Chapter Two

Shaping of the Present Landscape:

Extensional Tectonics and the "Basin and Range Event"

View northward along the Black Mountain front. Dark green rock in the foreground is the footwall of the Copper Canyon Turtleback.

First-time visitors to Death Valley National Park invariably and correctly sense that these mountains and valleys have formed quite recently in geologic time. Beginning about 16 million years ago, this part of Earth's crust was broken into a gigantic mosaic of mountain blocks, each bounded by major faults. Today's youthful appearance of the Death Valley landscape suggests that slip on these faults is still happening. Specific features of the Black Mountains rangefront that indicate its youthfulness are discussed in Chapter 1.

Cenozoic sedimentary and volcanic rocks deposited during the development of the present landscape provide a detailed record of extension in Death Valley. Many of these deposits are preserved within the intervening sedimentary basins, but some are exposed within the ranges (Fig. 3A). Among other things, these deposits tell us that Death Valley itself formed during the latest period of crustal extension. They also indicate that a precurser to Death Valley, called the Furnace Creek Basin, dominated the landscape from about 16 million years to about 4 million years ago.

The Faults

In the faults that bound the ranges and basins of the Death Valley region (Fig. 3A) as in the rest of the Basin and Range province, we find visible evidence of an extending crust. The faults are the principal ruptures along which the brittle, upper part of the crust has broken as the great block of the Sierra Nevada moved westward away from the west side of the Colorado Plateau. The land between the two has been literally pulled apart. The study of fault patterns generated in this way belongs to a branch of geology called extensional tectonics.

Classification

The faults that presently define the ranges and valleys of Death Valley National Park are broadly divisible into three kinds: strike-slip, high-angle normal and low-angle normal (see *Basics about faults*, p. viii–ix). Most of the ranges also contain older thrust faults that formed during a much earlier period of crustal compression. The strike-slip faults, along which movement has been dominantly parallel with the strike of the fault planes, are identified by arrows on Figure 3A that show sense of lateral movement. Note that most of these faults strike northwestward and that their southwest sides have moved relatively northwestward, producing a "right-lateral" sense of slip. Movement on the faults identified as normal has been mainly down-dip. The normal faults, by virtue of their geometries, are the simplest expressions of crustal extension; the lower the angle, the greater the opportunity for large-scale extension.

Most geologists in the Death Valley region view the major range-bounding faults as terminating at depth against nearly horizontal "detachment zones."

KH ALL RIGHTS RESERVED

In this way, deformation above the fault occurs independently of deformation below the fault. Some researchers place the principal detachment surface beneath much of the Death Valley region at mid-crustal levels (Serpa et al. 1988); others favor a much shallower depth (Wernicke et al. 1988).

High-angle normal faults. As described in the introduction and first chapter, much of the present-day topography of Death Valley is the result of slip on normal, or oblique-normal faults that dip westward at angles of 40º or more (Fig. 2). As these faults slip, they cause the adjacent rocks to rotate down towards the east. This combination of fault slip and rotation produces mountain ranges with steep, fault-bounded western margins and relatively gentle eastern sides. The west face of the Black Mountains stands out as one of the world's most spectacular examples of this type of fault-generated topography. The western margins of the Panamint and Cottonwood Mountains also provide outstanding examples of fault-bounded mountain fronts.

Low-angle normal faults. Much of the extension in Death Valley has been controlled by slip along low-angle normal faults. These faults are frequently called "detachment faults" because they allow their upper plates to deform independently of their lower plates. Some of the better-known and accessible detachment faults are the Boundary Canyon fault in the northern Funeral Mountains, the Turtleback faults and the Amargosa fault in the Black Mountains, and the Mosaic Canyon fault in the northern Panamint Mountains. The Turtleback faults are described in detail on page 5–7.

The Boundary Canyon fault is one of the most conspicuous of Death Valley's low-angle normal faults (Photo 17). It dips gently northwestward from the northern Funeral Mountains to beneath the highly folded and faulted formations of the Pahrump Group, the Johnnie Formation and the lower part of the Stirling Quartzite (Table 1). The upper plate contains the upper part of the Stirling Quartzite and all of the overlying formations through those of Mississippian age (Wright and Troxel 1993).

The Boundary Canyon fault is of special interest in that the rock units of the lower plate have been metamorphosed at temperatures and pressures that characterize mid-crustal levels, whereas the rocks of the upper plate remain essentially unmetamorphosed. The components of such a geologic setting are commonly and collectively called a metamorphic core complex and require large displacement along the low-angle normal fault that separates the two plates. Hoisch and Simpson (1993) estimated that the upper plate moved about 40 km (25 miles) along the fault towards the northwest.

The Boundary Canyon fault is easily discernable along the west face of the Funeral Mountains east of the highway as one approaches the mouth of Boundary Canyon from the south. It is also exposed on both sides of the lower part of the canyon. In this area the fault dips gently to the northwest and separates light colored, unmetamorphosed strata of the middle part of the Stirling Quartzite from drab exposures of strongly metamorphosed and deformed units of the middle and lower parts of the Johnnie Formation (Table 1).

KH ALL RIGHTS RESERVED

Photo 17. Boundary Canyon Fault, northern Funeral Mountains. The Boundary Canyon fault separates the greenish rocks below from the tan-colored ones above. The lower rocks, which belong to the Johnnie Formation, were brought up from mid-crustal depths along the fault. As a result, they show features indicative of metamorphism and deformation at high temperatures. The overlying rocks, however, which belong to the Stirling Quartzite, were deformed at much lower temperatures, and are only slightly metamorphosed.

ALL RIGHTS RESERVED

Equally metamorphosed rock units of the underlying Pahrump Group are superbly exposed in nearby Monarch Canyon, which drains westward from the crest of the Funeral Mountains. There, Mattinson et al. (2007) lent further detail to the story. They found that the Monarch Canyon fault, which is parallel to and underneath the Boundary Canyon fault, serves as another detachment fault, which separates the highly extended rock above from less highly extended rock below. In fact, the rock below the fault displays mostly features that formed by crustal compression during the late Cretaceous.

Chaos. A structural term for a mosaic of fault-bounded, typically gigantic blocks, derived from a stratigraphic succession and arranged in proper stratigraphic order, but occupying only a small fraction of the thickness of the original succession. In the Death Valley region, where Levi Noble coined the term, Chaos is normally viewed as a product of extreme crustal extension.

The Amargosa Fault and the Amargosa Chaos

Of the extension-related phenomena of the Death Valley region, one of the best known, most complex and most controversial is the Amargosa Chaos, first described by Noble (1941) and mapped in detail by Wright and Troxel (1984) and Castonguay (2013). Noble originally recognized three phases of the Chaos, but the one that he named the “Virgin Spring phase” is now viewed as true **Chaos** in the sense that he introduced the term. It is exposed in separate localities in the southern Black Mountains from near Virgin Spring and Rhodes Washes northward to Gold Valley (Photo 18). A topographically high area of basement rock divides the Chaos into a northern and southern section.

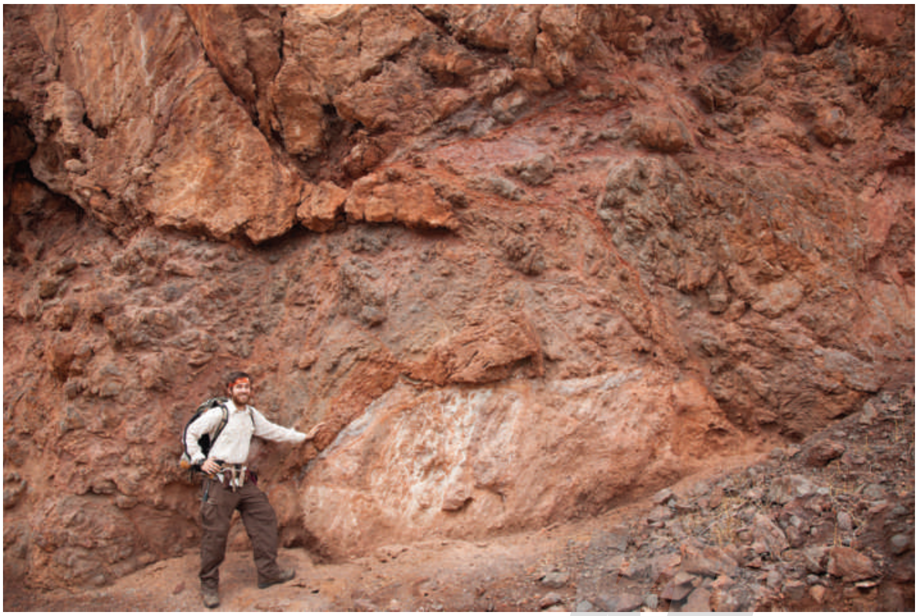

Photo 18. Some of the pervasive faulting and fracturing in the Amargosa Chaos. The geologist's hand rests on brecciated basement rock. Near the top of the photograph, one can see slightly more intact Noonday Dolomite.

ALL RIGHTS RESERVED

In simplest terms, the Chaos consists of a mosaic of fault-bounded blocks of Proterozoic and Cambrian formations, arranged in proper stratigraphic order, but highly attenuated to a small fraction of the actual combined thickness of the formations represented (Fig. 7). Most of the Chaos rests in fault contact upon intact occurrences of the Early Proterozoic crystalline complex. In some places within the Chaos, however, the base of the Proterozoic sequence rests depositionally on the basement. All of the faulting occurred in the shallow crust. In the Gold Valley area, in its northern part, the Chaos is intruded by granitic bodies that predate 10 million year old volcanic units. Thus the Chaos may be the oldest extension-related structural feature in the Black Mountains block. An excellent exposure of the Chaos lies immediately south of the highway at a point 2.4 km (1.5 miles) east of Jubilee Pass.

STOP AND LOOK

Noble (1941) originally interpreted the Chaos as remnants of a single, region-wide **thrust fault** and named by him the "Amargosa thrust." Wright and Troxel (1984) argued that the fault thins, rather than thickens the stratigraphic section, and so viewed it as a low-angle normal fault. Most recently, Castonguay (2013) and Castonguay and Miller (2013), found that the "Amargosa fault" in the southern part of the Chaos consisted instead of a high-angle, mostly strike-slip surface that had little to do with formation of the Chaos itself. They reported that the southern Chaos formed as the result of at least three earlier periods of faulting and/or folding.

Strike-Slip faults. Strike-slip faults have long been recognized as prominent structures throughout the region, as they are present in nearly every large

Thrust fault. A type of dip slip fault in which the block of rock beneath the fault surface (the footwall) has moved downwards relative to the block above the fault surface (hanging wall). Thrust faults typically bring older rocks over the top of younger rocks.

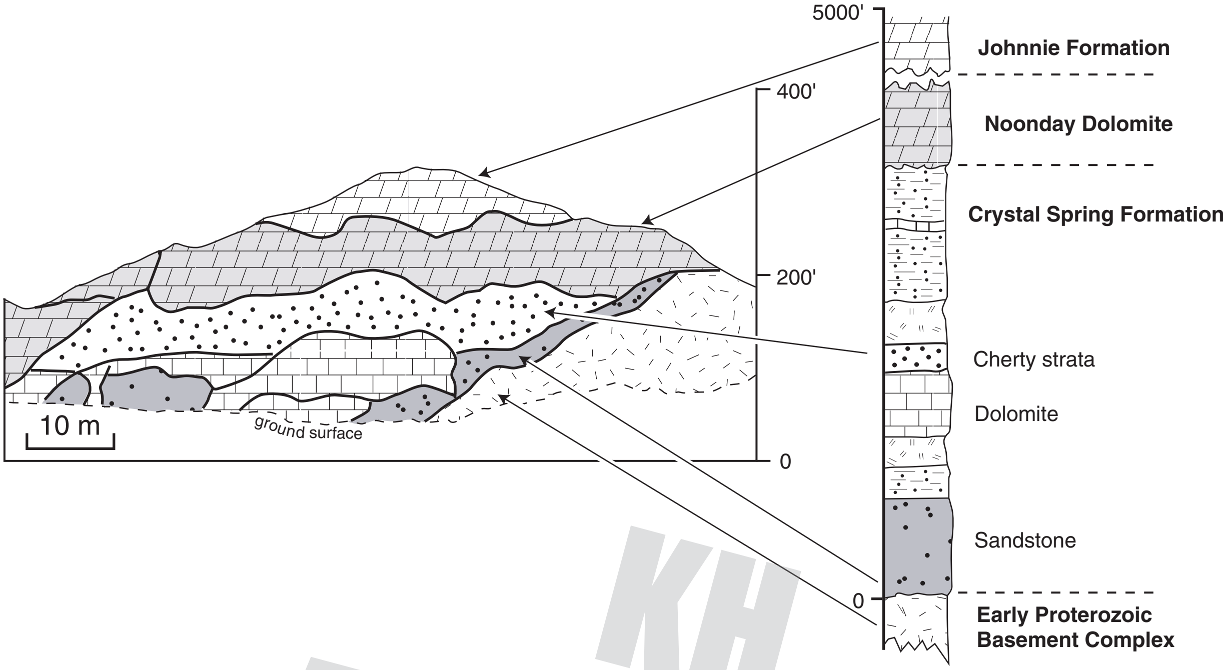

Figure 7. Sketch of an exposure of the Virgin Spring phase of the Amargosa chaos on the west wall of lower Virgin Spring Canyon. Note the greatly attenuated units of the Crystal Spring Formation as compared with the accompanying columnar section of the units with their natural thicknesses. Modified from Wright and Troxel, 1984.

KH ALL RIGHTS RESERVED

valley between the Sierra Nevada and Las Vegas, Nevada (Wright 1989). In Death Valley, strike-slip faults control the modern-day crustal extension, and likely exerted a controlling influence on earlier periods of extension.

The Death Valley Fault System and the Origin of Modern Death Valley

Figure 8 shows the active Death Valley fault system in solid red lines. It consists of three parts: the Northern Death Valley fault zone (NDVFZ), the Black Mountains fault zone (BMF), and the Southern Death Valley fault zone (SDVFZ; Machette et al. 2001). Each of these faults shows abundant evidence for recent activity, including offset stream channels and fault scarps (Klinger 2001b, Brogan et al., 1991); details of features along the Black Mountains fault zone are described in an earlier section of this book. This fault geometry, where the northern and southern Death Valley fault zones are linked by the Black Mountains fault zone, drives the modern extension in Death Valley. Central Death Valley is therefore a “pull-apart” basin, as its crust is being pulled apart between the two strike-slip fault zones (Fig. 8; Burchfiel and Stewart 1966).

The Furnace Creek Fault Zone

The best known of the ancient strike-slip faults exposed within the park boundaries compose the Furnace Creek fault zone (Figs. 3A, B). This fault zone

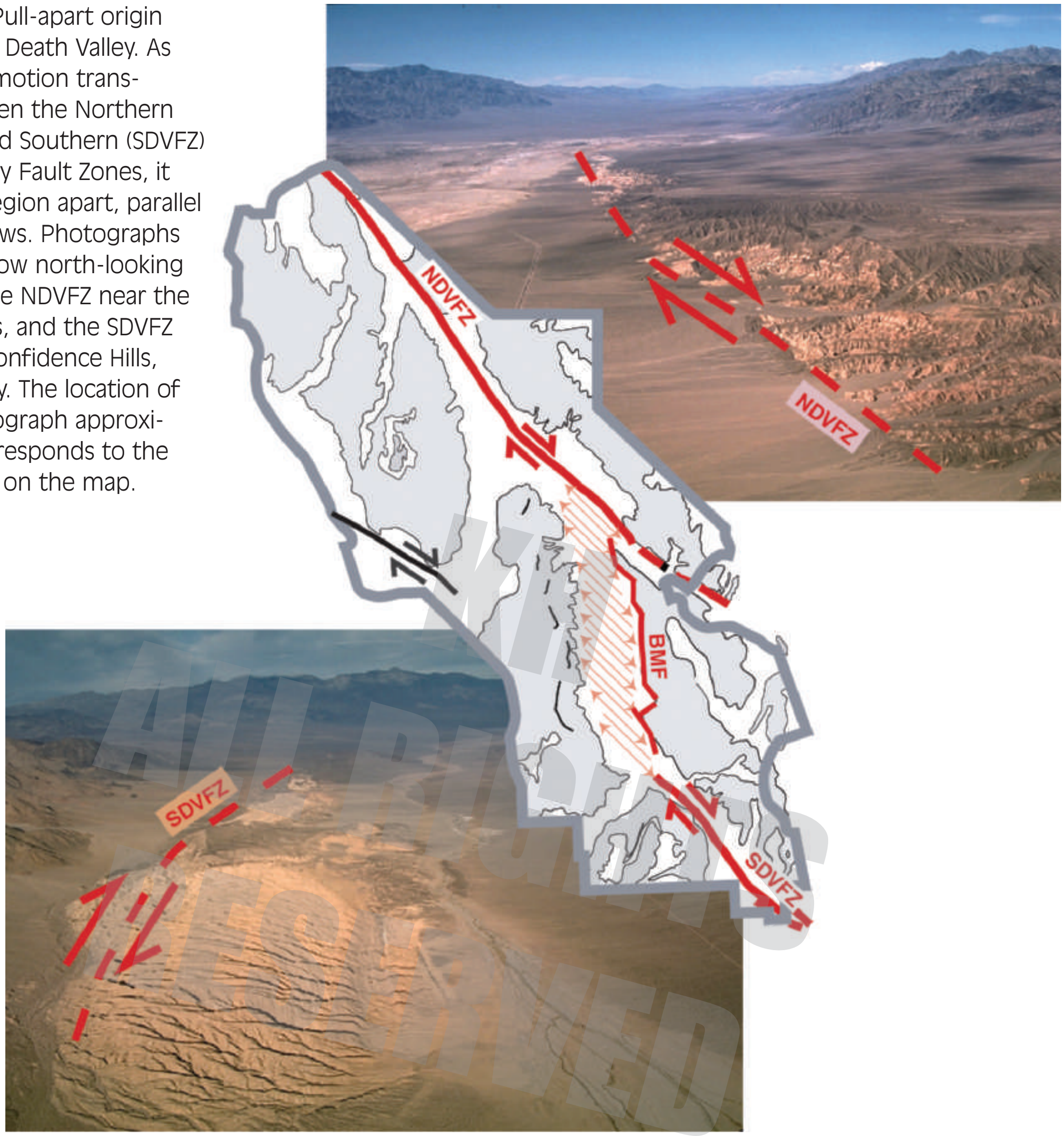

Figure 8. Pull-apart origin of modern Death Valley. As strike-slip motion transfers between the Northern (NDVFZ) and Southern (SDVFZ) Death Valley Fault Zones, it pulls the region apart, parallel to the arrows. Photographs A and B show north-looking views of the NDVFZ near the Kit Fox Hills, and the SDVFZ near the Confidence Hills, respectively. The location of each photograph approximately corresponds to the red arrows on the map.

defines a linear crustal rupture that extends from the vicinity of Eagle Mountain northwestward for about 250 km (150 miles), including Furnace Creek Wash and the full length of northern Death Valley. North of Furnace Creek, it coincides with the active, northern Death Valley fault zone (Machette et al. 2001a). South of Furnace Creek, it trends southeastward up Furnace Creek Wash as the dashed red line of Figure 8. There, it brings Miocene and Pliocene strata of the Furnace Creek Basin into contact with the Proterozoic and Paleozoic formations of the Funeral Mountains (Photo 19; McAllister 1970). The Miocene and Pliocene strata, being as much as 15,000 feet thick, also require a minimum vertical displacement of a comparable dimension.

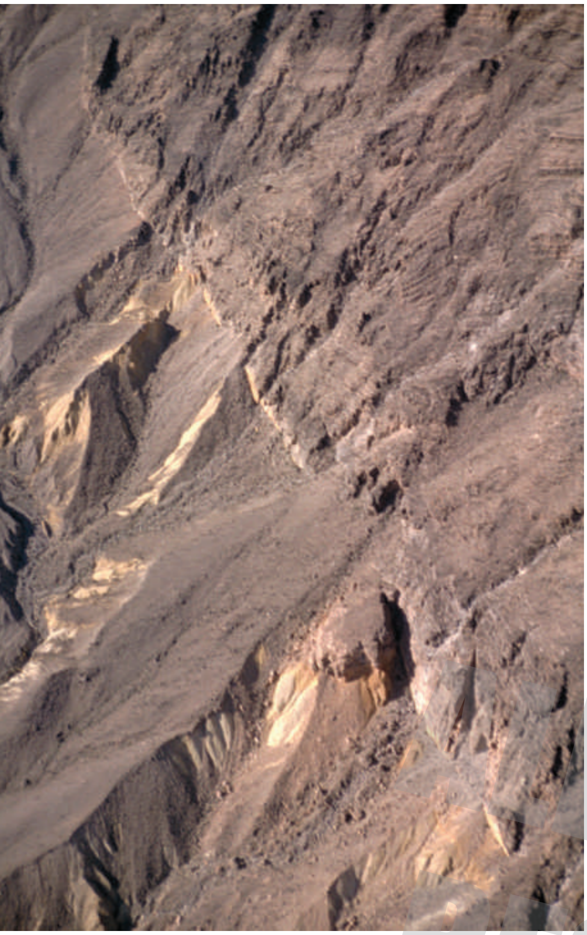

Photo 19. Aerial view of the Furnace Creek Fault Zone near Hole-in-the-Wall, Furnace Creek Wash. Here, the fault separates Paleozoic rock (right side-northeast) from the Tertiary Furnace Creek Formation (left side).

Geologists, beginning with Stewart and his coworkers (1968), have carefully inspected the pre-Cenozoic rocks on both sides of the Furnace Creek fault zone, and have observed features that were once joined and are now separated by movement along the fault zone. In making these matches, they find compelling evidence for displacements of tens of kilometers. However, details of this interpretation vary widely. Along the southern part of the fault, Snow and Wernicke (1989) and Snow (1992) argued for 68 km (42 mi) of right-lateral slip based on their proposed correlation of pre-Tertiary thrust faults and folds on either side of the fault. Stevens et al. (1991, 1992) suggested 80 km (50 mi) of right slip, based on an offset sedimentary facies boundary in Mississippian-aged rock as well as a different correlation of thrust faults and folds. Renik and Christie-Blick (2013) used a combination of offset pre-Tertiary faults, folds and igneous rocks to limit the maximum offset to 50 km (30 mi). They also showed evidence that the slip amount decreased towards each end of the fault.

Other important strike-slip faults in Death Valley include the active Hunter Mountain fault in the northern Panamint Valley, and the inactive Sheephead fault, in the southern Black Mountains. The Hunter Mountain fault zone offsets the Hunter Mountain batholith right-laterally by 8–10 km (5–6 mi) (Burchfiel et al. 1987). The Sheephead fault bounds the southern edge of magmatic rocks in the Black Mountains and is probably also right-lateral (Wright et al. 1991; Renik 2010). The Sheephead fault is enigmatic, however, because it is mostly obscured by alluvium. Additionally, the Southern Death Valley fault zone, which forms the southern edge of the modern pull-apart basin, shows evidence for a history that dates back at least several million years. Along this fault, alluvial fan gravels are offset right-laterally about 35 km (22 miles) from their source in the southern Panamint Mountains (Butler et al. 1988).

The Ranges

Fault-block range. A mountain range that has risen along a master fault zone. Most ranges in Death Valley are tilted fault blocks, because they have risen and tilted along normal faults.

Although the mountain ranges within Death Valley National Park have formed in a framework of interrelated Cenozoic faults and generally qualify as **fault-block ranges** (Fig. 2), some differ widely in other respects. Most importantly, they differ in the specific types of bedrock of which they are composed, and in the types of faults that control their internal structure.

Most ranges are dominated by the striped outcrops that identify the evenly bedded Proterozoic and Paleozoic formations (Photo 20). These ranges include the Panamint, Cottonwood, Last Chance, Funeral, and Grapevine Mountains.

Photo 20. View southeastward into Death Valley from Aguereberry Point. In the foreground, Paleozoic rock dips eastward. The prominent white unit is the Cambrian Zabriskie Quartzite.

RIGHTS RESERVED

Of these, the Funeral and Grapevine Mountains stand out because they lie end-to-end to form a single, northwest-trending topographic high, adjacent to the Furnace Creek fault zone. This composite range has extended internally along normal faults oriented approximately perpendicular to its backbone. The transition between the two ranges coincides with the Boundary Canyon low-angle normal fault, in that the Grapevine Mountains lie in the hangingwall and the Funeral Mountains lie in the footwall of the fault (Photo 17).

The Black Mountains and Greenwater Ranges are underlain largely by irregular bodies of Tertiary plutonic and volcanic rocks. They also contain most of the park's exposures of crystalline basement rock, mostly in the southern Black Mountains, but also in the cores of the three turtlebacks. As a consequence, these ranges exhibit a certain variability in their appearance: the Tertiary intrusive and crystalline basement rock present a somewhat dull and somber appearance whereas the Tertiary volcanic rocks tend to be brightly colored.

The Owlshead Mountains, in the southern part of the park, differ from the other ranges in that they are equidimensional in map view, and essentially coextensive with a cluster of granitic **plutons** of Mesozoic age (Fig. 3A). The plutons are discontinuously covered by Miocene **andesitic** and rhyolitic

Plutons. Bodies of intrusive rock.

Andesitic. A compositional term used to describe magmas or volcanic rocks that consist of between 60-65% silica.

lava flows and are also offset by strike-slip faults. Most of these faults strike northeast and have moved in a left-lateral sense.

The Basins

Cenozoic sedimentary deposits, which have accumulated in the basins between the ranges of the Death Valley region, consist mainly of debris eroded from the high areas and deposited in alluvial fans, ephemeral and **perennial lakes**, and stream beds. Also included are accumulations of evaporites, principally limestone, gypsum and salt, brought in solution by streams. The sedimentary fill is typically interlayered with extrusive volcanic rocks.

Perennial Lakes. Lakes that are constantly filled with water.

By observing the shapes of these basins and the distribution of the various kinds of sedimentary rocks that they contain, by dating the volcanic bodies in the basins, and, on occasion, by employing geophysical methods to detect subsurface features, geologists can reconstruct the development of the basins and the erosional history of the source areas. The task is hindered by a cover of Quaternary alluvium that hides much of the older Cenozoic deposits. Late Cenozoic faulting and folding, however, has exposed to erosion the pre-Quaternary rocks of several basins within the park boundaries.

The Cenozoic sedimentary basins of the Death Valley region evolved in a variety of ways, each in response to the interplay of the three major types of faults discussed above. Deposits of three basins are especially well displayed along the main roads of the national park. In the floor of central Death Valley sediments are accumulating today in the pull-apart basin bounded on the east by the zone of normal faults that defines the front of the Black Mountains (Fig. 3A). In Furnace Creek Wash, a thick succession of Miocene to Pliocene sedimentary deposits, volcanic ash, and lava flows defines the Furnace Creek Basin. Because it lies adjacent to the Furnace Creek fault zone, this basin has been called a "strike-slip" basin (Cemen et al. 1985). In the Emigrant Canyon-Towne Pass area on the northwestern flank of the Panamint Mountains, Late Miocene through Pliocene conglomerates and **basaltic** to **rhyolitic** lava flows of the Nova Formation defines the Nova Basin (Fig. 3A). The Nova Formation has been deposited above a low-angle normal fault called the Emigrant detachment.

Of the Cenozoic basinal deposits exposed within Death Valley National Park, those exposed within Furnace Creek Wash are the most obvious and scenic. These rocks define the Furnace Creek Basin, an accumulation of sedimentary units and basaltic to rhyolitic lava flows. These were deposited in Middle Miocene through Pliocene time on crust that lies between a major fault in the Furnace Creek fault zone (McAllister 1970, 1971, 1973; Cemen et al., 1985) and the Badwater Turtleback fault (Wright et al. 1999; Miller 1999). The crust there has moved downward, as well as laterally, to form the northeast margin of the elongate, trough-like Furnace Creek basin. The basinal deposits are about 3600 m (12,000 feet) in maximum estimated thickness in the northwestern part of the basin, but are much thinner in the southeastern part.

Basaltic. A compositional term used to describe magmas or volcanic rocks that consist of between 50-55% silica. Basaltic rocks are typically dark gray to black in color. Of or like the rock basalt. Generally, rocks with 55-60% silica are called basaltic andesites.

Rhyolitic. A compositional term used to describe magmas or volcanic rocks that consist of greater than 70% silica. Rhyolitic rocks tend to be light in color.

KH ALL RIGHTS RESERVED

The panorama of the Furnace Creek Basin deposits viewed from Zabriskie Point is among the most photographed in the entire National Park system. These rocks are folded into a broad but complex **syncline**. Beginning on the west side of the Black Mountains, the Middle and Late Miocene Artist Drive Formation dips northeastward. The successively overlying Late Miocene to Pliocene Furnace Creek Formation and Pliocene Funeral Formation also dip northeastward and coincide with Furnace Creek Wash. There, conglomerates of the Furnace Creek Formation reflect deposition on alluvial fans while thinly bedded mudstones and sandstones reflect deposition in lakes (Photo 21A). Further towards the Funeral Range, these rocks generally dip back towards the southwest.

STOP AND LOOK

Syncline. A fold in layered rock in which the youngest rock lies in the core. The beds on either side of a syncline generally slope towards from the core.

In contrast, the interlayered conglomerates and volcanic rocks of the Nova basin are more disordered and thus less completely displayed than those of the Furnace Creek basin. This is largely because the basin was fragmented concurrently with the deposition of the Nova Formation and with movement on the underlying Emigrant detachment fault (Hodges et al. 1989).

Photo 21A. Furnace Creek Formation at Zabriskie Point, looking southeastward. The conglomerate in the foreground accumulated in alluvial fans, whereas the light-colored, fine-grained rocks in the middle ground accumulated in lakes.

Photo 21B. East-dipping Nova Formation west of Towne Pass.

All RIGHTS RESERVED

The Nova formation is estimated to be more than 1800 m (6000 feet) thick. It is exposed along State Highway 190 both east and west of Towne Pass (Photo 21B). The upper part of the Nova is well exposed in Emigrant Canyon on both sides of the road that connects State Highway 190 with Harrisburg Flat and Wildrose Canyon. The conglomerates there, and elsewhere in the formation, are derived from the Proterozoic formations exposed in the higher parts of the Panamint Mountains.

Other sedimentary basins that pre-date modern Death Valley include the Ubehebe basin in the northern part of the park (Snow and Lux 1999), and the 5-3 million year old Copper Canyon basin in the Black Mountains (Fig. 3A, Photo 21C). The Copper Canyon basin lies in the hangingwall of the Copper Canyon turtleback and was folded into a series of northwest-trending **anticlines** and synclines. Its rocks, deposited in a setting of alluvial fans, rivers, and lakes, contain an unusual abundance of mammal and bird tracks (Santucci et al. 2012; Nyborg et al. 2010: Otten 1973; Drewes 1963).

Anticline. A fold in layered rock in which the oldest rock lies in the core. The beds on either side of an anticline generally slope away from the core.

The Central Death Valley Plutonic-Volcanic Field

The Black Mountains and Greenwater Range and the adjoining Furnace Creek Wash, being underlain mostly by Cenozoic igneous and sedimentary rocks, present a varicolored patchwork-like landscape. This landscape differs markedly from the striped forms of the surrounding ranges composed of the uniformly layered Proterozoic and Paleozoic formations. The difference is equally visible on the geologic map (Photo 22, Fig. 3A).

Photo 21C. Lake beds of the Copper Canyon Formation. These rocks grade laterally into alluvial fan deposits.

RIGHTS RESERVED

The history of Cenozoic igneous activity within the central Death Valley region began between 12 and 10 million years ago (Wright et al. 1991). Within that interval the composite pluton of the Willow Spring **gabbrodiorite** and the Smith Mountain granite intruded the Black Mountains. Dacitic lava flows of that age are also exposed in the Greenwater Range and near the Resting Springs Range, east of the park. From 11 to 10 million years ago, felsic magmas crystallized both as shallow plutons and as lava flows. The felsic plutons are distributed throughout the central Death Valley area, but most abundantly in the Greenwater Range; the lava flows of that age are especially well exposed in the vicinity of Sheephead Mountain in the southern part of the field.

The post-10 million year history of the Central Death Valley plutonic-volcanic field is recorded primarily in extrusive volcanic rocks that eventually covered almost the entire area now occupied by the Black Mountains and Greenwater Range and, in the later stages, much of the adjacent Furnace Creek Basin. These rock units range widely from rhyolitic through andesitic to basaltic in composition (Green 1997). Rhyolitic lava flows and associated air-fall tuffs, comprising the Shoshone Volcanics, the volcanic rocks at Brown Peak, and the Greenwater Volcanics, are the most abundant. Most of the ash-flow tuff is confined to a single formation — the Rhodes Tuff which is about 9.6 million years old. An outstanding exposure of similar-welded

Gabbro. A compositional term used to describe intrusive igneous rocks that consist of between about 50-60% silica. Gabbros are chemically equivalent to basalts. They are typically dark in color and contain no quartz.

Diorite. A compositional term used to describe intrusive igneous rocks that consist of between about 60-70% silica. Diorites are chemically equivalent to andesites.

Photo 22. View northwards along the crest of the northern Black Mountains. The brightly colored rocks are late Cenozoic volcanic rocks of mostly the Artist Drive Formation.

RIGHTS RESERVED

STOP AND LOOK

tuff of that age exists outside the national park on highway 178, approximately 6.5 km (4 miles) east of Shoshone, and described on p. 71 (Troxel and Heydari 1982). Overlying the Rhodes Tuff are the Shoshone Volcanics, which are about 8 million years old.

Felsic. A term used to describe igneous rocks that contain abundant feldspar.

Felsic volcanism apparently terminated 5 to 6 million years ago following the emplacement of the Greenwater Volcanics. The basaltic and andesitic flows occupy various positions in the volcanic pile. The available radiometrically determined ages suggest a clustering in intervals of 9 to 10, 7 to 8 and 4 to 5 million years.

Amount and Style of Crustal Extension in Death Valley

A great deal of scientific controversy concerns the magnitude and style of extension in Death Valley, especially with respect to the Black Mountains. As shown on the geologic map (Fig. 3A) and discussed in the preceding section, the northern Black Mountains are nearly devoid of the Late Proterozoic and Paleozoic sedimentary rock that underlies the surrounding ranges. Instead, the northern Black Mountains consist primarily of Tertiary intrusive,

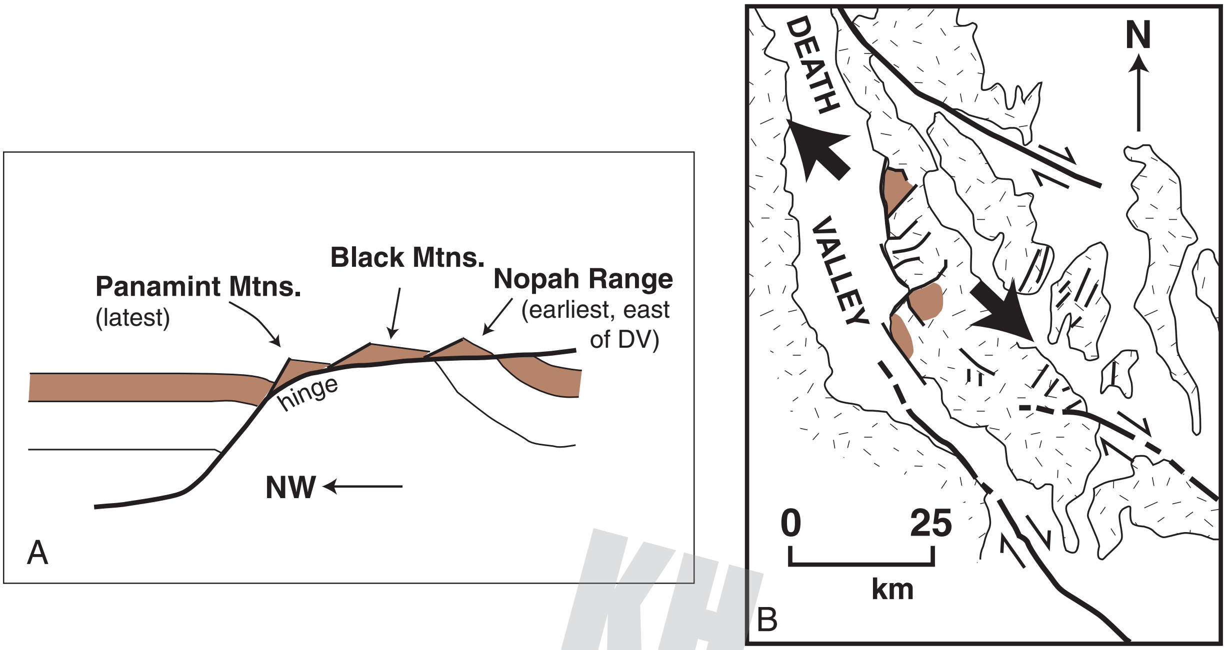

Figure 9. Models for late Tertiary extension in Death Valley, from Miller, 2001. A, Rolling Hinge model, in which active extension occurs at the hinge or bends in the detachment fault. As extension migrates to the northwest, so does the hinge. B, Pull-apart model, in which extension is driven by transfer of strain between terminations of large strike-slip faults. The two most likely faults for this scenario are the Furnace Creek Fault Zone and the Sheephead Fault, although Serpa and Pavlis (1996) suggested that the Garlock Fault may also play a role. In this model, the Black Mountains have been extended significantly more than the surrounding ranges.

KH
ALL RIGHTS
RESERVED

volcanic, and sedimentary rock that either intrudes, overlies, or is faulted against basement rock.

One model for extension in Death Valley proposes that the older sedimentary rock was removed along a shallow-crustal, low-angle normal fault system that extended the entire region by about 80 km (Stewart 1983; Wernicke et al. 1988; Holm et al. 1992; Snow and Wernicke 2000). This model is generally referred to as the "rolling hinge model," because it requires the low-angle fault to steepen at the locus of major faulting (the "hinge"); the hinge migrates, or rolls, westward through time (Fig. 9A). According to this model, the fault system is now exposed at the turtlebacks and the Amargosa Chaos, described earlier. It had to be most active after about 8 Ma, to detach the Shoshone Volcanics in the Amargosa Chaos area, and to account for the cooling of the Mormon Point and Copper Canyon turtlebacks (Holm et al., 1992).

By contrast, the other model, called the "pull-apart" model, holds that the older sedimentary rock was removed along a series of separate, deeply rooted fault zones (Fig. 9B; Wright et al. 1991; Serpa and Pavlis 1996; Wright et al. 1999). The pull-apart model therefore requires each turtleback and Amargosa Chaos to be separate features. Like the pull-apart model for modern extension, this model calls for extension to be driven largely by strike-slip. As a consequence, this model suggests that the Black Mountains have extended far more than the surrounding ranges, and in so doing, have made space for its voluminous Tertiary magmatism. Distinguishing between these two models is important because each calls on entirely different processes to extend the earth's crust. Moreover, because Death Valley is so well-known for crustal extension, the prevailing model in Death Valley naturally influences perspectives on crustal extension elsewhere.

In addition to the turtlebacks and the Amargosa Chaos, the Furnace Creek Basin plays a key role in testing these models. It contains a thick sequence of sedimentary and volcanic rock that is unbroken by any through-going detachment faults. The Rolling Hinge model therefore requires that the entire basin overlies the regional detachment fault and so was transported some 10s of km northwestward to its present location. In contrast, the pull-apart model requires that the basin formed in-place.

We favor the pull-apart model for a variety of reasons. It best explains the localization of voluminous magmatism within the distinctly rhombic-shaped region of the central and northern Black Mountains. In turn, this region is bordered by the Furnace Creek and Sheephead fault zones, along which right-lateral slip would naturally pull the area apart (Fig. 9B). Moreover, several observations of the Furnace Creek Basin, Amargosa Chaos, and the turtlebacks conflict with the rolling hinge model. At two localities in the northern Black Mountains, rocks of the Furnace Creek Basin rest depositionally on Paleozoic rock and are not faulted (mile 1.8 of Dantes View road guide; mile 66.2 of Black Mountains road guide). Additionally, Miller and Prave (2002) found that, prior to 14 million years, faulting at the Badwater turtleback likely influenced sedimentation in the Furnace Creek Basin. If true, then the basin must have formed in approximately its present location.

In the Amargosa Chaos, Wright and Troxel (1984) mapped numerous depositional contacts between the Proterozoic sedimentary rock and the crystalline basement, to show that the Amargosa fault is not a single, through-going detachment fault, as required by the rolling hinge model. Miller (2002), Castonguay (2013), and Castonguay and Miller (2103) found that the offset and importance of the fault was limited. Additionally, most activity within the Amargosa Chaos must have been before 10 million years, according to the age of a rhyolitic dike that intrudes it (Miller and Friedman 2003) and mapping and structural analysis by Topping (2003). These ages are long before the timing of major extension as required by the rolling hinge model.

At the turtlebacks, Miller and Pavlis (2005) described evidence that most of the extension along the ductile shear zones also occurred before 10 million years, before that suggested by the Rolling Hinge model. This timing of extension was supported by Miller and Friedman (2003) who dated a dike that cut the shear zone at Mormon Point at 9.5 million years. Furthermore, it is unlikely that the Panamint Mountains, for example, originated above and east of the Black Mountains as required by the rolling hinge model, because the Panamint Mountains contain Mesozoic intrusions that are not present in, or east of, the Black Mountains.

KH ALL RIGHTS RESERVED