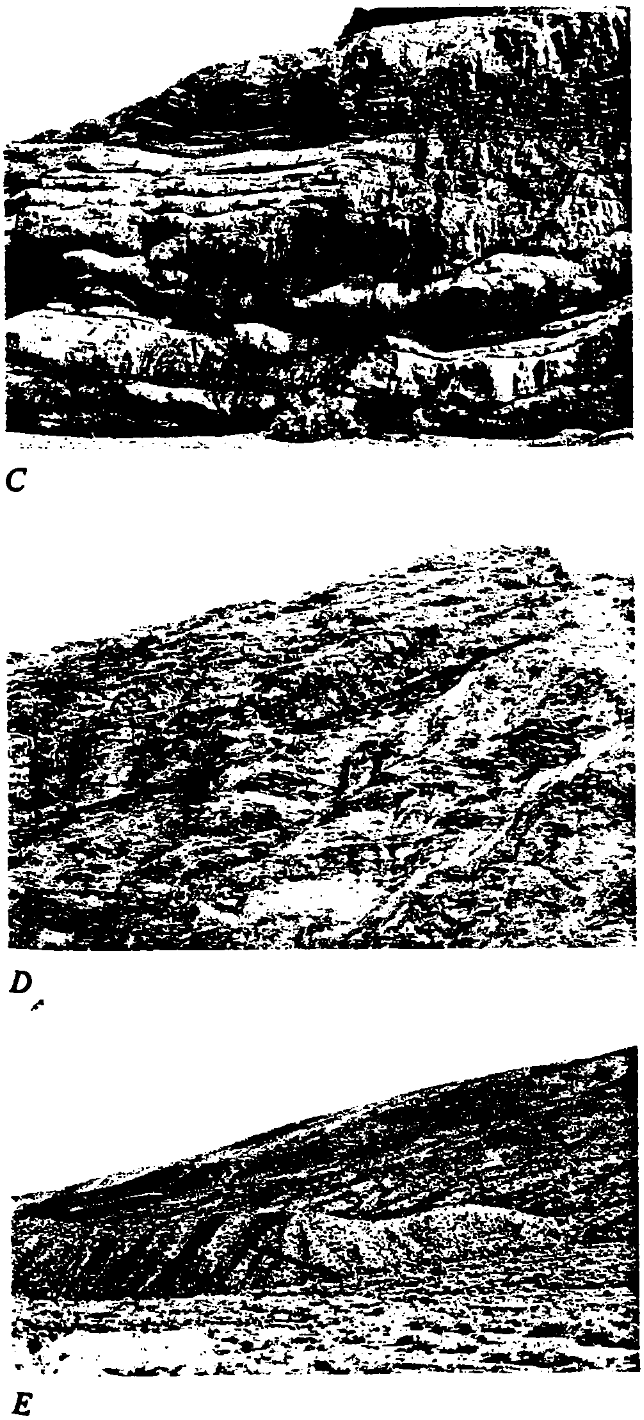


Figure 5.12. Continued.

A west-dipping range-front fault, which ended downward against the detachment, must have been eroded from above the Tucki dome (fig. 5.11). This fault separated pre-Tertiary upper-plate rocks, on the east, from Pliocene ones, on the west. The Cottonwood Mountains consist of Paleozoic rocks that presumably overrode the dome and were faulted away from east-flank rocks, which thus had a lesser slip relative to the dome than did the Cottonwood rocks, but a greater slip than did the Pliocene materials. An upper-plate fault at the north edge of the dome breaks relatively old Quaternary fanglomerate, and upper-plate materials may presently be sliding down the detachment fault into the deep Mesquite Flat basin to the north.

The Tucki detachment-fault system thus records a long period of slip that began when the lower plate was deep enough so that slip was ductile and synmetamorphic and that continued at least through Pliocene time as the lower plate was denuded tectonically and rose toward the surface. The Neogene upper-plate rocks did not exist when slip began, and the histories of various parts of the fault system were very different. The total amount of slip of pre-Tertiary upper-plate rocks across the lower plate increased westward, although the present tectonic cover low on the west flank is of Pliocene strata that may have slid only a few kilometers.

Central Panamint Mountains

The central and southern Panamint Mountains, as mapped and described by Albee and others (1981), Hunt and Mabey (1966), Labotka and Albee (in press), and Labotka and others (1980), consist of a great block, tilted to a general eastward dip of about 20° and eroded obliquely through a crustal section 10 or 12 km thick. This block is allochthonous above the Hanaupah detachment fault, which shares much of the eastward rotation of the block, but mostly lies structurally beneath the faults of the Tucki detachment system. The down-section progression of this huge block begins in the east with upper Miocene (Cemen and others, 1985) volcanic rocks and slide breccia, which dip less steeply eastward than do the underlying nonmetamorphosed Ordovician and Cambrian strata and hence may have been deposited after extension was underway. The crustal section continues westward and downward through increasingly metamorphosed Proterozoic rocks, bearing andalusite or tremolite at lower grades, and sillimanite or diopside in the deepest and highest temperature rocks. Shallow, crosscutting Miocene(?) granite is intruded above the middle of the crustal section, and semiconcordant Jurassic(?) muscovite granite occurs low in it; the amphibolite-facies metamorphism resulted from heat added by Jurassic granite and fluids (Labotka and Albee, in press). Normal faults, rotated with the block so that they now dip gently, break the east-dipping crustal section with small top-to-the-west slips that do not grossly disrupt the succession, and these faults presumably merge with the underlying detachment fault.

Offset on the relatively minor fault that bounds the east flank of the Tucki lower-plate dome decreases southward, as mapped by Wernicke and others (1986), and the fault apparently dies out within the little-broken main Panamint block near Wildrose Canyon and the north edge of the Telescope Peak quadrangle as mapped by Albee and others (1981).

The gently dipping west-flank fault of the Tucki complex, by contrast, continues southward as the boundary between the main Panamint block and east-tilted Pliocene or lower Pleistocene strata. As shown by Wernicke and others (1986, fig. 2) and as followed also by me, the trace of the fault swings around the Skidoo pluton of Hunt and Mabey (1966), trends southward beneath the fill of Harrisburg Flats, emerges at Emigrant Pass, and trends southwestward. I found the fault to continue southward across Wildrose Canyon near its mouth (fig. 5.13*A*); I infer that it trends thence generally south-southeastward in the northwest corner of the Telescope Peak quadrangle to become the fault mapped by Albee and others (1981), between Jail and Happy Canyons, that dips gently westward between a footwall of varied crystalline rocks and a hanging wall of spectacular eastdipping monolithologic slide breccia (fig. 5.13*B*, *C*). Labotka and others (1980) calculated that the source of the breccias lay about 3 km updip in the footwall, so the post-Pliocene slip on the fault has been small. The fault must have been a range-front structure when the breccia was deposited. Weakly cemented Quaternary gravels that lie unconformably on tilted Pliocene strata, near the fault trace around the mouth of Wildrose Canyon, are broken by normal faults with individual offsets of as much as several tens of meters, so slip likely is continuing on the gently dipping fault beneath, but probably not on the fault at its surface trace.

Hanging-wall breccias dip 15° to 20° eastward into the fault, which dips 20° to 30° westward (fig. 5.13*B*, *C*), but likely were deposited with dips of about 10° away from the fault. Hanging wall, fault, and footwall have apparently been rotated together about 30° eastward. The main tilting of the Panamint upper-plate block thus has taken place within late Pliocene and Quaternary time, presumably above a deep detachment fault. As the Hanaupah detachment fault and its lower plate, at the exposed east base of the Panamint block, have also been rotated about 20° eastward, some still-deeper detachment fault must be involved.

The unconsolidated slide breccias of the hanging wall of the main fault are being rapidly eroded away, leaving the stripped footwall exposed as a high scarp (fig. 5.13*C*). Many steep range fronts of large, tilted fault blocks in the Great Basin likely also have been stripped from rotated faults within the upper plates of detachment systems, rather than having been, as usually interpreted, eroded back from steep faults that directly bound adjacent alluviated basins.

The footwall where of granite has a thick mylonitic carapace (fig. 5.13*B*), and where of metasedimentary rocks has a veneer of ductile-deformation rocks (fig. 5.13*C*). Late slip on the fault, including the few kilometers of offset of Pliocene strata, took place near the surface; but I infer from the ductile structures that much greater slip took place earlier while the footwall was at middle-crust depths. The fault evolved with time from a deep detachment to a shallow range-front fault.

Klippen of east-dipping rocks, requiring large top-to-the-west offset above faults that now dip only very gently westward, cap ridges in the medial part of the main Panamint block north of upper Wildrose Canyon (Wernicke and others, 1986). Presumably these faults are analogous to those atop the Tucki dome farther north and record pre-range-front faulting on the detachment.

OPENING OF DEATH VALLEY

Death Valley is now being widened obliquely as the ranges to the west move relatively northwestward away from those to the east. The general eastern boundary of rapid extensional deformation in these latitudes lies within or at the east side of Death Valley. In the central sector, between the Panamint and Black Mountains, the boundary consists of the frontal faults along the Black Mountains. These faults, like the Black and Panamint Mountains and intervening central Death Valley, trend about 350°; but kinematic indicators along the Black Mountains front indicate the valley side to have moved obliquely northwestward away from the Black Mountains, not directly westward. In northern and southern Death Valley, by contrast, there are no active frontal faults, and the east limit of present major deformation is defined by active right-slip faults well out in the valleys—the Furnace Creek fault zone in the north, Death Valley fault zone in the south. These faults trend northwestward and end approximately at the north and south ends of the Black Mountains frontal-fault system. The northwest-trending strike-slip faults are thus transform faults to the extension recorded by the oblique slip on the north-trending Black Mountains frontal faults. Ranges to the west of Death Valley are moving northwestward relative to the region to the east.

Northern Death Valley

A gentle gravity gradient slopes southwestward from the trace of the detachment fault along the southwest side of the central Funeral Mountains (Chapman and others, 1971; Mabey, 1963), and I infer that the inactive detachment fault continues with gentle southwest dip, beneath an upper plate of deformed Neogene materials, for 8 to 10 km southwest from the fault trace. At that distance, where the likely depth to the detachment is 2 or 3 km, exposed late Neogene strata are broken by the active, northwest-trending, right-slip Furnace Creek fault (Hunt and Mabey, 1966; L.A. Wright and B.W. Troxel, unpublished map). Gravity gradients steepen slightly across that fault to define the east side of the Death Valley axial low east of Tucki Mountain; the gravity gradient that defines the west side of this low is more gentle. To the west of the northern Funeral Mountains and southern Grapevine Mountains, the gravity gradient across the strike-slip fault is steeper, and it continues into the deep Mesquite Flat gravity low north of Tucki Mountain. The gravity gradients may indicate that the bedrock floor of Death Valley deepens across the strike-slip fault, either by a step or steps or with average slopes steeper than those close to the Funeral Mountains; or they may indicate that the average age and density of Neogene materials above the basement decrease across the fault which marks the east limit of late Pliocene and Quaternary extension of Death Valley.

The southeast end of the Furnace Creek strike-slip fault, at least as a late Quaternary structure, is at the north end of the active, north-trending, oblique-slip Artist's Drive fault that defines the front of the northern Black Mountains. The strike-slip fault is a transform to oblique slip on the normal fault, and the 315° trend of the strike-slip fault is the direction of modern motion of the Cottonwood Mountains relative to the Funeral and Black Mountains. The Argus Range and Inyo Mountains are in turn moving northwestward relative to the Cottonwood Mountains, as discussed below.

The Furnace Creek strike-slip fault is commonly assumed to continue southeastward, past the Artist's Drive fault, to become the frontal fault of the Funeral Mountains, with which it is aligned; but the Funeral Mountains frontal fault has long been inactive (McAllister, 1970), and its late Pliocene motion had a large vertical component. Perhaps the two sectors shared Pliocene slip, but certainly only the sector within Death Valley is now active.

The Panamint and Cottonwood Mountains and Argus Range all trend about 350°, whereas the direction of their rapid late Neogene relative slip past and away from each other and the Black and Funeral Mountains is about 315°. The aggregate amount of extension in this direction increases both north-northwestward, as successive ranges move away from each other, and westward across it, as adjacent ranges are separated by strike-slip and oblique-slip faults. Such oblique motion cannot be explained in terms of the simple sliding of upper plates down the dip of normal faults inclined deep into the crust, a matter discussed later.

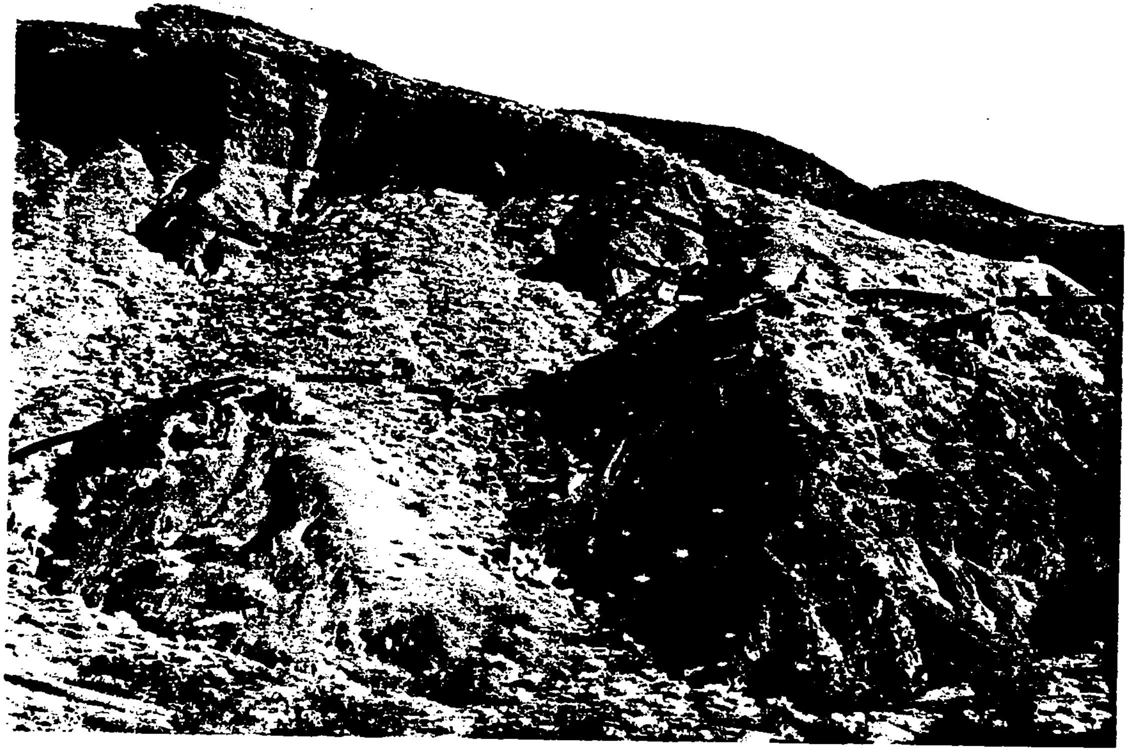
B.P. Wernicke (oral commun., 1987) told me that the Paleozoic and middle Miocene structural and stratigraphic assemblage of the northeasternmost Panamint Mountains is so similar to that of the southeasternmost Funeral Mountains that these blocks likely were adjacent and on north-south strike in middle Miocene time. The indicated 50 km of relative motion of the Panamint Mountains away from the Funeral Mountains, in the net direction of 305°, took place by some combination of sliding down the ramp fault equivalent to the west flanks of the Funeral Mountains and Black Mountains detachments, by motion of the Black Mountains away from the Funeral Mountains, and by the opening of Death Valley.

Central Death Valley

The active structures that at the surface bound central Death Valley, between the Panamint and Black Mountains, are the frontal faults of the Black Mountains (fig. 5.14). Those faults, like the valley itself and the flanking ranges, trend about 350°, but kinematic indicators show upper blocks to have moved obliquely northwestward on at least some of the faults.

That central Death Valley has opened by motion of the Panamint Mountains obliquely northwestward away from the Black Mountains is indicated also by the transform relation to the strike-slip Death Valley fault zone in the south. This active strike-slip fault, which offsets late Pleistocene materials, trends northwestward to end approximately at the southward projection of the Black Mountains frontal faults (Wright and Troxel, 1984).

Stewart (1983) argued, on the basis of isopachs and facies of miogeoclinal Late Proterozoic and lower Paleozoic strata, that the Panamint Mountains upper plate had moved 80 km relatively northwestward, above the Black Mountains on the Amargosa and turtleback detachment faults and across the full width of Death Valley on unspecified structures, from an initial position against the Resting Spring Range. The mylonitic and brecciated carapaces of Late Proterozoic rocks left on the Black Mountains detachment faults are remnants from the passage of the Panamint block, and the block of Late Proterozoic strata near Jubilee Pass in the Black Mountains is a fragment left behind. The Amargosa, turtleback, and Hanaupah detachment faults presumably are parts of the surface or surfaces upon which this 80 km of slip occurred. Great additional motion of the Resting Spring rocks away from the continental interior is required by other extensional structures farther east.



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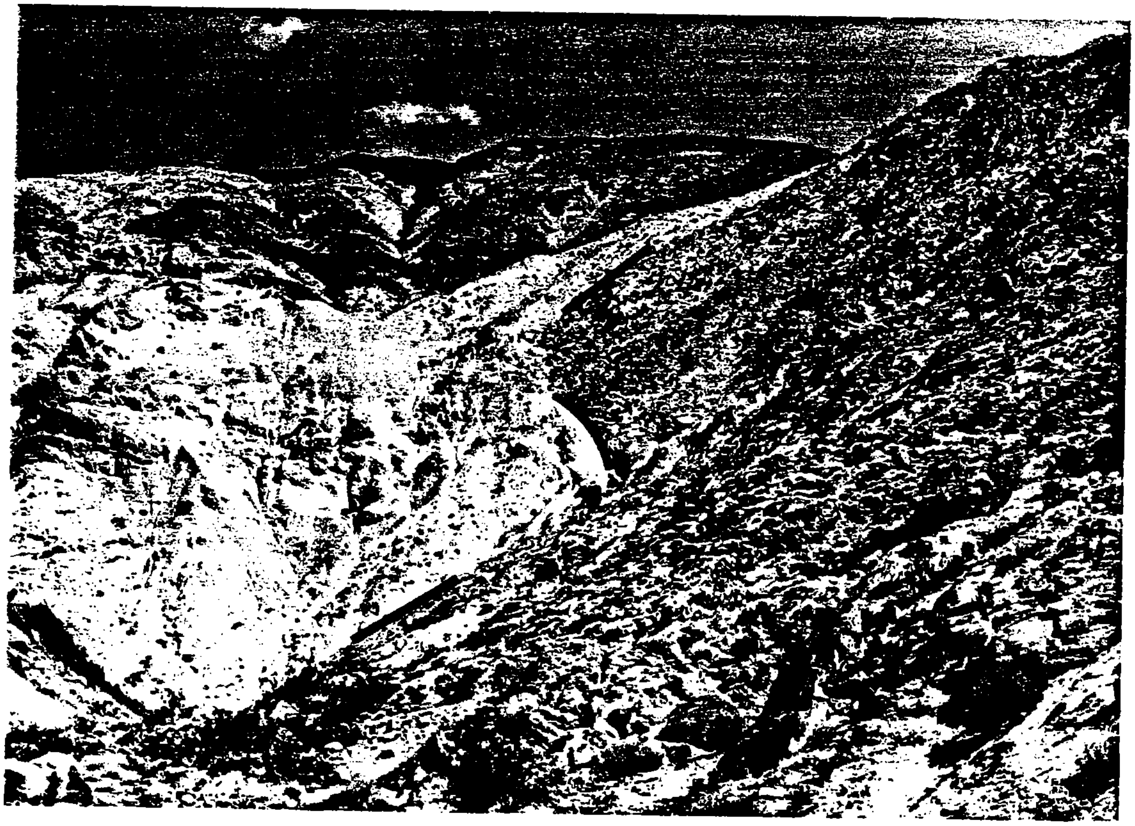

B

The Panamint Mountains have probably moved about 50 km west-northwestward relative to the upper plate of the southern Funeral Mountains, as noted previously; the upper plate of the Funeral Mountains had in turn moved relatively westward across the lower plate.

The physiography of central Death Valley indicates rapid eastward tilting (Hunt and Mabey, 1966). Along the turtlebacks sector, playa deposits and the evaporites of a latest Pleistocene lake lie in the east half of the valley, their surface as much as 85 m below sea level, and in places reach the basal scarps of the Black Mountains. These materials were tilted eastward as much as 6 m in late Holocene time, probably coseismically with the development of the young scarp along the Artist's Drive fault (Hunt and Mabey, 1966). The west half of this sector of the valley is formed of alluvial fans rising to an altitude of 400 m or so along the unbroken foot of the Panamint Mountains.

Gravity data indicate that low-density Neogene materials are probably nowhere deeper than 3 km beneath central Death Valley and that the structural axis lies about 40 percent of the way between the Black and Panamint Mountains (Hunt and Mabey, 1966; Mabey, 1963). The average

Figure 5.13. Tucki detachment fault on west side of Panamint Mountains. *A*, Detachment fault (dashed line) in lower Wildrose Canyon. Upper Pliocene or lower Pleistocene fanglomerate dips (black lines) southeastward into northwest-dipping fault. Lower plate consists of dark, metamorphosed Late Proterozoic Kingston Peak Formation, in which shearing parallel to the fault and alteration (lightening) can both be seen to increase upward toward the fault. Lower plate has thin carapace of mylonitized marble (light; best exposed across ridge right of center) about 2 m thick. *B*, Tucki detachment fault (marked by lines), a normal fault rotated to gentle dip. Stripped fault surface (smooth bedrock slope, right and foreground) concordantly tops mylonitized Mesozoic muscovite granite and dips 30° west. Light-colored Pliocene or Pleistocene landslide megabreccias of granite and metasedimentary rocks (skyline ridge, and nearby bluff on left) dip 20° east into fault. Fault had an early history of deep-seated motion, and a late history as a range-front fault with 3 km of slip; fault and breccias rotated 25° down to east. Jail Canyon. *C*, Rotated normal fault being exhumed as an apparent range-front fault. Stripped fault surface forms smooth bedrock face in upper slopes left of canyon, and crests of steep ridges right of canyon. Nonresistant slide megabreccias of the hanging wall form frontal hills and dip moderately back to truncation against fault but have been eroded from higher levels. View east at Hall Canyon.

the west-central Panamint Mountains before Pliocene extension rather than adjacent to them; of course, the Panamint block itself moved a long distance, above other detachment faults, relative to assemblages farther east.

The Argus Range thus is part of the upper plate that slid above the detachment fault now exposed along the west side of the Panamint Mountains.

Panamint Valley is marked by a broad, shallow gravity low of such low relief and gentle flank gradients that low-density materials probably extend no deeper than 1 km within it and cannot be bounded by high, steep bedrock contacts (Jones and others, 1987; Mabey, 1963). A well in central northern Panamint Valley penetrated 115 m of unconsolidated clastic sediments and bottomed in Paleozoic limestone, without intervening basalt (Smith and Pratt, 1957). Magnetic anomalies preclude the presence of Neogene basalt beneath most of the valley (Jones and others, 1987). The shallow, subhorizontal bedrock floor of Panamint Valley may consist largely of rocks that were beneath detachment faults in early Pliocene time, rather than being the trailing parts of plates above such detachment faults.

Extension is continuing at least along the west base of the central Panamint Mountains, where Pleistocene alluvial fans are offset as much as 200 m vertically on normal faults marked by little-eroded scarps (Albee and others, 1981). The surface of central Panamint Valley is tilted eastward, and a large playa lies close to the Panamint front; a 300-m-deep well in the playa penetrated only evaporites and unconsolidated clastic sediments (Smith and Pratt, 1957). Slight eastward tilting of a Panamint Valley bedrock panel pulled away from relatively minor range-front faults may be indicated, but major steep normal faults are precluded by the gravity data. The active faults lie only 2 to 4 km west of the trace of the western Panamint detachment fault; if the steep faults end downward at the detachment, then the subsurface part of that gently dipping structure is still active. Although dating of progressive deformation within short time intervals is much needed, it appears likely that the opening of Panamint Valley took place largely during Pliocene time, and that Quaternary extension has been of much lesser amount.

EXTENSION WEST OF PANAMINT VALLEY

West of the area shown in figure 5.2, a mountainous tract 50 km or so wide has undergone considerable internal fragmentation by normal faults, but only local tilting, and is bounded in turn by through-going Owens Valley, beyond which is the great raised and slightly tilted block of the Sierra Nevada. The extension within this region almost wholly postdates basalt of early Pliocene age (Duffield and others, 1980; Elliott and others, 1984; Larsen, 1979; Novak and Bacon, 1986; Schweig, 1985). The separation of the Sierra Nevada from ranges to the east and most of its rise to present high altitudes was of late Neogene age (references in Jones, 1987). Structures are seen at high crustal levels, and I know of no detachment faults exposed within this western region. Oblique- and strike-slip faults and the rotation directions of domino-block complexes indicate the general direction of extension to be northwestward relative to the Death Valley region.

EXTENSION SOUTH OF THE DEATH VALLEY REGION

The Death Valley-Panamint Valley-Owens Valley region of severe late Miocene through Quaternary extension is bounded on the south by the active left-lateral Garlock fault. South of the Garlock fault is the Mojave Desert, at least the eastern part of which was much extended within Oligocene through middle Miocene time; younger activity has been dominated by right slip on northwest-trending faults. The Garlock fault serves as a transform fault by which the northern region, Death Valley to Owens Valley, of active extension is bounded against the southern Mojave region of little young extension (Davis and Burchfiel, 1973; Hamilton and Myers, 1966). From its origin south of the Black Mountains, the Garlock fault trends westward across the south end of the Panamint Mountains, then curves west-southwestward and southwestward to become the south terminus of the Sierra Nevada. Slip on the fault increases from zero at its origin through a well-constrained 60 km in its middle sector; if the Pelona Schist of the southernmost Sierra Nevada and the Rand Schist of the northwest Mojave Desert are offset parts of an early Paleogene regional anticline, as I infer them to be, then slip in the west is about 100 km. The westward-increasing offset on the Garlock fault is equal to about half the width of the sectors to the north as measured from the fault origin, so the northern region has been doubled in width within late Miocene through Quaternary time. The Panamint Mountains, Black Mountains, and palinspastically adjacent Mojave Desert all underwent middle Tertiary extension also, and in that sector the 100 percent extension applies only to the subsequent deformation.

Late Neogene extension to the north of the Garlock fault has been in a generally northwestward direction relative to the continental interior, and northwest-trending right-slip faults cross the Mojave Desert. The Garlock fault has rotated clockwise, as though about a pivot at its east end, relative to the continental interior, as slip on it progressed; the initial fault had a much more northerly trend than does the modern one.

EXTENSION EAST OF THE DEATH VALLEY REGION

The southeastern Great Basin, a terrane 240 km wide between the area shown in figure 5.2 and the west margin of the little-faulted Colorado Plateau, was extended severely during late Oligocene and early and middle Miocene time.

Prior to extension, this region was part of the Sevier belt of eastward-imbricated thrust sheets of pre-Tertiary strata. Tertiary strata deposited early in the extensional history of a given sector tend to be broadly concordant to underlying pre-Tertiary strata, and the old rocks as well as the early syntectonic Tertiary strata mostly now dip moderately to steeply eastward. This generally eastward tilting of upper-plate blocks, including those in the Death Valley region, indicates that the extensional faults by which they were dismembered mostly had initial westward dips. Local rotation of upper plates to eastward dips can result from slip above downward-flattening west-dipping faults, whereas regional tilting is most easily explained as due to rotation toward the horizontal of a more planar west-dipping fault together with its upper- and lower-plate complexes (Wernicke, 1985).

Extension in the northeastern part of the southeastern Great Basin, north and east of the latitude and longitude of Las Vegas, took place mostly during middle Miocene time (Bohannon, 1983). Large imbricate normal faults have been rotated to gentle dips, and one in the Mormon Mountains has been deformed into a broad dome; only shallow crustal levels are exposed beneath the faults, and lower plates consist of nonmetamorphosed Paleozoic strata (Wernicke and others, 1984, 1985).

In the southeastern part of the southeastern Great Basin, south and east of the latitude and longitude of Las Vegas, a tract, 100 km wide, of Middle Proterozoic plutonic rocks was denuded tectonically by the slipping westward away from the Colorado Plateau of the Spring Mountains (Wernicke and others, 1982, 1984). Middle Miocene volcanic rocks were deposited directly on denuded Proterozoic rocks and themselves subjected to severe extension above detachment faults now widely exposed (Anderson, 1971; Weber and Smith, 1987)—perhaps half of the 100 km of relative transport of the Spring Mountains occurred during the middle Miocene, and half before. The western part of the lower-plate Proterozoic basement rocks southeast of the Spring Mountains formed at a depth of only about 10 km (Young and others, 1986), so a single west-dipping protofault cannot be invoked to explain the slip of the Spring Mountains; the detachment faults must represent a number of different rotated imbricate normal faults or a number of midcrust lenses, or both.

The Spring Mountains block, 90 km wide along the southwest side of the Las Vegas Valley shear zone but only about 50 km wide perpendicular to that, has remained almost intact, neither tilted nor fragmented, since Sevier belt thrusting (Burchfiel and others, 1974). The facies and thicknesses of upper-plate Paleozoic and Late Proterozoic strata, and the specific imbrications of those by Sevier belt thrust faults, require that the assemblages now strewn across the Nopah, Resting Spring, Funeral, Grapevine, Panamint, and Cottonwood Mountains were closed up against the southwestern Spring Mountains, in part even resting obliquely upon one another, before separation by imbricate extensional faults (Stewart, 1983; B.P. Wernicke, oral commun., 1987). Of the present cross-strike width, 130 km, of these upper-plate complexes, almost 100 km represents Cenozoic extension. As the Spring Mountains in turn moved about 100 km relatively away from the Colorado Plateau, about 200 km of the present distance of 300 km of the Cottonwood Mountains from the plateau must represent extension.

In the Nevada Test Site in the northwestern part of the southeastern Great Basin, voluminous middle Miocene ignimbrites and caldera complexes were erupted during ongoing extension (Byers and others, 1976; Christiansen and others, 1977). Successively younger middle Miocene units are successively less deformed, but even the oldest of them display only modest extension; dips are mostly gentle, and no large detachment faults are proved to break surface rocks east of Bare Mountain. The middle Miocene ignimbrites bury severely extended older terrane on the north. Thus, just north of the Nevada Test Site, upper Oligocene rocks are tilted with underlying Paleozoic strata to steep dips above normal faults rotated to gentle dips; lower Miocene rocks are less deformed, and middle Miocene ones still less; and upper Miocene rocks are little deformed (Ekren and others, 1971). The much-extended region (Wernicke and others, 1984) between the Nevada Test Site and the eastern terrane of middle Miocene extension likely was also deformed primarily during late Oligocene and early Miocene time, for although rocks of such ages are all but missing in this area, widespread deformation of this age is proved both to the north in Nevada and to the south in California.

The northwest-trending right-slip Las Vegas Valley shear zone is a transform complex of strike-slip faults and oroclines developed between terranes of different extensional patterns (Wernicke and others, 1982, 1984). To the north of the zone, from the Nevada Test Site to the Colorado Plateau, extension was distributed relatively evenly between many allochthonous blocks. To the south, by contrast, the large Spring Mountains block was little extended internally but moved 100 km westward away from the Colorado Plateau. Aggregate right-slip faulting and oroflexing across the shear zone is zero in the eastern Lake Mead area, increases to a maximum of about 60 km at the eastern Spring Mountains, and decreases northwestward to perhaps 30 km at the northwestern Spring Mountains. The latter slip fully affects rocks that may be as old as Oligocene (see Hinrichs, 1968), but it largely predated 13.5 m.y. ago, for ashflows of that age at Yucca Mountain are oroflexed only about 5 km (Scott and Rosenbaum, 1986).

DISCUSSION

The southern Great Basin is now 350 km wide—and at least 200 km of this represents crustal extension during middle and late Cenozoic time. Oligocene and early Miocene extension affected a broad medial region; middle Miocene extension affected this same region and also an additional region to the east; late Miocene extension affected primarily the far western part of the previously deformed terrane; Pliocene and Quaternary extension has affected in turn the western part of that sector plus a broad area of new deformation to the west of that. The average rate of extension has been about 7 km per million years, or 7 mm per year. Extension was concentrated within less than half the width of the widening province at any one time, and strain within a broad tract of active extension likely was on the order of 10 or 20 percent per million years.

Evidence for this amount of extension comes from many criteria. Matching of offset assemblages, and the constraints of transform faults, were emphasized in the preceding descriptions. Half the width of upper-plate rocks now lying against detachment faults consists of basin-fill materials that did not exist when extension began, and this by itself requires 100 percent extension. Palinspastic reconstructions of Mesozoic components in the cordillera make sense to me only in terms of Cenozoic extension on the order of 100 percent (Hamilton, 1978; Hamilton and Myers, 1966).

This extreme extension has been accommodated on structures of different types at different levels in the crust. The brittle structures of the upper crust—normal faults and rotated blocks—are seen to end downward against detachment faults that now have undulating surfaces, and many of these faults are seen to have originated as ductile faults in the middle crust. Rocks which formed the brittle upper crust before this extension began are now stranded as allochthonous, rotated blocks atop undulating detachment faults. Between these upper-plate blocks are rotated middle and upper Cenozoic sedimentary and volcanic rocks, within which tilting commonly decreases stratigraphically upward—deposition and extension were concurrent. Upper-plate rocks have mostly been rotated to eastward dips, so the faults that dismembered them mostly had initial westward dips; those faults have been rotated with the blocks and now dip gently.

The conventional assumption that basin-range structure is dominated by tilted bedrock panels, the high part of each forming a mountain range and the low part lying beneath a basin, in contact with one another at range-front faults, is largely invalid for the southern Great Basin. It is invalid also for the Mojave Desert, southeastern California, and southern Arizona, although it may be applicable to restricted parts of the northern Great Basin. Such deformation is uncommon at the large scale of ranges and basins. Ranges instead are mostly allochthonous perched blocks or exposures of subdetachment complexes. Also invalid are any models which require that major faulting related to now-domiform detachment faults represented sliding down the flanks of such domes; late, shallow deformation may indeed have such an origin, but major slip on the structures is independent of direction of present dip of the exposed surfaces. Above all the detachment-fault domes of the Death Valley region, upper-plate strata display a general regional rotation to eastward dips, and hence a consistent slip relatively westward across what are now oppositely dipping flanks of the domes. The domes did not extrude upward, shrugging slide masses off their flanks, as some geologists have postulated.

Rocks beneath the detachment faults of the Death Valley region were at midcrustal depths before extension began and rose to the surface as tectonic denudation removed overlying materials. Early deformation on the deeper parts of the lower plates was ductile, but late slip was at low temperature. Twenty kilometers of crustal section is missing across much of the Funeral Mountains-Bullfrog Hills detachment fault, and likely as much across the Hanaupah fault, where the upper plates are of Tertiary rocks, although those Tertiary rocks have slid far less on the faults than did bedrock upper plates. Favorably oriented detachments remain active even at the surface where upper plates are sliding into presently widening basins.

Many detachment faults studied elsewhere in the Basin and Range province have similarly evolved from zones of ductile slip, initially 10 to 25 km deep, through progressively less ductile regimes, to final zones of shallow, low-temperature, brittle slip (Anderson, in press; Davis and Lister, in press; Davis and others, 1986). Many of the faults show a temporal progression from early mylonite through coherent microbreccia to late gouge, which corresponds to a decrease in temperature of deformation from above 300 °C for quartzose mylonites (Sibson, 1983) to near-surface temperatures for the final gouge. Where early ductile deformation resulted in formation of mylonitic gneiss, temperatures were above 500 °C (Anderson, in press; Sibson, 1983), and this may have been the case beneath the turtleback detachment faults of the Black Mountains and the Hanaupah detachment fault of the Panamint Mountains. As extension progressed to 100 percent at strain rates such as the 10 or 20 percent per million years noted above for the southern Great Basin, the isotherms limiting ductile behavior would have risen to depths on the order of 60 percent of their initial depths (England and Jackson, 1987), so the shallow limit of ductile deformation rose as tectonic denudation progressed but lagged behind the uplift of the faults. Although the discrimination between mylonites that represent early detachment slip and mylonites that are old structures reused by young shear systems is often ambiguous, there are a number of cases now known in which middle Tertiary granite, little older than the detachment faults that cut them, display severe mylonitization and even mylonitic gneissification. Rises of lower plates by 10 to 20 km in times as short as a few million years, hence local extension rates that may exceed 1 cm/yr, seem indicated (Davis and Lister, in press).

Some detachment faults elsewhere in the Basin and Range province have upper-crustal rocks in their footwalls as well as their hanging walls and can be demonstrated to have cut downward through the upper crust with initial moderate to gentle dips and to have been rotated to still gentler dips or to subhorizontal or domiform configurations. Such a fault was tracked, in excellent seismic-reflection records in west-central Utah, from near-headwall outcrop to a depth of about 12 km by Allmendinger and others (1983). Wernicke and others (1984, 1985) demonstrated such upper-crustal detachment faulting by geologic mapping in the southeastern Great Basin.

Wernicke (1985) argued that exposed detachment faults are raised parts of great normal faults that originated as ramps cutting gently through the entire lithosphere. He reasoned that imbricate upper-plate normal faults sole downward into such master faults, which are flattened and raised toward the surface by isostatic response to tectonic denudation. The west-northwestward increase in probable depth of metamorphism in the Bullfrog Hills-Bare Mountain-Funeral Mountains lower-plate complex accords with the inference that it was raised from beneath a continuous inclined surface. That same detachment system appears to record a cessation of slip progressing westward with time, and the corresponding progressive stranding of allochthonous blocks at shallow levels; this can be explained as due to the westward progression of the hinge between risen, inactivated sectors of the master fault from still-dipping, active sectors.

Davis and others (1986) applied the Wernicke model to a middle Tertiary detachment fault in southeastern California and another in southeastern Arizona and showed that slip on ductile, semiductile, and brittle components of the now-undulating detachment systems was all in the same downdip sense, in terms of the model. Howard and John (1987) applied the model to detachment faults exposed in the lower Colorado River region, where the structures cut deeply into middle-crust rocks and where the indicated master faults dip toward and beneath the Colorado Plateau, not away from it as in the southern Great Basin. Howard and John demonstrated that the detachment faults obliquely truncated thick crustal sections, in both upper and lower plates, in the sense required by the model; they also showed that major anastomosing or imbricate faults had originated in the middle crust, not just a single master fault.

Much of the deformation observed in the Death Valley region and elsewherein the Basin and Range province is accounted for by the Wernicke model. The complications must be added that different master faults have operated sequentially or simultaneously within each region, that lower plates are themselves broken by new master faults, and that the faults anastomose at depth. Further, the dating of termination of slip on different sectors of a single master fault indicates that the uplift of a lower plate occurs progressively, and that a migrating hinge separates dipping sectors on which slip continues from flattened or undulating sectors on which it has ended. Allochthonous blocks thus become stranded at progressively later times as that hinge migrates beneath them. The aggregate slip of any one allochthon is a function of the duration of its slippage. Stranding occurred about 11 m.y. ago at Bare Mountain, 7 m.y. ago in the Bullfrog Hills and northeastern Funeral Mountains, 4 m.y. ago in the southwestern Funeral Mountains and eastern Black Mountains, and 2 m.y. ago in the medial Black Mountains; it has yet to occur in and west of Death Valley.

Wernicke visualized the plates above master ramp faults as greatly disrupted by distributed extension but the plates below them as unbroken. Much extension is in fact required within the lower plates. The many gently dipping normal faults within Bare Mountain, for example, indicate much extension there. Major ductile or semiductile faults within the lower plates have not yet been proved within the Death Valley region but have been identified beneath ductile detachment faults elsewhere in the Basin and Range province (Hamilton, 1987; Howard and John, 1987).

Further, the behavior of the deep crust, although still poorly understood, is unlikely to be that of the Wernicke model. Although Wernicke proposed that the inclined master faults cut completely through the lithosphere, continuity through the deep crust and upper mantle is improbable. Heat flow in much of the Great Basin requires temperatures at the base of the crust near those of granite melts; distinct faults could not be maintained under such conditions. A transition at some depth between structures dominated by unidirectional slip above and by ductile flattening below is to be expected on rock-mechanic grounds (England and Jackson, 1987). Such flattening should occur in discrete zones at relatively shallow depths but be more pervasive at greater depths (Kirby and Kronenberg, 1987). The upper mantle, by contrast, should display much less ductile behavior because of the much greater strength of olivine-rich rocks than of quartzo-feldspathic rocks. Extension within lower plates in the southern part of the Basin and Range province, when they were still at high temperatures and considerable depths, produced thick zones of mylonitic gneiss, not merely ductile faults (Davis and Lister, in press). Basal-crustal reflectors, as tracked continuously across much of Nevada in reflection profiles, are unbroken by steps such as predicted by Wernicke (Klemperer and others, 1986). That deep reflection discontinuity is a zone, some kilometers thick, of intercalated rocks of sharply contrasted acoustic properties; rebuilding of attenuated lower crust by sheets of gabbro melted in the mantle can be inferred.

Many seismic-reflection profiles in southeastern California and southern Arizona show the crust beneath undulating detachment faults to display large lenses of acoustically transparent rock between anastomosing zones of gently dipping reflectors that presumably record layering due to transposition by ductile flow (Hamilton, 1982, 1987; Morris and others, 1986; Okaya and Frost, 1986a, b; Okaya and others, 1986). More pervasive, subhorizontal reflection fabrics appear to typify the deeper crust. The lenses characterize what is now the upper part of the subdetachment crust, but as the rocks exposed beneath such detachment faults mostly originated in the middle crust, the lenses are developed in what was middle crust before extension. Profiles in the northern Great Basin similarly show a lower crust characterized by subhorizontal reflectors, and a middle crust that appears to display discontinuous, gently dipping zones of reflectors (Allmendinger and others, 1987; Potter and others, 1987).

I deduced from the presence of such lenses and from the geometry I perceived in the midcrust rocks exposed beneath detachment faults in southeastern California and southwestern Arizona a model of extensional deformation dominated by the spreading apart of lenses between zones of ductile shear, rather like the gravitational spreading of a pile of wet fish (Hamilton, 1982, 1987). This model resembles in important aspects that of G.H. Davis (1980), but not of his later work (1983). I viewed most detachment faults as the tops of great lenses that are separated by gently dipping,anastomosing ductile faults and that retain prefaulting fabrics in their interiors. As the lenses slide apart along ductile faults, the area of the composite top of the lenses—the detachment faults—increases. Shallow, brittle materials rotate in collapsing blocks as their substrate is widened, and in part are torn apart and in part are carried passively along on the lenses. Domiform and undulating fault shapes represent primarily deformation due to interactions between moving lenses.

I now see that (as colleagues tried to tell me) rotated great normal faults are much more important than accounted for by my model as just described. Wernicke's (1985) model accounts far better than mine for much of the deformation observed in the field—but his model, beyond its problems with deep-crustal mechanics, also leaves important deformation unexplained, and so cannot yet be complete.

High among the problems is the obliquity of extension in the southwestern Great Basin. Although Death Valley and Panamint Valley and their flanking ranges trend northward or north-northwestward, the relative direction of slip of western ranges away from eastern is northwestward, not westward. The east boundary of major active extension consists of the northwest-trending, right-slip Furnace Creek and Death Valley fault zones and an intervening north-trending oblique-slip fault along the Black Mountains. B.P. Wernicke (oral commun., 1987) suggested that the northwestward motion might be due to a push of upper plates from the south by an impinging Mojave plate. Although the northwestward shift of the massive Sierra Nevada can be visualized in these terms, they would also require that, improbably, the push be transmitted 300 km northward along the narrow, unshortened block of the Coso, Inyo, and White Mountains, which is moving northwestward with regard to terranes to the east.

The boundary between the North American and Pacific plates is the northwest-trending, right-slip San Andreas fault system. This plate boundary ends at the northern California triple junction with the north-trending Oregon trench and west-trending Mendocino transform fault. The triple junction is migrating northward, relative to the continental interior, at the slip rate of the San Andreas system, yet it is positioned in a zone of sharp change in the trend of the continental margin. Perhaps this is a coincidence, and the margin of North America south of the present triple junction happened to lie parallel to the direction of relative motion of the Pacific plate. It appears to me more likely, considering the patterns of crustal extension within the Western United States, that the shape of the continent is changing as needed to maintain contact with the Pacific plate south of the migrating triple junction. Among the elements of this change might be northwestward drag of components as far east as the Sierra Nevada, and oblique flattening of the deep crust in the Great Basin. Such flattening could be in a separating-lens mode in the middle crust and a more pervasive mode in the lower crust. The oblique extension underway at the surface in the Death Valley region may be a relatively passive response to the progressively more pervasive flattening beneath it.

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