C H A P T E R 48

Death Valley National Park

Eastern California and Southwestern Nevada

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Area: 3,299,840 acres; 5156 square miles
Proclaimed a National Monument: February 11, 1933
Established as a National Park: October 8, 1994
Designated a Biosphere Reserve: 1984

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The hottest, driest, lowest place in North America, is the floor of Death Valley. Ancient rocks and young rocks, in complex exposures, record a variety of faults and displacements. Snow-topped peaks rise abruptly thousands of feet from the valley floor, which is below sea level. Displayed in the barren landscape are salt pans and playas, young volcanic craters, large alluvial fans, imposing fault scarps, sand dunes, wineglass canyons, turtlebacks, abandoned mines, and more.

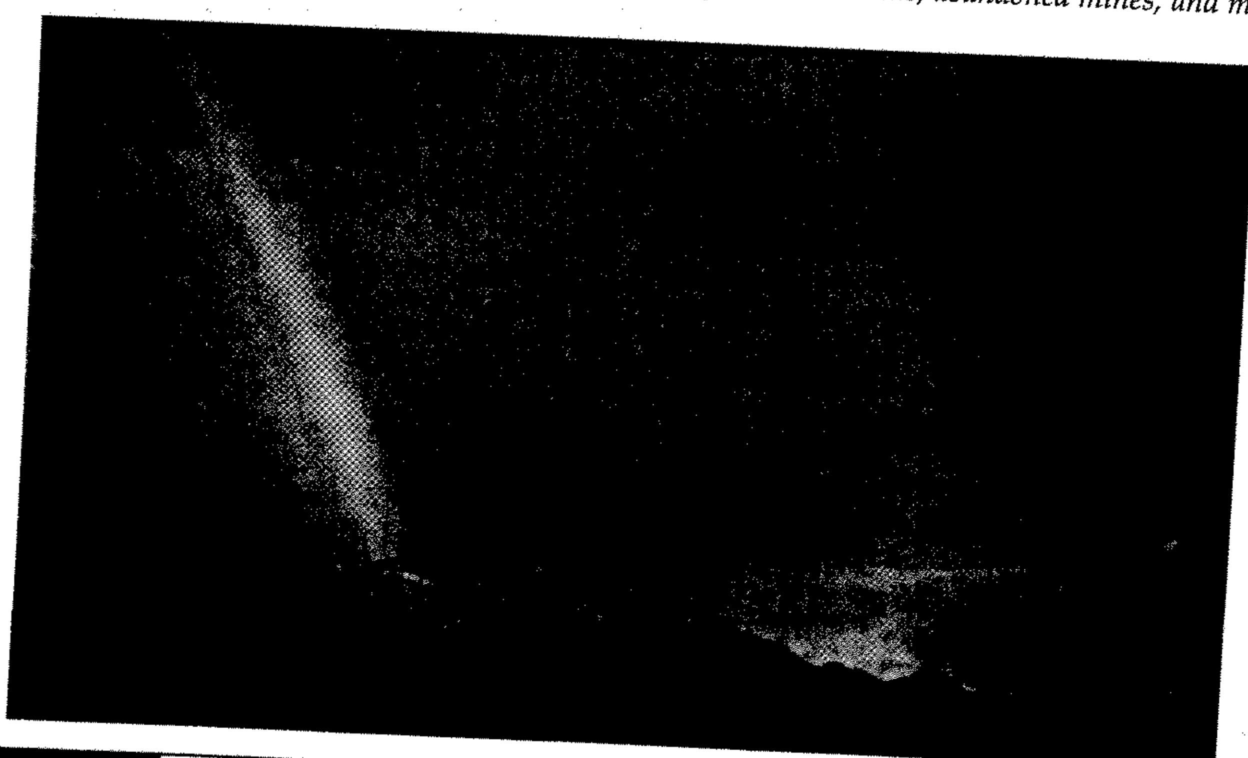

FIGURE 48.1 Double rainbow and central Funeral Mountains. Photo by Martin Miller.

Geographic Setting and Human History

True to its reputation, the floor of Death Valley is, indeed, the hottest, driest, and lowest land in the United States. Summer temperatures frequently exceed 120° F and the mean annual precipitation is only about 1.5 inches. But, more importantly, Death Valley National Park encloses one of the world's most spectacular desert landscapes and a mountain range that remains snow-capped during most winter seasons. Even on the floor of the valley, temperatures occasionally drop below freezing.

Death Valley lies in the Mojave Desert of southeastern California and is arid because it lies in the rain shadow of several more westerly mountain ranges, including the Sierra Nevada. It also contains the low point of a large region of interior drainage in the southwestern part of the Great Basin. The valley floor, which extends to a depth of –282 feet near Badwater (fig. 48.2), lies between north- to northwest-trending mountain ranges (fig. 48.3). The Panamint Mountains, west of Central Death Valley, being the highest, culminate in Telescope Peak at an elevation of 11,049 feet. The relief between there and the valley floor is one of the greatest obtained within the conterminous United States.

Prehistoric people occupied the Death Valley region for at least 10,000 years. They lived at lower elevations during the winters and at higher elevations in the summers, although at times of milder climatic conditions they could live on the valley floor throughout the year. They obtained water from the region's numerous springs and collected mesquite beans and pinyon nuts as dietary staples.

In 1849, the first people of European descent wandered into Death Valley, having lost their way to the newly discovered gold fields. For the next 80 years, mining dominated the thoughts of most visitors to the region, as prospectors located deposits of gold, silver, copper, lead, and, beginning in the 1880s, borate minerals and talc. The mining of metals was hindered by the extreme aridity. Only the Keane Wonder gold mine and the gold mines at Rhyolite and Harrisburg produced ore of significant value. Both borate and talc mining, however, proved profitable. During the 1880s, borax was recovered from evaporite deposits scraped from the salt pan of the valley floor. In the early 1900s, large deposits of borate minerals were discovered in the Miocene strata of Furnace Creek Wash. By the late 1920s, the Death Valley region had become the world's leading source of borax. Although mining continues in the vicinity of Death Valley National Park today, tourism is the region's principal industry. More than one million persons, including large numbers from other countries, enter the Visitor Center each year.

Shaping of the Present Landscape: Extensional Tectonics and the "Basin and Range Event"

General Features

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 and continuing today, this part of the earth's crust has been broken into a gigantic mosaic of mountain blocks (fig. 48.3) each bounded by major faults. Cenozoic sedimentary and volcanic rocks deposited in the intervening basins during the development of the present landscape provide evidence for how and when it formed and for the changing climates of that interval of time. Older sedimentary formations, deposited 35 to 16 million years ago, can be correlated, from place to place, over much larger areas than the deposits of the later and smaller basins. The older Tertiary formations, when reassembled, thus record a considerably less mountainous terrain than the one we observe today.

Most of the present ranges consist of Proterozoic, Paleozoic and/or Mesozoic formations that predate the forming of these ranges by many millions of years (Table 48.1). In fact, we owe much of our knowledge of the earlier events to the fact that these formations have been brought to view along the tilted faces of the ranges. We observe in the oldest rocks evidence of events that shaped and metamorphosed the crust more than 1.7 million years ago. An even clearer record of ancient marine and fluvial environments and accompanying igneous activity is contained in the extensive exposures of the Pahrump Group, emplaced within the 1.2- to 0.8-billion-year interval of time. Largely because the Pahrump rocks remain in essentially their pristine state and are so well exposed on the barren slopes, they have attracted the attention of geologists the world over. The stark mountain slopes also contain continuous exposures of the later Proterozoic and Paleozoic formations that record the pre-Mesozoic history of the western margin

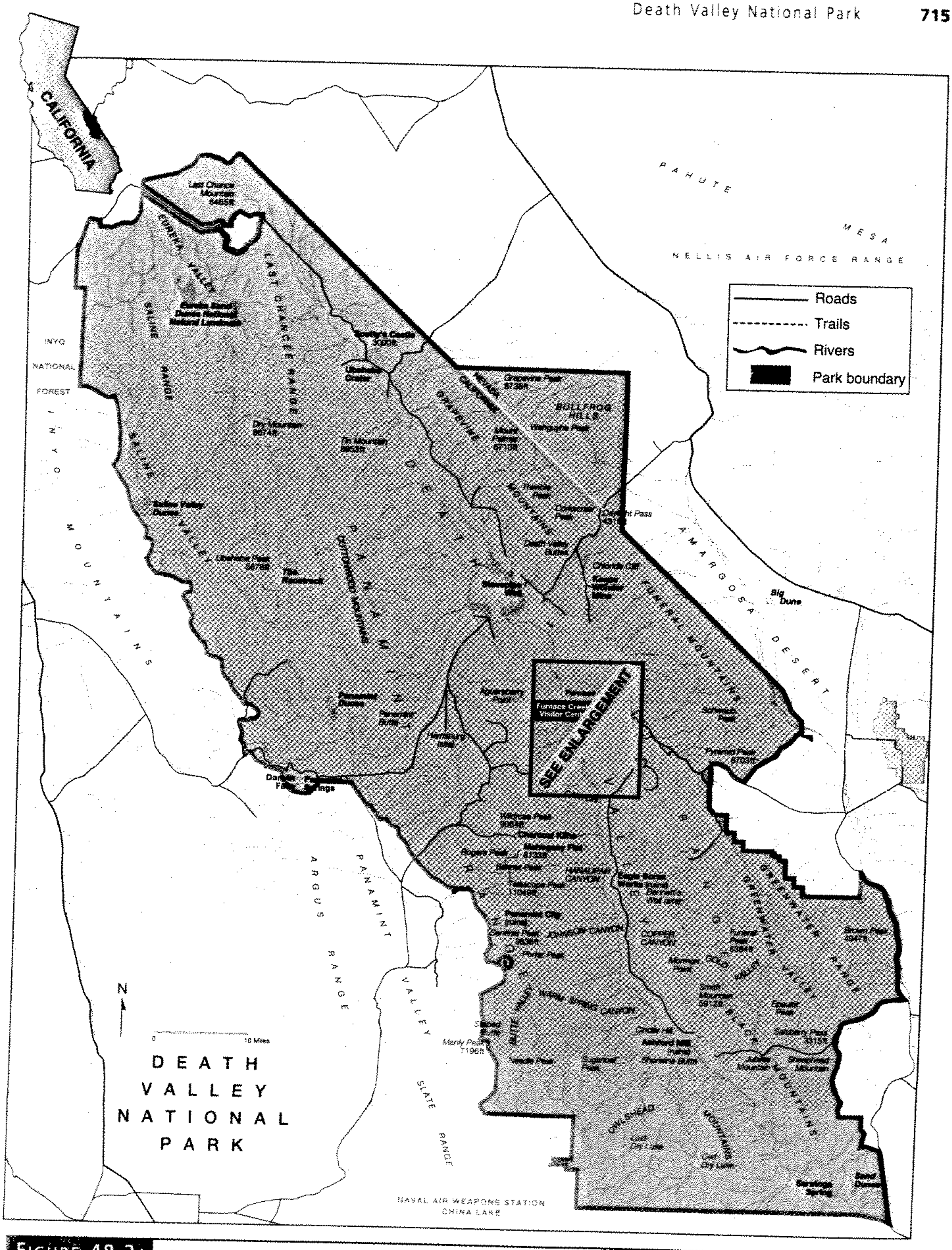

FIGURE 48.2A Death Valley National Park, California.

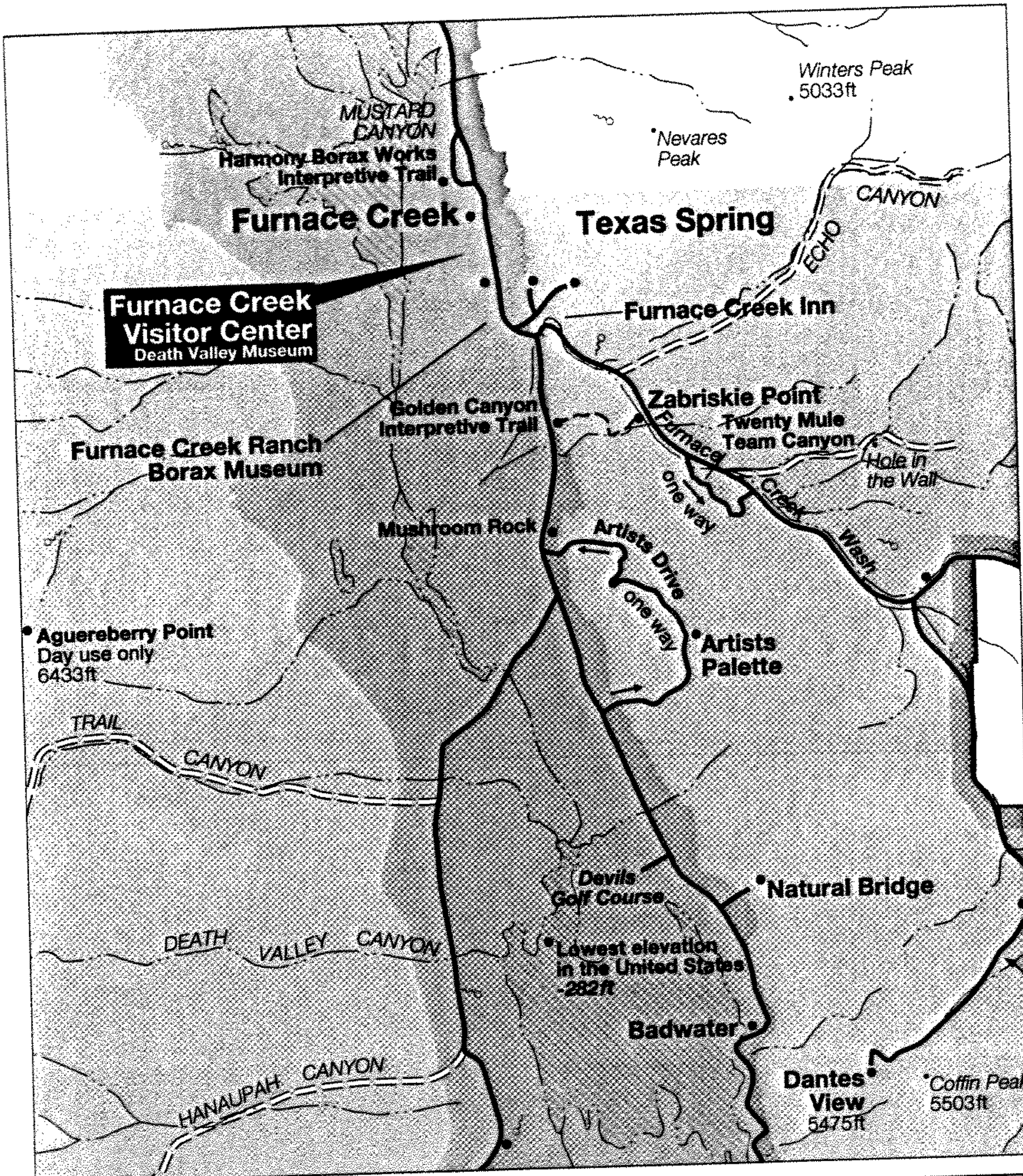

FIGURE 48.2B Enlargement.

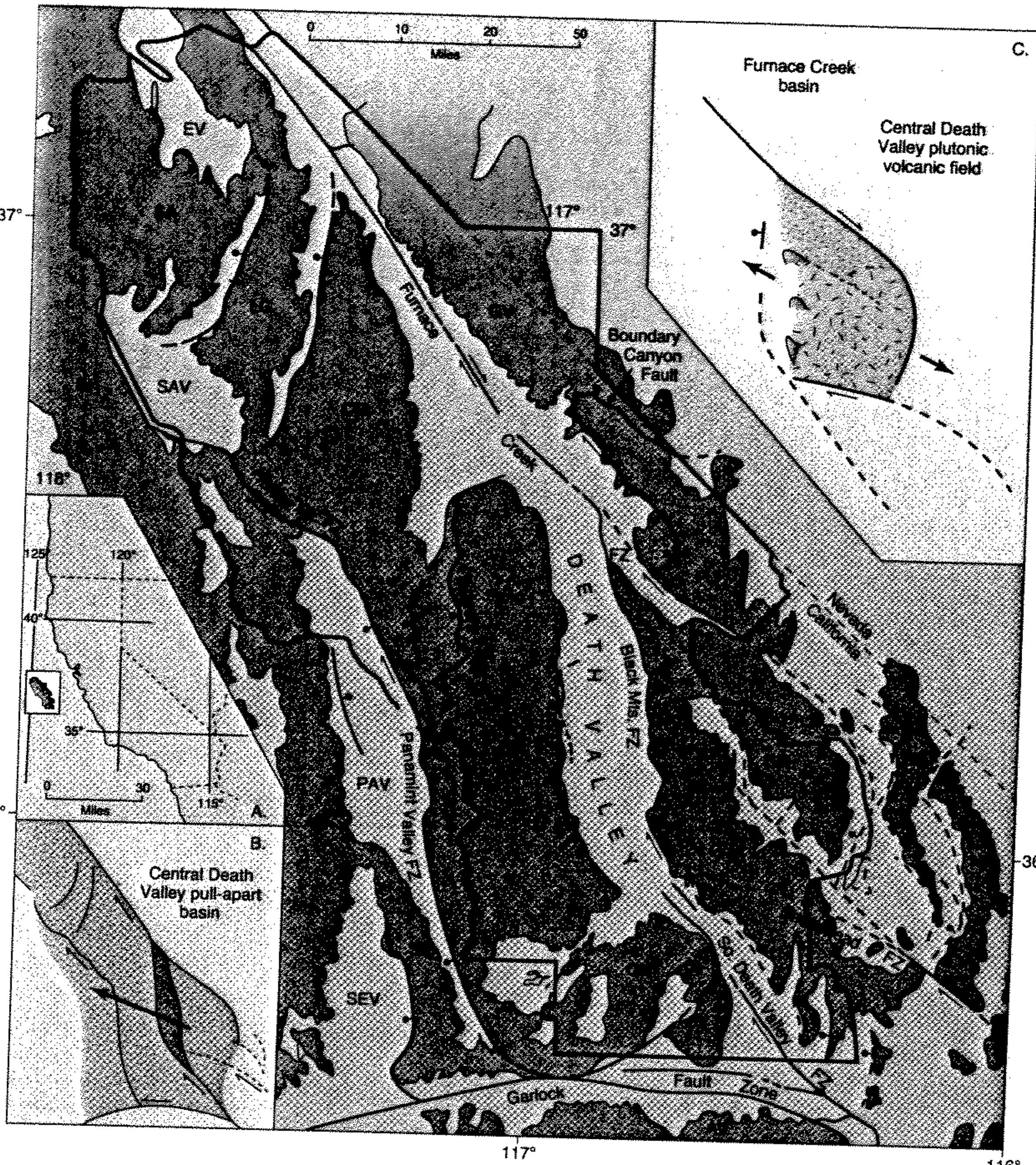

FIGURE 48.3 The Death Valley region has been broken into discrete blocks of crust—the ranges—bounded by major faults, as shown here.

Inset maps: *A.* Location of Death Valley National Park. *B.* Sketch map showing simplified fault pattern—the stippled area of relatively severe extension—between the Furnace Creek fault zone and the Garlock fault zone; also showing the Central Death Valley pull-apart basin between the Southern Death Valley fault zone and the active part of the Furnace Creek fault zone. *C.* Diagram showing an interpretation of the tectonic setting of the Furnace Creek basin and the Central Death Valley plutonic-volcanic field in a rhomboidal area between the Furnace Creek and Sheephead fault zones. **Key to ranges:** AR—Argus Range; AV—Avawatz Mountains; BL—Black Mountains; CO—Cottonwood Mountains; FU—Funeral Mountains; GR—Greenwater Range; GV—Grapevine Mountains; IN—Inyo Mountains; LC—Last Chance Range; NP—Nopah Range; OH—Owlshead Mountains; PT—Panamint Mountains; SA—Saline Mountains; SL—Slate Range. **Key to valleys:** EV—Eureka Valley; PV—Panamint Valley; SAV—Saline Valley; SEV—Searles Valley. **Key to turtlebacks:** B—Badwater turtleback; C—Copper Canyon turtleback; M—Mormon Point turtleback. (The curves in the fault trace along the west edge of the Black Mountain block locate the three turtlebacks.)

Table 48.1 Geologic Column, Death Valley National Park

Time Units			Rock Units		Principal Geologic Events
Era	Period	Epoch	Group	Formation	
Cenozoic	Quaternary	Holocene	Alluvial fans, stream, and playa deposits, dunes		Continued deposition in modern Death Valley
Cenozoic	Tertiary	Pliocene Miocene	Numerous sedimentary, volcanic, and plutonic units in separate and interconnected basins and igneous fields; includes Artist Drive, Furnance Creek, Funeral, and Nova Formations.		Opening of modern Death Valley Continuing development of the present ranges and basins Onset of major extension
Cenozoic	Tertiary	Miocene		Several Formations	Deposition on relatively subdued terrain
Cenozoic	Tertiary	Oligocene		Titus Canyon	
			Major Unconformity		
Mesozoic	Cretaceous/ Jurassic		Granitic plutons		Thrust faulting and intrusion of plutons related to Sierra Nevada batholith
Mesozoic	Triassic			Butte Valley	Shallow marine deposition
					Unconformity
Paleozoic	Pennsylvanian			Resting Spring Shale	Development of a long-continuing carbonate bank on a passive continental margin; numerous intervals of emergence, interrupted by deposition of a blanket of sandstone in Middle Ordovician time
Paleozoic	Mississippian			Tin Mountain Limestone Lost Burro	
Paleozoic	Devonian/ Silurian			Hidden Valley Dolomite	
Paleozoic	Ordovician			Ely Springs Dolomite Eureka Quartzite	
Paleozoic	Ordovician		Pogonip		
Paleozoic	Cambrian			Nopah Bonanza King Carrara Zabriskie Quartzite Wood Canyon	Deposition of a wedge of siliciclastic sediment during and immediately following the rifting along a new continental margin
Prototerozoic				Stirling Quartzite Johnnie Ibex Noonday Dolomite	Shallow to deep marine deposition along an incipient continental margin
					Unconformity
Prototerozoic			Pahrump	Kingston Peak Beck Spring Crystal Spring	Glacio-marine deposition Shallow marine deposition Rapid uplift and erosion
			Major Unconformity		
Prototerozoic			Crystalline basement		Regional metamorphism

of North America. So these exposures, too, continue to be of widespread interest.

On the other hand, the contiguous Black Mountains and Greenwater Range, in the eastern part of the park, are underlain largely by bodies of Tertiary igneous rocks, both extrusive and intrusive. These were added to the preexisting crust 12 to 4 million years ago. When the Tertiary record is combined with that of the older rocks preserved in the ranges, geologists can reconstruct an extraordinarily complete record of crustal evolution.

The Faults

In the faults that bound the ranges and basins of the Death Valley region (fig. 48.3), 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 has 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 define the ranges and valleys of Death Valley National Park (fig. 48.3) are broadly divisible into three kinds: strike-slip, high-angle normal and low-angle normal. The strike-slip faults, along which movement has been dominantly parallel with the strike of the fault planes, are identified by arrows showing 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 downdip. The large dots in the diagram identify the downthrown sides of both high-angle and low-angle normal faults. The normal faults, by virtue of their geometry, are the simplest expressions of crustal extension; the lower the angle, the greater the opportunity for large-scale extension.

Most students of the structural framework of the Death Valley region view the major range-bounding faults as terminating at depth against essentially horizontal "detachment surfaces." The crust theoretically behaves in a brittle fashion above these surfaces and in a ductile fashion beneath them. Some earth scientists place the principal detachment surface beneath much of the Death Valley region at mid-crustal levels (Serpa et al. 1987); others favor a much shallower depth (Wernicke et al. 1988).

Furnace Creek strike-slip fault zone. The best known of the strike-slip faults exposed within the park boundaries compose the Furnace Creek fault zone (fig. 48.3). These define a linear crustal rupture that extends from the vicinity of Brown Peak (fig. 48.2) northwestward for about 150 miles, including Furnace Creek Wash and the full length of northern Death Valley. A major fault in this zone is particularly obvious along the northeast side of Furnace Creek Wash where it brings Miocene and Pliocene strata of the Furnace Creek Basin into contact with the Proterozoic and Paleozoic formations of the Funeral Mountains (McAllister, 1970). The strike-slip fault truncates the southeast-tilted fault blocks of the Funerals. The Miocene and Pliocene strata, being as much as 15,000 feet thick, also require a maximum vertical displacement of a comparable dimension.

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 measurable in tens of miles.

High-angle normal faulting along the Black Mountains front. The precipitous west face of the Black Mountains is one of the world's most spectacular fault-controlled escarpments. It has been produced by movement on high-angle normal faults along which the Black Mountains are tilting eastward and the floor of Death Valley is dropping downward. Geomorphic features of this escarpment that indicate its recency are discussed below.

The Boundary Canyon low-angle normal fault. The Boundary Canyon fault is the most conspicuous of the low-angle normal faults in the Death Valley region. It is exposed in the northern part of the Funeral Mountains and dips gently northwestward beneath the highly folded and faulted formations of the Grapevine Mountains. Thus the Grapevines lie in the upper plate, and all but a small part of the Funerals lie in the lower plate. In the northern Funerals, the lower plate consists of Proterozoic rocks, including all three formations of the Pahrump Group, the Johnnie Formation and the lower part of the Stirling Quartzite (Table 48.1). The upper plate contains the upper part of the Stirling Quartzite and all of the overlying formations through those of Mississippian age (fig. 48.4).

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 (fig. 48.4). 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 (Chapters 45 and 46).

The Boundary Canyon fault is easily discernible along the west face of the Funeral Mountains east of the highway as one approaches the mouth of Boundary Canyon from the south, and 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 sheared units of the middle and lower parts of the Johnnie Formation (fig. 48.4). 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.

The Amargosa fault and the Amargosa chaos. Of the extension-related phenomena of the Death Valley region, 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). Noble originally recognized three phas-

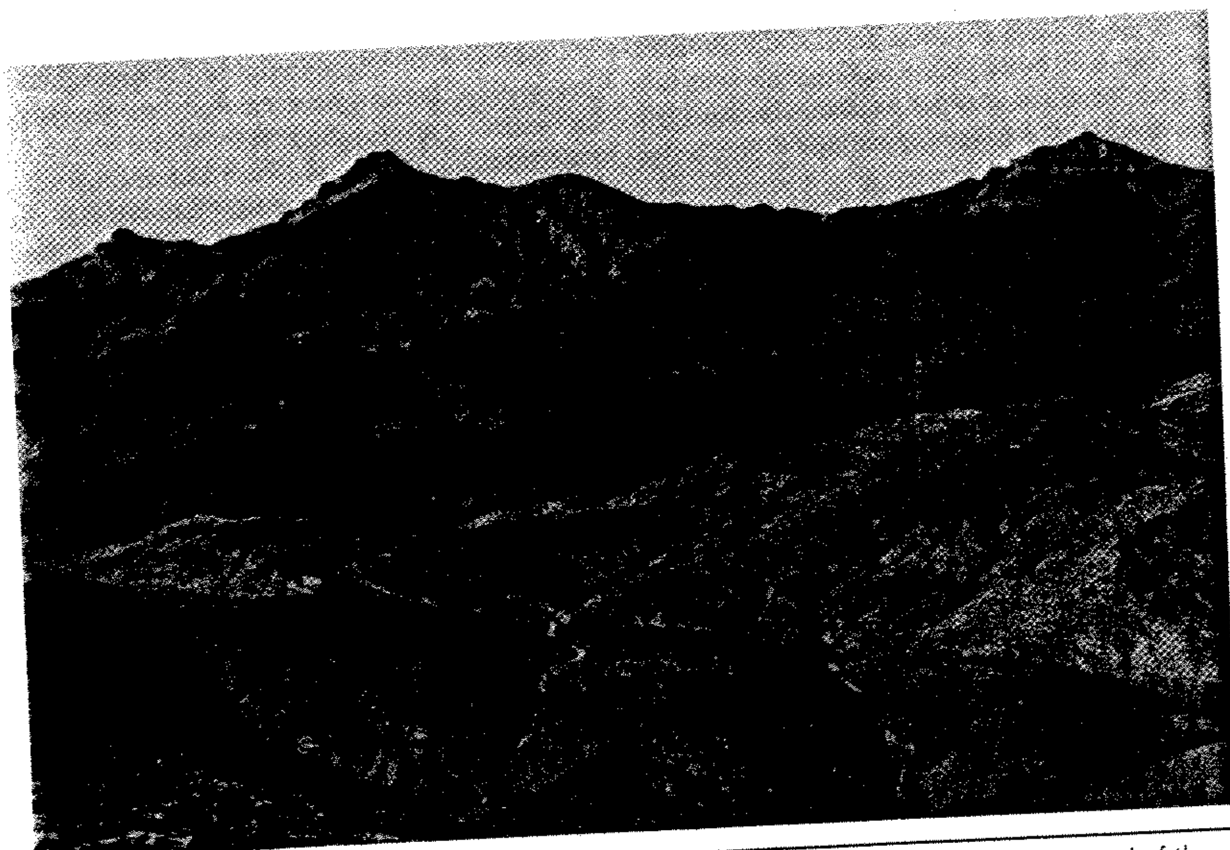

FIGURE 48.4 Northeastward view of the Boundary Canyon detachment fault at the northern end of the Funeral Mountains. The fault, which dips northeast to extend beneath the Grapevine Mountains on the skyline, separates underlying dark-colored, highly metamorphosed rocks of the Proterozoic Johnnie Formation and the Pahrump Group (foreground) from immediately overlying light-colored and essentially unmetaorphosed rocks of the Proterozoic Stirling Formation. Dark-colored Cambrian rock units form the higher slopes of the upper plate. Photo by Martin Miller.

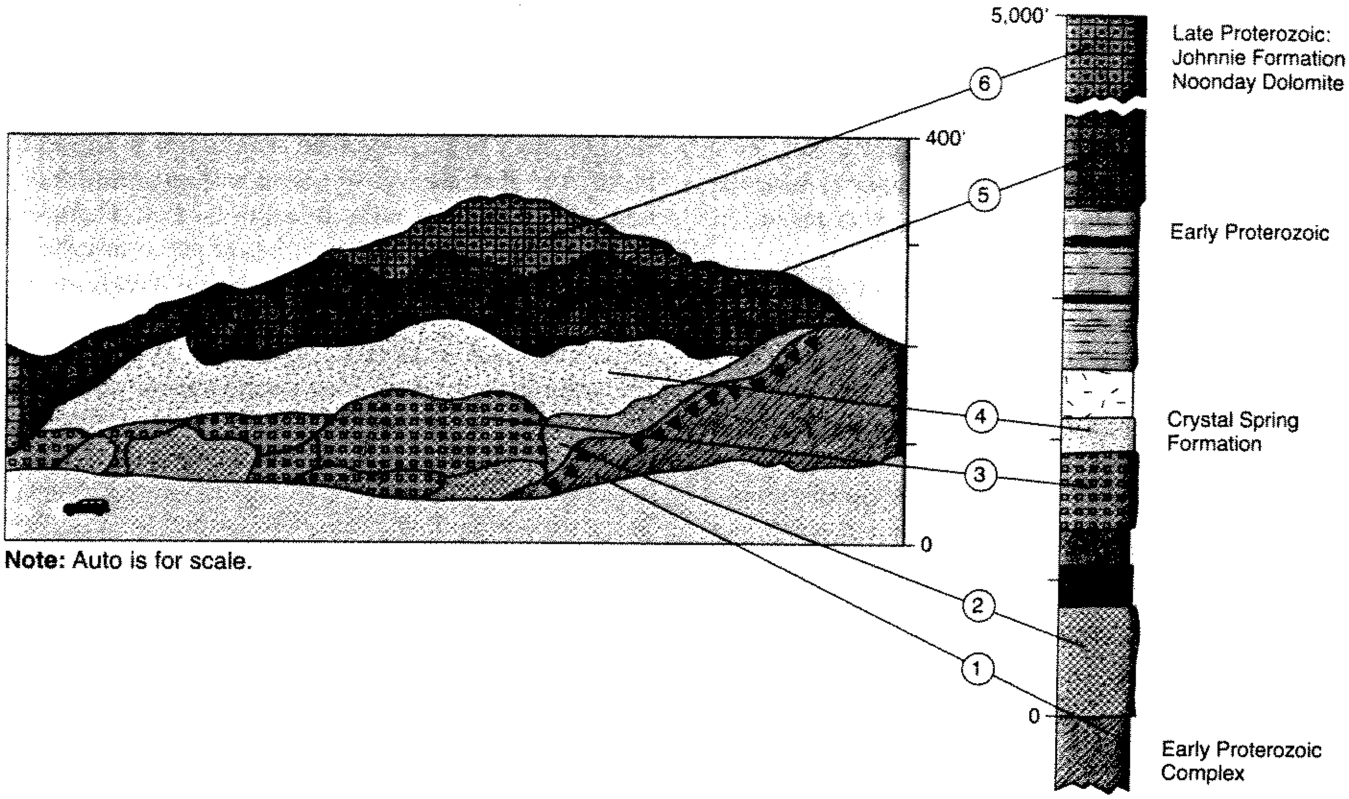

FIGURE 48.5 Sketch of an exposure of the Virgin Spring phase of the Amargosa chaos showing highly attenuated units of the Crystal Spring Formation compared with a columnar section of these units in their natural thicknesses. Modified from Wright and Troxell, 1984.

es 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 part of the Black Mountains from the vicinity of Virgin Spring and Rhodes Washes northward to Gold Valley. An excellent exposure of the chaos lies immediately south of the highway at a point 1.5 miles east of Jubilee Pass.

The general characteristics of this feature are shown in Figure 48.5. 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. Everywhere the chaos rests, with highly sheared fault contact, upon essentially intact occurrences of the Early Proterozoic crystalline complex. All of the faulting is brittle in nature. In the Gold Valley area, in the central part of the Black Mountains, 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. Noble originally interpreted the chaos as remnants of a single thrust fault of regional extent and named by him the "Amargosa thrust." It is now ordinarily viewed as composing segments of one or more low-angle normal faults along which the upper plate has been severely extended. The occurrences of the Amargosa chaos have been so disordered by later faulting and folding as to make its original configuration difficult or impossible to accurately reconstruct.

The Ranges

Although the mountain ranges within the boundaries of Death Valley National Park have formed in a framework of interrelated Cenozoic faults, they differ widely in their structural settings and in the principal rock bodies of which they are composed. Most of the ranges of the Death Valley region qualify as fault-block ranges in that they are bounded on one side by a major normal fault and have acquired much of their relief by tilting along that fault. Examples within the park are the Last Chance Range and the Panamint, Cottonwood, and Black Mountains. The Resting Spring and Nopah Ranges, east of the park boundary, also are of this type. Each trends approximately northward and tilts eastward (fig. 48.3). But this apparent simplicity is deceptive as each of these ranges contains other extension-related faults.

The Funeral and Grapevine Mountains differ from the other ranges in that they lie end-to-end forming a single, northwest-trending topographic high parallel with the Furnace Creek fault zone, which bounds it on the southwest. This composite range has extended along normal faults oriented approximately perpendicular to its backbone. Most of the extension has occurred along the Boundary Canyon low-angle normal fault described earlier. Normal faults that dip more steeply are a feature of the southern part of the Funeral Mountains. The Funerals and the Grapevines also have tilted northeastward as a result of a vertical component accompanying lateral movement on the Furnace Creek fault zone. So in this respect, even these ranges qualify as block-fault features.

Most of the ranges of the Death Valley region display the striped outcrops that identify the evenly bedded Proterozoic and Paleozoic formations. The Black Mountains and Greenwater Range stand out from the rest because they are underlain mostly by the less regular bodies of Tertiary plutonic and volcanic rocks. The Owlshead Mountains, in the southern part of the park, are also distinctive in that they are equidimensional in map view, and apparently coextensive with a cluster of granitic plutons of Mesozoic age. The plutons are discontinuously covered with Miocene andesitic flows and are also offset by strike-slip faults. Most of the latter strike northeast and have moved in a left-lateral sense.

The Basins

The Cenozoic sedimentary deposits that have accumulated in the topographic depressions 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 that terminate in the basins. The sedimentary fill is interlayered with extrusive volcanic rocks.

By observing the shapes of these basins and the distribution of the various kinds of sedimentary rocks that they contain, by dating the extrusive volcanic bodies in the basins, and, on occasion, by employing geophysical methods to detect subsurface features, we can reconstruct the development of the basins and the erosional history of the source areas. The task is hindered by the fact that a cover of Quaternary alluvium 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 have 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-traveled roads of the national park. In the floor of Central Death Valley sediments are accumulating today in a grabenlike "pull-apart" basin bounded on the east by the zone of normal faults that defines the front of the Black Mountains (figs. 48.3 and 48.7). A thick succession of sedimentary deposits and lava flows, of Middle Miocene to Late Pliocene age, is spectacularly exposed in Furnace Creek Wash. This succession defines the Furnace Creek Basin which, because it lies adjacent to the Furnace Creek strike-slip fault zone, has been called a "strike-slip" basin. In the Emigrant Canyon-Towne Pass area on the northwestern flank of the Panamint Mountains, we observe Late Miocene through Pliocene conglomerates and basaltic to rhyolitic lava flows of the Nova Formation which, in turn, defines the Nova Basin. The Nova Formation has been deposited above a low-angle normal fault called the "Emigrant detachment."

The "pull-apart" basin, of which Central Death Valley is representative, is so named because it involves crust that has been pulled apart between the *en echelon* terminations of two strike-slip fault zones in the manner shown in figure 48.3 (Burchfiel and Stewart, 1966). Although the Furnace Creek fault zone extends well to the southeast of the northern end of Central Death Valley basin, this segment has been less active in Pliocene and Quaternary time than the main, more northwesterly trace of the fault zone. So the fault zone has been viewed as effectively terminating in the vicinity of Furnace Creek Ranch during the development of the Central Death Valley basin. The alluvial fans, salt pan, and lake and fluvial deposits of this basin (Hunt and Mabey, 1966) are described later in this chapter.

Of the Cenozoic basinal deposits exposed within Death Valley National Park, those of the Furnace Creek basin are the most obvious and most admired by visitors. In Furnace Creek Wash and the adjoining northern part of the Black Mountains, we observe the various sedimentary units and basaltic to rhyolitic lava flows that identify the Furnace Creek Basin. These were deposited in Middle Miocene through Pliocene time on crust that lies southwest of a major fault in the Furnace Creek fault zone (McAllister, 1970, 1971, 1973; Cemen et al., 1985) and northwest of another major fault exposed in the vicinity of Badwater. The crust there has moved downward, as well as laterally, to form the northeast margin of the elongate, troughlike Furnace Creek basin. The basinal deposits are about 12,000 feet in maximum estimated thickness in the northwestern part of the basin, but are much thinner in the southeastern part.

The panorama of these deposits viewed from Zabriskie Point is among the most photographed in the entire National Park system. Owing largely to the downdip movement on the frontal fault of the Black Mountains, the sedimentary and extrusive volcanic rocks of this basin have been laid bare and are shown to have been folded onto a broad syncline. The northeast-dipping rock units that compose the Middle and Late Miocene Artist Drive Formation are exposed on both sides of the crest of the Black Mountains. The successively overlying Late Miocene Furnace Creek Formation and Pliocene Funeral Formation coincide with Furnace Creek Wash. The conglomerates of the Furnace Creek Formation, exposed on both sides of the wash, accumulated in alluvial fans that bordered a lake-dominated central part of the basin.

To the Death Valley traveler, the interlayered conglomerates and volcanic rocks of the Nova basin are less accessible than are the deposits of the Furnace Creek basin. They are also more disordered and thus less obviously displayed. 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. On the other hand, it is an excellent example of a basin that has evolved in a structural setting of this kind (Hodges et al., 1989).

The Nova Formation is estimated to be more than 6000 feet thick. It is exposed along State Highway 190 both east and west of Towne Pass. 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, as well as elsewhere in the formation, are derived from the Proterozoic formations exposed in the higher parts of the Panamint Mountains.

Geomorphic Features Related to Active Faulting along the Black Mountains Front

Transition from valley floor to mountain front. The extraordinarily abrupt topographic break between the Black Mountains escarpment and the sedimentary fill of the valley marks the approximate location of the Black Mountains fault zone. Here the mountains rise while the valley floor drops. In most places, relatively small alluvial fans spill out of deep canyons at the fault zone; where there are no canyons, the horizontal deposits of the valley floor meet a wall of rock. These features indicate recent vertical movement because erosion has not had time enough to cut back into the mountain front. Much of the mountain front, therefore, qualifies as a *fault scarp,* an exposed surface produced directly by movement on a fault and essentially unmodified by erosion or weathering. When plotted on a map, the mountain front is shown to be a composite of numerous straight-line segments, each representing a single fault rather than one continuous fault.

The morphology of the Black Mountains escarpment provides important information about the nature of the fault that produced it. When viewed from a distance, such as from the Devil's Golf Course, parts of the mountain front appear incredibly smooth and probably do closely coincide with the actual fault surface. If so, the fault dips westward, the Black Mountains are in the footwall, and the relief is an effect of crustal extension.

Fault scarps. Fault scarps in alluvial fans along the Black Mountains front provide additional and direct evidence that the front is presently active. That they are faults rather than stream-cut features is attested by the observation that they cut across stream-related features. Particularly obvious fault scarps cut the fan immediately south of Badwater (fig. 48.6) and other fans at Mormon Point. The scarp at Badwater is aligned with the spring that feeds the Badwater pond and suggests that the spring is controlled by the fault. Other scarps are very well defined between Furnace Creek Inn and Artist Drive and along the range front south of Natural Bridge.

Faceted spurs. Many west-trending ridges, or spurs, in the Black Mountains end abruptly at about an elevation of about 1500 feet. Below and west of the spurs lies the

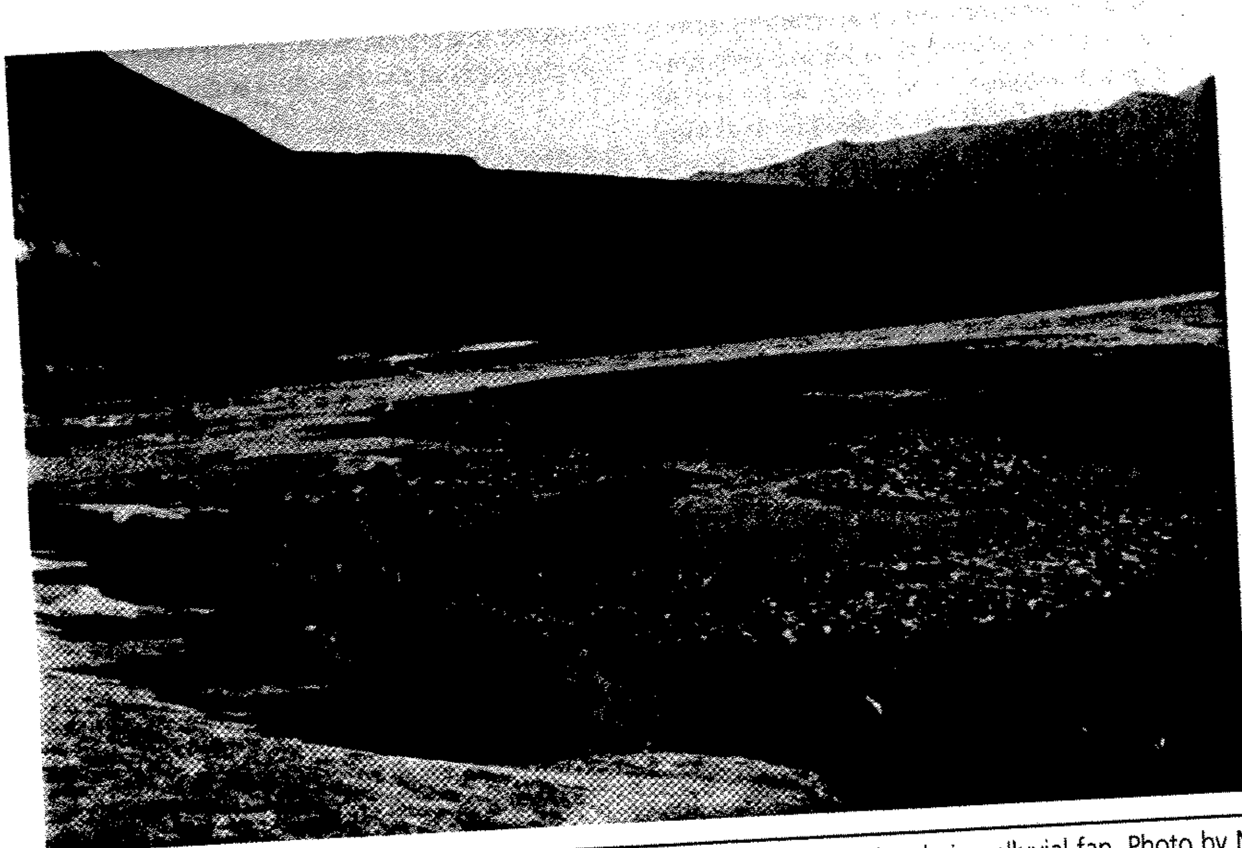

FIGURE 48.6 Spring-fed pond at Badwater aligned with fault scarps in bordering alluvial fan. Photo by Martin Miller.

relatively smooth, steep face of the mountain front which, between the bounding canyons, is triangular in shape. The spur thus appears "faceted," that is, abruptly truncated by the fault zone at the front of the range. Faceted spurs thus indicate that this lower part of the range has been exposed so recently, by the dominantly normal movement along the fault zone, that the spurs remain essentially uneroded.

Wineglass Canyons. On the west side of the Black Mountains escarpment, steep-walled incisions extend eastward into the mountain front. These are the wineglass canyons (fig. 48.7). When viewed from the valley floor, at a right angle to the escarpment, the canyons resemble the cross section of a wineglass. An alluvial fan forms the base of the wineglass; the narrow slot above is the stem; the higher, wider part is the bowl of the glass. The bowls display a rather steep lower part and a flaring, or less steep, upper part. Many of the wineglass canyons have a dryfall at the mouth, at the bottom of the near-vertical stem.

The wineglass stem records the most recent, and still continuing, episode of downdip movement on the frontal fault (i.e., the fault along the base of the mountain). The vertical walls are the result of rapid downcutting by stream action. The bottom of the wineglass bowl marks the former position of the valley floor and indicates a stable interval long enough to permit the canyon to widen by the processes of stream erosion and mass wasting. The less steep, higher part of the bowl is attributable to a still earlier and apparently longer interval of little or no downcutting. The longer period of time would have permitted the canyon to widen to a greater degree than it did during the preceding stable interval.

Particularly good examples of wineglass canyons along the Black Mountains escarpment are at Gower Gulch, immediately south of Golden Canyon, and at Tank Canyon, 0.3 mile south of Natural Bridge. Numerous others can be seen between Badwater and Mormon Point. Titus Canyon along the front of the Grapevine Mountains is still another.

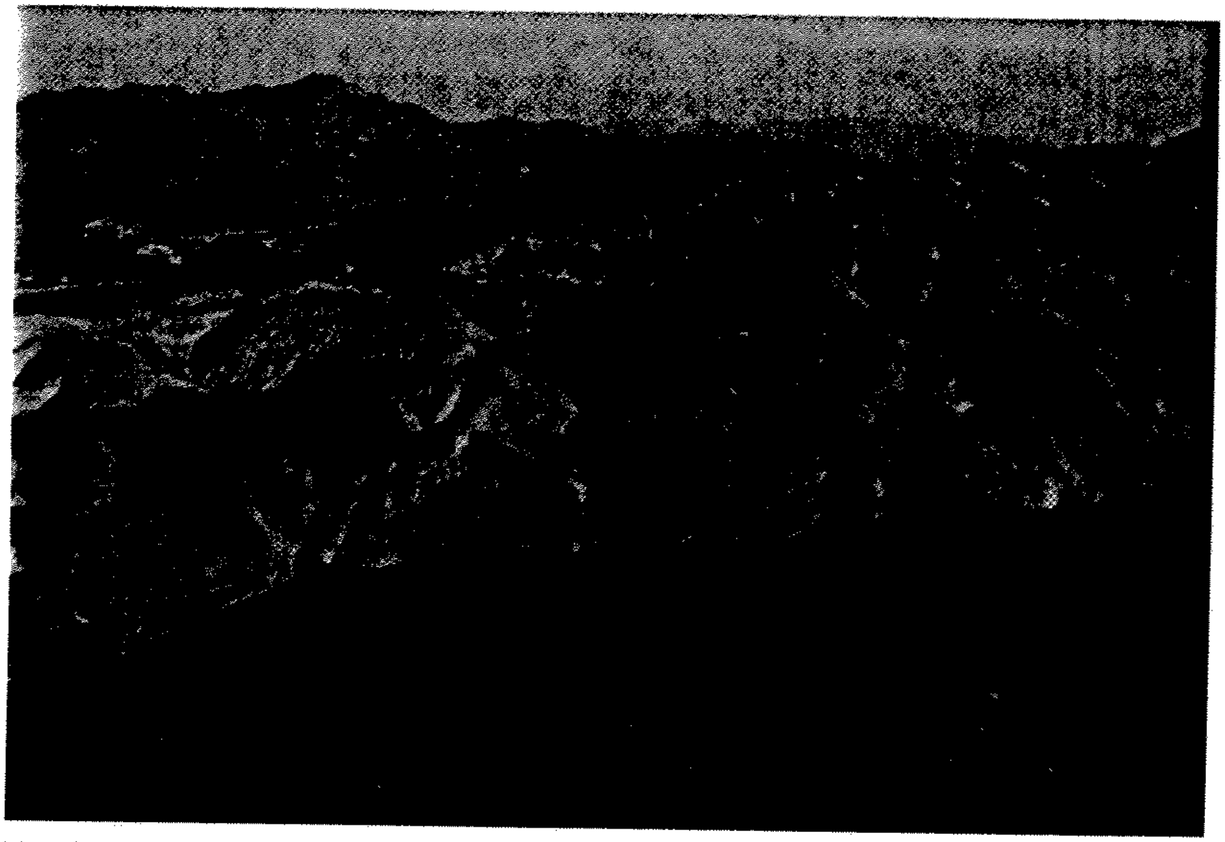

FIGURE 48.7 A wineglass canyon incised in the Black Mountains escarpment. Photo by Martin Miller.

Smaller faults. Much of the bedrock along the Black Mountains front is broken or crushed by movement along the frontal fault zone. Small-scale faults parallel the frontal fault zone and probably formed during movement on it. Where well exposed, these faults display striated surfaces formed by abrasion during slip, the striations being parallel to the direction of movement. The striations on many of these faults trend obliquely and suggest a strong lateral motion during the uplift of the Black Mountains.

Turtleback surfaces. At three places along the west face of the Black Mountains, the mountain front lacks the nearly planar appearance produced by the faceted spurs, and displays the well known and much debated "turtleback" surfaces. One is in the vicinity of Badwater, another immediately south of Copper Canyon (fig. 48.8), and the third at Mormon Point. Each of these features (1) is a convex upward topographic surface, shaped like a turtle shell; (2) curves northeastward into the mountains; and (3) is underlain by a core of the ancient basement complex, mantled by younger, metamorphosed units, consisting mostly of marble. The mantling rocks have been consistently correlated with the Noonday Dolomite and the Johnnie Formation. Both the basement complex and the overlying younger metamorphic rocks have been broadly folded along northwest plunging axes.

The turtleback surfaces owe their identity to the fact that they are also fault surfaces exposed so recently that they remain essentially uneroded. The faults themselves are excellently exposed along the base of each turtleback surface, where they place the cores of the ancient metamorphic rocks against overlying Cenozoic igneous and sedimentary rocks. Like the other faults along the Black Mountains front, the turtleback faults are normal faults. The turtleback faults differ from the range front faults, however, in that they form surfaces against which many faults in the overlying rocks terminate. In this way the turtleback faults allow the overlying rocks to deform independently of the underlying rocks. The distinctive turtle-shell shapes simply reflect the large folds in the metamorphic rocks below the faults. This control is enhanced by the ten-

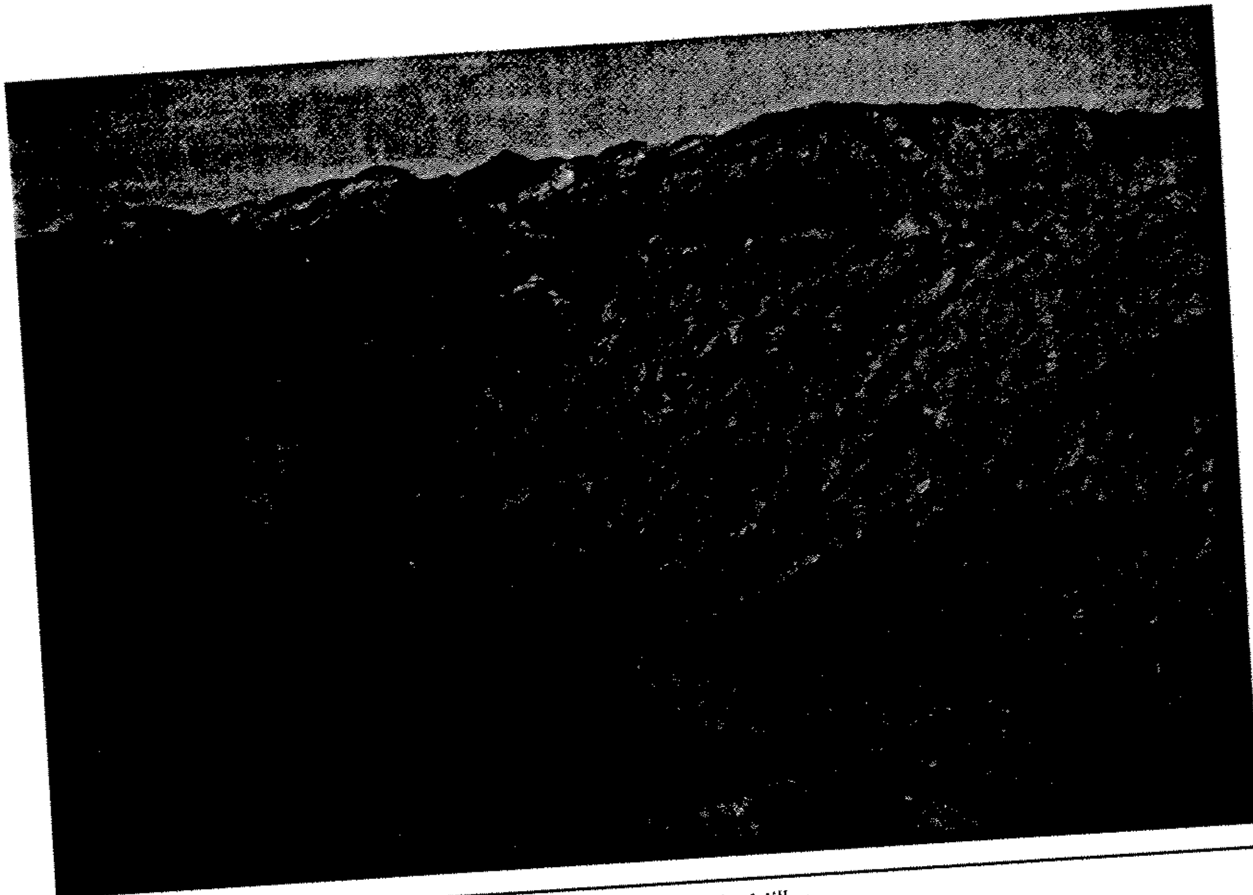

FIGURE 48.8 Badwater turtleback surface. Photo by Martin Miller.

dency of the turtleback faults to parallel the foliation in the folded metamorphic rocks (Miller, 1991).

The textures and compositions of the metamorphic rocks that mantle the ancient complex below the turtleback faults indicate that the folding occurred at higher temperatures than exist near the surface. The temperatures were hot enough to cause the rocks to flow instead of fracture. These features provide evidence that these metamorphosed rocks have risen from relatively deep crustal levels along downward projections of the turtleback faults.

The Black Mountains and the Basin Ranges from Dantes View

From Dantes View at the crest of Black Mountains, nearly 5800 feet above the valley floor, the visitor gains a perspective of Death Valley that is equally instructive but different from the one obtained from below. To the east and west, the landscape consists of alternating, nearly parallel mountain ranges and intervening basins. This basin-and-range topography characterizes much of the western United States, including all of Nevada, and parts of southern Idaho and southeastern Oregon, western Utah, eastern California, and southern Arizona. Like Death Valley, this topography exemplifies crustal extension, where mountains rose relative to basins along large normal faults.

The perspective from Dantes View also shows the asymmetry of the Black Mountains. Their west flank is steep! It drops more than a mile vertically to the floor of Death Valley, which is only about two horizontal miles away. By contrast, the east flank descends gradually into Greenwater Valley. This asymmetry reflects an eastward tilting of the range as it rises along the Black Mountains fault zone. On the drive down from Dantes View, for example, one can see, to the northeast, tilted volcanic flows along the crest of the Black Mountains.

A careful look across the valley at the Proterozoic and Paleozoic sedimentary rocks of the Panamint Mountains reveals that they also tilt eastward. This tilt is partly a result of normal faulting along the western margin of the range (fig. 48.9). One also observes that the alluvial fans on the west side of the valley are far larger than those on the east side (fig. 48.9). Much of this difference can be explained by the observation that the Panamint Mountains are about twice as high as the Black Mountains and have been more deeply eroded. The difference is probably also attributable to evidence that the floor of the valley is tilting eastward, causing the ends of the fans to be buried in playa sediments (Hunt, 1975).

Lake Manly

At many places in Death Valley we see evidence that this undrained depression was once occupied by a relatively deep and extensive body of saline water known as Lake Manly. Indeed, an actual lake, nonetheless only a few inches deep, does occupy Central Death Valley during seasons of above average rainfall. The most obvious evidence that the lake was once much deeper exists in narrow, horizontal benches, commonly veneered with beach gravels, formed when the lake level was stationary long enough for waves to cut them. These exist at many localities peripheral to Central Death Valley. They are most numerous and best preserved at Shoreline Butte west of the Ashford Mill site in southern Death Valley. They are also well preserved in the faulted alluvial fans exposed on the northeast side of Mormon Point (fig. 48.10).

As the lake advanced and retreated, gravel bars and accumulations of tufa (calcium carbonate) were deposited along its shores. An excellently preserved gravel bar is cut through by the highway to Beatty, about 2 miles north of Beatty Junction. Nearly horizontal accumulations of tufa, mixed with fragments of the underlying bedrock, cling to the Black Mountains front and are almost continuously in view between Badwater and Mormon Point.

Playa Lakes and the Death Valley Salt Pan

Death Valley National Park contains a number of ephemeral lakes, called playas. Of these, the best known are the salt pan of Central Death Valley and the

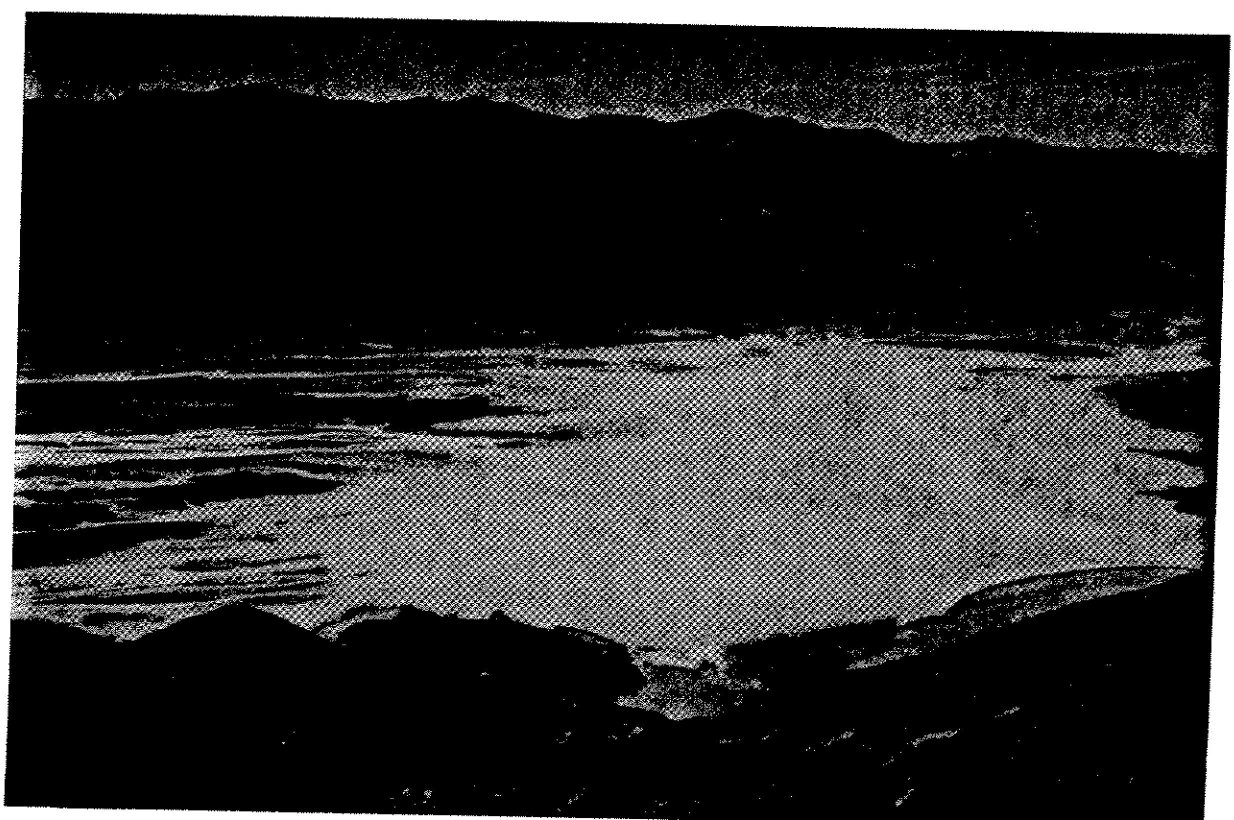

FIGURE 48.9 Looking west from Dantes View on the crest of the Black Mountains. The salt pan is below, with the Panamint Mountains rising beyond. Alluvial fans border both sides of the salt pan but those on the west side, along the base of the Panamints, are much larger. Photo by Martin Miller.

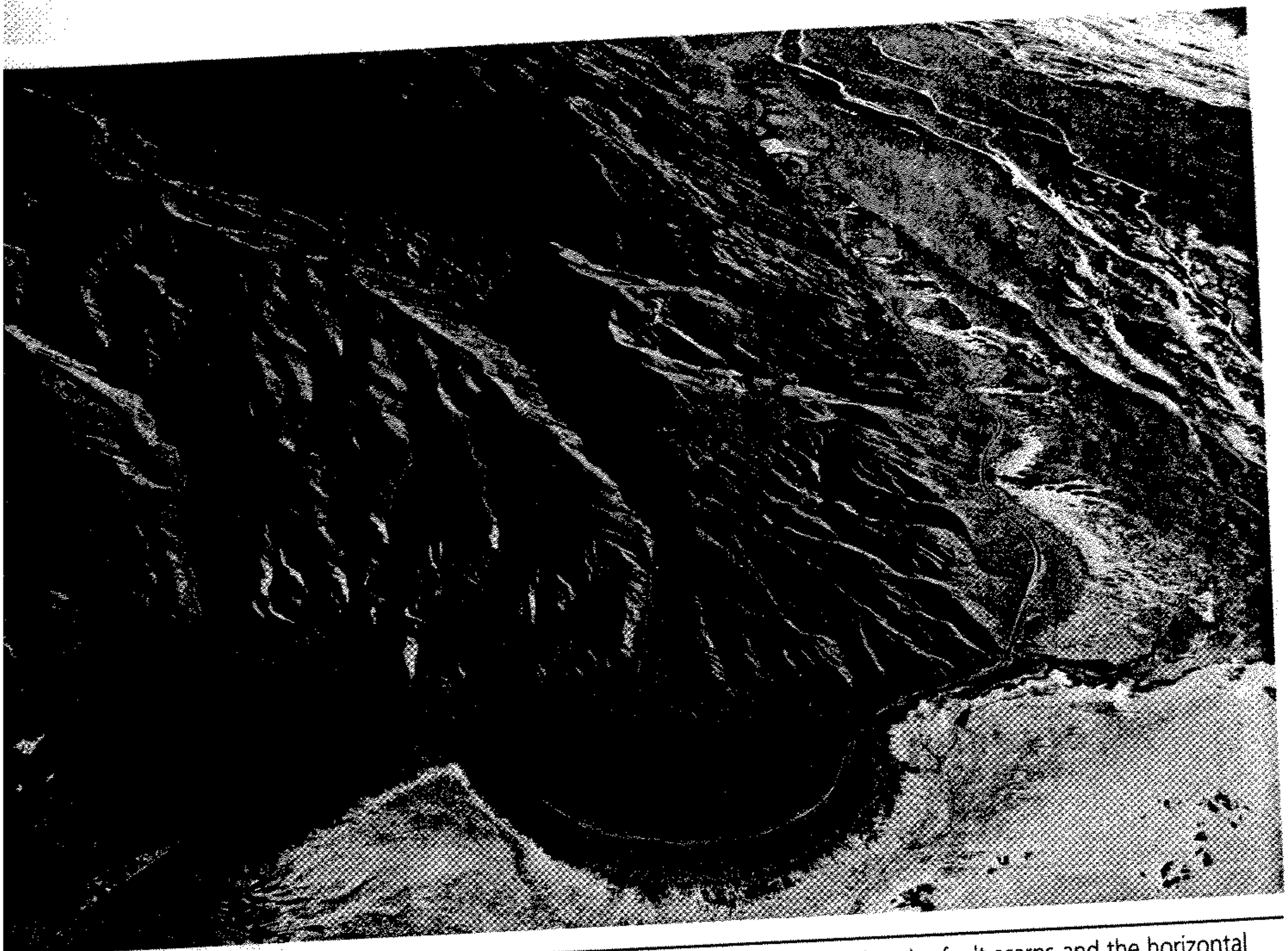

FIGURE 48.10 Dissected alluvial fans east of the Mormon Point showing the fault scarps and the horizontal benches cut by Lake Manly. Photo by Martin Collier.

Racetrack playa, although large playas also occupy much of northern Death Valley, northern Panamint Valley, and Saline Valley. During rainy periods these exceedingly flat features may become "flooded" with less than an inch to more than a foot of water. The aridity, however, causes the water to quickly evaporate and leave behind the sediment and dissolved minerals it carried into the playa. Most playas, therefore, are covered by dry, cracked mud commonly associated with evaporites.

The Death Valley salt pan is one of the largest modern salt pans on earth. Although its exact boundaries are poorly defined, it extends from the vicinity of the Ashford mill site northward to the Salt Creek Hills, a distance of about 40 miles. The salt pan is essentially a gigantic, flat sink without a drain. The Amargosa River, which is usually dry, empties into it from the south. It is fed from the north by Salt Creek and from various directions by runoff and spring water originating within the limits of Death Valley. Because this water contains dissolved salts that precipitate as the water evaporates, new salt is continually added to the pan. Much of the salt pan is actually the broad and flat distributary terminus of the Amargosa River. In a strict sense, this part is not a playa, but a low-relief river delta system with alternating channels and flood plain areas. From Dantes View these channels can be seen to extend as far north as Badwater.

Visitors to Death Valley can walk onto the salt pan from nearly anywhere along the Black Mountains front.

At the Devil's Golf Course one can see pinnacles of salt rising above the surface of the pan (fig. 48.11). Polygon-shaped blocks, from one to two meters across, are produced by desiccation of the salt pan. As the water evaporates and the mud beneath the surface dries, cracks develop between the blocks and are then filled with veins of new salt. These ordinarily stand with slight topographic relief above salt within the polygons.

Tire tracks, made by inconsiderate visitors, are visible at many places along the margin of the salt pan. These off-roaders are likely to become mired in the salt mush and require towing. As many of the tracks are more than 20 years old, they graphically record the length of time required for natural processes to heal these scars.

Zonation of the salt pan. Most of the salts in the salt pan are chlorides, of which halite, ordinary table salt, is the most common. Deposits of sulfate and carbonate evaporites, being less soluble than the salt, precipitate before it does and are distributed along the edges of the pan. Hunt and Mabey (1966) showed that the carbonate and sulfate zones are much wider and better developed on the east side of the salt pan than on the west side. They reasoned that the difference was due to a gentle eastward tilting of the salt pan along the normal faults of the Black Mountains front that caused the dissolved salt to migrate there.

Underneath the salt pan. Before Death Valley became a National Monument in 1933, the Pacific Coast Borax Company drilled several exploratory holes into the salt pan in the search for potash (Hunt and Mabey, 1966). These penetrated the valley fill to depths of as much as 1000 feet. Individual drill cores showed that the valley fill ranges in composition from mostly salt, through salt plus other evaporites and clay, to mostly clay with minor proportions of evaporites. The salt-rich parts of the cores thus bear evidence of an arid climate much like that of today, whereas the clay-rich parts indicate less arid times when the basin was occupied by a perennial saline lake from which evaporites were occasionally precipitated. Strong negative gravity anomalies beneath the present salt pan are indicative of the presence of materials of low specific gravity. The anomalies also show that the valley fill is several thousand feet thick and probably includes Late Tertiary as well as Quaternary strata.

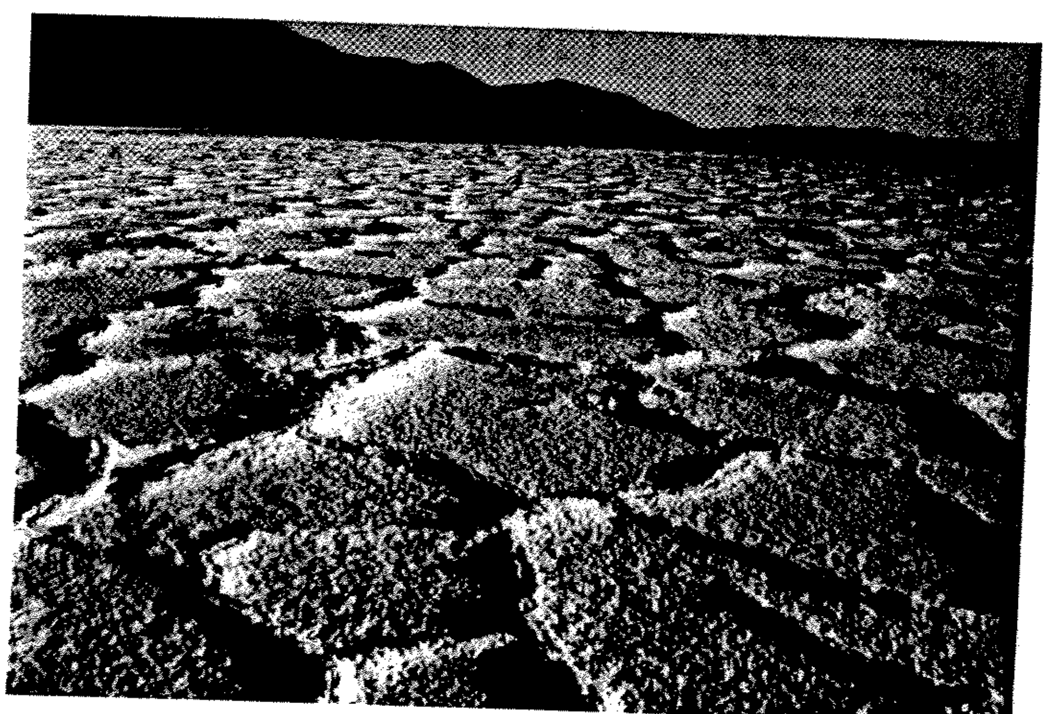

FIGURE 48.11 Polygonal blocks about three to six feet across, in the salt pan of Central Death Valley. Photo by Martin Miller.

Young Volcanic Features

Evidence of volcanic eruptions that have occurred within the last one million years can be viewed at two easily accessible localities within the park. At the northeast edge of the Cottonwood Mountains, Ubehebe Crater (fig. 48.12) and several smaller craters formed between 2000 and 3000 years ago. Ubehebe Crater is 450 feet deep, half a mile wide and centrally located in the midst of the other craters. They resulted from numerous explosions, generated when rising basaltic magma contacted groundwater and flashed it to steam. Small explosions that formed the smaller craters were followed by a much larger explosion resulting in the creation of Ubehebe Crater. No lava was extruded, but black cinders and ash, as much as 150 feet thick, blanket an area of about six square miles. Highly colored alluvial deposits underlie the cinders and are exposed in the walls of Ubehebe Crater. The colors are best attributed to oxidation, just prior to the eruptions, by percolating hot ground water.

In southern Death Valley, near its confluence with Wingate Wash, a basaltic cinder cone less than 400,000 years old projects above the valley floor. The cinder cone (fig. 48.13) appears as two red hills, easily visible from the highway southeast of Mormon Point. The hills mark the opposite sides of a cone, originally intact, but now offset several hundred meters by right-lateral movement on a strand of the Southern Death Valley fault zone.

Sand Dunes

Dune fields are widely distributed in Death Valley National Park, but, contrary to a common perception, they underlie a very small fraction of the total area of the park. The most frequented, most photographed and also one of the largest, occupies part of Mesquite Flat north of Stovepipe Wells (fig. 48.14). It borders State Highway 190 on the north and is also accessible from a picnic area at its eastern edge. Equally photogenic, but less accessible dune fields, include those near Saratoga Springs in southern Death Valley, in northern Panamint Valley, and in southern Eureka Valley.

Sand dunes require a steady supply of sand, wind, and a windbreak to bring the sand to rest. Most of the

FIGURE 48.12 Aerial view of Ubehebe and adjacent craters, about a half mile across, with a dark rim of basaltic cinders above colored walls. Photo by Martin Miller.

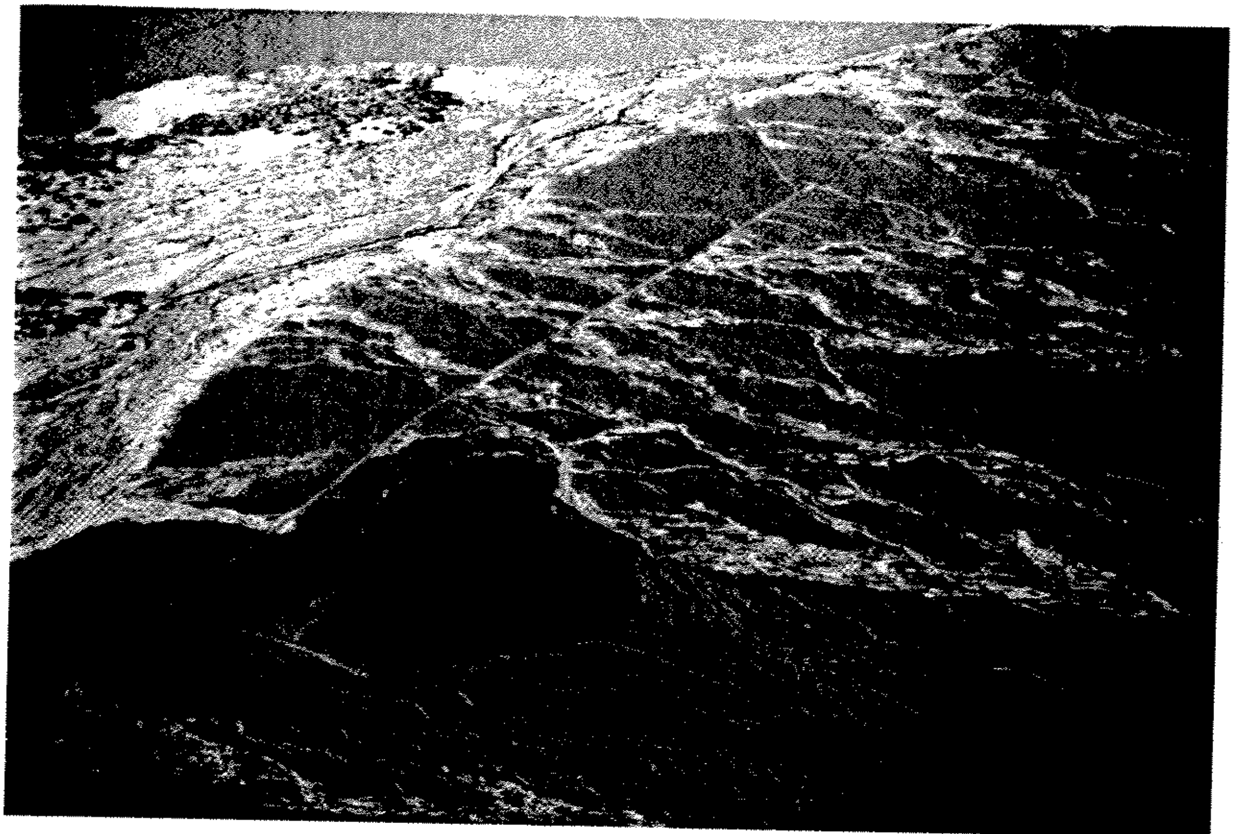

FIGURE 48.13 Quaternary cinder cone that has been offset (sliced in two) by a fault in the Southern Death Valley fault zone. The straight line beyond the cinder cone is a state highway. Photo by Martin Miller.

sand in dune fields of the park originated as water-transported detritus carried from the mountains to areas intermediate between the edges of the alluvial fans and the silty central parts of the inter-mountain playas. Dunes of the Death Valley area tend to form close to the source areas. They are small in the central part of Death Valley as much of the sand there has become cemented in the salt pan (Hunt and Mabey, 1966).

The Central Death Valley Plutonic-Volcanic Field: a Fault-controlled Igneous Terrane

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 reason for the localization of the Cenozoic rocks probably lies in the tectonic setting of the rhombic area that contains them. Like the still younger pull-apart basin of Central Death Valley, this terrane is bounded on the northeast and southwest by the apparent *en echelon* terminations of two right-lateral strike-slip fault zones, the southeastern part of the Furnace Creek fault zone on the northeast and the northwestern part of the Sheephead fault zone on the southwest (fig. 48.3). The igneous bodies that compose the Central Death Valley plutonic-volcanic field are thus theoretically confined to a part of the crust that has been extended more than the surrounding region (Wright et al., 1991). In the early stages of the extension, the Proterozoic rocks that once underlay this area were highly faulted and greatly reduced in thickness as in the Amargosa chaos. These rock bodies are largely hidden beneath the less deformed cover of volcanic and Cenozoic volcanic and sedimentary rocks.

The history of Cenozoic igneous activity within the Central Death Valley region began between 12 and 11 million years ago. Within that interval the composite pluton of the Willow Spring gabbrodiorite was intruded at the site of the Black Mountains and dacitic flows were extruded at the location of the Resting Spring

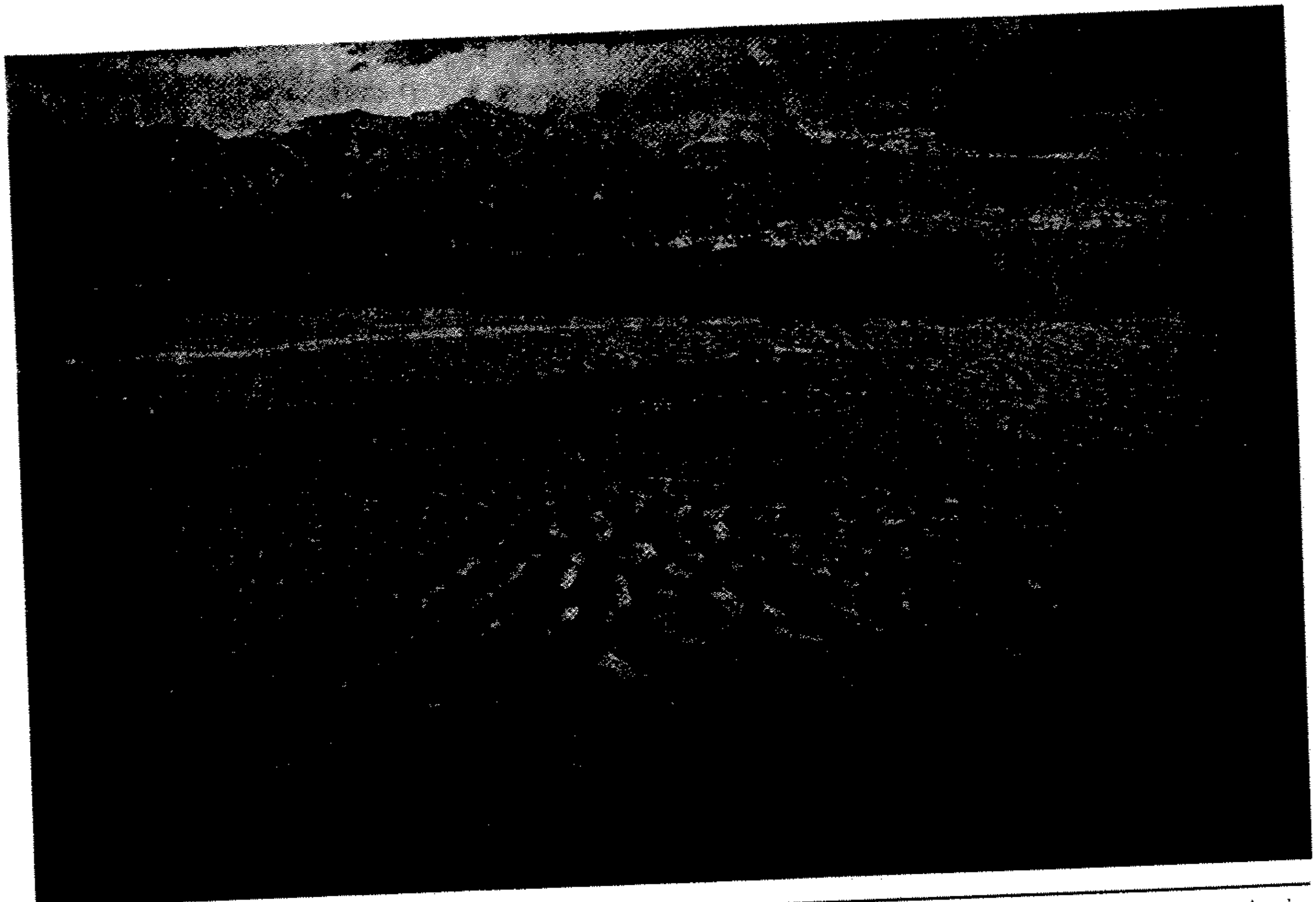

FIGURE 48.14 Aerial view, looking east, of sand dunes near Stovepipe Wells, with the Grapevine Mountains in the distance. Star dunes, with three or more arms, lie near the lower right of the photo; crescentic dunes, with only two arms, are the elongate dunes on the lower left. Star dunes are apparently the result of variations in the prevailing wind directions. Photo by Martin Miller.

Range, east of the eastern boundary of the park. From 11 to 10 million years before the present, 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 exposed in the vicinity of the 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. 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 9.2 million years old. 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 before the present.

Springs

Parts of Death Valley have a surprising abundance of spring water. Springs in the area of Furnace Creek Wash, for example, discharge approximately 2000 gallons per minute, easily enough to supply the park village. Elsewhere in Death Valley, particularly along the mountain fronts, springs provide most of the water that supports its diverse and fascinating ecology. Here, as in other areas, springs mark the places where ground water, flowing from higher to lower levels, reaches the surface of the land. Most of the springs in the Death Valley region emanate from fault zones or the toes of alluvial fans (Hunt, 1975). Fault-controlled springs abound along the fronts of the Grapevine, Funeral, and Black Mountains. Some of the more accessible of these are the spring at Badwater, Travertine Spring in Furnace Creek Wash, and the Keane Wonder Spring at the front of the Funeral Mountains just north of the Keane Wonder mine. Klare Spring, along the road down Titus Canyon in the Grapevine Mountains, issues from a fault zone within the mountains.

Water discharges from the toes of alluvial fans where the highly permeable sand and gravel of the fan grades abruptly into the less permeable sand, silt, and clay of the bordering playa. The alluvial fan at the mouth of Furnace Creek is a spectacular example of this kind of spring environment. Numerous spring-fed lines of vegetation originate at the fan-to-playa transition and radiate outward onto the playa. Many other springs, such as Shorty's Well and Bennett's Well, lie at the toes of the fans that slope eastward from the Panamint Range.

The springs that supply water to Salt Creek, on the floor of northern Death Valley, formed differently. North of the springs, ground water moves easily through the permeable alluvium on the floor of the valley. The springs mark the places where the ground water rises upon encountering the impermeable fine-grained strata of the Miocene Furnace Creek Formation. Southward and downstream from there, Salt Creek disappears back into the alluvium.

Most of the water that feeds the fault-controlled springs in the Funeral and Grapevine Mountains originates in the high country of southwestern Nevada. The limestone and dolomite in the Paleozoic formations of the region serve as aquifers. Devil's Hole, a fault-controlled spring on the east edge of the Amargosa Desert and an outlier of Death Valley National Park, provides a "window" into the carbonate aquifer. There, water discharges from a cave in limestone bedrock, but does not escape to the surface. Instead, it forms a pool that is the sole habitat for a rare species of pupfish. Most of the water then continues upon its journey to the springs of Death Valley.

Geologic History

Events That Preceded the Formation of the Present Basins and Ranges

To reconstruct the geologic history that preceded the formation of the present basins and ranges of the Death Valley region, one must theoretically fit these pieces back to where they were before this latest fragmentation began. This procedure involves a restoration of the displacements on the major faults that bound the present ranges. It is not a simple task and markedly different reconstructions have been proposed. But geologists concerned with deciphering the earlier events generally agree that they include the ones shown in Table 48.1 and described in the summary that follows.

1. The ancient basement and prolonged erosion.

The oldest rocks in the Death Valley region are those of an Early Proterozoic crust that served as a basement for the thick accumulations of younger Proterozoic and Paleozoic rocks that underlie most of the ranges of the Death Valley region. This basement consists of a complex of metamorphosed sedimentary and igneous rocks and is characterized by abundant quartz and feldspar. Commonly called a "crystalline complex," it is ordinarily recognizable from a distance by its somber gray color and the nearly featureless nature of most of its exposures. The complex underlies each of the turtleback surfaces along the Black Mountains front. It also is abundantly exposed in the southern part of the Black Mountains and in the Talc and Ibex Hills still farther to the south. The metamorphism has been dated by radiometric methods at about 1.7 billion years bp. This is also the age of similar complexes exposed elsewhere in the southwestern United States. The complex contains belts of pegmatite dikes and widely distributed bodies of granite. A body of this ancient granite in the Panamint Mountains has been dated radiometrically at about 1.4 billion years bp. Except for the intrusion of the granite, little is known of the geologic history of the Death Valley region during the 500-million year interval between the metamorphism of the basement complex 1.7 billion years ago, and the deposition of the lowest beds of the overlying Pahrump Group probably about 1.3 billion years ago. Clearly, however, this was an interval of long-continuing erosion because deep erosion is required to expose a bedrock formed under conditions of higher temperatures and pressures than existed at the surface. Thus, before the basal beds of the overlying Pahrump Group were laid down, large volumes of detritus must have been removed and redeposited, but no one knows where (fig. 48.15).

2. The Pahrump Group: Proterozoic basins and uplands.

The sedimentary rocks of the Pahrump Group are characteristically several thousands of feet thick. The Pahrump Group is composed, in upward succession, of the Crystal Spring Formation, the Beck Spring Dolomite, and the Kingston Peak Formation. These formations underlie much of the west side of the Panamint Mountains. In the northern Funeral Mountains they occupy the northern part of the lower plate Boundary Canyon fault. They also are exposed at numerous localities in a belt that extends eastward from the southern Panamints to the east side of the Kingston Range. In the Funeral Mountains and in the central and northern part of the Panamint Mountains, these formations have been highly metamorphosed. Elsewhere they remain but little changed from their original state. Within the park boundaries, the most accessible exposures lie along and east of the front of the Black Mountains, east and southeast of the Ashford Mill site (Wright and Troxel, 1984). All of the Pahrump units described below, as well as the overlying Noonday Dolomite, Ibex Formation, Johnnie Formation, and Stirling Quartzite, can be inspected in a half-day traverse of that locality.

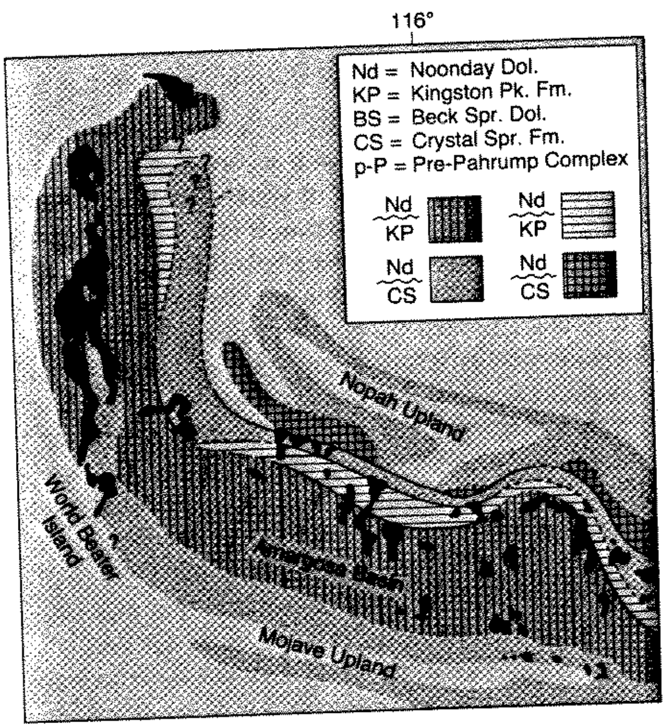

FIGURE 48.15 Map showing paleogeograpic and paleogeologic features of the Death Valley region just before the Noonday Dolomite was deposited. Dark green areas indicate the present exposures of the Pahrump Group. These extend from the Panamint Mountains on the west to the Kingston Range on the east and from the Silurian Hills on the southeast to the northern Funeral Mountains on the north. Linear and dotted patterns indicate the rock units that underlie the Noonday Dolomite. Stipple patterns show high areas from which debris was shed in Kingston Peak time. The original pattern has been distorted by Mesozoic compression and Cenozoic extension. Modified from Wright and Prave, 1992.

The Pahrump chronicles a succession of events beginning more than a billion years ago when, in the region in and about Death Valley National Park, uplands of the crystalline complex rapidly rose above a shallow sea. The uplands were then dissected and partly buried in eroded sediment ranging from arkosic conglomerate to muddy debris. These strata form the lower part of the Crystal Spring Formation.

The entire seascape was then blanketed by a vast bank of dolomite and limestone growing in shallow water and covered by a laterally continuous algal mat. This deposit forms the middle part of the Crystal Spring Formation. The algae-related and variously shaped columnar structures, known as stromatolites, are abundantly preserved in it. The mat was destroyed by the influx of fine-grained detritus preserved in the siltstones and sandstones in the upper part of the Crystal Spring. This event was followed by the intrusion of sills of diabase above and below the carbonate body. The lowest of the sills extended over hundreds of square miles of this ancient terrane and caused the basal carbonate strata to alter to bodies of commercial talc.

Then the environment reverted to that of a shallow sea and another algae-blanketed carbonate bank, now evidenced in the thinly laminated beds of the Beck Spring Dolomite. These and other Proterozoic algal mats survived on such an extensive scale mainly because animals that feed on algae had not yet evolved.

Again the crust was broken into blocks that formed islands in the Proterozoic sea, and Crystal Spring and Beck Spring rocks were exposed to erosion. Consequently, thick deposits of conglomerates containing abundant clasts derived from these earlier units, along with finer-grained clastic sediments, accumulated in basins between the new or rejuvenated high areas. These strata comprise the Kingston Peak Formation. Some of the conglomerates qualify as *diamictites* in that they are poorly sorted and contain a wide range of particle sizes. Diamictites thus resemble glacial till. Other parts of the Kingston Peak consist of thinly laminated sandstone and siltstone in which clasts of boulder size and larger are embedded. For obvious reasons, these clasts are called "dropstones." The combination of the two textures provides evidence for a glacio-marine environment. Many geologists associate these deposits with a wave of glaciation that swept over the crust of North America 700 to 800 million years ago. Basaltic flows, locally present in this upper part of the Pahrump Group, mark the renewal of mafic magmatism.

3. The Noonday Dolomite, Ibex Formation and Johnnie Formation: foreshadowing the environment of a passive continental margin

The Noonday Dolomite, its deeper water equivalent called the Ibex Formation, and the overlying Johnnie Formation occupy an intermediate stratigraphic position between the Pahrump Group and the thick succession of uppermost Proterozoic and Paleozoic strata that has been long viewed as deposited along an evolving *passive continental margin,* (i.e., a margin associated with rifting). The deposition of the three formations thus theoretically just preceded the splitting of a preexisting continent into two continents separated by a widening expanse of oceanic crust.

The Noonday, which is ordinarily about 1000 feet thick, is yet another algal carbonate unit. Being a cliff-former and colored a distinctive pale yellowish gray, its exposures are particularly easy to recognize, even from miles away. The Noonday and its lateral transition to the Ibex Formation are well exposed above the Pahrump Group at the locality east of the Ashford Mill Site.

There and at other places extending from the Panamint Mountains as far east as the Kingston Range, the contact between the Noonday Dolomite and the underlying Pahrump is an angular unconformity that truncates progressively older units of the Pahrump Group northward. In its most northerly exposures along this belt, the Noonday Dolomite overlies the ancient basement complex. These relationships define a high area in the ancient topography from which much or all of the Pahrump Group was eroded before the Noonday was deposited (fig. 48.16). At more southerly localities, either the Noonday or the Noonday-correlative Ibex Formation lies concordantly upon the Kingston Peak Formation. In the lateral transition from the Noonday Dolomite to the Ibex Formation, the shallow water, algae-related carbonate strata abruptly give way to a succession composed mostly of thinly bedded siltstone and limestone deposited in deeper water in a setting reminiscent of a continental shelf on a small scale.

4. The Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite: the clastic wedge of a developing continental margin

These Late Proterozoic to Early Paleozoic formations (Table 48.1), are widely exposed in the Death Valley region. Within the park, the Wood Canyon is particularly accessible. In this region the formations average about 6000 feet in combined thickness. As they consist mostly of well cemented sandstones and conglomerates, they are more resistant than the underlying, varicolored and shaly Johnnie Formation and the overlying, also varicolored Carrara Formation. The Wood Canyon Formation is particularly accessible west and north of the highway in the vicinity of Hells Gate between the Funeral and Grapevine Mountains. All three formations are well exposed on the north face of Tucki Mountain at the north end of the Panamint Mountains.

By analogy with sedimentary wedges that have accumulated along existing continental margins, geologists view this succession as deposited during the rifting stage of an early margin. They have reasoned that, at that earlier time, the ancient quartz- and feldspar-rich basement complex was split in two and was exposed along the edges of the two developing continents. Thus the Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite are interpreted as debris eroded from the edge of the more easterly continent and deposited as a wedge on the newly rifted crust (fig. 48.16).

These formations also provide the earliest evidence, in the Death Valley region, of complex life forms. They contain the remains of metazoan life forms, particularly trilobites, and also other features, such as tracks and burrows, left by these creatures that rapidly appeared and populated the early oceans. In recent years, fossils of the enigmatic Late Proterozoic Ediacara fauna have been found in the Wood Canyon Formation.

5. The Paleozoic and Early Mesozoic carbonate shelf

The rest of the Paleozoic section in the Death Valley region is dominated by dolomites and limestones and is about 20,000 feet thick (fig. 48.16). These formations constitute the sedimentary record of a long-continuing and slowly subsiding continental shelf. Here they were deposited, with little evidence of disturbance, above the wedge of clastic sediments deposited during the preceding stage of rifting. The carbonate sedimentation was interrupted by numerous periods of emergence and, in Middle Ordovician time, by the deposition of the

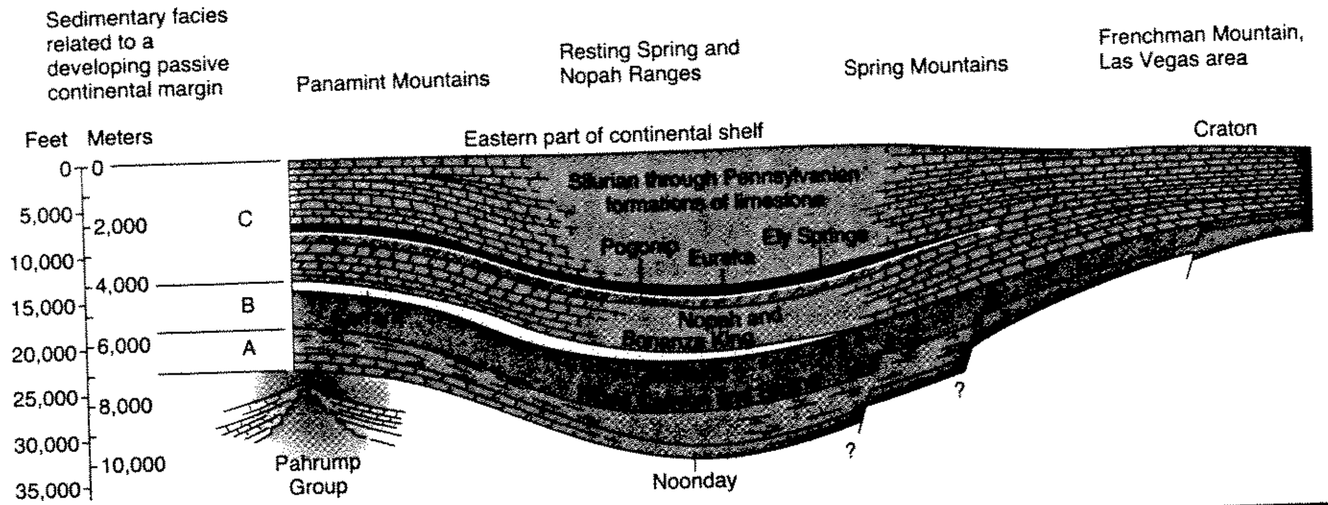

FIGURE 48.16 Stratigraphic cross section of Proterozoic and Paleozoic rock units of the southern Great Basin, including the formations mentioned in this chapter. Simplified from Wright et al., 1981.
A. Upward change from carbonate to mixed carbonate and siliciclastic strata. Earliest evidence of thickening westward away from an incipient continental margin.
B. Siliciclastic strata deposited during and immediately after major crustal rifting to form the margin of the Late Proterozoic and Paleozoic continent. Source of sediments was the ancient basement of the craton.
C. Almost entirely limestone and dolomite recording a slowly subsiding and long-continuing carbonate bank.

Eureka Quartzite. The Eureka is part of a sheet of quartz-rich sand that spread across much of the width of that Paleozoic continent. Carbonate rocks continued to be deposited into Triassic time. But then the sea withdrew and did not return. The oceanic crust, which was theoretically forming as the continental shelf evolved, lay many miles to the west of the site of Death Valley.

Where exposed within the park boundaries, the carbonate succession is about 20,000 feet thick. It underlies large parts of the Panamint, Cottonwood, Grapevine, and Funeral Mountains and is particularly visible in the southern part of the Funeral Mountains. There the Eureka Quartzite can be recognized from a distance as a single, nearly white band, repeated several times by normal faulting. It is underlain by the Pogonip Group, colored various shades of gray, and overlain by the nearly black Ely Springs Dolomite. In Death Valley National Park, the Triassic strata are preserved only in the Butte Valley area at the southern end of the Panamint Mountains.

6. The closing of the Paleozoic ocean in Mesozoic time; thrust faults, and bodies of igneous rock

At numerous localities within Death Valley National Park, we observe that the Proterozoic and Paleozoic rocks have been faulted so that older formations override younger formations. These contacts are the thrust faults that record severe compression of the crust. Together with associated folds and with granitic plutons, also present within the park boundaries, and Mesozoic granitic rock, the thrust faulting marks the end of the passive continental margin and records a foreshortening of the former continental shelf. Features of this kind, together with zones of volcanic rocks, characterize a belt that extends beyond the park area for the full length of North America. The plutons exposed within the park lie along the periphery of a belt composed mostly of igneous bodies and containing the Sierra Nevada batholith to the west. This belt is called the Cordilleran Mesozoic magmatic arc.

In the Death Valley area the foreshortening is expressed mainly by thrust faults that have caused Proterozoic and Cambrian formations to override younger Paleozoic formations. But they are difficult for the short-term visitor to quickly discern amidst the later faults formed while the crust was extending. Among the relatively accessible thrusts are the Schwaub Peak (Wright and Troxel, 1993) and Clery thrusts (Cemen et al. 1985) in the southern part of the Funeral Mountains.

The Mesozoic plutons of Death Valley National Park are of Jurassic and Cretaceous age. They are distributed close to the western boundary of the park, where they underlie most of the Owlshead Mountains, are discontinuously distributed in the western part of the Panamint Mountains, and form the Hunter Mountain batholith at the southern end of the Cottonwood Mountains. Most of the plutons are accessible by unimproved roads.

7. The missing sedimentary record of Jurassic through Early Tertiary time and the initiation of the Basin and Range event in the Death Valley area

No sedimentary rocks of Jurassic through Eocene age have been found in the area of Death Valley National Park, although volcanic rocks of probable Jurassic age are exposed in the Butte Valley area of the southern Panamint Mountains. In the national park and the surrounding region, this apparently was a time of uplift and erosion concurrent with and following the thrust faulting and the emplacement of the Mesozoic plutons. During this interval much of the succession of Proterozoic and Paleozoic sedimentary rocks that once covered the Death Valley region was eroded away. In fact, the erosional denudation probably continued over much of the Death Valley region until the inception of the basins and ranges that form the present landscape. Little is known of the river system that must have functioned during this interval, or where the eroded material was deposited. Much of the debris probably was carried into a Cretaceous sea and its environs in the interior of the continent. In the Cottonwood, Grapevine, and Funeral Mountains, however, remnants of this earlier terrain are sealed beneath corresponding remnants of a sedimentary cover deposited in Oligocene and early Miocene time.

8. The Oligocene and Early Miocene flood plain and the bordering upland

The Oligocene and early Miocene formations of the Cottonwood, Funeral, and Grapevine Mountains were deposited on a much more subdued landscape than the one we observe today. This conclusion stems from the observation that the contact is characteristically devoid of the major irregularities that would accompany the infilling of an irregular topography. We also note that basal Tertiary beds consistently dip almost as steeply as the underlying Proterozoic and Paleozoic formations of the present ranges. Thus, when rotated back to their original, nearly horizontal positions, these beds are seen as deposited on a broad surface of low relief drained by laterally migrating streams and rivers. The oldest of the Tertiary strata compose the Oligocene Titus Canyon Formation and consist of conglomerates, sandstones, and mudstones. The clasts of the conglomerates are exceptionally well rounded and polished and can be seen in road cuts at Daylight Pass along the Death Valley to Beatty highway. Clasts of granitic rock point toward a western source area in which Mesozoic plutons were exposed.

In a more southward area that includes most of the Panamint Mountains and the Owlshead and Black Mountains within the national park and also the Resting Spring and Nopah Ranges east of the park boundary, Tertiary rocks older than 14 million years are apparently absent, and the pre-Basin and Range surface is thus obscured. If so, the missing rock units of earlier Tertiary age have either been eroded away or were never deposited. In this area, the 14-million-year and younger Tertiary sedimentary rocks, are part of the evolving Basin and Range terrain.

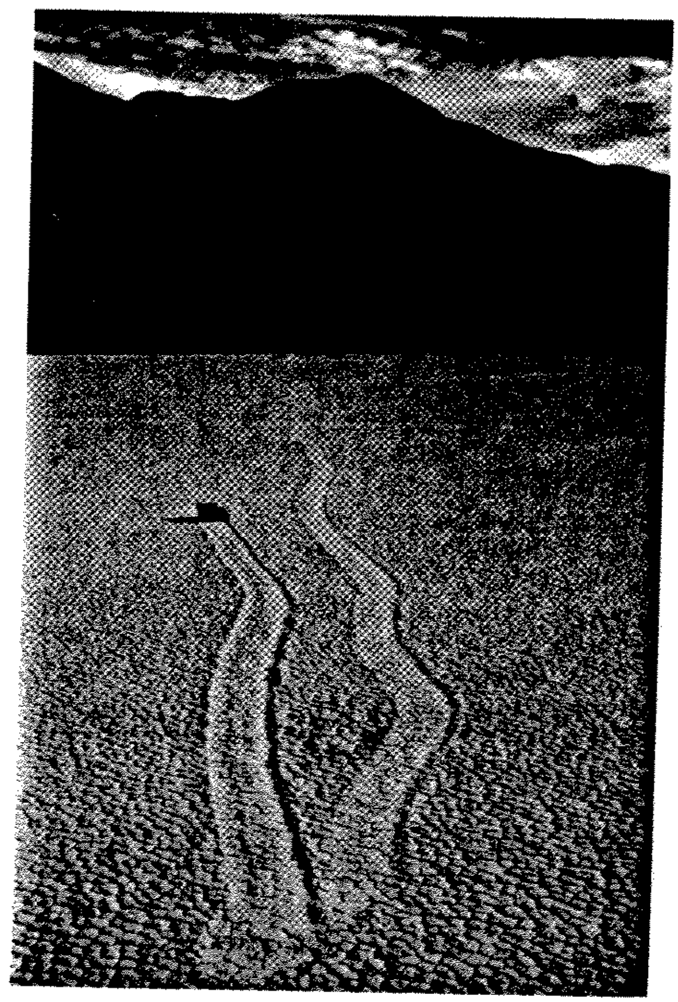

FIGURE 48.17 A "sliding boulder" on the Racetrack playa. These objects have moved, as yet unobserved, under an unusual combination of weather and surface conditions. The exact nature of these conditions continues to be debated, although strong winds are consistently invoked. Photo by Martin Miller.

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