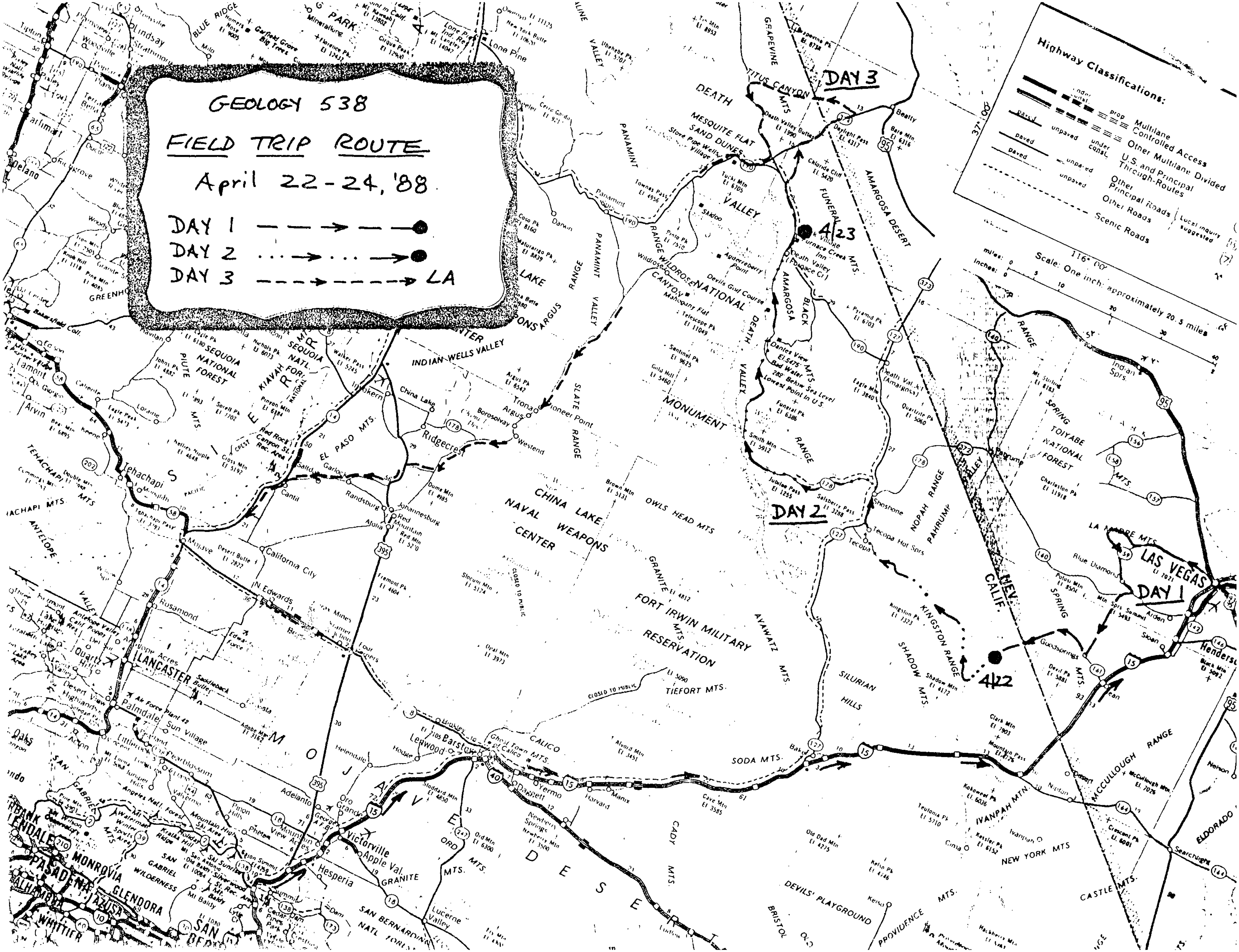
GEOLOGY 538
FIELD TRIP ROUTE
April 22-24, '88
DAY 1
DAY 2
DAY 3
LA
DAY 1
DAY 2
DAY 3
4/22
4/23
Highway Classifications:
Multilane Controlled Access
Other Multilane Divided
U.S. and Principal Through-Routes
Other Principal Roads
Other Roads
Scenic Roads
paved
unpaved
under const.
prop.
Local inquiry suggested
Scale: One inch approximately 20.5 miles
miles: 0 5 10 20 30 40
inches: 0 1 2
116° 00'
37° 00'
NEV.
CALIF.
LAS VEGAS
DEATH VALLEY NATIONAL MONUMENT
AMARGOSA DESERT
CHINA LAKE NAVAL WEAPONS CENTER
FORT IRWIN MILITARY RESERVATION
MOJAVE DESERT
KINGSTON RANGE
SPRING MTS.
Barstow
Baker
Shoshone
Tecopa
Beatty
Furnace Creek Inn
Stove Pipe Wells Village
Trona
Ridgecrest
Mojave
Lancaster
Palmdale
Victorville
Pasadena
Glendora
Tehachapi
SEQUOIA NATIONAL FOREST
SPRING TOIYABE NATIONAL FOREST
SAN GABRIEL WILDERNESS
SAN BERNARDINO NATL FOREST

MESOZOIC THRUST FAULTS AND CENOZOIC LOW-ANGLE NORMAL FAULTS, EASTERN SPRING MOUNTAINS, NEVADA, AND CLARK MOUNTAINS THRUST COMPLEX, CALIFORNIA

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INTRODUCTION

This field trip examines Mesozoic tectonic relations along the eastern margin of the Cordilleran foreland fold and thrust belt, southeastern Nevada and adjacent California, and the distribution and nature of Cenozoic extensional faults that are superposed on this part of the foreland belt.

The late Mesozoic foreland fold and thrust belt of the Cordilleran orogen can be followed continuously from northern Canada to southeastern California (Fig. 1). Along much of its length the geometry and structural style of this east-vergent belt are largely controlled by two thick sequences of rift-related sedimentary rocks -- Proterozoic Belt rocks and the uppermost Precambrian-Paleozoic Cordilleran miogeocline (Fig. 1). Crystalline basement rocks are involved only locally in the deformation, e.g. in southern Idaho and central Utah. A major change in the tectonic style of the foreland belt takes place in southeastern California where thrust structures leave the Cordilleran miogeocline and trend irregularly across cratonal North America. The transition from structures "typical" of the geosynclinal foreland fold and thrust belt, north of southern Nevada, to cratonal structures that extensively involve Precambrian crystalline rocks and Mesozoic plutons occurs within the area of this field trip (Fig. 2). Characteristics of this transition will be pointed out at various stops during the excursion.

Cenozoic extension probably began in southern Nevada about late Miocene time and has continued locally to the present (Fig. 3). Most of the extension can be related to movement on west-dipping, low-angle normal faults whose hanging walls contain both rotated planar normal faults and listric normal faults. Several major strike-slip fault zones developed contemporaneously with the normal faults. They are intimately related to extension and most have functioned as accommodation faults, transferring extension from one area to another.

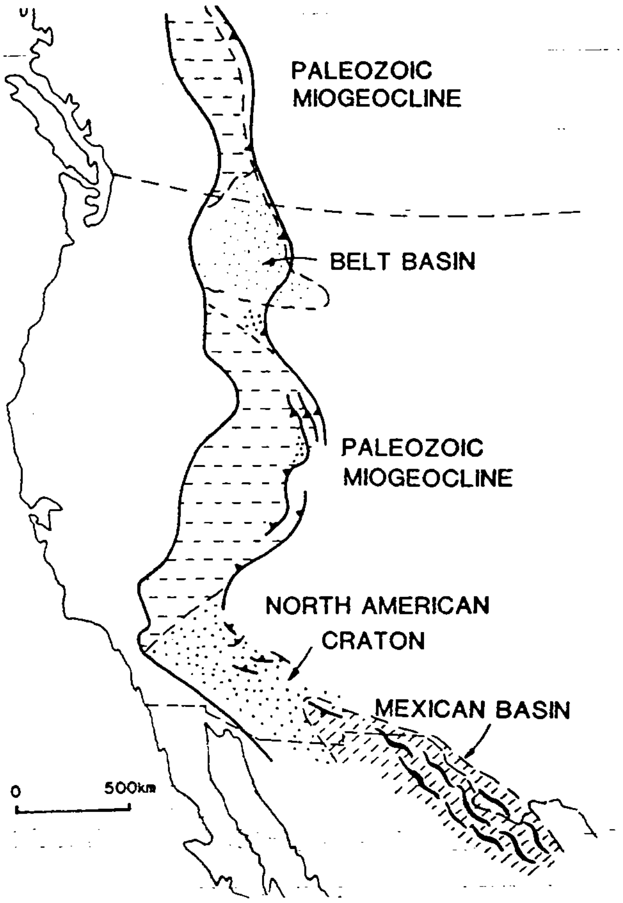


Figure 1. Eastern limit of the foreland fold and thrust belt of the Cordilleran orogen and the major paleogeographic elements through which it passes. Areas where the thrusts and folds involve crystalline basement rocks are shown in stippled pattern.

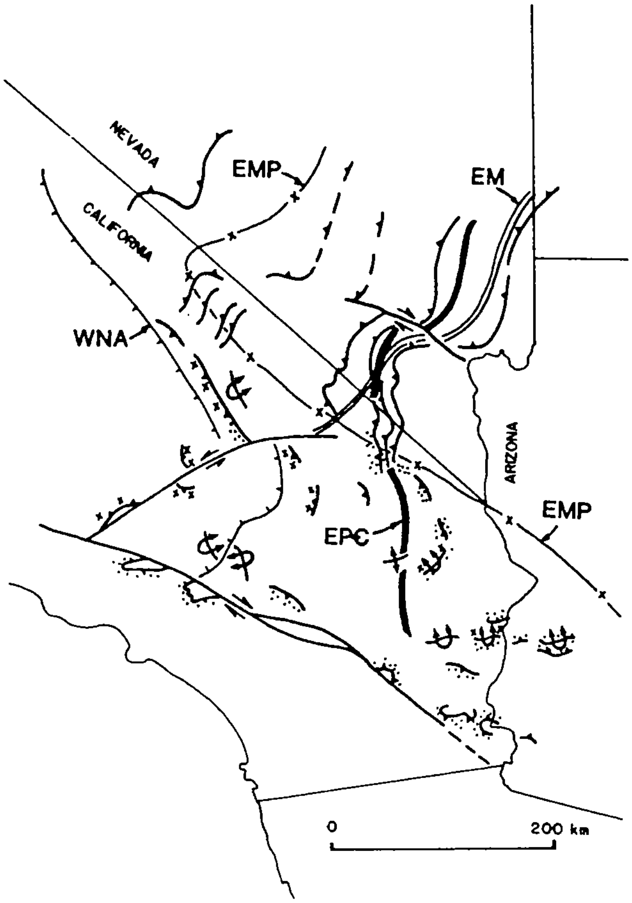


Figure 2. Schematic tectonic map of the southwestern part of the Cordilleran orogen showing relations between major structural and paleogeographic elements. Structures that involve Precambrian crystalline rocks and Mesozoic plutonic rocks are decorated by stippled and crossed patterns respectively. The figure shows the geography of the transition between structures formed within the miogeocline and those formed within the craton. It also shows spatial relations between the western limit of North American Precambrian crystalline basement (WNA), and the eastern limits of the Paleozoic miogeocline (EM), upper Precambrian sedimentary rocks (EPC), and large Mesozoic plutons (EMP). Figure modified from Burchfiel and Davis (1981) and Brown (1986).

Within the area of extended upper crustal rocks is a structural block largely unaffected by Cenozoic normal faults; it includes the Spring Mountains and Las Vegas Range of Nevada (Wernicke and others, 1983) and the Mesquite and Clark Mountains of California. Within this block, Mesozoic structures can be studied without significant Cenozoic modification. Nevertheless, within the Clark Mountains and southern Spring Mountains, we have recently recognized that several faults originally mapped by us as thrust faults (Burchfiel and Davis, 1971) are west-dipping low-angle normal faults. At some localities the normal faults appear to have followed older Mesozoic thrust faults, but at most localities it is clear that they do not. Parts of the second and third days of the field trip will be devoted to the problems of recognition of Cenozoic normal faults within the Mesozoic thrust belt and their tectonic significance there.

FIELD TRIP GUIDE

First Day

Introduction

The first day of the trip focuses on the Mesozoic thrust belt along the relatively unextended eastern side of the Spring Mountains, west and southwest of Las Vegas (Figs. 3, 4). Thrust faults in this area are the easternmost faults of the Cordilleran foreland fold and thrust belt at this latitude and involve rocks of Cambrian to Jurassic age (Fig. 5). The objectives of this part of the field trip are to demonstrate that: (1) older thrust faults lie east of younger thrust faults, thus indicating that the thrust belt did not form by progressive migration of thrust faults toward the craton; (2) Mesozoic high-angle faults formed at several times between thrusting events; and (3) detachment of most thrust faults was within the Cambrian Bonanza King Formation 70 to 150 m above the Cambrian Bright Angel Shale.

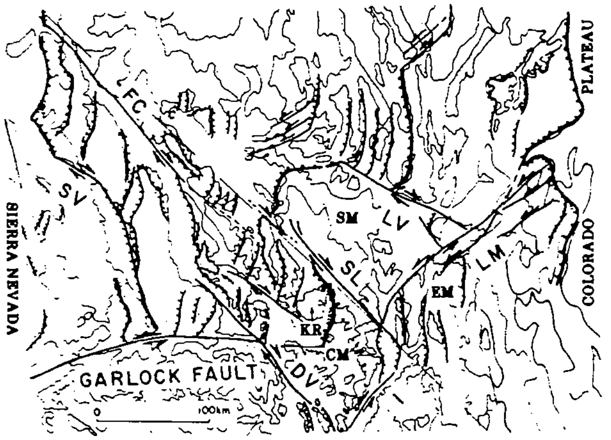


Figure 3. Schematic map of the major structures formed during Cenozoic extension. Normal faults are shown with hatchured lines and strike-slip faults with relative motion arrows. Major breakaway faults for extended terranes are shown with heavy hatchured lines. Major strike-slip fault zones: Lake Mead (LM); Las Vegas shear zone (LV); State Line (SL); Death Valley (DV); Furnace Creek (FC); Saline Valley (SV). Geographic areas: Kingston Range (KR); Clark Mountains (CM); Spring Mountains (SM); El Dorado Mountains (EM).

Within the eastern Spring Mountains are several major, west-dipping thrust faults. From east to west they are the 1) Birdspring,
2) Red Spring-Wilson Cliffs-Contact, and (3) Keystone thrust faults (Fig. 6). Structurally higher thrust faults lie farther west, but are not relevant to this discussion. Rocks east of the Birdspring thrust form the authochthon of the North American craton. The Birdspring thrust places Cambrian Bonanza King Formation above the lower Jurassic Aztec Sandstone in its southernmost exposures (Burchfiel and others, in progress). Unconformably overlying Aztec Sandstone below the thrust is a 0 to 50 m-thick sequence of conglomerate, sandstone, and shale of unknown age. Toward the north, the Birdspring thrust loses displacement. At its northern recognized end, just south of the La Madre fault (Fig. 6), it only duplicates Permian redbeds. Three geographically discontinuous segments of thrust faults lie structurally above the Birdspring thrust. From north to south they are the Red Spring, Wilson Cliffs, and Contact thrust faults (Fig. 6). All are interpreted here to be segments of the same fault. The Red Spring thrust was first recognized by Longwell (1924, 1926) and Glock (1929), was studied locally by Davis (1973) and was mapped in detail by Axen (1981, 1984). It places Cambrian Bonanza King Formation above Aztec Sandstone and a thin, discontinuous sequence of overlying conglomerate. This is the conglomerate of Brownstone Basin, and it is similar to the conglomerate below the Birdspring thrust. The Red Spring thrust plate has been cut by north- to northwest-striking high-angle faults that rotated the thrust fault; it now dips generally northeastward. These high-angle faults are interpreted to have formed before emplacement of the structurally higher Keystone thrust, because they have much larger displacements in the Red Spring footwall of that thrust than in its Keystone hanging wall (Longwell, 1926; Davis, 1973; Axen, 1984). These relations are part of the evidence for an older thrust fault, the Red Spring thrust, lying east of and below the younger Keystone fault.

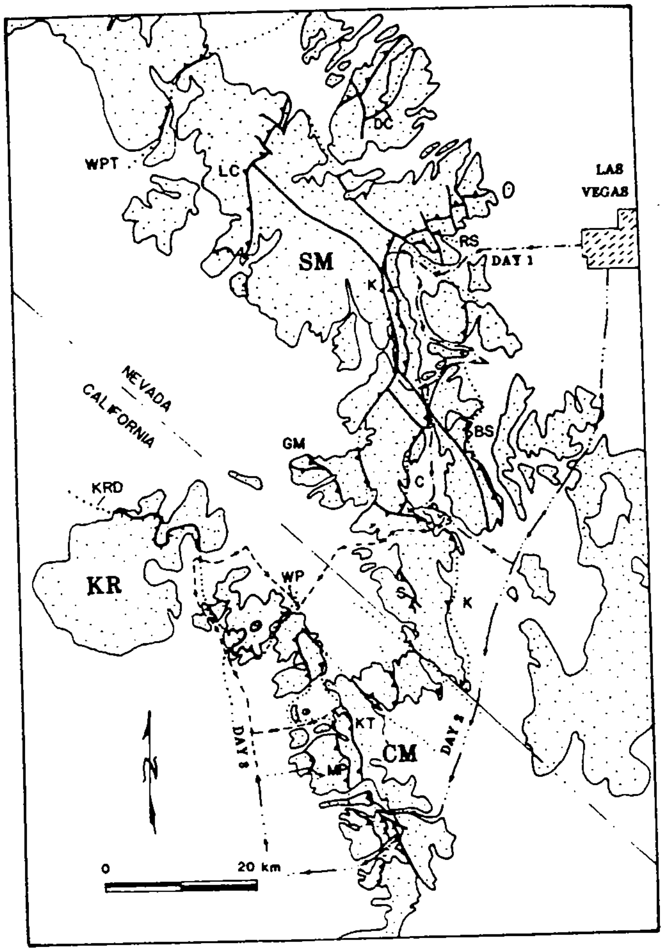


Figure 4. Generalized map of the field trip region showing the location of major structural features relevant to the field trip. The field trip routes for each day are shown: day 1 (—.—.—); day 2 (——···——); day 3 (– – – – –). Major thrust faults (from north to south): Red Spring (RS); Keystone (K); Bird Spring (BS); Green Monster (GM); Contact (C); Sultan (S); Winters Pass (WP); Keaney/Mollusk Mine (KT); Mesquite Pass (MP). The Kingston Range detachment fault (KRD) is a low-angle extensional fault.

Between the La Madre and Cottonwood high-angle faults (Fig. 6), all older maps label the magnificently exposed thrust at the top of the Aztec Sandstone in the Wilson Cliffs as the Keystone thrust fault (Longwell, 1926; Secor, 1962; Longwell and others, 1965; Davis, 1973; Burchfiel and others,

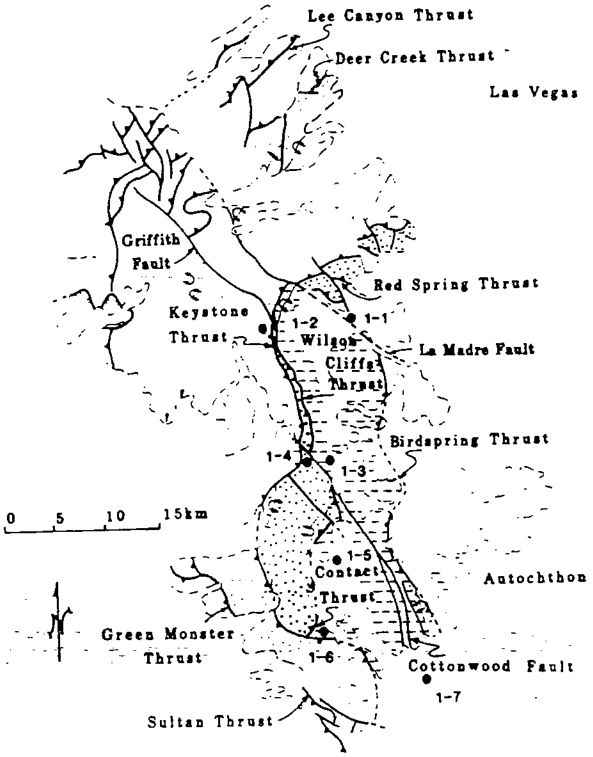


Figure 6. Major structural units in the eastern Spring Mountains. Locations of stops for the first day are indicated.

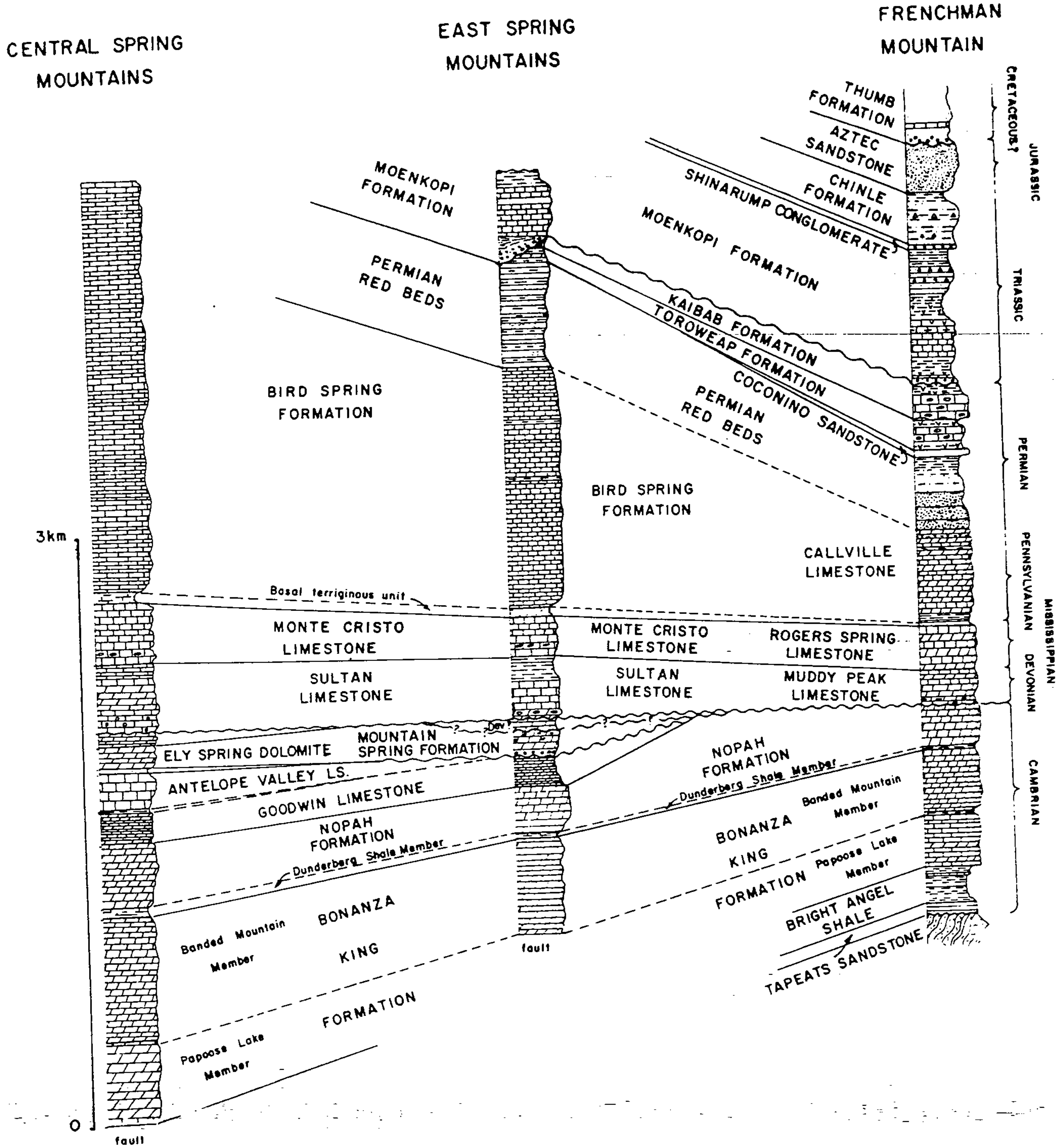


Figure 5. Generalized stratigraphic sections in the Frenchman and Spring Mountains areas.

1974). Recent mapping by Burchfiel and Royden (1983, and in preparation) has demonstrated that there are two major thrust faults above the Wilson Cliffs. The lower of the two places Bonanza King Formation above the Aztec and is called the Wilson Cliffs thrust. The higher of the two is the true Keystone thrust. It places the Bonanza King Formation above younger Cambrian rocks of the Wilson Cliffs plate. The identity of this higher thrust as the Keystone is demonstrated by its continuity with the type Keystone thrust near Goodsprings, Nevada (Carr, 1983; Carr and Pinkston, 1987).

The Keystone and Wilson Cliffs thrust plates have very different internal structures. The Keystone thrust plate in the Mountain Springs area is essentially a panel of relatively undeformed lower Paleozoic rocks, whereas the Wilson Cliffs plate consists of imbricate thrusts, isoclinal folds and a folded thrust (Fig. 7b). The recognition of the two thrust plates in this area and the differences in their internal structures was made possible by mapping subunits within the Bonanza King Formation. Cross sections show that the Keystone thrust must cut the Wilson Cliffs thrust at depth, just as mapping shows a similar crosscutting relation south of the La Madre fault (Fig. 6). Although crosscutting relations between the two thrusts suggest that the Keystone thrust is younger, the two faults could conceivably be parts of a single progressive deformation.

Just south of the La Madre fault, the Keystone thrust cuts downward at a low angle across the Wilson Cliffs thrust to place Cambrian rocks above overturned Triassic rocks. Cretaceous(?) sandstone and conglomerate deposits lie below the Keystone plate just south of where it cuts out the Wilson Cliffs thrust (Fig. 6). The sandstone unit consists of reworked Aztec sandstone and has beds of conglomerate with clasts derived exclusively from the Bonanza King Formation (Mcgl, Fig. 7a). These sedimentary rocks clearly lie below the Keystone thrust, but their relation to the Wilson Cliffs plate is unclear because of poor exposure. Detailed mapping suggests, however, that the sandstone and conglomerate rest on an eroded remnant of the Wilson Cliffs thrust plate (Fig. 7a). This interpretation leads to the conclusion that the Wilson Cliffs thrust plate was emplaced, deeply eroded, and perhaps largely removed by erosion just south of the La Madre fault before the Keysone thrust plate was emplaced. If this conclusion is correct, it requires that the overturned syncline in the footwall of the Keystone thrust just south of the La Madre fault actually developed in the footwall of the older Wilson Cliffs plate (Fig. 6); it is not related to the Keystone thrust. Finally, because of these interpretations, the Wilson Cliffs plate now can be correlated with the Red Springs plate farther north.

South of the Cottonwood fault (Figs. 6 and 8) the Contact thrust of Hewett (1931) places Cambrian rocks above the Aztec Sandstone (Cameron, 1974). The Contact thrust plate contains east-vergent folds that are cut obliquely by the thrust at its base, so that different Paleozoic units lie above the thrust fault in different places. Different Mesozoic formations are also present below the thrust at different localities, a relationship best explained by interpreting that high-angle faults had offset footwall rocks before emplacement of the Contact thrust plate.

All previous maps of the area show the northwest-striking Cottonwood fault cutting the Contact thrust, but not offsetting, or at most offsetting by only a few tens of meters, the Keystone thrust (in reality, the Wilson Cliffs thrust). This relationship was interpeted as indicating a post-Contact, pre-Keystone age for the Cottonwood fault. Burchfiel and Royden (1983 and in progress) have remapped the Cottonwood fault in the Mountain Springs area. Continuity of Bonanza King subunits between the Keystone thrust plate in its type area near Goodsprings and the newly recognized thrust above the Wilson Cliffs plate demonstrates the true, higher position of the Keystone thrust in this area. By mapping subunits within the Bonanza King Formation it can be demonstrated that movement on the Cottonwood fault is mostly, if not entirely, post-Keystone in age. Subunits in the Keystone plate and higher formations are continuous across the Cottonwood fault, but are folded along its projected trend, i.e. displacement along the high-angle

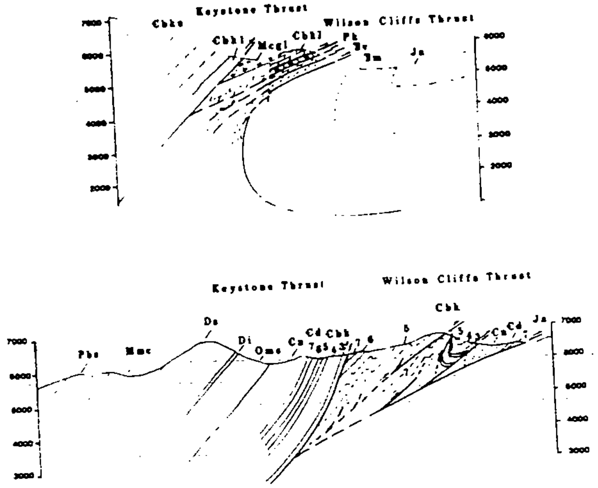


Figure 7. Cross-sections of the Keystone and Wilson Cliffs thrust plates.

Figure 7a (upper). East-west cross-section across the northern end of the Wilson Cliffs plate showing the relations between the Mesozoic conglomerate (Mcgl) and the Keystone and Wilson Cliffs plates. The east-vergent syncline in Jurassic Aztec Sandstone (Ja) is related to emplacement of the Wilson Cliffs plate. Other stratigraphic units of the section: upper and lower members of the Cambrian Bonanza King Formation (€bku, €bkl); Permian Kaibab Limestone (Pk); Triassic Moenkopi-Chinle redbeds (Trm); Triassic Monenkopi, Virgin Limestone member (Trv).

Figure 7b (lower). East-west cross-section about 7 km north of the Cottonwood fault showing differences in the structural styles of the Keystone and Wilson Cliffs plates. Units of the Bonanza King Formation are numbered. Other units: Dunderberg Shale (Cd); Nopah Formation (€n); Mountains Springs Formation (Oms); Ironside Dolomite (Di); Sultan Formation (Ds); Monte Cristo Formation (Mmc); Birdspring Formation (Pbs).

fault is taken up by warping in the Keystone plate (Fig. 8). In contrast, the Wilson Cliffs (Contact) thrust and its hanging wall structures are offset by that fault (Fig. 8). All earlier workers had erroneously connected without offset a thrust south of the Cottonwood fault, believed to be the Keystone, with the Wilson Cliffs thrust north of the fault. These relations indicate that most, if not all, of the displacement on the Cottonwood fault is post-Keystone in age. Because piercing points cannot be established along the Cottonwood fault, its direction of net slip is unknown. Separation along the fault is south side down or left-lateral, and the sense of slip could be normal, left-slip, or oblique-slip. There are no post-Mesozoic rocks along the Cottonwood fault so its age is also unknown; it could be either late Mesozoic or Cenozoic.

At its south end, the Contact thrust is cut by the Keystone thrust (Fig. 6). In this area the Keystone thrust deviates from its general south trend, to an east trend for about 12 km before trending south again. Below both the Contact and Keystone plates in this area is a thick sequence of conglomerate, sandstone, and tuff that Carr (1980) called the Lavinia Wash Formation. These rocks were interpreted as synorogenic deposits for the Contact thrust, and a tuff within them yielded a K-Ar age of 150±10 Ma. Until recently these rocks indicated that the age of emplacement of the Contact thrust was late Jurassic, but more recent work in this area by Carr and others (in press) challenges this interpretation. They suggest that the emplacement of the Contact plate was early Mesozoic, and that the age of the Lavinia Wash Formation is uncertain. Geologic relations described above indicate that after emplacement the Contact-Red Spring plate was disrupted by northwest-striking faults in the Red Spring area (and perhaps along the Cottonwood fault) and extensively eroded prior to emplacement of the Keystone allochthon.

The Keystone thrust plate can be followed continuously throughout the eastern Spring Mountains (Fig. 6) where its structure is relatively simple. It appears to be an undeformed panel of Paleozoic and lower Mesozoic rocks that dips west in its eastern part and becomes horizontal with some east-vergent folds in its western part. This geometry can be explained by the presence of a west-dipping thrust ramp located near the surface trace of the thrust. The Keystone plate contains older structures west of Goodsprings, Nevada (Carr, 1983). Movement along the Keystone thrust was complex. During part of its evolution it had a northward component of movement, as north-trending folds in the Contact plate are refolded by east-trending folds (Carr, 1983). The Keystone plate was thus emplaced across a structurally complex footwall. The age of Keystone emplacement cannot be constrained in the Spring Mountains area. Carr and others (in press) present preliminary geochronologic evidence to suggest that not only is the Contact thrust early Mesozoic, but that the Keystone thrust may also be that old. It is too early at the time of this writing to evaluate their preliminary results.

Two other results of mapping in this area are of interest. First, initial detachment of all the thrust faults described above appears to have occurred within the predominantly dolomitic Bonanza King Formation (Burchfiel and others, 1982). Regional studies suggest detachment was generally within a 100 m-thick interval of section near the contact between the Papoose Lake and Banded Mountain members of the formation (Fig. 5). What makes this surprising is that the thick Bright Angel Shale lies only about 200 m lower in the section. (Fig. 5). Detachment within the Bonanza King occurred repeatedly during thrust faulting events of significantly different ages. Second, the Keystone, Contact-Red Spring, and Birdspring thrust plates all lie above channel-confined conglomerate units, a relationship that suggests that these plates moved across erosional surfaces. The clasts in some channels appear to have been derived from an advancing thrust plate (cf. Davis, 1973). The footwall below the Wilson Cliffs plate contains only rare channel fills cut into the Aztec Sandstone. Rounded clasts in these channels are usually only pebble size, and contain resistant rock types (chert, quartzite); locally they contain small angular fragments of Cambrian dolomite. The Keystone plate rests on sandstone and conglomerate south of the La Madre fault and on possible terra rosa deposits near Goodsprings (Carr, 1984).

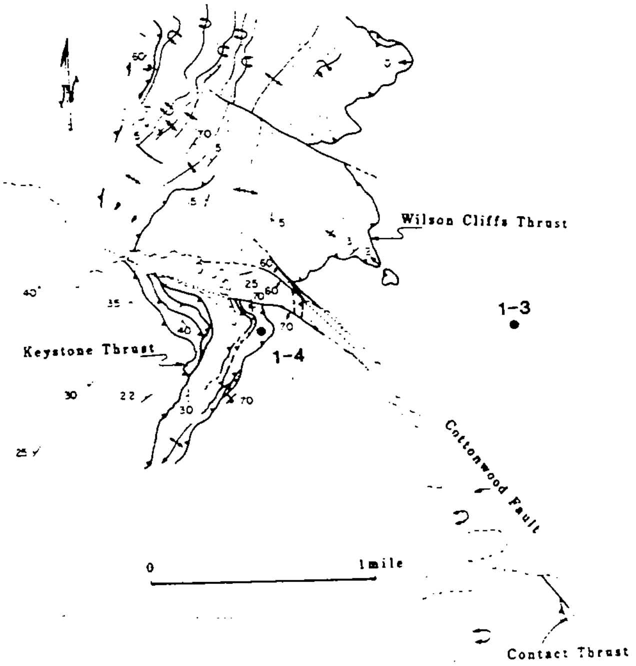


Figure 8. Geologic map along the Cottonwood fault at Mountain Springs Pass, Spring Mountains. Mapping indicates that the Wilson Cliffs and Contact thrust plates (stippled) are equivalent. The Keystone plate lies above the Wilson Cliffs/Contact plate. It has been warped by displacement on the Cottonwood fault, but is not offset by it.

Fieldtrip Stops

Leaving Las Vegas, we will drive west on Charleston Blvd. toward Red Rock State Park. On the western edge of Las Vegas, the view to the west and northwest is dominated by northeast-dipping gray and white striped Paleozoic units of the Red Spring thrust plate that form the large hills. The intervening valleys are underlain by red Aztec Sandstone. In each valley, the contact between the Paleozoic and Jurassic rocks is the Red Spring thrust fault on the northeast side and a post-thrusting high-angle fault on the west or southwest side. The highest ridge to the west in the background consists of Paleozoic rocks of the Keystone thrust plate. The angular discordance between the rocks of the Red Spring and Keystone plates is clearly seen.

Stop 1-1 Red Spring thrust fault (Fig. 6)

The first stop is about 1.5 miles east of the park entrance. At this stop the view to the northeast shows the planar nature of the Red Spring thrust. Bonanza King Formation lies above Jurassic Aztec Sandstone and the local Conglomerate of Brownstone Basin. The Turtlehead Mountain high-angle fault cuts the Red Spring thrust. A major conglomerate-filled channel lies above Aztec sandstones and below the Red Spring thrust to the west of the fault (Davis, 1973). To the east, the Aztec Sandstone is overlain by Paleozoic rocks along a very irregular contact. This mass of brecciated Paleozoic rocks, originally mapped as part of the thrust by Longwell (1926) was interpreted as a Mesozoic surficial deposit by Davis (1973) and as a landslide deposit by Axen (1984).

To the south, the flat-topped hill is capped by Permian Kaibab Limestone with Permian red beds in the slope. At the base of the hill the Permian red beds are repeated by the Birdspring thrust. The La Madre fault passes between the small hills south of the road and the higher flat-topped hill farther south.

Continue west to Red Rock State Park and take the park road toward the northeast. The road passes several extraordinary outcrops of festoon cross-bedded Aztec Sandstone on the northeast. Where the ridge of Aztec ends to the west, the higher ridge to the northeast consists of Paleozoic carbonate rocks that belong to the Red Spring thrust plate. The highest mountains to the northwest are underlain by Paleozoic rocks of the Keystone thrust plate. The Paleozoic units in the Keystone plate show continuity within the highest mountains, whereas the Paleozoic rocks of the Red Spring plate strike obliquely into them. To the south is a broad valley that is carved out of the soft Triassic red beds of the upper Moenkopi and Chinle formations. These rocks dip gently west from the flat-topped ridge of Permian Kaibab seen at stop 1-1, and they dip below the massive tan and red cliffs of the Aztec Sandstone that makes up the Wilson Cliffs to the west. At the westernmost point of the State Park loop, we turn west and pass Willow Springs. The pavement ends, but a dirt road continues through a valley cut in the Aztec Sandstone.

Stop 1-2 Wilson Cliffs and Keystone thrust plates (Figs. 6, 7a)

If the road is passable, continue for about another mile along the steep eastern slope of the Spring Mountains. This stop is to examine the relations between the Wilson Cliffs and Keystone thrust plates. Sandstones consisting of reworked Aztec Sandstone and interbedded conglomerate with clasts of Cambrian dolomite lie below the Keystone thrust plate. They are inferred to lie above the Wilson Cliffs thrust plate, which here has been reduced to a very thin sliver of Cambrian dolomite thrust over thin slices, in descending order, of cherty Permian Kaibab limestone, Triassic Moenkopi limestone, and red beds of either the upper Moenkopi or Chinle formations. These slices rest on overturned Chinle and Aztec strada. Geologic relations at this stop demonstrate (1) the erosional interval between the emplacement of the Wilson Cliffs and Keystone plates, (2) the intra-Bonanza King detachment at the base of the Keystone plate, and (3) that the overturned syncline in the Mesozoic rocks lies below the Wilson Cliffs plate - not below the Keystone plate.

If the road is not passable, stop 1-2 will be several hundred feet beyond where the road crosses the large dry wash above Willow Springs. The Wilson Cliffs thrust plate is missing here, having been cut out by the Keystone thrust to the south. The Keystone plate rests on the overturned footwall syncline that is related to the older Wilson Cliffs plate.

Return to the park loop road and to the state park exit. Turn south toward Blue Diamond. Yellow-weathering, gently west-dipping limestones of the lower Moenkopi Formation make up the hills above the Blue Diamond settlement. They are capped by a large, unstudied landslide of brecciated Paleozoic rocks. The ridge east of the settlement is composed of cherty Kaibab limestone. Permian red beds appear in its eastern slope where the road passes through the ridge. The first small hill south of the road and east of the red beds is underlain by folded, yellow-weathering lower Moenkopi limestone. These limestones are in the footwall of the Birdspring thrust, and the Permian red beds are in its hanging wall. The displacement in the Birdspring thrust has increased from that seen at stop 1-1. At the intersection with State Highway 16, turn west, passing contorted Moenkopi limestone in the hills to the north, and then driving through outcrops of Kaibab in the Birdspring thrust plate. These rocks and the stratigraphically higher yellow weathering Moenkopi limestone are overlain by a landslide of Paleozoic debris.

Stop 1-3 Contact thrust plate view stop (Figs. 6, 8)

To the west are massive cliffs of Aztec Sandstone capped by dark Cambrian carbonates of the Wilson Cliffs plate. These cliffs end to the south at the Cottonwood fault. The gray carbonate rocks south of the road and west of the stop are Cambrian to Pennsylvanian rocks of the Contact thrust plate (which is equivalent to the Wilson Cliffs plate). Although older rocks lie south of the Cottonwood fault, it has a southside down separation because the Paleozoic rocks lie structurally above the Aztec Sandstone. South along the skyline ridge, the Paleozoic carbonates are folded into a large, east-vergent anticline in the hanging wall of the Contact plate. Overturned Paleozoic rocks are thrust over tan- and red-weathering Aztec sandstones. The anticline may appear to be a frontal anticline for the Contact plate, but farther south several other folds lie en echelon to the anticline and each rests directly on the Contact thrust.

Proceed west from stop 1-3. On the ridge south of the road the east-vergent anticline is clearly seen in Devonian carbonate rocks. The trace of the Cottonwood fault lies in the valley occupied by the power lines. The clear juxtaposition of tan and red Aztec sandstones on the north and the gray Paleozoic carbonates on the south mark the fault.

Stop 1-4 Cottonwood fault; Wilson Cliffs thrust fault (Fig. 8)

Walk up the dirt road to the north, crossing the Cottonwood fault. The Wilson Cliffs thrust is well defined by dark Cambrian dolomite overlying Aztec Sandstone. The thrust surface is poorly exposed, but the character of the rocks above and below the thrust can be examined. Some channels filled with pebbles of resistant rocks are present in the Aztec. Contacts relations between the gray carbonate rocks are difficult to see unless details of the subunits in Bonanza King have been mapped, but it is in this area that detailed mapping in this area demonstrate the young (i.e. post-Keystone) age of the Cottonwood fault.

Return to the east on Highway 16 to the dirt road that turns south to Goodsprings between the Birdspring Range and the Spring Mountains. The road crosses the first ridge to the south of highway 16 just where the Cottonwood fault juxtaposes Aztec Sandstone against lower Moenkopi limestone.

Stop 1-5 Footwall relationships, Contact thrust (Fig. 6)

Proceed south to where the valley widens. The two ridges of red Aztec Sandstone to the west lie within the footwall of the Contact thrust plate. These two ridges end abruptly to the south. The next outcrop below the thrust to the south is in the Chinle Formation, where rocks have the same strike and dip as the Aztec to the north. The Contact thrust plate is continuous across these two outcrops of footwall rocks. These relations are interpreted to indicate the presence of a pre-Contact, northwest-striking, high-angle fault between Aztec and Chinle rocks in the footwall of the Contact plate; the fault is not exposed.

East of the road are west-dipping beds of the Pennsylvanian-Permian Birdspring Formation. The geometry of these beds suggests that they overlie a west-dipping ramp in the Birdspring thrust at depth beneath the range. Drive into Goodsprings and follow the paved road that goes west out of town. As the road loops south around the hill just south of town, take the dirt road west into Lavinia Wash.

Stop 1-6 Lavinia Wash Formation (Fig. 6)

Boulder and cobble conglomerate, sandstone and tuff form the upper(?) Jurassic Lavinia Wash Formation of Carr (1980). These rocks were interpreted to be syntectonic orogenic deposits related to emplacement of the Contact thrust plate. Gray carbonates to the west are upper Paleozoic rocks of the Contact thrust plate. Dark gray carbonates to the south are Cambrian dolomite of the Keystone plate. Note the truncation of the south-trending Contact thrust plate by the higher, east-trending Keystone plate at the head of a small valley to the southwest. The Lavinia Wash and underlying Moenkopi formations are folded along east-west axes. To the north are white-weathering outcrops of a small potassium feldspar porphyry pluton. The porphyry intrudes both hanging and walls of the Contact plate. Preliminary work on the age of this pluton and other intrusions in the area by Carr and others (in press) suggest that these igneous rocks are of early Mesozoic age.

Return to paved road east through Goodsprings toward Jean, Nevada.

Stop 1-7 Birdspring thrust fault (Fig. 6)

To the north, rocks in the western part of the Birdspring Range dip moderately west. Toward the east they become nearly horizontal. This is interpreted to be the result of a ramp-flat geometry in the Birdspring thrust (Burchfiel and others, in progress). The hidden trace of the Birdspring thrust lies in the valley that separates white and gray carbonate rocks on the west (Bonanza King Formation) from tan and reddish limestone on the east (Kaibab Limestone). The thrust places Cambrian rocks over Triassic Moenkopi Formation in the valley. At this stop the Birdspring thrust must have at least 5-6 km of displacement, considerably more than where the thrust was crossed to the north earlier in the day.

To the east, topographically above Jean, Nevada, are north-dipping Paleozoic carbonate rocks that are repeated several times by Cenozoic normal faults. All the ranges east of Interstate Highway 15 contain numerous Cenozoic normal faults and the rocks show eastward rotation on these faults. Highway 15 marks the boundary between the Spring Mountains-Las Vegas Range block and a broad region to the east that has been strongly affected by Cenozoic extensional faulting (Figure 3).

Return to Las Vegas.

Second Day

Introduction

Today, we drive southeastward on Interstate Highway 15 to the Clark Mountains, the first mountain range crossed by the highway inside California (Fig. 4). The Clark Mountains, the Mesquite Mountains to the north, and the Mescal Range and Ivanpah Mountains to the south, contain the southwestern continuation of the foreland fold and thrust belt seen in the Spring Mountains. The structure of the Clark Mountain thrust complex which crosses Interstate 15 to the west of Mountain Pass (Bailey Road exit), was mapped by Hewett (1956) before the 1920's in broad reconnaissance. This area is the southernmost, relatively continuous expression of the foreland fold and thrust belt in the southwestern United States. Some structures in the eastern part of the belt can be traced southward across Kelso Valley into the New York Mountains (Burchfiel and Davis, 1977), but Mesozoic plutons, Tertiary volcanic cover, and Cenozoic alluvium collectively obscure the continuity of the belt farther south.

The Clark Mountain thrust complex comprises three major thrust plates with a total minimum northeastward displacement of 65-80 km (Fig. 9). From east to west and from structurally lowest to highest, the three plates are the Keaney/Mollusk Mine, Mesquite Pass, and Winters Pass thrust plates. In earlier publications we (Burchfiel and Davis, 1971, 1977) correlated the lowest thrust plate with the Keystone plate of the southern Spring Mountains. However, subsequent mapping by Burchfiel south of Mesquite Valley between the Clark and Southern Spring Mountains has revealed that the Keystone thrust loses displacement in that area. It dies out southwestward in the footwall of the Keaney thrust, the lowest major thrust in the Clark Mountain area, and is thus not present in the Clark Mountain thrust complex. Below the Keaney thrust in the northern part of the complex and its equivalent fault to the south, the Mollusk Mine thrust, are authochthonous and parautochthonous sequences of Paleozoic and Mesozoic rocks. A nearly complete section of Paleozoic and Mesozoic strata is present below the Mollusk Mine thrust south of Interstate 15 and west of the pre-thrusting, high-angle Kokoweef and South faults (Fig. 9). This 4000 m-thick section contains formations in the or cratonal sequence of the

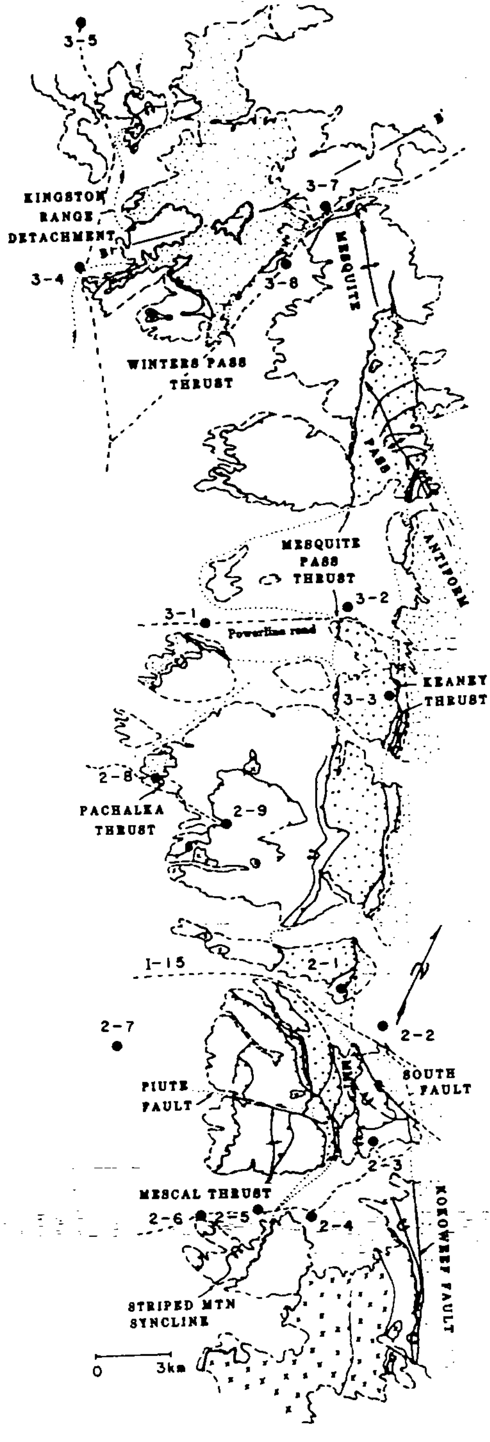


Figure 9. Generalized tectonic map of the Clark Mountain thrust complex, California showing locations of fieldtrip stops for second (2-1 to 2-9) and third days (3-1 to 3-8). Mesozoic thrust faults and Cenozoic extensional faults are shown with barbed and ticked contacts respectively. MMT (south of Interstate Highway 15) is the Mollusk Mine thrust which is equivalent to the Keaney thrust north of the Interstate. The Keaney/Mollusk Mine thrust plate is patterned with a heavy stipple. Precambrian crystalline rocks and Mesozoic intrusive rocks are patterned with a light stipple and x's respectively.

Cordilleran orogen, beginning with the basal Cambrian Tapeats Sandstone and ending in Jurassic volcanic rocks, the Delfonte volcanics, that overlie the Aztec Sandstone and represents the earliest and easternmost development of a Mesozoic volcanic arc across the region.

The Clark Mountain thrust complex is geologically significant for several reasons: (1) excellent exposures in this desert region demonstrate a complicated history of Mesozoic and Cenozoic deformational events; (2) field relationships between igneous plutons and thrust structures document multiple ages of thrust faulting within this rather narrow (<10 km wide) belt; and (3) the structural style of this belt differs from most segments of the foreland fold and thrust belt to the north. The most important difference is that the two highest thrust plates contain Precambrian crystalline basement rocks that exhibit Mesozoic deformation with a significant ductile component.

Each of the three thrust plates exhibits a different structural style. The fault at the base of the lower, Keaney/Mollusk Mine thrust plate lies within several hundred feet of the same Cambrian Bonanza King stratigraphic horizon that controlled thrusting in the Spring Mountains. In the central part of the Clark Mountain thrust complex, the Keaney/Mollusk Mine thrust is a "younger-over-older" fault. Here, Bonanza King Formation is thrust over Bright Angle Shale, Tapeats Sandstone and, very locally, Precambrian gneiss. In this area the thrust fault appears to have the characteristic of the sole portion of a décollement thrust. However, south of Interstate 15 and the South fault (Fig. 9), a pre-thrusting high-angle fault in the footwall of the Keaney/Mollusk Mine thrust, Bonanza King carbonates in the thrust plate overlie Mesozoic carbonate, clastic, and volcanic rocks. Thus here the Keaney/Mollusk Mine plate is of "older-over-younger geometry. The source terrain for the plate must, therefore, lie far to the west of its geologically complicated footwall (Burchfiel and Davis, 1968).

The Mesquite Pass thrust is clearly not a décollement fault because it cuts across most of the upper Precambrian and Cambrian sedimentary units in its upper plate, and locally (south of the powerline road, Fig. 9) it cuts across Precambrian crystalline basement. Furthermore, the Mesquite Pass thrust plate contains an array of anastomosing thrusts that divides the plate into three major thrust slices. The style of the structure in this plate is quite different from that in the Keaney Pass plate because rocks of the Mesquite Pass thrust plate exhibit considerably more flow, folding and complicated thrusting.

The Winters Pass thrust plate, the highest thrust plate, is distinctly different from the lower two in that it contains extensive exposures of Precambrian crystalline rocks. At Winters Pass the thrust cuts across all stratigraphic units and passes southwestward down into Precambrian crystalline basement. It is clearly not a decollement-type thrust, although the thrust does flatten with depth toward the west and has a "thin-skinned" type of geometry. Unlike the underlying Mesquite Pass thrust plate, the Winter Pass plate does not contain an internal anastomosing pattern of smaller thrusts. Rocks directly above and below the Winters Pass thrust fault typically exhibit extensive crystal-plastic flow. Thrust-related mylonitic rocks are present at stops 2-5 and 2-6.

Fieldtrip Stops

Stop 2-1 Keaney/Mollusk Mine thrust fault

Exit Interstate 15 at the Bailey Road offramp and drive west along the paved frontage road north of the freeway. Drive up the graded dirt road to the microwave relay station on the eastern end of Mohawk Hill; park in the dirt turnout area directly north of the microwave station (Fig. 9). It is only a short walk northward to an excellent exposure of the planar Keaney/Mollusk Mine thrust fault with its highly brittle deformational style. The thrust here dips 33° to the west and places the lower part of the Bonanza King Formation over shattered and weathered(?) Precambrian crystalline rocks. Because of geometric arguments which will be discussed at this stop, we believe that the thrust plate moved at or very near the land surface. Hewett (1956), interpreted this fault as a shallow-dipping normal fault. However, the structural continuity of hanging wall rocks exposed here with the upper plate of an "older-over-younger" (Cambrian over Jurassic) thrust fault south of the Interstate highway demonstrates that his interpretation was in error.

Stop 2-2 Footwall structure for the Keaney/Mollusk Mine thrust (Fig. 9)

This is a view stop from the parking area just northwest of the Bailey Road offramp to the south, toward the Keaney/Mollusk Mine thrust plate in the Mescal Range where it overrides Jurassic Delfonte volcanic rocks. The thrust is a planar surface (resembling that seen at stop 2-1) that separates folded rocks in its upper and lower plates. The Delfonte volcanic rocks have been downdropped relative to the crystalline basement rocks of stop 2-1 along the northwest-striking South fault; this fault must therefore have a stratigraphic throw of approximately 4000 m. This stop shows that major displacement along the South fault must predate emplacement of the Mollusk Mine thrust plate because the base of the plate is only slightly displaced by late movements on the South fault. The Delfonte volcanic section beneath the Mollusk Mine thrust is repeated by an older parautochthonous thrust with a displacement of approximately one and one-half km. The thrust and its upper and lower plates have been folded into a syncline plunging 45° to the northwest and overturned slightly towards the northeast.

Cross the Interstate highway and turn east (left) on the paved frontage road. This road soon becomes a graded dirt road that leads to Piute Valley on the southern flank of the Mescal Range. Stops 2-3 through 2-5 are northward view stops that enable us to study a spectacular cross-section through the Clark Mountains thrust complex (Fig. 10).

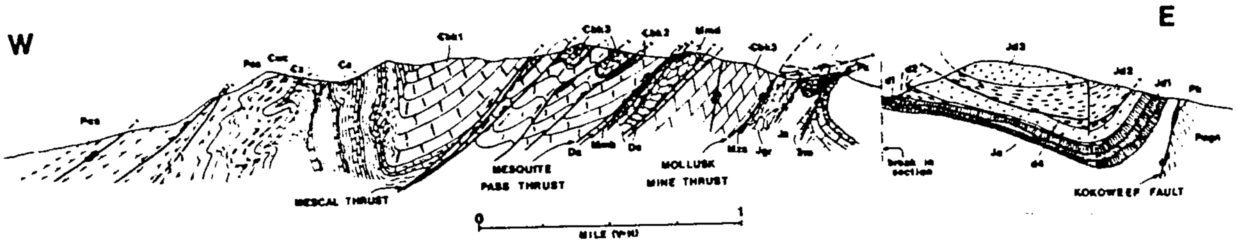


Figure 10. Cross-section through the southern Mescal Range (south of Piute fault, Fig. 9) of the Clark Mountain thrust complex. Various parts of this section will be seen at stops 2-3, 4, 5, and 6. Rock units from west to east: Stirling Quartzite (P€s); Wood Canyon Formation (€wc); Zabriskie Quartzite (€z); Carrara Formation (€c); Bonanza King Formation (€bk) with subunits 1-3; Bullion and Dawn Anchor Members of the Monte Cristo Formation (Mmb and Mmd); Sultan Formation (Ds); Jurassic pluton (Jgr); Mesozoic clastic sediments (Ms); Kaibab Limestone (Pk); Moenkopi Formation (Trm); Aztec Sandstone (Ja); Delfonte Volcanics (Jd) with subunits 1-4; Precambrian gneissic basement (P€gn).

Stop 2-3 Parautochthonous structure in eastern Mescal Range (Figs. 9, 10)

Walk to the top of a small rounded hill just west of the Delfonte Aztec sandstone quarry. The hill is underlain by Aztec Sandstone and affords an excellent view of complex structural relationships below the Keaney/Mollusk Mine thrust fault. To the northeast we see the Aztec-Delfonte stratigraphic section on the eastern, upright limb of the Kokoweef syncline, a major fold in the autochthon (Fig. 9). Basalts underlie the strike valley between the resistant Jurassic sandstones and higher volcanic units. The thrust that repeats the Delfonte volcanic sequence (stop 2-2) is not obvious from this vantage point. To the north-northwest, we see the lower part of the Mollusk Mine plate where it lies discordantly on southwest-dipping Aztec and Chinle(?) strata in the western overturned flank of the Kokoweef syncline. A small, isolated conglomeratic channel filling lies directly below the thrust plate several hundred feet south of the break-in-slope on the skyline. Its sandy matrix was derived from Aztec Sandstones, and its clasts are largely of Moenkopi limestone. In the thrust plate a prominent orange-weathering silty dolomite member of the Bonanza King Formation defines a large, west-plunging overturned syncline (Fig. 10). A series of complicated parautochthonous thrust slices involving Moenkopi and Kaibab carbonate rocks can be seen in areas to the northwest and west of this view stop.

Stop 2-4 Mollusk Mine and Mesquite Pass thrust plates (Fig. 10)

From a Piute valley locality farther to the west (Fig. 9) we will study a cross-sectional view of the Mollusk Mine thrust plate and the Mesquite Pass plate above it (Fig. 10). The Mollusk Mine thrust plate (up to the Mesquite Pass thrust fault) is very thin here and consists only of a few minor slices, some internally folded, of Paleozoic carbonate rocks. Late Jurassic granitic rocks lie in the footwall of the Mollusk Mine thrust, as does a thin (0-20 m), overlying section of weathered granite and stream-reworked arkosic sediments derived from the pluton. The presence of these sediments and the channel fill discussed at stop 2-3 directly beneath different slices of the Mollusk Mine thrust plate argues strongly for their movement across the earth's surface.

Above the Mollusk Mine plate lies the Mesquite Pass thrust and an upper-plate sequence of what appears to be interlayed light and dark gray limestones and orange-weathering silty dolomite beds. Mapping demonstrates that the six or seven orange-weathering carbonate "beds" are in all cases the same Bonanza King marker bed (last seen above the Mollusk Mine thrust at stop 2-3). The bed is repeated by folding and thrusting in an imbricate zone at the base of the Mesquite Pass thrust plate (Fig. 10; Evans, 1980, erroneously maps this imbricated Cambrian sequence as the Mississippian to Permian Bird Springs Formation). The folds plunge southward toward Piute Valley at almost the same angle as the slope of the hill, and, thus, the beds appear to be parallel to one another. Locally, one can observe convergence, divergence, or truncation of the silty "beds" in this imbricated sequence. The imbricated sequence is intruded by a pre-Jurassic pluton in the core of the Mescal Range (Figs. 9, 13), a relationship that establishes the Mesquite Pass thrust as being older than the underlying Mollusk Mine thrust. To the west along the skyline, a thick section of older, massive gray Bonanza King carbonate rocks is thrust over the imbricate sequence along the Mescal thrust, one of two thrust faults that divide the Mesquite Pass thrust plate into three major thrust slices.

Stop 2-5 Striped Mountain syncline; Mescal thrust (Fig. 10)

From still farther west in Piute Valley we look northward toward a large and complicated syncline above the Mescal thrust in the upper Mesquite Pass thrust plate. This syncline, the Striped Mountain syncline, is locally overturned toward the east. Gray Bonanza King limestones and overlying dolomites which form the core of the syncline are extremely attenuated on its steep western limb (Fig. 10). To the west, the Cambrian-Precambrian clastic sequence (from east to west the Carrara Formation, Zabriskie Quartzite, Wood Canyon Formation, and the Stirling Quartzite) lies conformably below the Bonanza King Formation in a vertical to overturned position. Major "S" folds can be seen along the Bonanza King-Carrara contact and within the resistant cliff-forming quartzites of the Zabriskie. The Striped Mountain syncline demonstrates that the Mescal thrust below it is not of décollement type.

The thrust lies near the base of the Bonanza King Formation on the eastern flank of the fold, but does not reappear in a folded position on the western flank. It must, therefore, cut stratigraphically downward to the west across the steep to overturned clastic section in the western limb of the fold. A corollary to this observation is that the Mescal thrust must postdate formation of the Striped Mountain syncline, a fold presumably formed beneath a higher east-directed thrust fault (= Winters Pass?).

Stop 2-6 Quartzite tectonites, Stirling Quartzite, Striped Mountain

This is a brief stop to examine mylonitic quartzites of the Stirling Quartzite exposed on the northwesternmost corner of Striped Mountain. The quartzites possess a well-developed, shallow southwest-dipping mylonitic foliation and a southwest-plunging stretching lineation. These tectonites are inferred to underlie a higher thrust plate, although alluvium to the west of Striped Mountain conceals the suspected plate. The most spectacular section of Stirling mylonitic quartzites is exposed on the next rounded hill to the south. On the southern hill, a structural sequence of cross-bedded quartzites approximately 700 m thick displays an increasingly penetrative development of mylonitic fabrics upsection. Cross-bedded rocks in some parts of the section exhibit spectacularly complex fold geometries (Fig. 11; Stewart and Burks, 1987). Many of the mylonitic rocks exhibit well-developed S-C fabric relationships in thin-section that indicate northeast-directed ductile shearing of the quartzitic sequence (Fig. 12). The Stirling quartzite tectonites in the Striped Hills have inherited detrital quartz, microcline, and magnetite. Muscovite and biotite are the metamorphic equivalents of original subordinate pelitic constituents in the quartzites. Quartzite fabrics clearly indicate that metamorphic recrystallization was syntectonic with eastward thrusting of an overlying plate.

Stop 2-7 (optional) A Cenozoic allochthon in the Mescal Range (Fig. 13)

Continue westward on the dirt road of stop 2-6. The road intersects the paved Cima Road near a large wooden corral. Turn north toward Interstate 15 and, if time permits, make a short view stop west of the prominent east-west-trending valley in the southern Mescal Range. The steep to overturned western limb of the Striped Mountain syncline lies south of this valley, but it is obvious that the brown-colored clastic section of that limb does not continue northward across the valley. Mapping reveals that the Mescal thrust and the synclinal hinge are offset along the floor of the valley by a steep, east-striking fault, the Piute fault (Fig. 13). Displacement on the Piute fault is left-lateral and totals approximately one and one-half km. We (Burchfiel and Davis, 1971) originally interpreted this steep fault as a tear fault in the Mesquite Pass thrust plate. Recent mapping (Burchfiel and Davis, unpub.) has changed this interpretation dramatically.

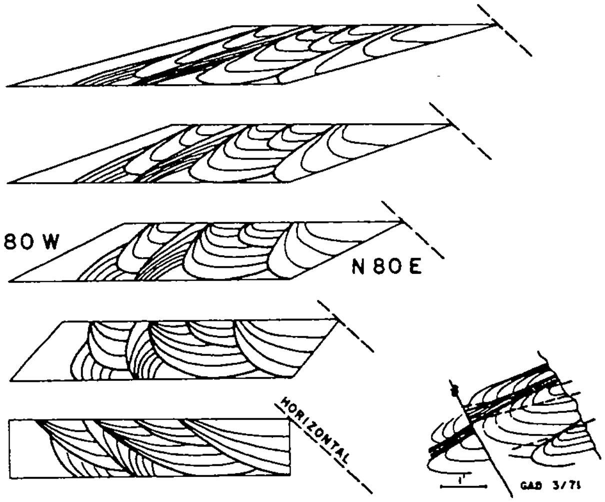


Figure 11. Lower right corner: field sketch, parallel to a prominent stretching lineation, illustrating the geometry of distorted, overturned cross beds in Stirling Quartzite mylonitic tectonites, southwestern Striped Mountain. The five sections illustrate progressive deformation by homogeneous simple shear of idealized cross-bed geometry (lower section). The geometry of the most deformed stage (upper section) approximates the geometry of the field-observed example. "Horizontal" refers to present position of horizontal with respect to the deformed cross-beds. [From G. A. Davis, unpub. field trip handout, 1971.]

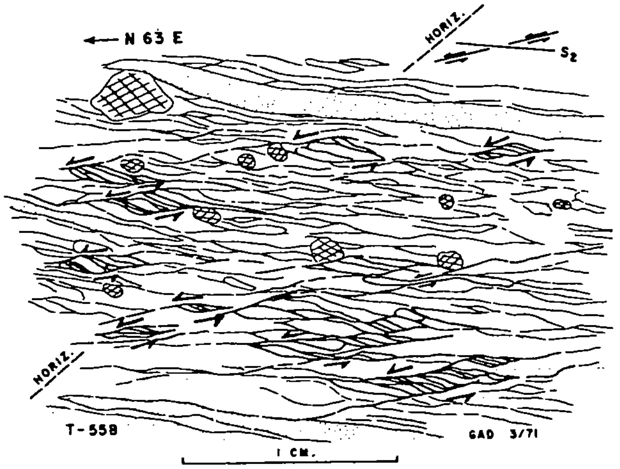


Figure 12. S-C fabric relationships within a thin-section of a Stirling mylonitic quartzite, from the southwestern corner of Striped Mountain. The section is cut parallel to a prominent stretching lineation. The foliation (S2 = S) is transected by shear surfaces (= C) with a geometry that indicates a northeastward sense-of-shear. Both S and C fabric elements dip southwestward with respect to the horizontal reference plane. The stippled grains are flattened, stretched lithic fragments; cross-hatched grains are feldspar. [From G. A. Davis, unpub. field trip handout, 1971.]

The Piute fault is a strike-slip fault along the southern margin of a 10 km-square Cenozoic extensional allochthon that has been displaced westward with respect to the Mescal Range. The northern margin of the allochthon is a shallow, west-southwest-dipping brittle fault that lies above and roughly parallel to the Mesquite Pass thrust. Burchfiel and Davis (1971) interpreted this shallow fault as a Mesozoic thrust fault. Between the eastern ends of the Piute fault and the north boundary fault lies a north-northwest-striking breakaway zone where rocks in the allochthon have pulled away from the non-extended headwall. The breakaway zone is characterized by extreme _in situ_ shattering and brecciation and an eastward rotation of upper-plate strata into the "hole" created by westward movement of the allochthon. In addition, a thick section of footwall-derived Tertiary conglomerate and sedimentary breccia records the filling of a pull-apart basin(s) in the breakaway zone (Fig. 13). Geometrically similar relations have been described by Dokka (1986) along the western headwall of the Barstow detachment terrane in the central Mojave region. At this time we do not know whetehr the Mescal Range Cenozoic allochthon is a local, asymmetrical, scoop-shaped gravity-driven block that has slid westward into Shadow Valley, or whether it is a southeastern portion of the crust-extending Kingston Range detachment complex (to be discussed at length on the third day of this trip).

Continue north on Cima Road, cross Interstate 15, and drive north to a poorly graded dirt road that leads eastward toward Pachalka Spring on the west flank of the Clark Mountains. The turnoff lies not far to the north of a round metal water tank on the east side of the road.

Stop 2-8 Pachalka Spring road: the Pachalka thrust (Fig. 9)

Our first stop will be in the first narrow valley containing bedrock exposures of Precambrian(?) granite and granitic gneiss. The thrust contact between these crystalline rocks and underlying Wood Canyon Formation quartzites of the miogeoclinal section (Mesquite Pass plate) is extremely well exposed on the north side of the valley at the level of the road. Although we refer to this thrust fault as the Pachalka thrust, we believe that it is correlative with the Winters Pass thrust to be seen on the third day. The thrust contact is knife-edge sharp and separates upper-plate mylonitic gneisses from lower-plate mylonitic quartzites [NOTE: please do not collect samples from the thrust contact exposed along the road; it is an exceptional locality and should be preserved]. Directly below the contact is a layer, one to four cm thick, of black "ultramylonite". This "ultramylonite" is seen in thin section to be a very fine-grained aggregate of white mica, biotite, and an opaque ore mineral (probably magnetite). Rocks more than 100 m above and as much as 5 m below the shallow west-dipping thrust are characterized by a penetrative mylonitic foliation and a stretching lineation that plunges S 80° W at low angle. S-C fabrics in the mylonitic gneisses are well-developed and consistently indicate eastward transport of the thrust plate parallel to the mylonitic lineation. The lineation trends at a very high angle to the hinges of large folds with steep to overturned eastern limbs in the footwall of the thrust. We are confident in correlating the lineation seen here in both walls of the Pachalka thrust with the lineation present in lower-plate Stirling Quartzite tectonites in the western Striped Hills (stop 2-6).

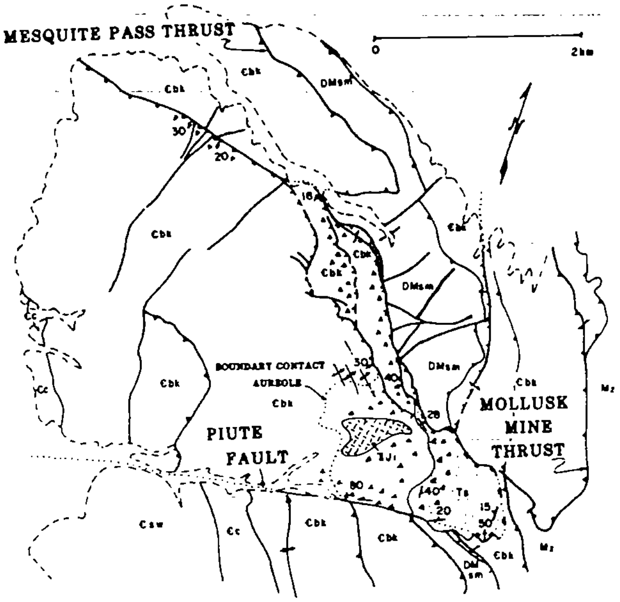


Figure 13. Highly simplified tectonic map of northern Mescal Range, Clark Mountains thrust complex. Interstate Highway 15 lies directly north of the map area (cf. Fig. 9). Most of map area lies within an extensional Cenozoic allochthon that has developed across the Mesozoic thrust belt. The allochthon is bounded on the south by the steep Piute fault (a tear or transfer fault), on the east by a complex, west-dipping breakaway zone, and on the north by a single, low-angle oblique slip extensional fault. The breakaway zone is characterized by (1) the eastward tilting and extreme shattering and brecciation of Bonanza King carbonate rocks (€bk), and (2) by Tertiary conglomerates and sedimentary breccias (Ts) deposited in a restricted breakaway basin. Other rock units (oldest first): undifferentiated Sterling, Wood Canyon, and Zabriskie formations (€sw); Carrara Formation (€c); undifferentiated Devonian and Mississippian sedimentary rocks (DMsm); Triassic/Jurassic intrusion (TrJi); and undifferentiated Mesozoic rocks (Mz).

Hornblende dioritic dike rocks were apparently intruded along the thrust fault at the base of the Pachalka thrust plate during its emplacement. Highly sheared and foliated dike rocks underlie the crystalline plate along much of its exposed base north of the valley containing stop 2-8. Locally, these dike rocks cross into the upper plate where they are generally less deformed than in exposures directly beneath the plate. Samples of the diorite have been collected for possible dating.

From the thrust contact exposed along the road, walk eastward through an overturned section of Wood Canyon quartzites and Carrara Formation to observed the deformational style of the lower plate. The Zabriskie Quartzite that normally lies between these two units is missing along the road, presumably because of tectonic thinning, disruption or both. It reappears in typical development not far north of the road and along it to the east. The first gray limestone ledge encountered above Carrara phyllites is in the overturned limb of a major syncline below the thrust plate. The syncline can be seen in cross-section along the skyline to the north. This Carrara limestone is separated from the Wood Canyon quartzites by green phyllites of the lowermost Carrara Formation. Foliation development, small similar folds, and boudinage within the limestone indicate that it was extremely ductile during deformation. The next limestone ledge to the east is the same limestone bed repeated on the normal limb of the overturned syncline. Farther east along the road, below Carrara phyllites, are several exposures of the Zabriskie Quartzite in anticlinal hinges. The folds contain a well-developed, southwest-dipping axial plane cleavage.

Stop 2-9 (optional) Bonanza King-Carrara foliated contact

Time permitting, continue driving up the Pachalka Spring road; take the right-hand fork just past the folded outcrops of Zabriskie Quartzite. Park along the ridge crest above the trees to the northeast that mark the location of Pachalka Spring. Several prominent box-like folds are exposed in white and gray carbonate rocks of the lower Bonanza King Formation on the hill directly above the spring. Bedding below the folds, as shown by orange-weathering carbonate ledges in the upper Carrara Formation, is subhorizontal and unfolded. The contact between these two in-sequence formations appears at first to be a classic zone of décollement. However, for the following reasons we believe that it is not.

(1) Stretching lineations (parallel to those of stop 2-8), pressure shadows adjacent to pyrite cubes, fluting (not seen at this locality), and boudinage in the contact zone all indicate an eastward direction of movement (upper plate relative to lower). However, the folds that are prominently displayed above the spring have east-west-trending hinges.

(2) Higher on the hillside, numerous north-south cross folds indicate an eastward direction of transport. Mapping demonstrates that these folds are younger than and crosscut the east-west folds. We believe that this indicates that movement on the Carrara-Bonanza King thrust zone, or at least the last movement on the zone, was in an east-west direction and was later than the deformation that produced the east-west trending folds.

The ductiley sheared contact between the two units is extremely interesting. It is marked by a gradational zone of variable thickness (<20 m) of flow-laminated limestone and dolomite. Movement was accomplished by flow in both the lower Bonanza King and upper Carrara carbonates; no single contact can be mapped as the thrust at this locality. Eastward, several hundred feet up the south side of the main valley into the Clark Mountains, is an exposure of the thrust zone where boudinaged igneous dike rocks are prominently displayed within Carrara carbonates and phyllites. The boudins trend roughly north-south and indicate east-west transport of the upper plate. Several small thrust slices occur within the Bonanza King Formation above the boudin locality. The spectacular subisoclinal "fold" seen in black and white Bonanza King carbonate rocks to the north of the boudin locality is not a fold at all; it is merely an image created by the intersection of south-dipping carbonate beds with the uneven topographic surface.

Depart for Baker, California. Note the white mylonitic rocks exposed on the southwest end of the narrow canyon of stop 2-8. These highly strained rocks are mylonitized aplitic dikes in the granitic gneisses. They are, unlike the gneisses, L-tectonites (i.e. they lack a planar mylonitic foliation). The strong rodding of the aplites is parallel to the mylonitic lineation and to hinges of abundant, geometrically complex isoclinal folds. Unfortunately, these outcrops have been bulldozed, apparently in the search for ornamental stone. Turn south on Cima Road and then west on Interstate 15.

Synopsis for the Second Day

This part of the fieldtrip establishes the structural sequence of Mesozoic thrust plates in the Clark Mountain thrust complex and compares their deformational style. Stops 2-1 through 2-3 introduced the geometry and brittle deformational character of the frontal, Keaney/ Mollusk Mine thrust and the parautochthonous slices below it in the eastern Mescal Range. The Cretaceous Mollusk Mine thrust (as seen at stops 2-1 and 2-2) and a structurally higher, overlapping thrust fault, the base of the Mollusk Mine plate to the south (stop 2-3), appear to have overriden surficial sedimentary deposits that postdate late Jurassic plutonic intrusion in the Mescal Range and related(?) parautochthonous deformation.

In contrast, stops 2-4 through 2-9 examined the higher Mesquite Pass and Winters Pass (Pachalka) thrust plates. Deformation in these plates clearly occurred at deeper crustal levels than for the frontal thrust and was accompanied by low-grade recrystallization, especially in the footwall of the Winters Pass thrust. Intrusion of the folded and thrust-imbricated sequence of Bonanza King rocks at the base of the Mesquite Pass plate (stop 2-4) by a Triassic pluton in the central Mescal Range establishes a pre-190 to 200 Ma age for this plate (Sutter, 1968; Burchfiel and Davis, 1971). The age of emplacement of the overlying Winters Pass plate is, at the time of this writing, equivocal. Arguments were given at stop 2-5 that the impressively ductile Striped Mountain syncline had formed beneath the Winters Pass plate prior to development of the Mescal thrust, one of the major thrust faults within the Mesquite Pass plate. Yet some field relationships in the Pachalka Spring area can be interpreted as circumstantial evidence that the Pachalka thrust plate (= Winters Pass?) was not emplaced until the Cretaceous. We are unconfortable with such a young age of thrusting for this highest thrust sheet in the complex. Hopefully, dioritic rocks intruded along the Pachalka thrust during late stages of displacement can be dated to resolve this question of timing.

Third Day

Introduction

Return to the northern part of the Clark Mountain thrust complex, north of Interstate 15. Having established the Mesozoic tectonic framework of the complex yesterday, we now focus on Cenozoic extensional modifications of it. We have recognized four examples of such modifications:

(1) extensional faulting in the west-central Mescal Range (stop 2-7 and Fig. 13);

(2) normal faulting, down to the west, within the base of the Keaney/Mollusk Mine thrust plate from the powerline road north of Clark Mountains (stop 3-3 and Fig. 9) to the northern Mescal Range;

(3) low-angle detachment faulting near the base of the same plate near Mesquite Pass, 3-4 miles north of stop 3-2 (Fig. 9); Mesquite Pass and Winters Pass plate rocks above this detachment have been extended along southeast-dipping normal faults during an episode of probable Cenozoic extension unrelated to (2) above; and

(4) major low-angle detachment faulting in the eastern Kingston Range and at structurally high levels of the Mesquite Mountains (between the Kingston Range and Clark Mountains); this domain of southwest-directed extension (relative to lower-plate rocks) constitutes the southeastern breakaway margin of a major, probably composite, late Tertiary extensional province that extends as far to the west as the Sierra Nevada (Fig. 3).

Of the four examples of Cenozoic extension, only (4) appears at this time to have regional implications. The trace of a major west-dipping, low-angle normal fault, the Kingston Range detachment, is present in the northeastern Kingston Range (Burchfiel, Hodges, and Walker, in prep.). Most of the range consists of complexly faulted, east- and northeast-tilted Precambrian, Cambrian, and upper Cenozoic strata (Figs. ~~14, 15~~ 15,1). The Kingston Range detachment (Fig. 3) separates a region to the east and south, including the Mesquite and Clark Mountains, that has been little affected by Cenozoic extension, from a region (as far to the west as the Sierra Nevada) that has been strongly affected by such extension. For this reason, the Kingston Range detachment forms the eastern breakaway zone for the extended regions to the west (Burchfiel and others, 1983). South of the Kingston Range, the continuous trace of the Kingston Range detachment is largely covered by young alluvium, but it probably lies just west of the Mesquite Range close to Cima Road. Isolated blocks of upper Precambrian, Cambrian, and

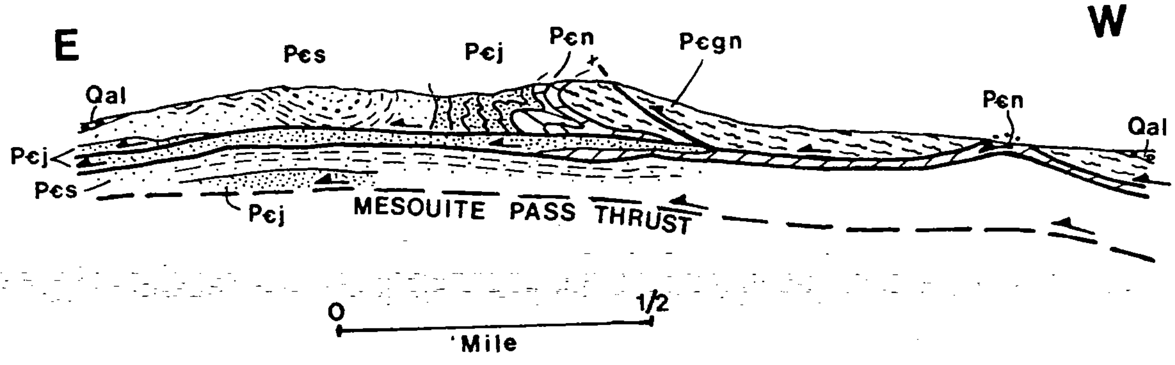


Figure 14. Cross-section through the Mesquite Pass thrust plate, hill south of powerline road (cf. Fig. 9), illustrating involvement of basement crystalline rocks in the thrust belt. Geologic relationships are explained at stop 3-1. Rock units (oldest first): Precambrian gneisses (Pꞓgn); Noonday Dolomite (Pꞓn); Johnnie Formation (Pꞓj); Sterling Quartzite (Pꞓs); Quaternary alluvium (Qal).

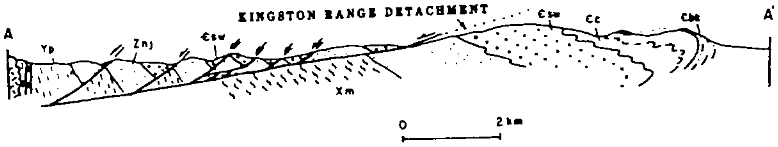
Cenozoic rocks that rest on the detachment fault in the western Mesquite Mountains are erosional klippen of its hanging wall (stop 3-4, Fig. 15). The detachment fault is locally exposed beneath these klippen and dips only an average of 3 degrees to the southwest, the direction of relative upper-plate displacement along it.

Upper Precambrian and Cambrian rocks are folded along northwest-trending axes in the footwall of the Kingston Range detachment (Figs. 15, 16). The folds are overturned to the northeast and are well exposed in the eastern foothills of the Kingston Range. These folds are on strike with similar folds in the Mesquite Mountains to the southeast that are in the hanging wall of the Mesozoic Winters Pass thrust. We suggest that these folds formed during an early episode of northeast-directed thrusting along the Winters Pass thrust. Because the older rocks were folded by Mesozoic deformation it is difficult to assess how much of their tilting within the upper plate of the Kingston Range detachment occurred during Cenozoic rotation. Upper Cenozoic strata rest unconformably on folded Cambrian rocks at one locality on the northeast slope of the Kingston Range in the footwall of the detachment. They dip 10 to 20 degrees northeastward, suggesting some Cenozoic rotation of the footwall rocks. It is not clear, however, whether this rotation is related to detachment faulting or to warping along the northeastern flank of the Mesquite Pass antiform (Fig. 9).

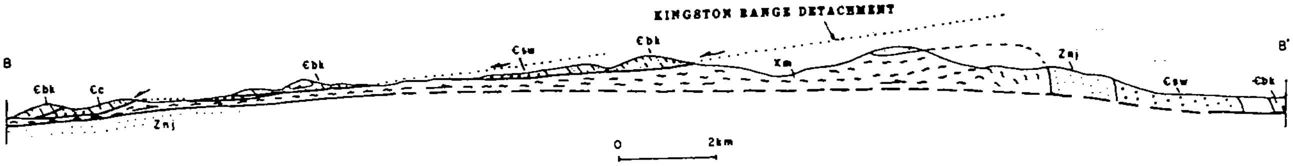
Rotation of upper-plate rocks above the Kingston Range detachment is clearly recorded by tilted upper Cenozoic strata. Conglomerate, sandstone, lacustrine limestone, and volcanic rocks dip 30 to 35 degrees northeastward into the detachment fault in the easternmost part of the hanging wall. In some fault blocks in the central part of the Kingston Range they dip vertically into Precambrian crystalline rocks of the lower plate.

The geometry of upper-plate faulting is very complex and consists of numerous, closely spaced, southwest-dipping, planar and listric normal faults and associated northeast-striking tear or transfer faults. Some of the normal faults have clearly been rotated into shallower dips. Many of the faults are strongly curved in plan view and, presumably, in cross section. This suggests that some of the hanging wall faults are spoon-shaped. Extensional duplexes can be seen locally in erosional windows. The matching of hanging-wall to footwall cutoffs of the northeast-dipping Noonday Dolomite indicates that the easternmost and lowest fault of the detachment complex has about 3 to 4 km of displacement (stop 3-6).

The Noonday Dolomite rests unconformably on crystalline metamorphic and igneous rocks in the footwall of the Kingston Range detachment with only thin (a few tens of meters), intervening local deposits that may be equivalent to the upper Precambrian Pahrump Group. However, the hanging wall contains a thick sequence (several kilometers) of Pahrump Group rocks below the Noonday Dolomite. The dolomite rests unconformably on rocks of the Pahrump Group and progressively rests toward the north on older Pahrump units until it lies across crystalline



NORTHEAST KINGSTON RANGE



NORTHWEST MESQUITE MOUNTAINS

Figure 15. Cross-sections through the northeast Kingston Range and the northwest Mesquite Mountains that illustrate the shallow dip and upper-plate structure of the Kingston Range detachment fault. The locations of sections AA' and BB' are shown on Figures 16 and 9 respectively. Unit designations not explained for previous figures are: Xm = Precambrian metamorphic rocks; Yp = Precambrian Pahrump Group; Znj = Precambrian Noonday Dolomite and Johnnie Formation. The patterned unit at A, section AA', is the Miocene Kingston pluton. The heavy dashed line near the bottom of section BB' is the Mesozoic Winters Pass thrust fault.

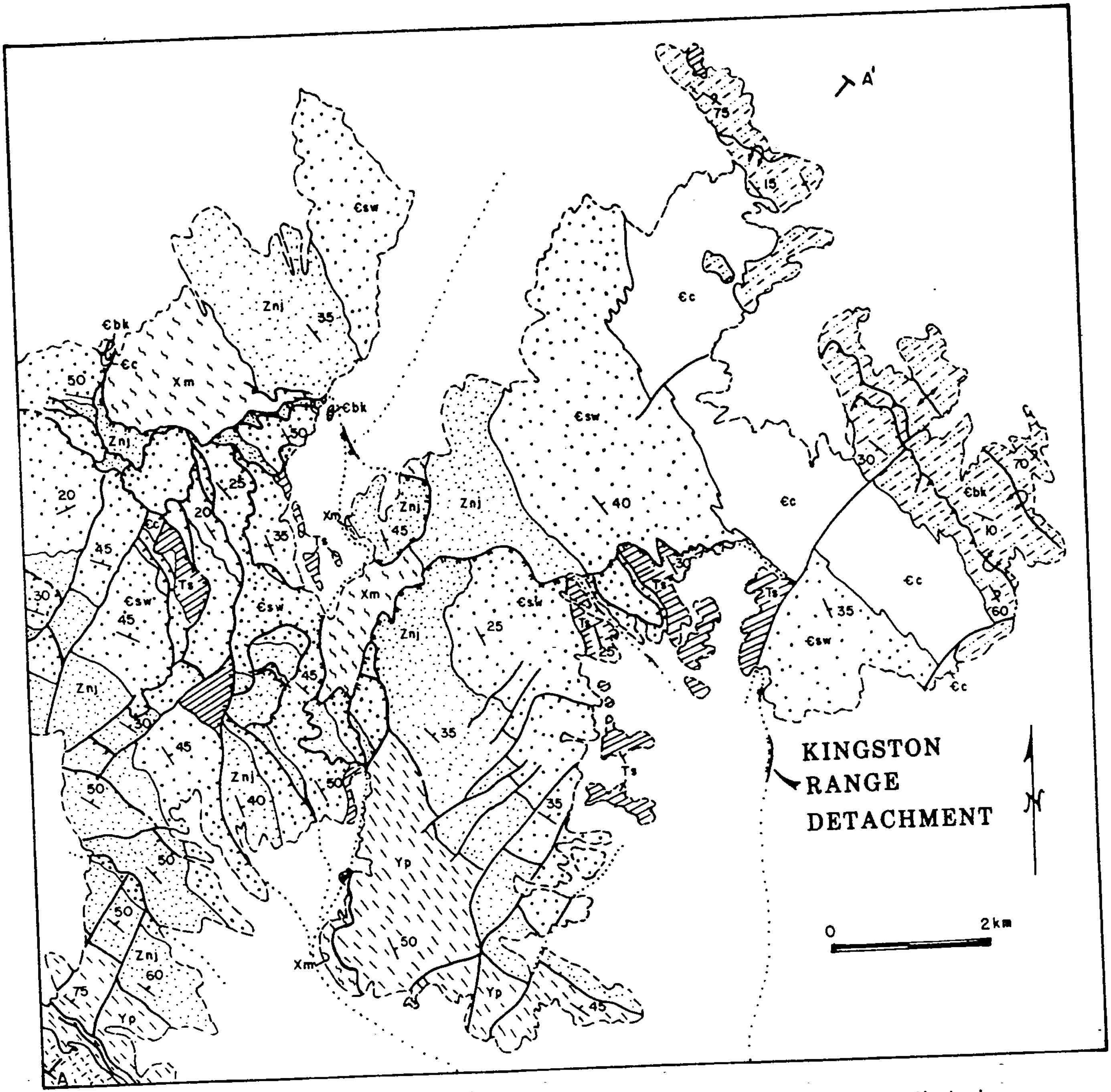


Figure 16. Simplified geologic map of the northeastern Kingston Range (cf. Fig. 4) showing location of the Kingston Range detachment fault and its upper-plate structure. The unlabeled patterned unit at the southwestern corner of the figure is the Miocene pluton. Abbreviated designations for rock units have been explained in previous figures.

basement rocks in the northern Kingston Range. These relations indicate that the Pahrump Group was faulted and tilted prior to deposition of the Noonday Dolomite. It also suggests that the Kingston Range detachment fault either reactivated or followed closely the old eastern boundary fault of the Pahrump Group.

Volcanic rocks from two localities in the hanging wall of the detachment have been dated at 12.5 and 12.1 Ma (J. Spencer, person communication to BCB, 1983; P. G. Tilke, personal communication to BCB, 1985). These volcanic rocks were clearly deposited prior to the onset of detachment faulting. The large Miocene Kingston Range pluton (12 to 13 Ma, Armstrong, 1970) is intruded into Precambrian strata of the Kingston Range, but whether the pluton is older or younger than the detachment faulting is not yet known. Paleomagnetic data indicate that the pluton has been rotated (Jones, 1983), but it is not clear whether this rotation is the result of detachment faulting or post-detachment strike-slip faulting. At present there is no good upper age limit to displacements on the Kingston Range detachment.

Fieldtrip Stops

Return to Cima Road and drive north along it from Interstate 15. Turn east on the powerline road approximately 9 miles north of the freeway.

Stop 3-1 (optional) Style of deformation in Mesquite Pass thrust plate (Fig. 14)

In the westernmost hill south of the powerline road are exposures of several thrust slices that characterize the structural style in the lower part of the Mesquite Pass thrust plate (Fig. 14). At this view stop, look south toward the hill and the three thrust-bounded slices within it. At the base of the hill is a tectonic slice containing, in normal sequence, the upper Precambrian Johnnie Formation and the middle and lower parts of the Stirling Quartzite. An important feature of this lowermost slice is its lack of internal folding. Above it is a slice of very thin, essentially unfolded Noonday Dolomite seen as the prominent brown ledge near the middle of the slope. Eastward, this second slice also contains Johnnie Formation rocks separated from the Noonday by a minor(?) thrust; the Noonday rocks are cut out to the east. Rocks in the third, highest slice belong to a complete sequence from Precambrian crystalline rocks to the Zabriskie Quartzite. The style of this slice is very different from the other two, because its rocks are highly folded. The folds are overturned to the east, exhibit a well-developed axial plane cleavage, and are truncated by the thrust fault at the base of the slice. Precambrian crystalline rocks appear in the cores of the westernmost folds and, like the sedimentary rocks above them, also possess an axial plane cleavage. The Noonday Dolomite, which directly overlies the basement rocks, has been squeezed into the cores of folds and is tectonically thinned or missing along their flanks farther to the south.

Stop 3-2 Contact between the Mesquite Pass and Keaney thrust plates

Stop and look northward from the intersection of the powerline road and the Mesquite Pass road leading north. The contact between the Mesquite Pass and Keaney thrust plates is clearly evident in the southern Mesquite Mountains across the broad open valley. Brownish, upper Precambrian clastic rocks in the Mesquite Pass thrust plate (Stirling Quartzite, Johnnie Formation) form the large, dark hill to the west of a small valley along the Mesquite Pass thrust. The well-bedded black, gray, and white carbonate rocks east of the valley lie in the Keaney thrust plate and include the Bonanza King, Sultan, and Monte Cristo formations. Northeast-striking, southeast-dipping, high-angle faults in this plate lie in the hanging wall of a Cenozoic detachment fault. The low-angle fault is located just below the Keaney thrust in Bright Angel shales and carbonates, but it cannot be seen from this stop.

Continue driving east on the powerline road. Turn right, approximately one mile past stop 3-2, onto a dirt road that leads southward. This road lies variably within and below the basal portion of the Keaney thrust plate. Drive through a complicated footwall zone of Mesozoic parautochthonous thrust slices in Tapeats Sandstone and Bright Angel Shale before stopping near the base of the plate approximately 1.35 miles south of the powerline road.

Stop 3-3 Low-angle Cenozoic normal faults, basal Keaney plate

The Keaney thrust fault juxtaposes Cambrian carbonate rocks over older units (Precambrian basement, Tapeats Sandstone, Bright Angel Shale) from the Mesquite Pass area (cf. stop 3-2) southward to Mohawk Hill (stop 2-1). We believe that this is the consequence of the uplift and erosion of a Cambrian-Jurassic cratonal section from the northern wall of the South fault (stop 2-2), prior to emplacement of the Keaney/Mollusk Mine thrust plate across the lowest part of this section; the complete cratonal section is still preserved south of that fault (stop 2-3). Sharp (1984) was the first to recognize that the thrust zone at the base of the Keaney/ Mollusk Mine plate has been overprinted by down-to-the-west normal faulting of Cenozoic age. His studies in the Colosseum Mine area, 1 mile south of this stop, established that a zoned, mineralized aureole around a Cretaceous granitic stock had been downdropped approximately 1500 feet.

At this stop we examine a shallow-dipping zone of brittle faults that is presumably of Cenozoic age and normal fault displacement. The fault zone is exposed in several prospect pits and small mine workings above and west of the dirt road. Copper mineralization typical of the normal fault zone (malachite, azurite) is seen in these workings, as is the characteristic presence of sheared fluorite. Just below one of the prospect pits we will contrast the brittle Cenozoic deformation with an exposure of the Keaney thrust. This sharp, foliated thrust contact separates upper-plate Bonanza King carbonates from lower-plate Bright Angel(?) carbonates. The foliated nature of this contact, in contrast to the brittle fault seen at stop 2-1, may indicate that lower-plate rocks in this area had a considerably higher temperature due to nearby igneous intrusion (Colosseum Mine area) than in areas farther south. Our remapping of the Keaney thrust in areas to the south indicate that the base of the Keaney plate is now locally defined by a shallow-dipping (<35°) normal fault or faults. This relationship is perhaps best seen in the bulldozed pit of the Pacific Fluorite Mine west of the Colosseum Mine.

Return to Cima Road and turn right (north) along it. Stop approximately 3 miles north of the northeast-trending side road to Winters Pass.

Stop 3-4 (optional) Complexity of slicing below Winters Pass thrust plate

At this stop we will walk through upper Stirling Quartzite in the Mesquite Pass thrust plate, and climb upward across several thin tectonic slices of Noonday and Stirling rocks below the Winters Pass plate. Mylonitic gneisses at the base of the plate have the shallow dipping mylonitic foliation and southwest-plunging stretching lineation seen at stops 2-6 and 2-8. The black layers in some of the mylonitic gneisses at the top of the hill are not mylonitic in origin, but are composed of magnetite.

To the north are klippen in the northeast-southwest-trending train of klippen above the shallow (3°) southwest-dipping Kingston Range detachment (Fig. 15). Cambrian strata dip eastward into the detachment surface and are repeated again and again by southwest-dipping upper-plate normal faults (one of which can be pointed out from this locality). Massive Bonanza King rocks overlie Carrara Formation in the nearest klippe. The major dark gray ridge west of Cima Road, surrounded by alluvium, is composed largely of tilted Bonanza King carbonates, but a thick, tilted Tertiary section of sedimentary and volcanic rocks lies concordantly above it.

It is clear from this stop that the Kingston Range detachment fault developed across crystalline rocks in the Winters Pass plate in this area. It did *not* reactivate the Winters Pass thrust fault which lies only a hundred meters or so below the detachment fault in this area. The close parallelism of the Cenozoic detachment fault and the subhorizontal older thrust fault throughout the northern Mesquite Mountains should dispel arguments by some geologists that low-angle detachment faults cannot have a primary, shallow-dipping geometry. The 2 to 3 degrees southwest dip of the Kingston Range detachment fault in this area, across a distance of at least 15 km, must be very close to the *original* dip of the detachment fault in this, its breakaway area.

Continue driving north on Cima Road. Turn right (eastward) onto a dirt road not far south of the white talc tailings in the Kingston Range. Stop 3-5 and 3-6 are along this road.

Stops 3-5, 3-6 View stops of Kingston Range detachment fault relations as seen from the road between the eastern Kingston Range and the northern Mesquite Mountains (Figs. 15, 16).

Upon reaching Mesquite Valley, turn right (south) and drive to the well-graded road between the settlement of Sandy, in the valley, and Winters Pass in the Mesquite Mountains. Turn right (west) and drive into Winters Pass.

Stop 3-7 Winters Pass thrust fault, Winters Pass area

The Winters Pass road follows the trace, mostly concealed, of the Winters Pass thrust fault. The northeast strike of the fault here is due to its position on the northwest-plunging nose of a large Cenozoic(?) antiform (Mesquite Pass antiform) that warps all three major thrust plates in the area. The Winters Pass plate northwest of the road consists of a well-exposed, northeast-dipping, miogeoclinal section approximately 3200 m in thickness. This section extends from crystalline basement into the Cambrian Bonanza King Formation. The basal unit of the section, the Noonday Dolomite, rests unconformably on Precambrian gneiss and granitic rocks. Locally, a thin (several m) basal conglomerate is developed on the irregular erosion surface beneath the Noonday. The contact is only locally and mildly deformed, in marked contrast to the highly deformed contact discussed at stop 3-1. A thick sequence of generally brownish clastic rocks overlies the Noonday Dolomite (including Johnnie, Stirling, Wood Canyon, Zabriskie, and lower Carrara formations). The thin Zabriskie Quatzite is strongly small folded. Several ledges of thick grey limestone, some containing numerous algal structures (*Gervinella* sp.) are interbedded in the lower Carrara Formation with greenish phyllitic shales. We have seen one such limestone (highly deformed) in the overturned syncline below the Pachalka thrust plate (stop 2-8).

Southeast of the road in Winters Pass is a small exposure of the Precambrian and Cambrian clastic sequence that lies above the Winters Pass thrust; this is the only segment of the thrust in Winters Pass that is not buried beneath alluvium. If time permits, we will walk to an exposure of the foliated thrust contact. The footwall of the thrust here is a section of overturned Bonanza King Formation. The hinge of the overturned synclinal fold trends northeast-southwest, parallel to the trace of the thrust fault. Several thin, tectonic slices of orange-weathering silty carbonates of the upper Carrara Formation lie exposed below the Winters Pass thrust, but the Carrara beds are not in stratigraphic continuity with the overturned Bonanza King carbonate rocks.

Stop 3-8 (optional) Kingston Range detachment fault and klippe

Time permitting, we will drive southeastward on the Winters Pass road to Winters Pass at the summit of the small grade. From here we can look back down along the obvious trace of the Winters Pass thrust. The prominent isolated gray hill on the skyline to the northwest is largely underlain by Bonanza King carbonate strata dipping 20 to 40 degrees northeastward. The hill is the most northeasterly of the klippen above the Kingston Range detachment fault, here seen as the planar, shallow-dipping (2 to 3 degrees) contact between upper-plate carbonate rocks and Precambrian gneisses which form the low rolling terrane surrounding the hill.

The trip ends here. Return to Las Vegas via Sandy, Goodsprings, and Jean, Nevada.

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Davis

GUIDEBOOK:

DEATH VALLEY REGION, CALIFORNIA AND NEVADA

PREPARED FOR THE 70th ANNUAL MEETING OF THE CORDILLERAN SECTION
THE GEOLOGICAL SOCIETY OF AMERICA
FIELD TRIP NUMBER 1

CONTENTS

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PART 2: ARTICLES

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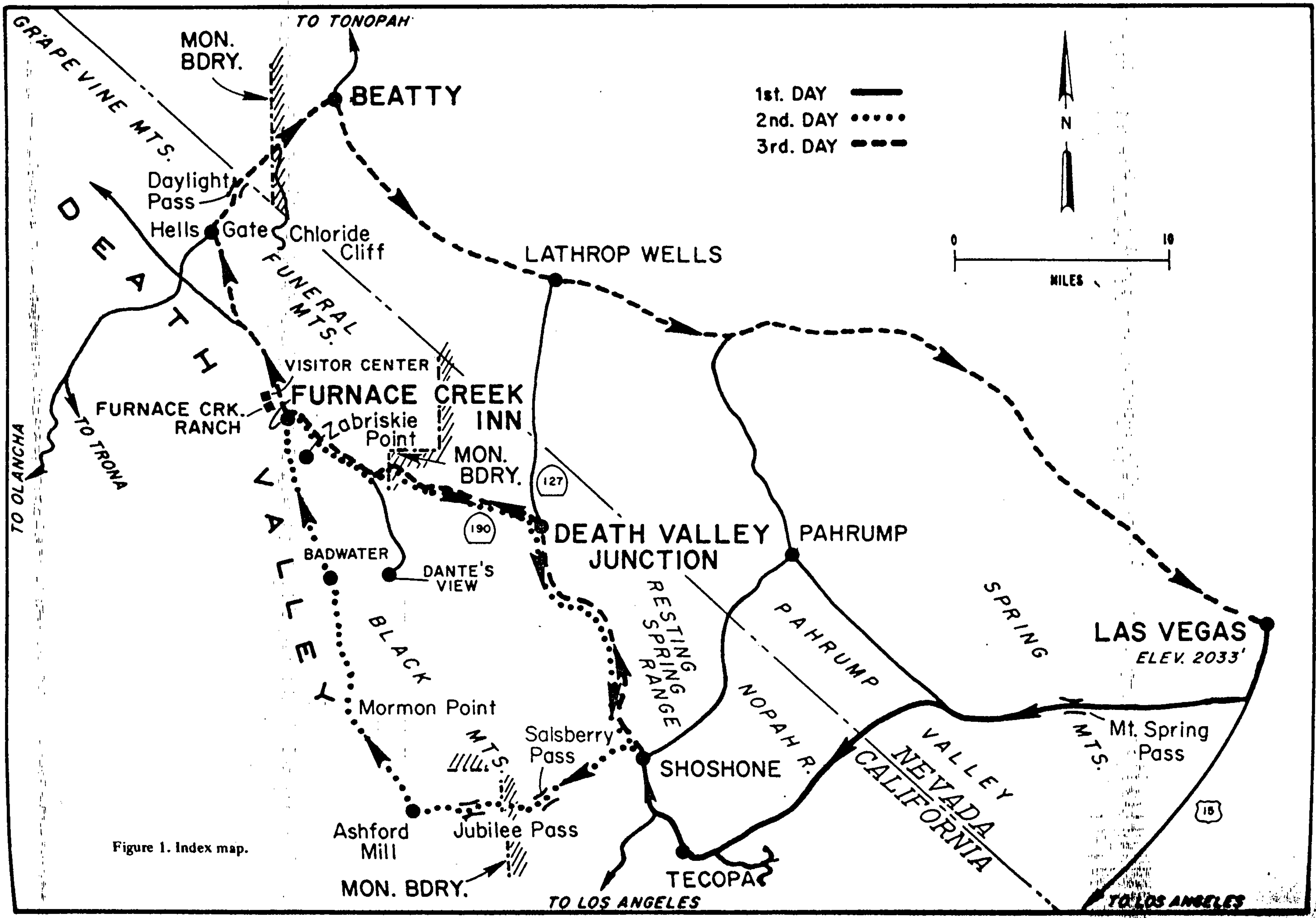

Figure 1. Index map.

PART 1

Geologic Guide to the Death Valley Region, California and Nevada

Bennie W. Troxel[1]

INTRODUCTION

This guidebook was prepared for use on a 3-day bus trip of the Death Valley region, that starts and ends in Las Vegas, Nevada. The second and third day's trips begin in Shoshone, California. The guide may be useful to others who wish to follow selected segments of the trip or to review in more detail some of the geologic features of part of the Death Valley region which are highlighted in this guide. The guidebook can and should be supplemented by additional reports and maps. General papers and selected papers pertaining to areas along the route are included in the references.

The guidebook consists of a general guide (Part I) and preprints of several new papers, as well as reprints of others, that pertain to the Death Valley and Las Vegas regions (Part II).

Information for the general guide is derived from the published sources listed in the references, personal observations, and work in progress by the authors of the papers in Part II. Unfortunately, specific citations to individual works are lacking in many parts of the guidebook, especially to work underway.

Features most obvious from the roads are emphasized in this guide. Although no detailed road maps are provided, care has been taken to use reference points that are marked by signs on the road or are on common road maps.

On the trip, information will be provided along the route, as noted below, by:

NAME	AREA	SUBJECT
B. W. Troxel (general leader)		Geology along route
L. A. Wright (general leader)		Geology along route
B. C. Burchfiel	Las Vegas–Pahrump Valley	Geology along route
G. A. Davis	Las Vegas–Pahrump Valley	Geology along route
P. E. Diehl	Nopah Range	Wood Canyon Formation
L. A. Wright	Nopah Range	Noonday Dolomite
M. T. Roberts	Alexander Hills	Crystal Spring Formation
J. K. Otton	Black Mountains (vic. Mormon Point, Copper Canyon)	Structure and Precambrian rocks
J. F. McAllister	Furnace Creek	Structure; Paleozoic and Tertiary stratigraphy
M. W. Reynolds	Grapevine Mountains	Structure; Paleozoic and Tertiary stratigraphy
B. C. Burchfiel	Lathrop Wells–Las Vegas	Geology along route
G. A. Davis	Lathrop Wells–Las Vegas	Geology along route

LAS VEGAS, NEVADA, TO NOPAH RANGE, CALIFORNIA

The rocks exposed in the steep east face of the Spring Mountains and visible from a distance of many miles consist of gray Cambrian and younger Paleozoic rocks in the crest of the range and bright red- and cream-colored Mesozoic sandstone in the cliffs.

The Cambrian rocks were thrust over the Mesozoic strata along the Keystone thrust fault, a major fault that can be traced easily along the top of the distinctively colored rocks in the east front of the range (see Burchfiel and others in Part II for the geology of the Spring Mountains).

West from the Las Vegas–Los Angeles highway (U.S. 15), the road to Pahrump passes through low hills made up of gently to moderately folded sedimentary rocks of late Paleozoic and Mesozoic age. Some of the rocks are an important source of gypsum, which is mined and made into various products at a large mine and plant situated north of the road to Pahrump.

Farther west, large masses of monolithologic breccia of gray carbonate rock crop out near the highway. Still farther west, the road crosses the Spring Mountains and extends into Pahrump Valley (Figs. 1 and 2).

The Keystone thrust fault is not exposed in roadcuts, but it can be observed in a small canyon north of the highway a few hundred yards east of Mountain Spring Pass, in the Spring Mountains.

It is easy to observe from points along the highway west of the pass that the rocks in the west part of the mountains are folded.

West of the Spring Mountains is Pahrump Valley, which has been developed in the last decade into farms whose main crop is cotton. The Pahrump Valley is bounded on the west by the Nopah Range.

NOPAH RANGE

The Nopah Range contains a very complete and well-exposed section of Precambrian and Paleozoic sedimentary rocks. The rocks in it dip eastward and are cut by many west-dipping faults. The oldest rocks are Precambrian gneiss at the southwest end of the range, whereas the youngest underlie a thrust fault at the northeast end of the range, where Cambrian and late Precambrian strata have been thrust over folded upper Paleozoic strata. Wright (1973) has described the geology and prepared a map of the southern part of the Nopah Range and the Alexander Hills.

At Emigrant Pass, where the county highway from Pahrump Valley to Tecopa crosses the Nopah Range, well-cemented coarse Cenozoic fanglomerate rests on Cambrian carbonate rocks of the Bonanza King Formation (Fig. 3).

At the first turnoff on the left (south) side of the road, a few hundred feet below the pass, there are several interesting features. The crest of the range north and south of the pass is underlain by east-dipping strata of the Bonanza King Formation. Underneath that is the Carrara Formation, which consists of an upper portion consisting of well-layered brown carbonate rocks, exposed at the bases of cliffs, and a lower silty and shaly portion downslope from the cliffs. Within the Carrara Formation are algal-rich girvanella carbonate beds that form small ridges and a green shale unit that yields good fragments of several trilobite species. They can be found in the rocks adjacent to the graded parking area at the turnoff.

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[1] *Geological Society of America, Boulder, Colorado 80301.*

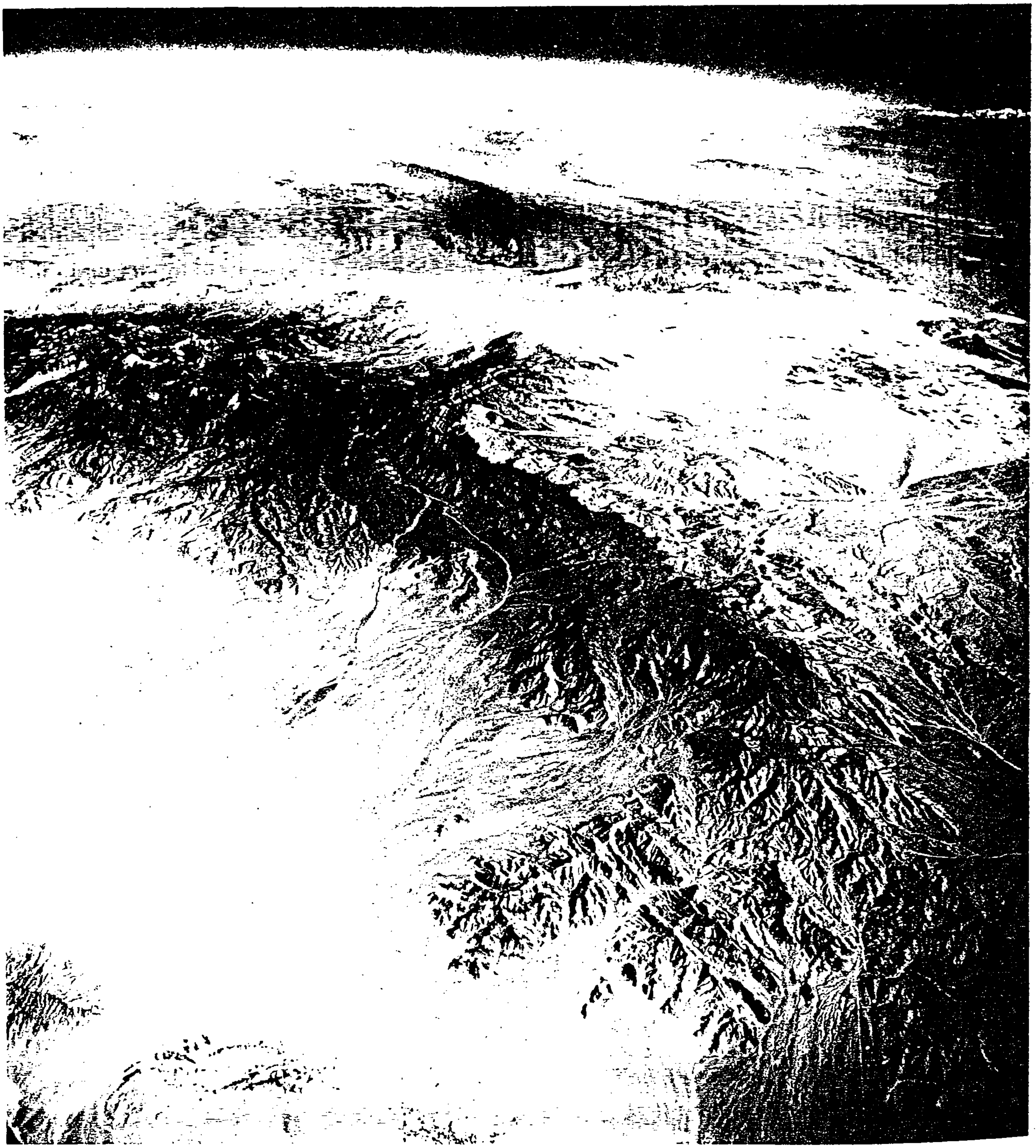


Figure 2. Oblique view northeast across Spring Mountains. Keystone thrust fault overlies pale-colored rocks on east side of mountains. Pahrump Valley in foreground. Las Vegas in valley on right side of photo. Route of trip crosses lower (near) end of pale rocks beneath thrust fault. U.S. Geological Survey photograph. U.S. Geological Survey - U.S. Air Force photograph.

To the north are several obvious low-angle normal faults that dip to the west, drop the overlying rocks west, and rotate the rocks downward to the east.

Below the Carrara Formation lies the Zabriskie Quartzite. It crops out in several places along or near the road west of the trilobite locality. The quartzite is recognized by its small, rugged outcrops, by its lavender-to-pink color, and locally, near its base, by the presence of locally abundant *Scolithus* tubes approximately 0.25 to 0.5 in. in diameter.

Below the Zabriskie is the Wood Canyon Formation, which is discussed in detail by Diehl in Part II.

West from Emigrant Pass, the road is parallel and north of the southwestern segment of the Nopah Range. In the afternoon sunlight one can easily recognize the following east-dipping Cambrian and older sedimentary units from east to west: Bonanza King Formation (dark to pale gray, striped; forms prominent outcrops in high parts of range), Carrara Formation (brown to gray and pale green; usually exposed in faces of cliffs), Zabriskie Quartzite (pale pinkish gray; forms ridges), Wood Canyon Formation (dark, reddish to lavender; mostly fine- to coarse-grained quartzite; moderately subdued topography with rounded slopes), Stirling Quartzite (upper part, pale pink; middle part, dark lavender; lower part, pale pink; forms regular slopes and ridges), Johnnie Formation (mostly siltstone and quartzite with thin beds of dolomite; forms subdued topography, generally brown colored from a distance), and Noonday Dolomite (prominent pale-tan, two-toned bold outcrops) in the southwest part of the range.

The Noonday Dolomite lies on various units of Precambrian rocks and is separated from them by a regional unconformity. In the southern Nopah Range and the Alexander Hills farther southwest, the Noonday Dolomite rests, from north to south, on successively younger rocks: Precambrian gneiss and schist, Crystal Spring Formation, Beck Spring Dolomite, and Kingston Peak Formation. At places a few tens of miles even farther south and southwest, the Noonday appears to be conformable upon the Kingston Peak Formation. Both tilting and downdropping appear to have occurred in Kingston Peak to Noonday time. (See the article by Wright and others in Part II.)

At the south end of the band of Noonday Dolomite, which crosses the Nopah Range, there are good exposures of the sedimentary features within the Noonday. A narrow paved road to a mine on the south side of the range crosses outcrops of the Noonday Dolomite. On the right (east) side of the road, just before the road crosses the Noonday, there is a small hill underlain by the lower part of the Noonday, which is an excellent site to see details of the Noonday Dolomite (see sketch by Wright and others and article by Williams and others in Part II). Farther east is the well-exposed section described by Hazzard (1937), well worth the review by those interested in Noonday, Johnnie, Stirling, Wood Canyon, and Zabriskie rocks. This section has become the standard reference section for the southern Death Valley region since Hazzard measured and described it over three decades ago.

ALEXANDER HILLS

The Alexander Hills, southwest of the southern Nopah Range, contains a complete section of east-dipping sedimentary rocks below the Wood Canyon Formation. The west edge of the hills has small exposures of Precambrian gneiss, which is overlain by the Crystal Spring Formation. The Crystal Spring has been intruded by a large, thick sill of diabase, which, during its intrusion, caused the formation of talc bodies where it came into contact with dolomite and limestone. One of the larger talc mines of the Death Valley region is the Western talc mine in the Alexander Hills. Above the Crystal Spring Formation is the Beck Spring Dolomite, which forms a prominent gray band across the Alexander Hills. On the north side of the Alexander Hills it is overlain by the Noonday Dolomite. Only about 1 mi farther south, however, a complete section of the Kingston Peak Formation is preserved between the Beck Spring and Noonday Dolomite. Successively above the Noonday (eastward) are the Johnnie Formation, the Stirling Quartzite, and the lower part of the Wood Canyon Formation. These are more easily accessible but not as well exposed as the sections in the southern Nopah Range.

Figure 3. Vertical air photograph of southern Nopah Range. Emigrant Pass near lower end of straight segment of road on right (east) side of Range. Alexander Hills along lower edge of photo. U.S. Geological Survey - U.S. Air Force photograph.

West of the Western talc mine in the Alexander Hills are good exposures of the lower units of the Crystal Spring

Formation. The formation is the subject of an article by Roberts in Part II.

NOPAH RANGE TO SHOSHONE

Precambrian metamorphic rocks crop out in an area a few square miles in extent in the southern Nopah Range. They are easily accessible from the road along the south side of the range. The rocks have been divided into several types by Wright (1974).

West from the Nopah Range, in the intersection of several valleys, there are very young lake beds that were deposited in an area several tens of square miles in extent, which were later dissected. The beds have yielded pumicite, clay, and borates, and contain other minerals of economic interest.

From Shoshone, the Charles Brown State Highway leads eastward, and about 4 mi east it crosses the Resting Springs Range. On the west side of the range, a few hundred feet northwest of the pass, there is a remarkable roadcut in Tertiary rocks, where many interesting geologic features are exposed. The parking area on the right side of the road is underlain by well-cemented breccia composed of carbonate clasts. It is also exposed in small patches at the base of the roadcut. The breccia is overlain conformably by volcanic-rich sedimentary rocks, ash flows, and altered ash. An unconformable extrusive flow with a black glassy center forms the north half of the roadcut exposure. All of the rocks are cut by small normal faults.

SHOSHONE TO SALSBERRY PASS

From an intersection 1 mi north of Shoshone, U.S. Highway 178 leads west through the Greenwater Range and Dublin Hills, Greenwater Valley, and the Black Mountains via Salsberry Pass and Jubilee Pass to Death Valley.

The road first passes along the north side of the Dublin Hills, which contains Cambrian and late Precambrian strata overlain by a succession of Tertiary rhyolite in flows. The rocks are cut by low-angle normal faults (Chesterman, 1973). North of the road is the Greenwater Range, the southern part of which contains Tertiary granite, Tertiary rhyolite, and Tertiary to Quaternary basalt. (See the article by Haefner in Part II.) Some of the west-dipping faults that cut the rocks can be seen from the highway.

Beyond Greenwater Valley, and well exposed at Salsberry Pass, are rocks of a Tertiary volcanic and sedimentary sequence that extends for many miles northward in the Black Mountains. Nearly everywhere these rocks have been cut by numerous normal faults, which causes them to have a patchwork pattern. Thus they were given the informal name of Calico volcanic rocks by Levi Noble (1941).

The southern limit of these and other volcanic rocks in the Black Mountains is formed by the Sheepshead fault, a major fault that extends from the vicinity of the southern Nopah Range to a point near the west edge of the Black Mountains several miles northwest of Salsberry Pass. Segments of the fault have been inactive since the time of volcanism as evidenced by rhyolite that has intruded parts of the fault zone. The road crosses a poorly exposed segment of the fault about 1 mi southwest of the pass.

SALSBERRY PASS TO ASHFORD MILL SITE

West from Salsberry Pass, the road follows the upper part of a broad drainage channel that drains into Death Valley. The drainage channel was the path of a flash flood caused by an intense rainstorm of a few hours' duration in October 1973, which washed out several miles of road.

Near the Death Valley National Monument boundary west of Salsberry Pass is a prominent small peak on the right side of the road, which is underlain by Precambrian gneiss. Deep-red east-dipping beds of Tertiary conglomerate crop out on each side of the road at the monument boundary. The conglomeratic rocks are seemingly older than the volcanic rocks at Salsberry Pass, since they are devoid of any clasts of the volcanic rock. An early to middle Tertiary age is most likely for them but is unconfirmed. The nearby outcrops south of the road at this point are deeply weathered and red-stained Precambrian crystalline rocks that are overlain by red-stained conglomerate that contains interbedded monolithologic breccia and andesite. The andesite has a trachytic texture and occurs throughout most of the southern Death Valley region but seldom in large masses.

West of the monument boundary, the road traverses the area where Levi Noble identified highly broken rock units that he named "chaos," in his classic paper published in 1941. Noble defined chaos as a product of brecciation by thrust faulting on the Amargosa thrust fault, and he recognized three episodes of faulting, each of which produced a phase of the chaos. He termed them the Jubilee phase, the Virgin Spring phase, and the Calico phase. Work begun with him by L. A. Wright and me in the early 1950s led the three of us to propose an origin for these rocks of gravity faulting rather than thrust faulting. (During his last few years of field work, Noble had accepted many aspects of this concept of gravity faulting to produce the chaos.)

Thus, the Amargosa fault is no longer identified as a continuous plane that developed as a thrust fault; rather, it is a plane or a series of planes that commonly occurs between Precambrian metamorphic rocks and the overlying younger rocks, which range in age from late Precambrian to Tertiary. Noble's Virgin Spring and Calico phases are products of normal faulting, but the Jubilee phase is composed mainly of megabreccia and is of sedimentary origin.

Between approximately 1 and 3 mi west of the monument boundary, many small prominent hills are evident near the highway. Most of these are isolated remnants of late Precambrian rocks and lie above faults. The prominent steep hill just south of the road and at the point where the road turns abruptly south about 3 mi from the monument boundary has an excellent north-facing exposure. The features exposed in the hill slope are typical of the features observed in the chaos. In the lower part of the exposure are thoroughly shattered Precambrian crystalline rocks. These are overlain in fault contact first by sedimentary rocks of the Crystal Spring Formation and then by the Noonday Dolomite and the Johnnie Formation. Not all units of the three formations are present, but those that are present are in their proper stratigraphic order and are greatly thinned down, brecciated, and bounded by faults on all sides. Some units are more steeply dipping than others (even overturned). Throughout this general area, the broken units of pre-Tertiary rocks in fault contact with the Precambrian metamorphic rocks are in similar condition—highly brecciated, greatly thinned down, but always in proper stratigraphic order. They commonly dip eastward.

About 3 mi farther west, the road rises out of the wash to a small pass (Jubilee Pass) after it has swung south and then northwest around a large mass of the Funeral Formation. The Funeral Formation here is composed primarily of coarse conglomerate and has a prominent basalt flow in it. At Jubilee Pass, the Funeral Formation contains megabreccia units composed of Precambrian gneiss derived from Jubilee Peak, the prominent peak south of the pass.

From the vicinity of Jubilee Pass there is a good view of the structural complexity in rocks to the northwest, where Levi Noble coined the term "chaos." The high dark-gray peak about 3 mi distant is Ashford Peak, which is along the axis of a feature named the Desert Hound anticline by Noble. The gray rocks in the peak are Precambrian gneiss and schist, locally containing abundant Precambrian pegmatite dikes. Left (southwest) of the peak in the main part of the range are bands and patches of rocks of contrasting colors, but they are in moderately small units of outcrop; farther southwest, each patch of rock is larger. The boundary between the crystalline rocks and the patches of differently colored rocks is the plane Noble named the Amargosa thrust fault, which here dips southwest. The rocks above (southwest) the fault are sedimentary strata of Crystal Spring Formation, Beck Spring Dolomite, Kingston Peak Formation, Noonday Dolomite, Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite. These rocks are in their proper stratigraphic order, though not everywhere present nor continuous along strike. The blocks of rocks become progressively larger southwest and away (upward) from the fault zone.

The low, rugged isolated hills in the foreground beyond the outcrops of the Funeral Formation are underlain by a succession of Tertiary sedimentary rocks composed in large part of monolithologic breccia masses. The hills near the north side of the road about 1 mi west of Jubilee Pass are made up of a wide variety of rock types. One can distinguish in them many individual sheets, each of which is composed of a single type of brecciated rock. Noble originally proposed a tectonic origin for the brecciated rocks, but he later recognized their sedimentary origin. A common weathering phenomenon is the development of a cavernous surface on the brecciated rocks.

The prominent hills near the left side of the road below Jubilee Pass contain excellent exposures of east-dipping Tertiary conglomerate. Pale-colored tuff exposed in the south part of the hills is interbedded with the conglomerate. The conglomerate appears to be older than the volcanic rocks exposed at Salsberry Pass, since no clasts of that type of volcanic rocks have been noted in the conglomerate.

Rocks on the south side of the road at the foot of the range are east-dipping multicolored Crystal Spring and pale-gray Beck Spring Dolomite. North of the road are, from west to east, east-dipping Beck Spring Dolomite (gray), Kingston Peak Formation (red), Noonday Dolomite, and the Johnnie Formation. A west-trending fault must be projected approximately parallel to the road to explain the offset in strike projection of rocks on both sides of the road.

As the road emerges from the west front of the Black Mountains, the Owlshead Mountains loom ahead on the opposite side of Death Valley. The Owlshead is composed mainly of Mesozoic granite rocks that are overlain in many areas by Tertiary and Quaternary volcanic rocks. The northeast end of the Owlshead contains a nearly complete section of north-tilted Crystal Spring Formation intruded and locally metamorphosed by the Mesozoic rocks.

ASHFORD MILL SITE TO MORMON POINT

The floor of Death Valley in this area is interrupted by a long, low, barren ridge called the Confidence Hills, which extends about 8 mi southeast from Shoreline Butte (Fig. 4). Shoreline Butte, the prominent dark mass at the northwest end of the Confidence Hills, contains many remnants of shoreline cut by Lake Manly, which occupied much of Death Valley. The Confidence Hills contains late Tertiary and Quaternary lake beds, conglomerate, and basalt that were folded and uplifted during movement along branches of the Death Valley fault zone, which flank and traverse the Confidence Hills. The southeastern end of the fault zone merges with the Garlock fault a few tens of miles to the southeast, on the northeast side of the Avawatz Mountains. The northwesternmost trace of the Death Valley fault zone is in a small cinder cone about 1 mi north of Shoreline Butte (Fig. 5).

The Death Valley fault zone and its northern en echelon counterpart, the northern Death Valley–Furnace Creek fault zone, have been the subject of considerable discussion regarding the amount of right-lateral slip that has occurred along it. Stewart (1967) and Stewart and others (1968) presented arguments for right-lateral slip of 40 mi or more, whereas Wright and Troxel (1967) argued that no more than 6 to 10 mi can be demonstrated. In either case, small-scale right-lateral slip can easily be demonstrated at many points along the faults.

The small cone in the floor of the valley, for example, is cut by a branch of the Death Valley fault zone and is offset in a right-lateral sense and in very recent time. The cinder cone and related tephra provide evidence for very recent lateral slip and normal fault movement. The cone is andesitic in composition, about 600 ft long, 500 ft wide, and 100 ft high; it is only slightly dissected. The fault branch that cuts it trends northwest and divides the cone into two segments, the western segment of which comprises about two-thirds of the cone. The eastern segment has been relatively offset approximately 300 ft to the southwest. Tephra that has a chemical similarity to tephra on the flanks of the cone is preserved in gullies in at least 12 places within 5 or 6 mi of the cone. In each locality, the tephra is protected from erosion by younger gravel and the younger gravel is cut by normal faults.

There is much evidence of normal faulting in the gravel along the east side of central Death Valley. This central segment of the valley trends more northerly, and the valley floor is asymmetrical, compared with the northerly and southerly segments. It is this segment of Death Valley that is interpreted (Burchfiel and Stewart, 1966) as being an opening that has developed between two en echelon right-lateral faults.

The fans along the east side of Death Valley between Shoreline Butte and Furnace Creek Wash are cut by hundreds of faults, many of which are very young. Some of the faults have scarps of only a few inches or feet, but others have scarps of 50 ft or more. Some are single traces, others occur in swarms; most are relatively near the front of the Black Mountains.

The west-facing scarp along the east side of the road, extending north from the vicinity of the turnoff marked West Side Road north of Shoreline Butte, is an example of young faulting along the east side of Death Valley. The prominent outcrop of Quaternary basalt forms a linear trace of a fault. Many small and younger faults cut the very young fans at the base of the basalt scarp.

Smith Mountain, the prominent mass rising along the east side of Death Valley north of Shoreline Butte, has a steep west front that also is an expression of moderately young faulting (Fig. 4). The slope is as steep as 30° in places and has been only slightly modified by erosion. Canyons emerging from it have narrow slots at the mountain fronts that are the result of downcutting in elevated stream channels.

Tertiary and Quaternary gravel and conglomerate in the small hills at the base of Smith Mountain indicate the magnitude of some of the normal faulting. One of the normal faults that extends along the edge of Smith Mountain dips west beneath the gravel hills at a moderately low angle. An older reddish conglomerate unit in the hills rests on the hanging wall of the fault and contains clasts that have a source only on the east side of the range. The clasts do not include Precambrian gneiss, diorite, or Tertiary quartz monzonite, which are exposed in the present mountain front. Thus, normal slip amounts to a minimum equal to the height of the mountains (at least 6,000 ft). The younger (tan) gravel contains clasts that were derived in part from the rocks in the crest of the range and the west front. This indicates that the major movement occurred after the red gravel was deposited but before the younger rocks were deposited. Subsequent faulting has cut the younger gravel as well.

Figure 4. Oblique view southwest over southern Death Valley. Black Mountains in foreground, Panamint Range (right) and Owlshead Mountains (left) beyond Death Valley. Confidence Hills, Shoreline Butte, and offset cinder cone in floor of the valley. Note sharp boundary of Black Mountains and Death Valley. Mormon Point situated where valley abruptly widens toward bottom of photo. U.S. Geological Survey - U.S. Air Force photograph.

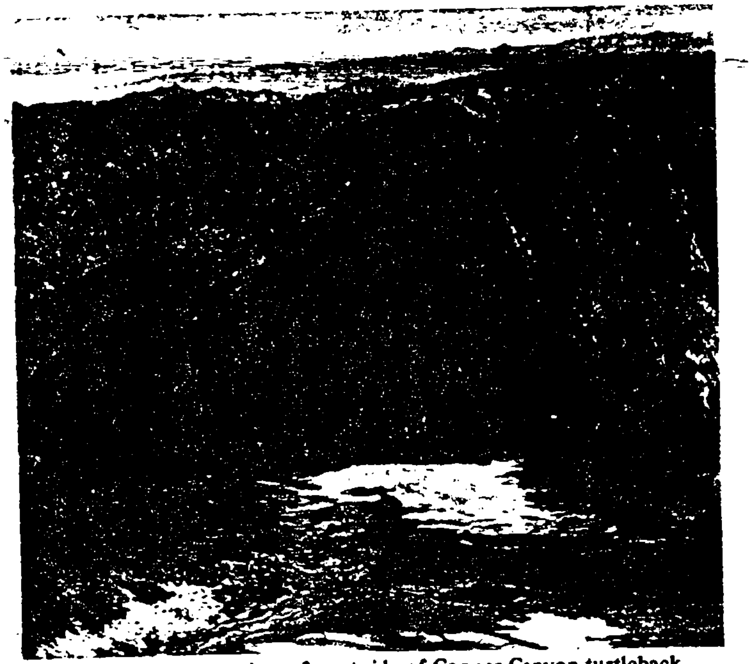


Figure 6. Oblique view of west side of Copper Canyon turtleback. Tertiary rocks overlie turtleback surface plunging to northwest (left). Photograph by L. A. Wright. U.S. Geological Survey - U.S. Air Force photograph.

The south half of the front of Smith Mountain is not an expression of a single fault plane, but rather it contains a series of normal faults that strike obliquely into the mountain a few degrees southeast of the trend of the range front. A short distance in the range, these faults turn abruptly east, then farther in the range they turn northeast, where they appear to die out. The main zone of faults along the southwest side of Ashford Peak (Noble's Amargosa fault) can be traced to the range front south of Smith Mountain, where they, too, turn north and follow the west flank of the range.

From near Mormon Point, one can see the change in the trend of the valley (Fig. 4) from northwest between the Avawatz Mountains and Mormon Point to a nearly north trend between Mormon Point and Furnace Creek Wash. At Furnace Creek Wash the valley again assumes a northwest trend parallel to the northern Death Valley–Furnace Creek fault zone and more or less in line with Furnace Creek Wash.

Mormon Point offers an excellent view of the Copper Canyon turtleback, which lies northeast across the playa from Mormon Point. Its plunging northwest-trending axis is near the somber-colored skyline crest nearly east of Mormon Point. The axis of the Mormon Point turtleback is the same in trend and plunge as the Copper Canyon turtleback and is near the crest of the ridge that terminates at Mormon Point (Fig. 6). (See the articles by Otton and by Wright and others, 1974, in Part II.)

MORMON POINT TO BADWATER

Gravel of the Funeral Formation lies east of Mormon Point on the south side of the road. Faults that trend northeast cut and bound the gravel and shorelines of Lake Manly that are preserved on the gravel slopes. Younger faults that also trend northeast cut the modern fans in this area.

The steep fans dipping off the west slope of the Copper Canyon turtleback also show various hues of desert varnish.

You can easily hike to the mountain front near Copper Canyon from the road and thus observe detailed features of the turtleback surfaces and the rocks above and below it. The rocks exposed along the mountain front for a few miles north of Copper Canyon are similar to the Tertiary rocks exposed along the road between Salsberry Pass and Death Valley. Here, too, coarse, dark-red, well-cemented conglomerate is associated with andesite that has a trachytic texture.

BADWATER TO FURNACE CREEK WASH

Badwater, at the lowest point of elevation of the United States (282 ft below sea level) lies along the flank of the third and probably most picturesque turtleback. The Badwater turtleback plunges beneath Tertiary rocks at the canyon containing the natural bridge. Foot trails in the canyon follow the arcuate trace of the plunging turtleback surface. The west front of the range south of the canyon has remnants of Tertiary rocks still preserved in fault contact with the Precambrian rocks.

Dante's View, an excellent viewpoint from the crest of the Black Mountains, lies above Badwater, 25 mi by road from Badwater. The view from this location is especially good in bright morning sunlight.

Rocks exposed in the range front north from the Badwater turtleback are multicolored Tertiary sedimentary and volcanic rocks that are incompletely understood. Near Furnace Creek Wash, the rocks are subdivided into the older Artist Drive Formation, the Furnace Creek Formation, and the Funeral Formation. Each has coarse and fine facies.

The northern part of the Black Mountains does not appear to have been uplifted as much as the southern part. For example, north of the Badwater turtleback, Tertiary rocks are exposed on both sides of faults at the range front, no pre-Tertiary rocks are exposed in the mountains, the fans are much larger, and the range gradually dies out northward at Furnace Creek.

One mile north from the turnoff to Desolation Canyon, the paved road crosses the channel of a stream that now drains most of Furnace Creek Wash. The drainage from Furnace Creek Wash was diverted into this channel (Gower Gulch) at a point a few hundred yards east of Zabriskie Point. The diversion was created in order to protect man-made features in Furnace Creek Wash and at Furnace Creek Inn from damage from flash floods. Before the diversion, flood waters and debris that flowed through this small channel originally were derived from a drainage basin of less than 2 sq mi carved in soft sedimentary rocks. The original fan at Gower Gulch is modest in size and consists mostly of gravel rarely larger than pea size, except for occasional boulders a few feet in diameter that were deposited from flash floods.

Since the diversion, however, the channel has had to carry a much larger volume of flowing water and debris draining from a much larger basin. (See the article by Troxel in Part II.)

FURNACE CREEK INN TO ZABRISKIE POINT

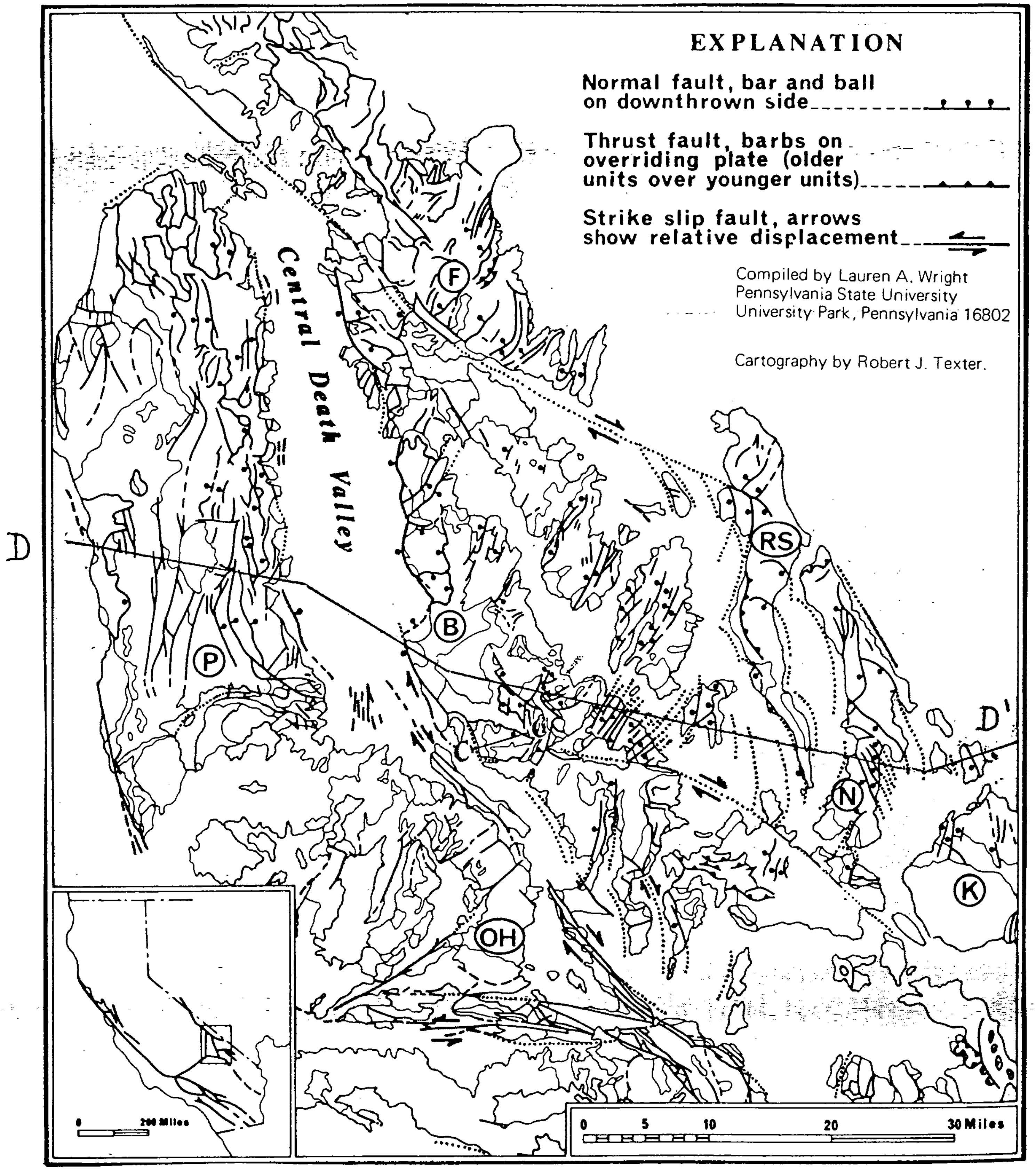
A brief description and detailed map of the lower part of Furnace Creek Wash by McAllister (1970) should be used by those who want specific information on this region. Portions of his report are included in Part II of this guidebook.

Furnace Creek Wash, which separates the Funeral and Black Mountains, is underlain by the Artist Drive Formation (Oligocene(?) to Pliocene), Furnace Creek Formation (Pliocene), and Funeral Formation (Pliocene and Pleistocene(?)). These three formations each consist of sedimentary and volcanic rocks and are folded into a syncline whose axis is parallel to and near the center of Furnace Creek Wash. The folded rocks are cut by numerous faults and are overlain by Pleistocene gravel.

State Highway 190 follows along the southwest limb of the syncline between Furnace Creek Inn and the Zabriskie Point turnoff. The rocks near the road are beds of coarse gravel of the Furnace Creek Formation. They grade laterally and vertically into fine-grained sediments, most of which are lacustrine in origin.

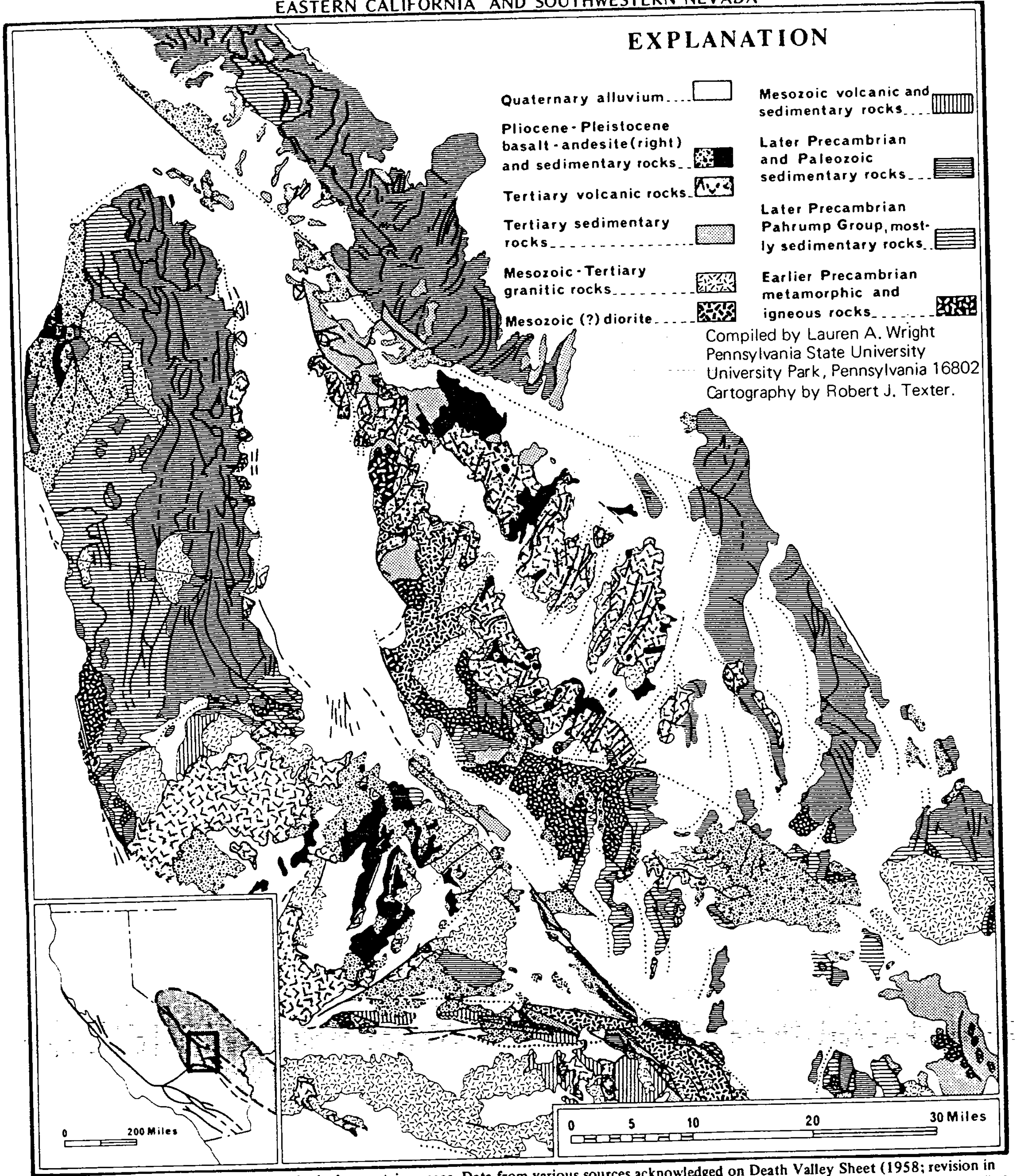
At many places along the road in Furnace Creek Wash are good exposures of geologic features such as sedimentary

FAULT MAP OF THE REGION OF CENTRAL AND SOUTHERN DEATH VALLEY, EASTERN CALIFORNIA AND WESTERN NEVADA



Shaded pattern denotes Quaternary alluvium; blank areas denote pre-Quaternary rocks. B = Black Mountains; F = Funeral Mountains; K = Kingston Range; N = Nopah Range; OH = Owlshead Mountains; P = Panamint Range; RS = Resting Spring Range. Reproduced by permission and modified from *Gravity and Tectonics*, edited by Kees A. De Jong and Robert Scholten (New York: John Wiley & Sons), 1973.

GEOLOGIC MAP OF THE REGION OF CENTRAL AND SOUTHERN DEATH VALLEY, EASTERN CALIFORNIA AND SOUTHWESTERN NEVADA



Compiled by Lauren A. Wright
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Cartography by Robert J. Texter.

See fault map for identification of principal mountain ranges. Data from various sources acknowledged on Death Valley Sheet (1958; revision in preparation, 1973), and Trona Sheet, Geologic Map of California, California Division of Mines and Geology. Reproduced by permission and modified from *Gravity and Tectonics*, edited by Kees A. De Jong and Robert Scholten (New York: John Wiley & Sons), 1973.

Turtleback Surfaces of Death Valley Viewed as Phenomena of Extensional Tectonics

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ABSTRACT

The controversial turtleback surfaces of Death Valley may be colossal fault mullions resulting from severe crustal extension which were localized along undulating and northwest-plunging zones of weakness that were in existence prior to this deformation. Supporting evidence includes (1) a coincidence between the surfaces and carbonate layers in folded metamorphic rocks beneath the surfaces, and (2) striations, slickensides, and extensional fractures with orientations compatible with northwest extension.

The three peculiar domical fault surfaces that feature the Black Mountains along the east side of Death Valley have puzzled students of Basin and Range geology since these features were described and given the name "turtlebacks" by Curry (1938). Although the three surfaces occupy relatively small areas (Fig. 1), they are more than geologic curiosities; various interpretations of their origin support widely different views of the deformational and erosional history of the southwestern Great Basin in Cenozoic time.

As indicated by Curry, each turtleback surface is little eroded and broadly curved to resemble the carapace of a turtle. Each plunges from a height of 865 to 1,350 m in the Black Mountains northwestward to the floor of Death Valley. Each surface is coincident with an anticlinal fold in metasedimentary units of Precambrian age. Beyond the limits of the turtleback surfaces, the mountain front is underlain by other rock units, mainly by bodies of Mesozoic(?) and Tertiary igneous rocks. Resting with fault contact upon each turtleback surface are remnants of a cover of Cenozoic sedimentary and volcanic rocks which is more deformed than the underlying, broadly folded units.

The carapace-like form of the turtleback surfaces has been attributed to

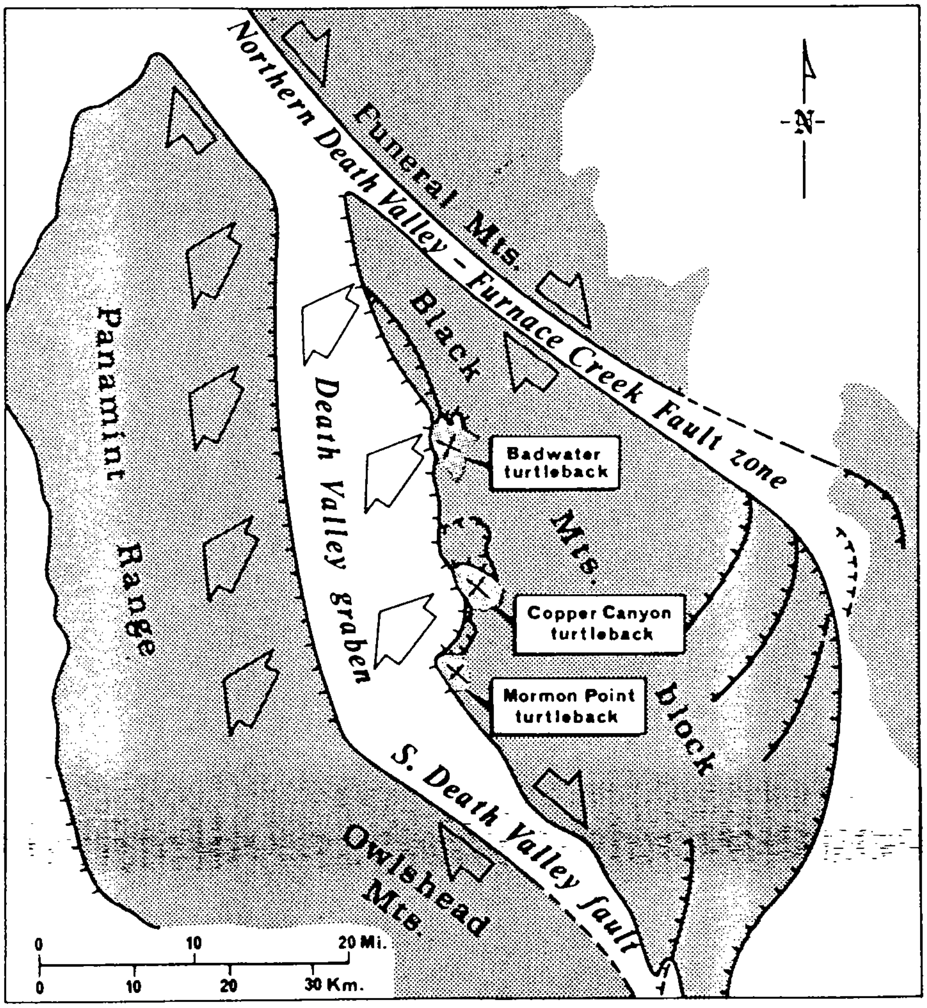

Figure 1. Generalized structural map of Death Valley region, showing position of three turtleback surfaces of Black Mountains. Hachured lines mark positions of major normal faults; full arrows show inferred direction of crustal extension; half arrows show relative displacement on strike-slip fault zones.

(1) compressional folding of a regional thrust fault (Curry, 1954; Hunt and Mabey, 1966; Noble, 1941); (2) differential erosion to produce an undulating topographic surface upon which the Cenozoic rocks were deposited and from which they later slid, propelled by gravity (Drewes, 1959); (3) uparching related to the intrusion of shallow plutons (Sears, 1953); and (4) compressional folding of both the basement rocks and the cover, the cover being essentially autochthonous (Hill and Troxel, 1966).

We propose yet another hypothesis, simpler than those already mentioned, but, we believe, more compatible with the available field data and with the generally held view that most or all of the Great Basin has been undergoing severe crustal extension since mid-Tertiary time. This hypothesis, which is subject to testing through detailed geologic mapping, holds that the turtleback surfaces are gigantic fault mullions developed along planes of weakness in a zone of normal faulting that penetrates the crust (Fig. 2). The cover of Cenozoic rocks is visualized as having been deposited along the fault zone following the inception of faulting. The cover then moved downward, generally parallel with the axes of the turtleback surfaces, as the hanging-wall side of the fault moved downward and northwestward to deepen Death Valley in the manner shown in Figure 2.

We formulated this pull-apart hypothesis in recent years during numerous visits to the Mormon Point and Copper Canyon turtlebacks, where we observed that these surfaces exhibit abundant linear features related to movement along the fault surface. They range in scale from minute slickensides to fault mullions tens or hundreds of meters in amplitude. All are similarly oriented and tend to lie parallel to the axes of the turtleback surfaces. Consequently, at the nose of each of the two turtlebacks, the linear features plunge moderately valleyward; along the crest and flanks, the linear features are horizontal to gently plunging. We also noted that the turtleback surfaces are well developed only on the folded metasedimentary units and tend to coincide with carbonate-rich layers, which would probably yield to stress more readily than the schist and gneiss units with which the carbonate layers are associated. In addition, the metasedimentary rocks are thoroughly broken by fractures that tend to lie normal to the turtleback axes, many of the fractures being occupied by dikes of Cenozoic age.

These features seem more compatible with the pull-apart hypothesis for turtleback formation than with the origin suggested by others. This interpretation is, in turn, compatible with the observations that the entire Death Valley region is characterized by innumerable normal faults that trend northward to northeastward; that central Death Valley is essentially a graben, formed in late Cenozoic time, between the en echelon ends of two northwest-trending, high-angle faults of right-lateral displacement as shown in Figure 1 (Burchfiel and Stewart, 1966); and that the graben is part of a rhombochasm that has been forming through a much lengthier segment of geologic time (Wright and Troxel, 1967, 1971) and also in an environment of northwesterly crustal extension.

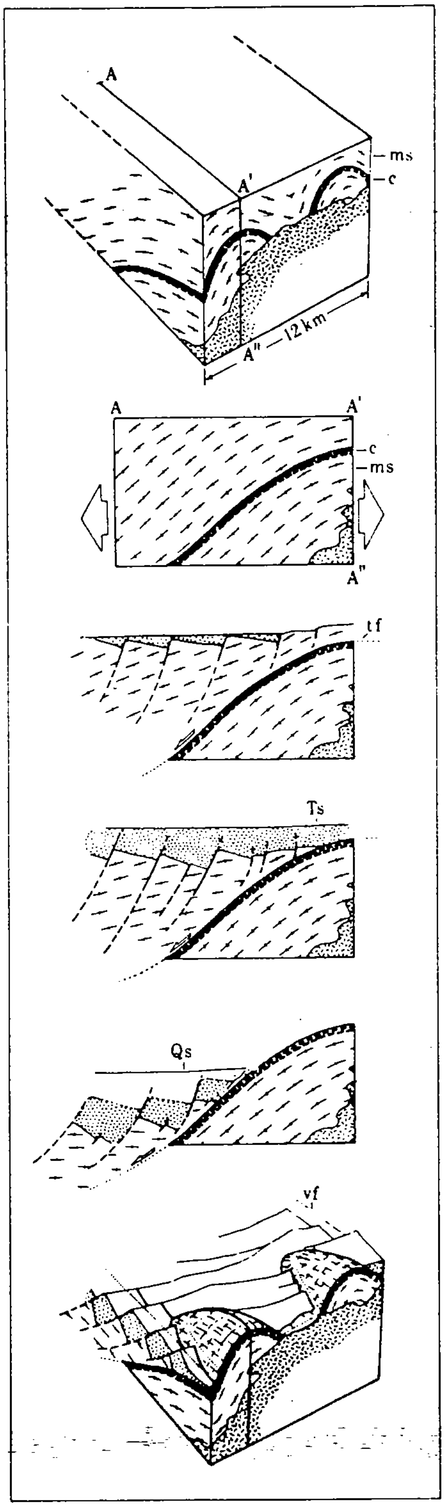

Figure 2. Idealized block diagrams and cross sections, illustrating pull-apart concept of turtleback formation; based on observations of Copper Canyon and Mormon Point turtlebacks, Death Valley. c = Carbonate layers; ms = mixed metasedimentary rock; Qs = Quaternary sediments; tf = turtleback fault; Ts = Tertiary sedimentary rock; vf = valley floor.

If the turtlebacks were formed by a pull-apart mechanism, these surfaces can no longer be cited as evidence for large-scale Cenozoic thrusting in the Death Valley region, for northeast compression during or after turtleback formation, or for structurally controlled relief on an eroded surface that received the Tertiary sedimentary and volcanic units.

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Geologic Features of the Central Black Mountains, Death Valley, California

James K. Otton[1]

INTRODUCTION

The Black Mountains, which form the eastern margin of the central part of Death Valley, California, contain complex lithologic and structural features that have been difficult to integrate with the geologic framework of the surrounding region. They are underlain mostly by a crystalline complex composed of folded pre-Cenozoic metasedimentary units, in part marble bearing, and of intrusive igneous rocks of Precambrian, Mesozoic(?), and Cenozoic age. Especially abundant in the complex is diorite that postdates the sediments, now metamorphosed, and predates other intrusive bodies that are more acidic and largely to wholly Cenozoic in age. Overlying the complex, generally with fault contact, are structural units composed variously of Precambrian and Paleozoic sedimentary rocks and Cenozoic sedimentary and volcanic rocks. These constitute a relatively thin, discontinuous, and faulted cover of the complex.

The following is a report on the progress of a mapping project in the southwestern Black Mountains. The area (Fig. 1) includes the southwestern quarter of the Funeral Peak and the southeastern part of the Bennetts Well 15′ quadrangles. In this area, the igneous and metamorphic complex—a dislocated cover of Cenozoic rocks—and two of the peculiar domical features known as turtlebacks are well exposed. Although many questions concerning the geologic history of the Black Mountains remain unanswered, the mapping to date has documented several features relevant to this history and the evolution of the region.

The general geologic features of the Black Mountains have been shown on several published maps, namely those of Curry (1954), Noble and Wright (1954—generalization of Curry's map), Drewes (1963), the Death Valley sheet of the State Geologic Map of California (scale 1:250,000), and Wright and Troxel (1973). Curry (1954) outlined the rock units and structural features along the western margin of the north and central Black Mountains and was the first to describe the turtleback surfaces. He concluded that they were parts of a folded and eroded thrust fault, and he correlated the fault with the Amargosa thrust fault that Noble (1941) had identified in the southern Black Mountains.

Drewes, working in the Funeral Peak quadrangle and in an adjacent part of the Bennetts Well quadrangle (Drewes, 1963), also described the rock units and structural features; he concluded that the turtleback surfaces and the Amargosa thrust were separate features. He favored the hypothesis that the turtlebacks were produced by differential erosion of a terrane of folded metamorphic rocks, producing an undulating surface on which Tertiary rocks were deposited and from which they slid along normal faults.

The geologic features of the area in Figure 1 present numerous avenues of investigation, including the following: (1) the stratigraphy and age of the sedimentary rocks now metamorphosed; (2) their metamorphic history and the role of the various intrusive events in the metamorphism; (3) the nature and time of folding of the metamorphic rocks; (4) the age and mode of emplacement of the diorite and the bodies of younger igneous rock; and (5) the evolution of the fault pattern, including the faulted surfaces between the complex and the bodies of rock that overlie it.

LITHOLOGIC AND STRUCTURAL FEATURES OF THE METASEDIMENTARY ROCKS

The metasedimentary rocks of the crystalline complex can be subdivided into two gross units. The stratigraphically lower unit is composed of augen gneiss, biotite schist, amphibolite, biotite-hornblende gneiss, quartz-feldspar gneiss, and gneissic granite. This unit lithologically resembles the older Precambrian complex extensively exposed in the more southerly parts of the Black Mountains and is here correlated with it. The stratigraphically higher unit is carbonate bearing and consists variously of massive light-brown to gray dolomitic marble; well-bedded tan stromatolite-bearing dolomitic marble (Fig. 3) with cherty lenses and nodules; tan dolomitic marble containing thin layers of hornfels; chert; quartzite; and light-gray limestone. It displays a maximum thickness of about 600 ft.

Wherever the two units are in contact, the carbonate-bearing unit overlies the generally gneissic unit. In addition to their lithologic differences and stratigraphic relations, differences in style of deformation and metamorphism are distinctive. The gneissic unit is characterized by variously oriented mesoscopic, isoclinal, locally recumbent folds and by textures attributable to shearing. The carbonate unit, on the other hand, is characterized by upright macroscopic folds that consistently plunge northwestward. The older unit is pervasively metamorphosed to lower amphibolite or upper greenschist facies. The metamorphism of the carbonate-bearing unit ranges widely in intensity and apparently is related to distance from contacts with the diorite. At localities farthest from diorite contacts, chert nodules are devoid of prograde metamorphic minerals and of evidence of recrystallization. Chert bodies in exposures of the carbonate-bearing unit close to contacts with diorite are altered to talc, epidote, and (or) garnet and have been recrystallized. Finally, the contact between the carbonate-bearing unit and the older complex is discordant with foliation in the complex.

Between Copper Canyon and Sheep Canyon (Fig. 1), the older Precambrian schist and gneiss form an elongate dome that is mantled by a thin, discontinuous sheath of the carbonate-bearing unit. The morphology of this dome is displayed in a structure contour map of the contact between the gneissic unit and the carbonate-bearing unit (Fig. 2). The dome is steepest on its southwestern flank, which is marked by a broad fault zone containing abundant large fragments of carbonate rock. Diorite lies on the southwestern downdropped side of this fault. The type turtleback (Curry, 1954) is located on the northwestern nose of this dome. Geometrically, this structure resembles a mantled gneiss dome (Eskola, 1949), in that it consists of a core of gneiss that underlies a cover of younger, structurally discordant metamorphosed rocks.

The older Precambrian rocks mapped in the Mormon Point area are also mantled by a sheath of carbonate-bearing rocks. The sequence preserved there is thicker than on the other dome and obscures most of the older Precambrian units. The exposures of carbonate-bearing rocks terminate, however, along

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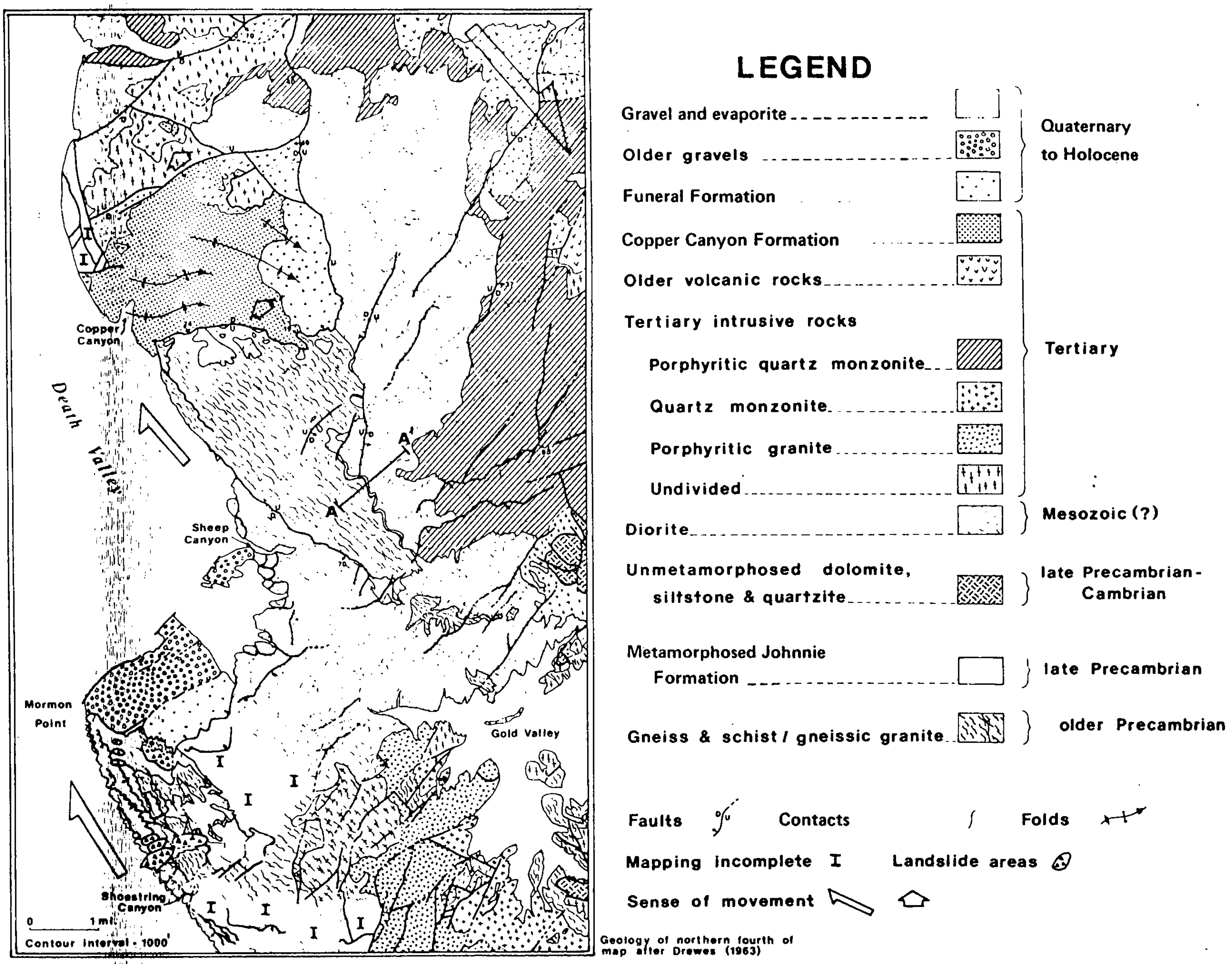


Figure 1. Generalized geologic map, central Black Mountains, Death Valley, California.

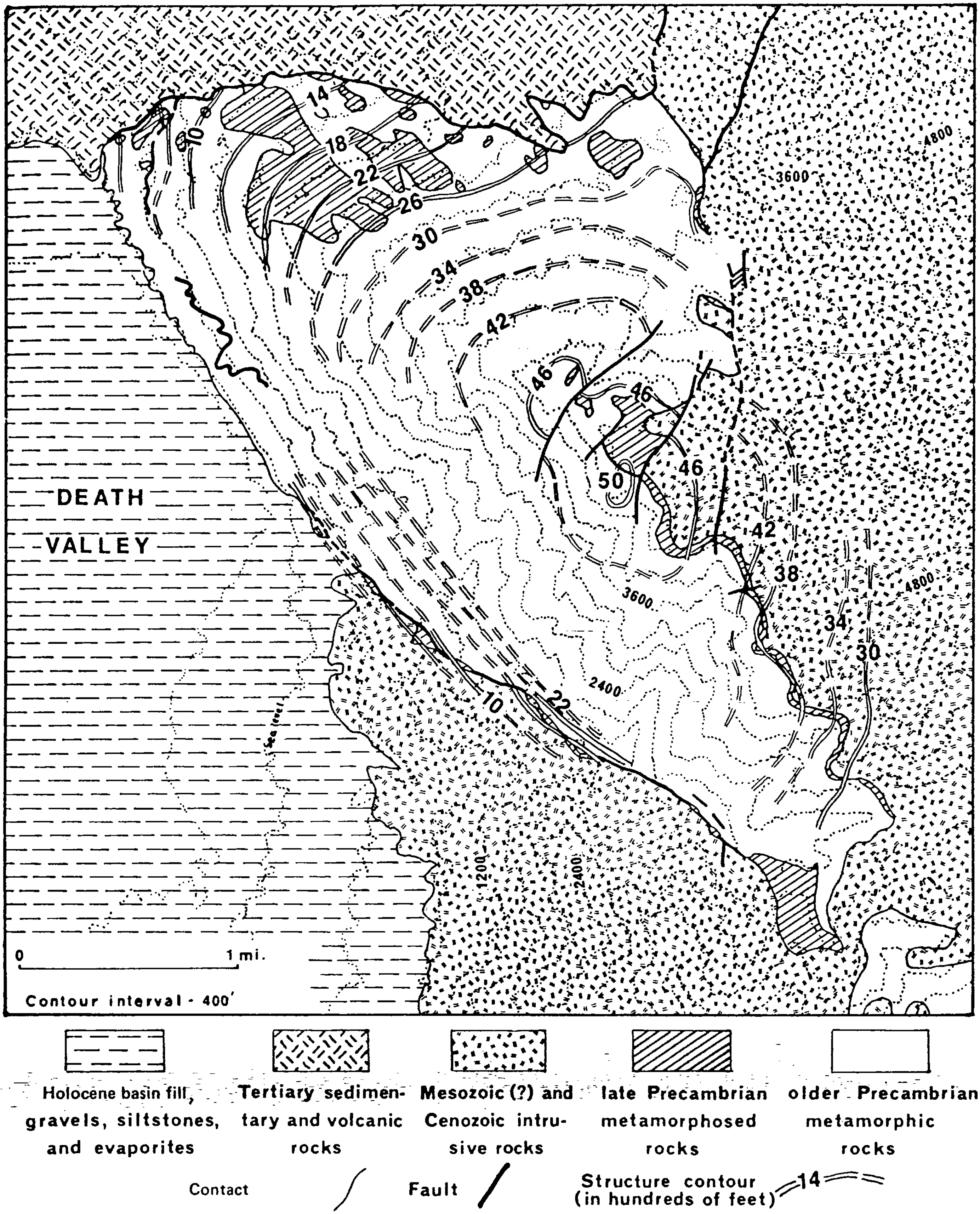


Figure 2. Generalized geologic map of a part of the Black Mountains showing structural contours on contact between older Precambrian and late Precambrian units.

lengths over 2 mi. This planarly oriented system of dikes is restricted to the older Precambrian rocks of the ridge. The dikes terminate to the southwest against the range front fault and to the northeast against the turtleback fault. Some of the dikes cross the intrusive contact into the diorite, but where they do, they change orientation.

A second system of dikes occupies the northerly and northwesterly faces of a ridge of diorite just to the south of the mouth of Sheep Canyon. Dikes in this system are essentially planar but interfinger more than the dikes of the previously described system. They strike N. 75° E. and dip 35° to 45° to the southeast. These dikes also consist of porphyritic quartz monzonite. They are more closely spaced than the other system—as close as 100 ft or less.

Most of the silicic dikes and all of the silicic plutons of the region lack a visible foliation. One swarm of dikes, composed of gray aphanitic to slightly porphyritic rock, shows well-developed layering. Layers are distinguished by varying shades of gray, or gray and reddish gray. Layer thickness varies from a few millimeters to a few centimeters. The layering is interpreted as flow layering because isoclinal folds symmetric with dike margins are common in the layers. In larger dikes, the central portions commonly are unlayered.

The age of these igneous bodies is uncertain. Drewes (1963) reported two lead-alpha age determinations on zircon in the monzonitic rocks, 45 ± 10 and 30 ± 10 m.y. These determinations, made in 1959, are probably too old by a large factor (Rose and Stern, 1960). Fleck (1970) reported K-Ar whole-rock age dates on the older volcanic rocks of the region of 6 to 8 m.y. Because these units were deposited on or were involved in faulting that cuts the monzonitic rocks, these dates probably can be considered a minimum age for the monzonites. The time of intrusion for these rocks seems best placed between 10 and 15 m.y. ago.

TERTIARY AND QUATERNARY SEDIMENTARY AND VOLCANIC ROCKS

Drewes (1963) described in detail the lithology of the Tertiary and Quaternary rocks of the region, the older volcanic rocks, the Copper Canyon Formation, the Funeral Formation, and gravel of various ages. The older volcanic rocks include rhyolite and rhyodacite flows and tuff with interbedded tuff-breccia and agglomerate and minor volcanigenic sediments. The Copper Canyon Formation comprises over 10,000 ft of reddish conglomerate, yellowish-gray siltstone, and evaporites and intercalated basalt. Based on mammalian fossils, it is thought to be Pliocene in age (Curry, 1941). The Funeral Formation consists of tan conglomerate and diorite megabreccia.

STRUCTURAL FEATURES

The structural features of the central Black Mountains appear to have developed in two or more stages. The latest stage has produced faults which are compatible with a northwesterly crustal extension of the Black Mountains–central Death Valley terrane. The earliest stages involved the development of the major structural features of the crystalline terrane before extension began. This earlier deformation resulted in a tectonic fabric that controlled, in part, the faulting during the northwest crustal extension of the later stage. The silicic plutons may mark the beginning of the extensional stage.

The features of the latest stage include many northeast-trending intermediate to high-angle normal faults with displacements generally within the range of a few tens of feet to a few hundred feet. The features of the latest stage mainly consist of faults that are either clearly normal or seem best interpreted as normal in sense of movement. The most abundant of the well-defined normal faults strike northeast and ordinarily show displacements measurable in tens or hundreds of feet; some of the displacements are 1,000 ft or more. One of the larger of the northeast-trending faults bounds the western side of the depression that contains the Copper Canyon Formation (Fig. 1). The faults that derive their configuration from earlier structural features and that are also interpreted here as being normal include the turtleback faults at Mormon Point and Copper Canyon and extensions of the turtleback faults. Linear features, including slickensides, fault mullions, and drag folds, on the surfaces of these faults indicate that the downward movement of the hanging wall has been in a northwesterly direction.

Apparently related to the normal faults are two high-angle faults that strike northwest and can be traced for 5 mi or more (Fig. 1). The linear features of movement on the planes of these faults indicate movements in a normal sense and also in a right-lateral oblique-slip sense. One of these faults terminates along strike in the lower part of Sheep Canyon.

The nature and distribution of the faults of the Black Mountains escarpment support the long-held view that the Black Mountains front is essentially an irregular fault scarp developed during the latest stage of deformation. It consists of

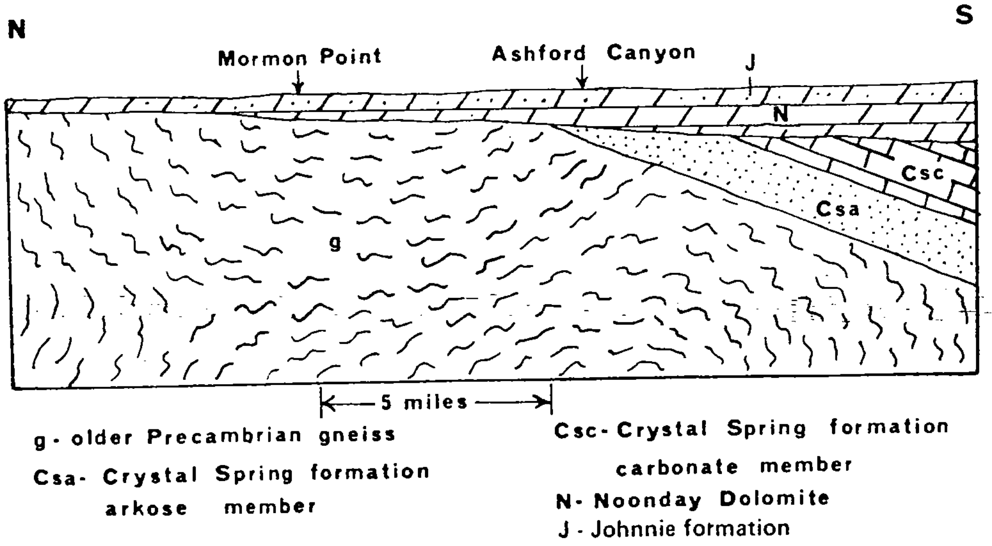
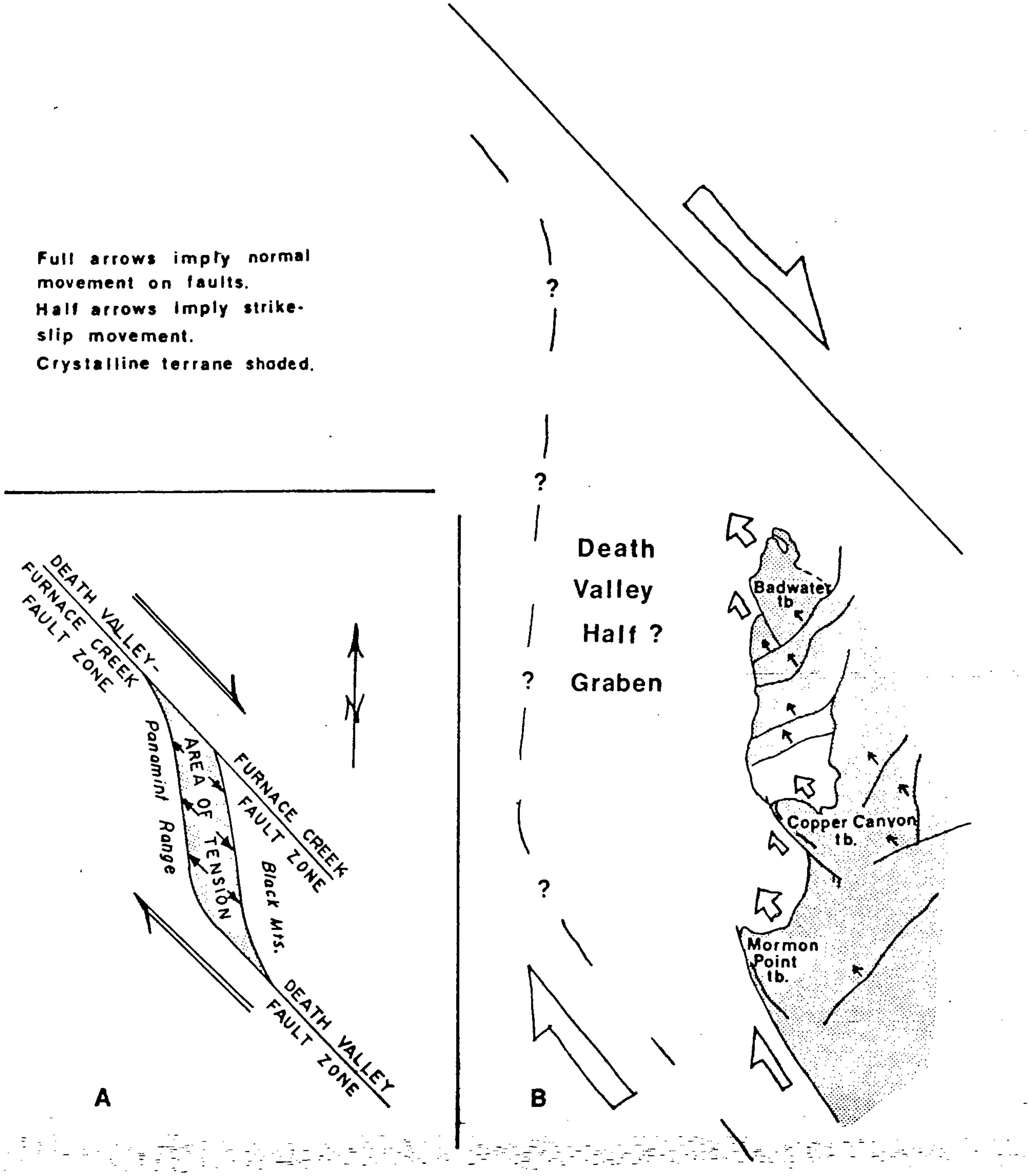


Figure 5. Cross section of hypothetical late Johnnie Formation Black Mountain terrane showing onlap of Noonday Dolomite, in turn overlain by Johnnie Formation.

Otton 1974



Full arrows imply normal movement on faults.
Half arrows imply strike-slip movement.
Crystalline terrane shoded.

Figure 8. A. Diagrammatic map showing interpretation of strike-slip movement and area of tension (from Burchfiel and Stewart, 1966). B. Detailed map of east wall of area of tension (generalized from Death Valley sheet, Geologic Map of California).

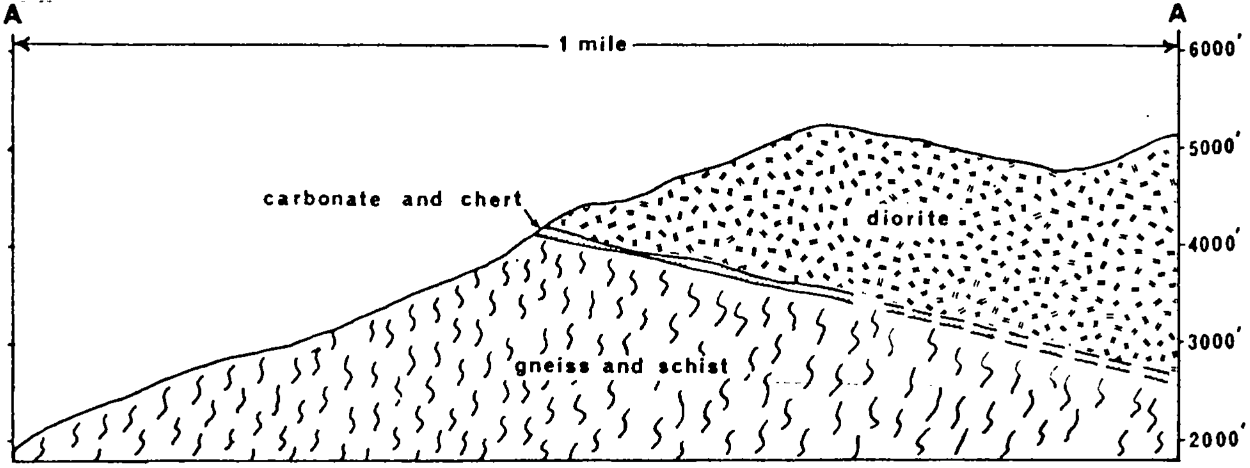


Figure 6. Cross section of ridge between Sheep Canyon and Copper Canyon showing diorite contact.

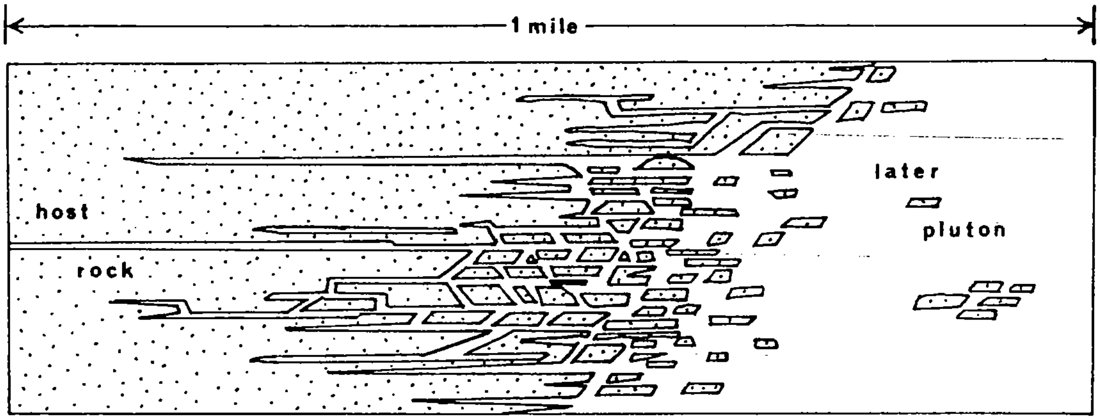


Figure 7. Schematic cross section of gradational contact between silicic plutons and host rock.

northwest-trending en echelon faults with linking northeasterly irregular zones. The irregular zones, however, contrary to previously expressed interpretations, are also related to crustal extension. They coincide geometrically with weak horizons (the carbonate-bearing units) in the early fabric of the crystalline rocks. This suggests that the orientation and position of these zones was controlled by zones of weakness in the inherited fabric.

This view of the Black Mountains front has recently been expressed by Wright and others (1974, reprinted in this volume) and is compatible with the pull-apart model for the origin of the central segment of Death Valley (Burchfiel and Stewart, 1966). Figures 8A and 8B are a modification of that model and show the structural features of the east wall of the central part of Death Valley in greater detail.

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Geology of the Grapevine Mountains, Death Valley, California: A Summary

Mitchell W. Reynolds[1]

INTRODUCTION

The Grapevine Mountains, limited on the south by Boundary Canyon and on the north by Grapevine Canyon, form the eastern wall of northern Death Valley (Fig. 1). The mountains are rugged and have poor accessibility, but their high relief and barrenness provide excellent exposures of the complicated geology characteristic of the Death Valley region. Upper Precambrian and Paleozoic rocks exposed in the core of the mountains are the most northerly complete section of miogeosynclinal facies strata on the east side of the northern Death Valley–Furnace Creek fault zone. In the core of the mountains, a thrust fault of early or medial Mesozoic age juxtaposes upper Precambrian, Cambrian, and Ordovician rocks over middle and upper Paleozoic strata. Cenozoic rocks flank the core and include both the oldest dated Tertiary strata in the southwestern part of the Great Basin and an extensive succession of younger sedimentary and volcanic rocks. These and older strata are broken by late Cenozoic high-angle normal faults that flatten with depth east and west off the core of the range. In the southern part of the mountain core, folding and faulting of late Tertiary age produced a north-trending S-shaped fold system composed of a recumbent syncline and anticline. A low-angle fault, along which rocks are rotated and extended, replaces the upright limb of the anticline, and the entire fold system is separated from underlying metamorphosed Precambrian rocks by a low-angle fault that also displaces Tertiary strata at shallow depths. Strike-slip faults of late Cenozoic age displace rocks and structures in the range, as well as Quaternary deposits in adjacent Death Valley.

In this summary of the geology of the Grapevine Mountains, emphasis is on the southern part of the mountains, since this area is accessible by road through Boundary and Titus Canyons. The geology of the Grapevine Mountains has been mapped largely by me; mapping by Cornwall and Kleinhampl (1964) in the southeasternmost part of the mountains and by L. A. Wright and B. W. Troxel (1971, written commun.) along the southern edge has provided a base for more detailed mapping and structural interpretations of those parts by me.

STRATIGRAPHY

Nearly 9,100 m (30,000 ft) of pre-Mesozoic and Cenozoic sedimentary and volcanic rocks are exposed in the Grapevine Mountains (Fig. 2). For about 9.6 km (6 mi) southeast of Boundary Canyon to Chloride Cliff, the oldest rocks crop out in the anticlinal core of the Funeral Mountains (Wright and Troxel, 1970; 1971, written commun.). These rocks belong to the Pahrump Group of Precambrian age. Northwestward, a nearly continuous succession of pre-Mesozoic rocks is preserved down structural plunge from Chloride Cliff to the north end of the Grapevine Mountains, where strata of Pennsylvanian age crop out. The lowest quarter of the succession, widely exposed in Boundary Canyon, is a thick sequence of terrigenous clastic rocks, whereas much of the remainder of the section is composed of carbonate rock with only thin, interbedded terrigenous units. Some of the Precambrian, Cambrian, and Mississippian rocks may have accumulated in moderately deep marine waters, but the carbonate and terrigenous rocks were generally deposited in shallow-marine and intertidal environments on a slowly subsiding shelf. Siltstone, sandstone, and conglomerate beds among upper Paleozoic rocks were derived from uplands presumably to the northwest and north resulting from the Antler orogeny.

Terrigenous strata in the pre-Mesozoic sequence have generally been the loci of failure during deformation. Preferred units of failure are designated by asterisks in Figure 2. The Stirling and Zabriskie Quartzites, for example, controlled positions of faulting during both Mesozoic and Cenozoic deformation: these formations form the sole of the allochthon of the major thrust fault of Mesozoic age in the northern part of the Grapevine Mountains, and form the soles of flat faults of Cenozoic age in Boundary Canyon. Recumbent folding, probably late Tertiary in age, in the southern Grapevine Mountains involved rocks only as old as the Stirling Quartzite, which acted as a sole for detachment above metamorphosed and deformed older rocks. High-angle faults of Cenozoic age are commonly flattened with depth to follow siltstone and quartzite beds in Paleozoic strata.

Cenozoic rocks crop out widely along the east flank and the northwest front of the Grapevine Mountains and locally near Death Valley Buttes, west of the mouth of Boundary Canyon. Rocks on the northwest front differ in origin and age from those on the east and south. At the latter localities, strata of fluvial and lacustrine origin belonging to the Titus Canyon Formation of Oligocene and Miocene(?) age (Reynolds, 1969, 1974) rest unconformably on Paleozoic rocks and are, in turn, overlain unconformably by ash-flow tuff, lava flows, and sedimentary rocks of lacustrine and fluvial origin. This succession of volcanic and sedimentary rocks is about 22 to 20 m.y. old, and sources for most of the volcanic rocks lay within the Nevada Test Site east and northeast of the Grapevine Mountains.

Cenozoic rocks are exposed along the mountain front in the northern part of the Grapevine Mountains northwest of Fall Canyon and at the southern end of the mountains in the Kit Fox Hills (Fig. 1). Rocks northwest of Fall Canyon are divided into three parts–the lowest exposed part and the upper part are dominantly of fluvial origin, and rocks of the middle part are of lacustrine origin. The lower fluvial and lacustrine rocks are conformable, but the upper fluvial sequence lies unconformably on the lacustrine rocks. Thin, coarse basaltic intrusions occur in the lowest two units. Clasts in the lower fluvial sequence were derived from granitic intrusive rocks exposed at the north end and west of Death Valley; clasts of welded ash-flow tuff were eroded from units northeast and east in the Grapevine Mountains and beyond, but clasts of locally derived pre-Mesozoic rocks are not abundant. By contrast, the upper fluvial rocks are composed mainly of fragments eroded from pre-Mesozoic rocks in the Grapevine Mountains, onto which the fluvial strata lap or are faulted. The lower two units are here correlated with the Furnace Creek Formation as defined by McAllister (1970) and the upper unit with the Funeral Formation, both in the central part of Death Valley. Cenozoic lacustrine and fluvial rocks of the Kit Fox Hills west of Death Valley Buttes (Fig. 1) contain clasts derived from ash-flow tuff units of Miocene and early Pliocene age exposed east of Death Valley (Fig. 2), and hence are considered to be

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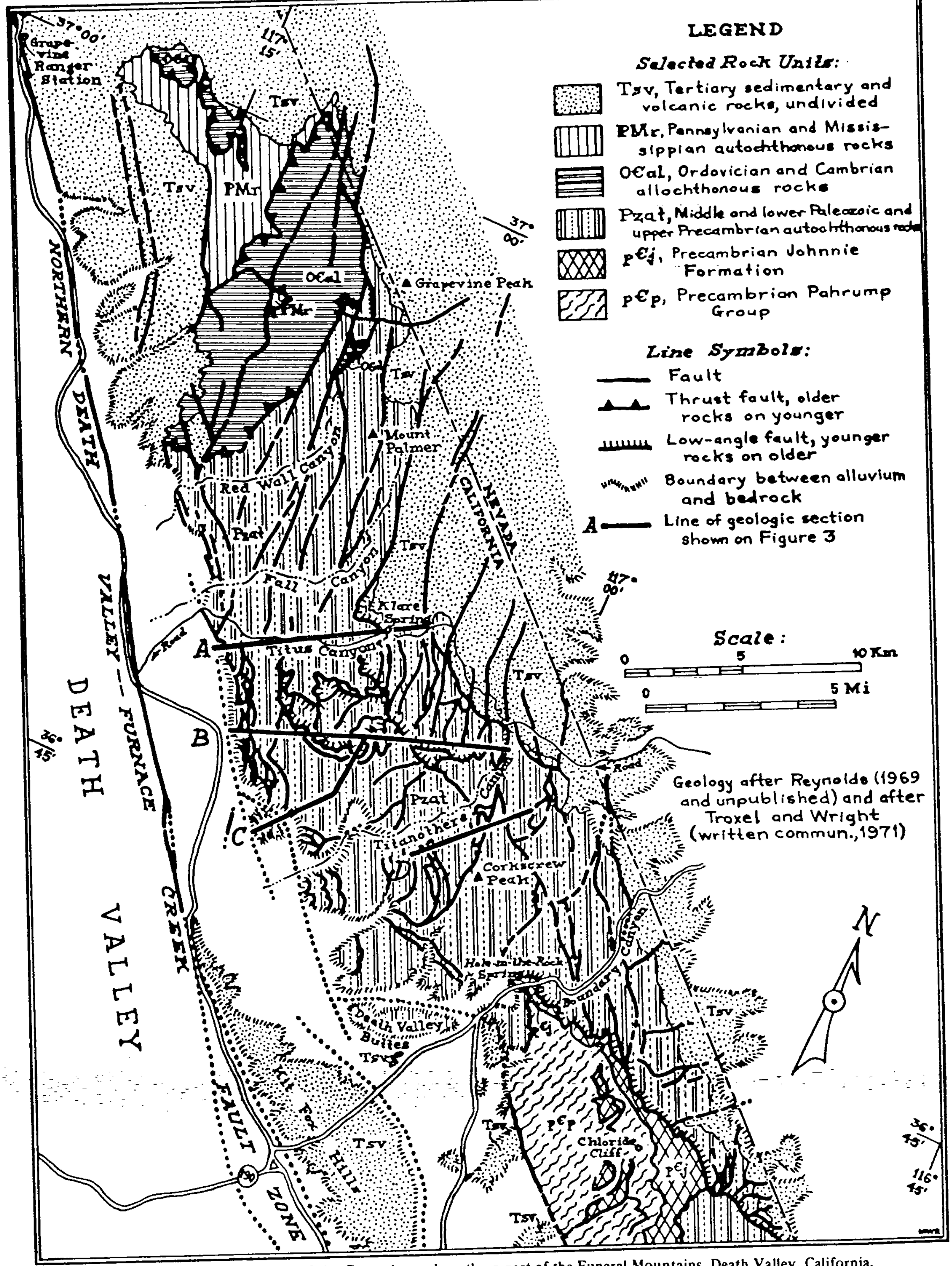


Figure 1. Generalized geologic map of the Grapevine and northern part of the Funeral Mountains, Death Valley, California, showing localities referred to in the text.

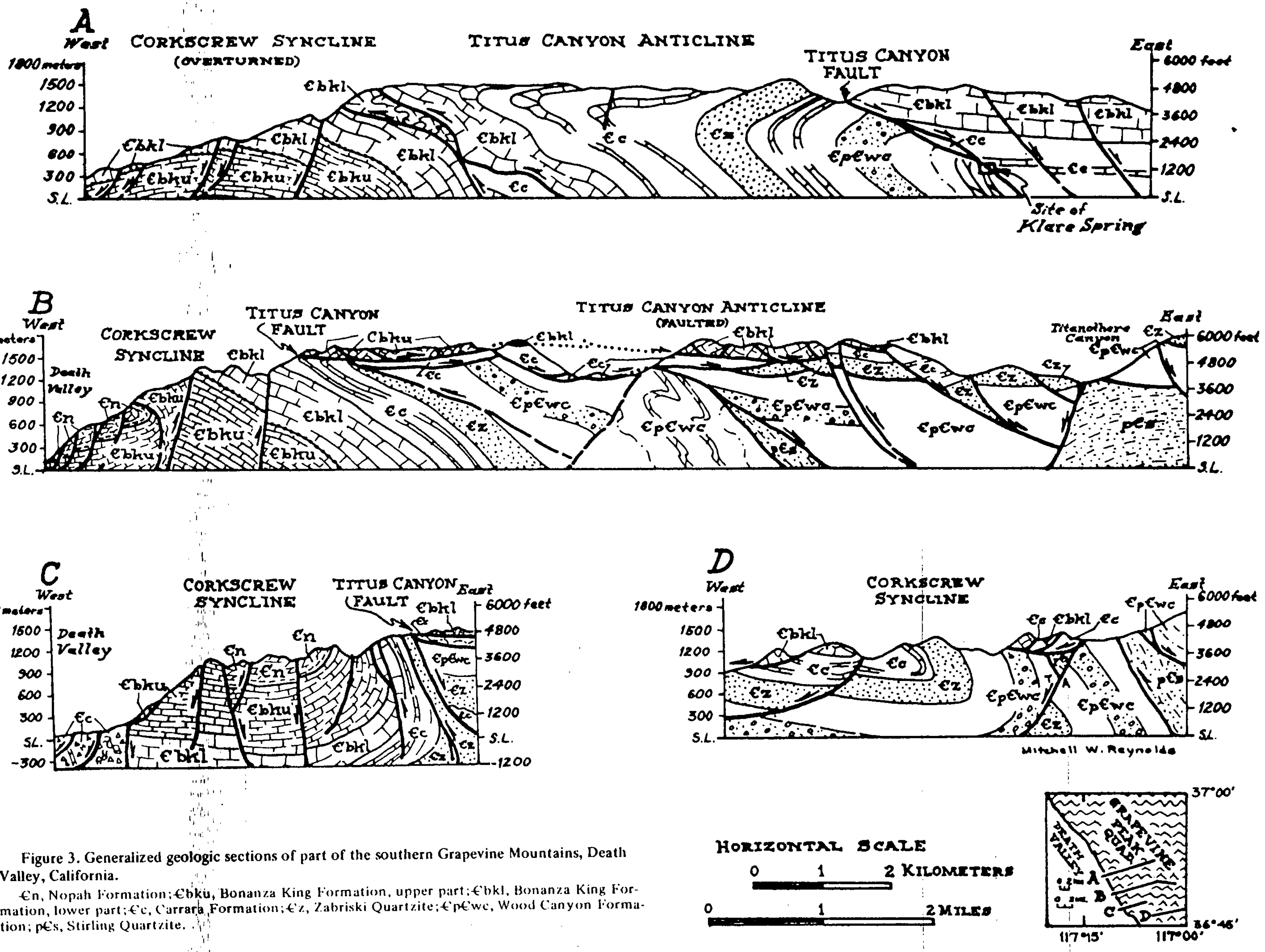


Figure 3. Generalized geologic sections of part of the southern Grapevine Mountains, Death Valley, California.

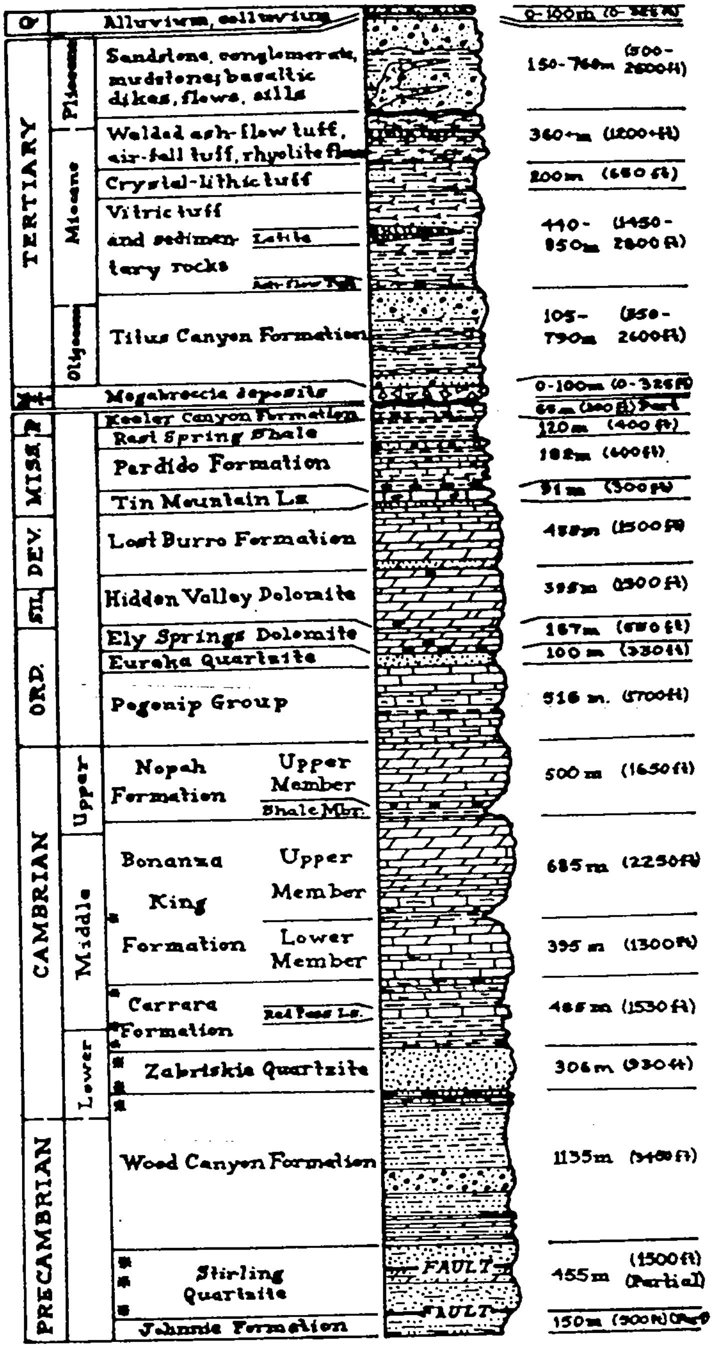
Ꞓn, Nopah Formation; Ꞓbku, Bonanza King Formation, upper part; Ꞓbkl, Bonanza King Formation, lower part; Ꞓc, Carrara Formation; Ꞓz, Zabriski Quartzite; ꞒpꞒwc, Wood Canyon Formation; pꞒs, Stirling Quartzite.

of middle or late Pliocene age, equivalent to the Furnace Creek Formation (compare with Hunt and Mabey, 1966, p. A57).

Alluvium eroded from the mountains spreads into Death Valley from major canyons and rills. Hunt and Mabey (1966) and Reynolds (1969) recognized four ages of alluvium northward from Boundary Canyon. The alluvium is both faulted against the mountain front from Titanothere to Red Wall Canyon (Fig. 1) and banked depositionally against several fault scarps, demonstrating intermittent movement along different segments of the mountain front. Alluvium adjacent to the mountains is unfaulted south of Titanothere Canyon to beyond Boundary Canyon, although locally warped. Clay, silt, and evaporite minerals are accumulating on a playa adjacent to the steep front of the Grapevine Mountains between Titus and Titanothere Canyons. The eastward displacement of the playa with respect to the axis of Death Valley toward the frontal scarp of the mountains suggests that that segment of the valley is tilting downward to the east. Both alluvium and playa sediments are displaced by faults along the northern Death Valley–Furnace Creek fault zone.

The general geologic structure of the Funeral and Grapevine Mountains is a broad anticlinorium with the deepest structural level exposed in the culmination near Chloride Cliff in the northern part of the Funeral Mountains. Progressively shallower structural levels are exposed northward across the Grapevine Mountains and southeastward across the southern part of the Funeral Mountains. Shallower structural levels are also exposed down the dip of the east flanks of the mountains and locally on the west flanks. The exposed structures developed during two principal times of deformation: the older during early Mesozoic time (probably Late Triassic or Early Jurassic [Burchfiel and others, 1970]), and the younger encompassing middle and late Cenozoic time. Different styles of deformation characterized by thrust faulting in which upper Precambrian and lower Paleozoic rocks were thrust over middle and upper Paleozoic rocks. The later deformation, however, is primarily distinguished by normal faulting and doming associated with regional tectonic extension and igneous activity. The following summary describes structures of early Mesozoic age and emphasizes structures of Cenozoic age.

Structures of Mesozoic Age. Across the northern part of the Grapevine Mountains, rocks of Precambrian, Cambrian, and Ordovician age are thrust over rocks ranging in age from Ordovician into Pennsylvanian. The fault is called the Grapevine thrust fault (Reynolds, 1971). At the base of the allochthonous plate about 8 km (5 mi) west-northwest of Mount Palmer, strongly contorted beds of the Stirling Quartzite are tectonically interleaved with deformed beds of the Wood Canyon Formation. There these rocks rest on the autochthonous Perdido Formation and Rest Spring Shale of Mississippian and Pennsylvanian(?) age. North and west-southwest of Mount Palmer, the Wood Canyon Formation is the lowest exposed unit of the allochthon. Rocks of the upper plate generally dip north across the north end of the Grapevine Mountains, so that the Cambrian Zabriskie Quartzite, Carrara, Bonanza King, and Nopah Formations, and the Ordovician Pogonip Group successively form the sole of the upper plate. Rocks of the upper plate are folded in a tight north-trending anticline 3.2 km (2 mi) southwest of Grapevine Peak, in the core of which the Wood Canyon Formation is exposed, but otherwise the plate was not strongly deformed during thrusting.



*Denotes interval of common failure during folding and faulting. Thicknesses are approximate. MzT denotes Mesozoic(?) and Tertiary age. Data of Mitchell W. Reynolds.

Figure 2. Generalized columnar section of rocks exposed in the Grapevine Mountains, Death Valley, California.

The authochthon includes the entire succession of Paleozoic and Precambrian rocks exposed from outcrops of the Grapevine thrust fault southward up the regional plunge to the major culmination of the anticlinorium near Chloride Cliff. Immediately beneath the fault, middle and upper Paleozoic rocks are strongly deformed: 9.7 km (6 mi) west of Grapevine Peak, the Mississippian Perdido Formation, the Rest Spring Shale, and the Pennsylvanian Keeler Canyon Formation are locally overturned west or northwest beneath the fault. This overturning suggests that the allochthon moved southeast and east. West of Mount Palmer the Devonian Lost Burro Formation is locally contorted in disharmonic folds beneath the thrust fault. Farther south the autochthon seems to have been little deformed during thrusting.

Stewart and others (1966) suggested that the Grapevine thrust fault may be equivalent to the Last Chance thrust fault that they described from extensive exposures west of Death

Valley. The Last Chance thrust fault is structurally the highest and youngest thrust fault and seems to have the greatest displacement in a succession of thrust faults west of Death Valley, including the Lemoigne, Gap Hills, Big Horn, Quartz Springs, and Racetrack thrust faults (McAllister, 1952; Hall and Stephens, 1962). I (1971) tentatively accepted the correlation of the Last Chance and Grapevine thrust faults and noted that the Grapevine thrust fault continues east from the Grapevine Mountains through exposures in the Bullfrog Hills to Bare Mountain, where Cornwall and Kleinhampl (1961) described a thrust fault at Meiklejohn Peak, which shows similar structural and stratigraphic relations. Although the specific surface of thrusting is not likely the same across the region, the exposed fault surfaces are probably part of the Last Chance thrust system. Thrust faults equivalent to the older described faults on the west side of Death Valley do not seem to be present on the east side in either the Grapevine Mountains or the northern part of the Funeral Mountains. Plutons of quartz monzonite that intrude the thrust faults west of Death Valley have approximate radiometric ages of 156 and 165 m.y., and Burchfiel and others (1970) consider that thrusting occurred during latest Paleozoic and early Mesozoic time, most likely during Middle Triassic to Early Jurassic time. That age of thrusting is also accepted for the Grapevine thrust fault.

No stratigraphic record of tectonic events younger than thrusting but older than Oligocene age is preserved in the Grapevine Mountains. Deformed Precambrian and Paleozoic rocks were tilted northward prior to erosion of the surface on which rocks of the Titus Canyon Formation (Oligocene and Miocene(?)) accumulated. That formation rests on Precambrian–Cambrian Wood Canyon Formation east of Chloride Cliff (L. A. Wright and B. W. Troxel, 1971, written commun.) and on progressively younger strata to the north where, near Grapevine Peak, it rests unconformably on allochthonous rocks of the Grapevine thrust fault. The relation suggests that the area of the Funeral Mountains was a structural high prior to the erosion and that the present anticlinorium represents a middle and late Cenozoic rejuvenation of that earlier structure.

Structures of Cenozoic Age. The most conspicuous geologic structures in the Grapevine Mountains and northern Funeral Mountains developed during Cenozoic time. Deformation was episodic in pulses between 20 and 16, ~14 and 13, and 11 and 7 m.y., and has been nearly continuous since (Reynolds, 1974). The first two episodes were characterized by uplift in the southern part of the area and by faulting along northeast and north trends. The episode between 11 and 7 m. y. seems to have been particularly intense, for, during that time, doming, recumbent folding, and extensive faulting along a north trend occurred. Intermittent younger deformation has produced much of the relief evident along the mountain fronts and right-lateral faulting that displaces Quaternary units in northern Death Valley.

In section view from north-northwest to south-southeast along the Grapevine Mountains and northern Funeral Mountains, the general structure that developed during Cenozoic time is an anticlinorium with a major culmination in the vicinity of Chloride Cliff and a second culmination between Mount Palmer and Grapevine Peak (Fig. 1). From east to west the ranges are anticlinal with tilted, faulted Tertiary rocks on the east and west flanks. Minimum structural relief between the culmination at Chloride Cliff and the northern end of the Grapevine Mountains is 10.6 km (6.6 mi). Southeast down plunge from Chloride Cliff the apparent structural relief exceeds 6 km (3.7 mi). Structural relief between the crest of the second culmination near Mount Palmer and the equivalent stratigraphic horizon in the adjacent depression that lies between Titus and Titanothere Canyons is about 3 km (1.9 mi). Part of the relief had developed prior to Oligocene time, but most developed in Pliocene time, as demonstrated by strata of early Pliocene age tilted to angles of 45° on the flanks of the folds.

About 8 km (5 mi) east-southeast of Chloride Cliff, high-angle faults that displace rocks as young as Pliocene flatten westward and northward with depth, merging to form a single low-angle fault (L. A. Wright and B. W. Troxel, 1971, written commun.). Progressively north along the east flank of the range, north-trending faults also flatten with depth to join the master low-angle fault. In its southernmost exposures that fault is within the Stirling Quartzite, but from about 5 km (3 mi) east of Chloride Cliff to Boundary Canyon the fault forms a surface of décollement between the Precambrian Johnnie Formation below and the Stirling Quartzite and younger strata above. Across that area, Tertiary, Cambrian, and Precambrian strata, in blocks bounded by the high-angle faults that flatten to join the master fault, are rotated downward to the east or northeast to angles as steep as 75°. The low-angle master fault is well exposed between the Stirling Quartzite and Johnnie Formation on the north side of Boundary Canyon from south of Hole-in-the-Rock Spring east for about 1 km (0.7 mi).

From Boundary Canyon north as far as Titus Canyon in the Grapevine Mountains, the Stirling Quartzite, Wood Canyon Formation, and Cambrian beds are folded in an S-shaped fold system that consists of a recumbent syncline on the west and a structurally higher upright-to-recumbent anticline on the east (Fig. 3). The low-angle fault visible beneath the Stirling in Boundary Canyon is the surface of décollement between the recumbently folded strata and metamorphosed deformed older rocks. A limestone unit in the lower part of the Carrara Formation outlines the tight core of the recumbent syncline on Corkscrew Peak, and the Stirling and Wood Canyon beds east for 2 km (1.3 mi) from Hold-in-the-Rock Spring outline the broader, lower part of the syncline. The anticline is defined by outwardly opposing dips in the Wood Canyon Formation exposed on the northwest side of the highway through Boundary Canyon about 6.5 km (4 mi) above the spring. In Boundary Canyon, the anticline is faulted downward approximately 1.6 km (1 mi) against the overturned east limb of the syncline.

Traces of the fold axes trend about N. 60° W. toward a salient in the S-shaped fold system near Titus Canyon; north of the salient they trend north. The folds plunge northwest off the culmination of the Funeral Mountains anticlinorium. The trace of the axial surface is exposed in progressively younger beds northwest from Boundary Canyon in the recumbent syncline, so that between Titanothere and Titus Canyons the Upper Cambrian Nopah Formation forms the core of the fold (B and C in Fig. 3). Beds of the Cambrian Bonanza King Formation are the youngest exposed on the upright limb of the anticline near Titus Canyon, but farther north progressively younger Paleozoic rocks are continuous above the Bonanza King. Otherwise, only older strata are exposed in the anticline, and generally the overturned limb on the west has been faulted out. The axial surface of the syncline dips 20° to 60° to the east; for about 5 km (3 mi) southeast from the mouth of Titus Canyon, the recumbent syncline has been rotated downward toward Death Valley so that the axial surface dips about 15° to the west (A and B in Fig. 3). At Boundary Canyon the axial surface of the anticline is nearly vertical, but it dips northeast at progressively lower angles toward Titanothere Canyon. The recumbent part of the anticline is fully preserved only north of Titus Canyon where the axial surface dips from 5° to 10° to the east (A in Fig. 3).

Between Titus and Titanothere Canyons, where the west-directed salient of the fold system coincides with the structural depression in the range, beds of the upright limb of the anticline are broken by numerous normal faults (B in Fig. 3). Along these faults the strata have been rotated downward to the west and effectively extended over a wider area. The faults flatten eastward to join a single, nearly flat fault called the Titus Canyon fault; it separates the upright but faulted beds from the overturned limb of the recumbent syncline beneath (Fig. 1; B in Fig. 3). That low-angle fault replaces the axial surface of the anticline south of Titus Canyon, whereas north from Klare Spring in the canyon, the fault steepens to become nearly vertical and parallel to the trace of the upper part of Fall Canyon (Fig. 1; A in Fig. 3). Displacement along the vertical segment of the fault is down on the east, and the fault offsets strata as young as early Pliocene.

I have (1969, 1970, 1971) interpreted the flat fault as a lag fault along which the upright limb of the recumbent anticline broke from and lagged behind the developing recumbent fold system. The fault steepens where the recumbent anticline remains intact (A in Fig. 3). Tertiary rocks are absent from the western part of the faulted limb, although east near Leadfield the Titus Canyon Formation is locally preserved in blocks rotated downward toward the principal low-angle fault. These relations, together with the displacement of lower Pliocene rocks along the steep segment of the fault and the style of faulting, all suggest that the recumbent folding and faulting occurred at shallow depths in the crust probably during middle Pliocene time. Evidence further corroborating the young age of the recumbent folding is derived from dating the décollement fault at the base of the fold system as probable middle Pliocene, because that fault offsets strata of early Pliocene age east of Chloride Cliff. The folding was accomplished before late Pliocene and Quaternary time, because beds of fanglomerate of those ages southwest and west of Death Valley Buttes and north of Fall Canyon contain clasts derived from rocks not exposed in the mountains prior to the folding and erosion.

North-trending normal faults on the east flanks of the Grapevine Mountains and northern Funeral Mountains displace the sequence of Tertiary rocks progressively down toward the east. These faults flattened eastward, or locally westward, with depth to follow horizons nearly parallel to bedding in the Cambrian Zabriskie Quartzite or in the upper part of the Wood Canyon Formation (Fig. 2; B in Fig. 3). Displacement on separate faults is as much as 1,000 m (3,200 ft). The offsets suggest that the Cenozoic rocks were extended in a west-northwest–east-southeast direction as they tore from and moved against the subjacent Paleozoic and Precambrian rocks that were being arched in the mountain core.

The abrupt west-southwest and south fronts of the Grapevine Mountains mark zones of normal faulting and warping along which the mountains have risen with respect to Death Valley. Gravity data of Mabey (1963) and the distribution of Tertiary rocks in the southern part of the Grapevine Mountains suggest that vertical separation on the pre-Tertiary surface between the valley and the mountains may be at least 4.3 km (2.7 mi). Fault scarps dip 44° to 75° toward the valley, and antithetic faults dip into the mountain front to break it into a mosaic of strongly fractured small blocks. Warping toward Death Valley accounts for an unknown but substantial part of the structural relief on the range front, for the axial surface of the recumbent syncline of probable middle Pliocene age has been warped 15° down toward Death Valley (A and B in Fig. 3). As a result of both the warping and recumbent folding, beds of the Cambrian Bonanza King Formation at the mouth of Titus Canyon have been rotated through as much as 235° from original horizontality. North of Fall Canyon the apparent vertical separation between Death Valley and the mountain front diminishes and right-lateral strike-slip faulting becomes important within the range. Movement seems to have recurred through latest Tertiary and Quaternary time.

From Death Valley Buttes to Titus Canyon along the steep mountain front, strata in blocks as much as 1.9 km (1.2 mi) across are faulted downward toward the valley along faults that flatten with depth to become nearly horizontal (Fig. 1; C and D in Fig. 3). The flat toes of such faults are commonly exposed at elevations higher than the valley floor. Clearly, these are block-glide landslide structures that formed during or after development of the high relief on the mountain front.

Evidence of Quaternary movement along the northern Death Valley–Furnace Creek fault zone is present almost continuously for 3.2 to 6.5 km (2 to 4 mi) west of the Grapevine Mountains in Death Valley. The linear west front of the Kit Fox Hills, west of Death Valley Buttes (Fig. 1), passes north-northwest into a linear fault trace along which alluvium and playa sediments are furrowed, and springs emerge. The northern Death Valley highway just south of its junction with the Titus Canyon road rises onto a scarplet in alluvium that varies from 0.6 to 2 m (2 to 7 ft) high; the west side is up relative to the east side. Northwest of Red Wall Canyon an old alluvial fan is displaced right-laterally about 46 m (150 ft) with no significant vertical offset, yet 12 km (7.5 mi) farther northwest, displacement on the fault is about 4.5 m (15 ft) west side up. Near Grapevine Ranger Station, at the north end of the Grapevine Mountains, the east side of the fault is elevated with respect to the west. The linear trace of the fault, patterns of offset of Quaternary deposits, and physiographic features characteristic of strike-slip faulting demonstrate that the fault is nearly vertical and that movement has been in a right-lateral direction. Right-lateral movement on the fault zone, probably occurring largely since middle Cenozoic time, has been variously estimated as being a few miles (Wright and Troxel, 1967, 1970) to scores of miles (Stewart, 1967; Stewart and others, 1968; Burchfiel and others, 1970).

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