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.
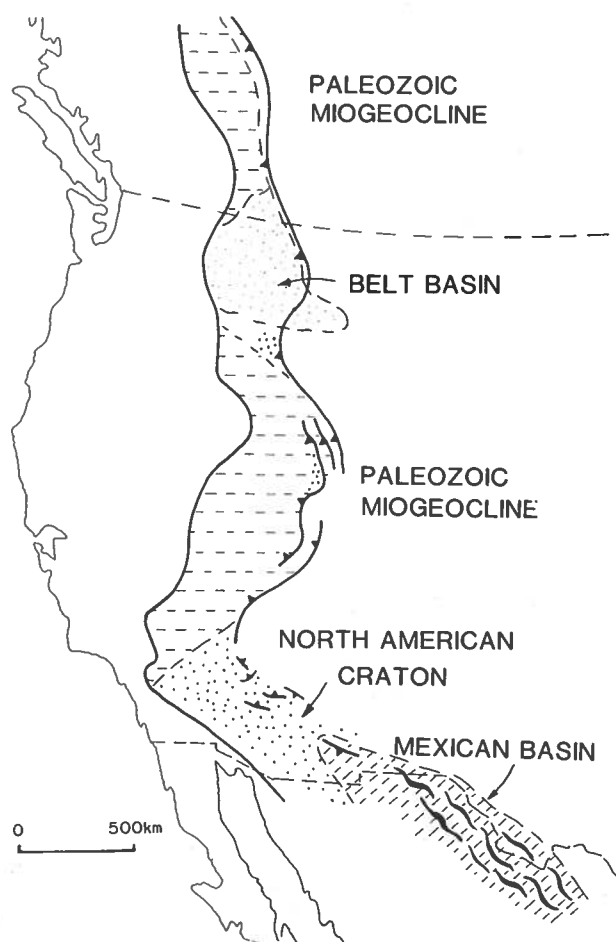

Figure 1. Eastern limit of the foreland fold and thrust belt of the Cordilleran orogen and the major paleogeographic elements through which it passes. Areas where the thrusts and folds involve crystalline basement rocks are shown in stippled pattern.
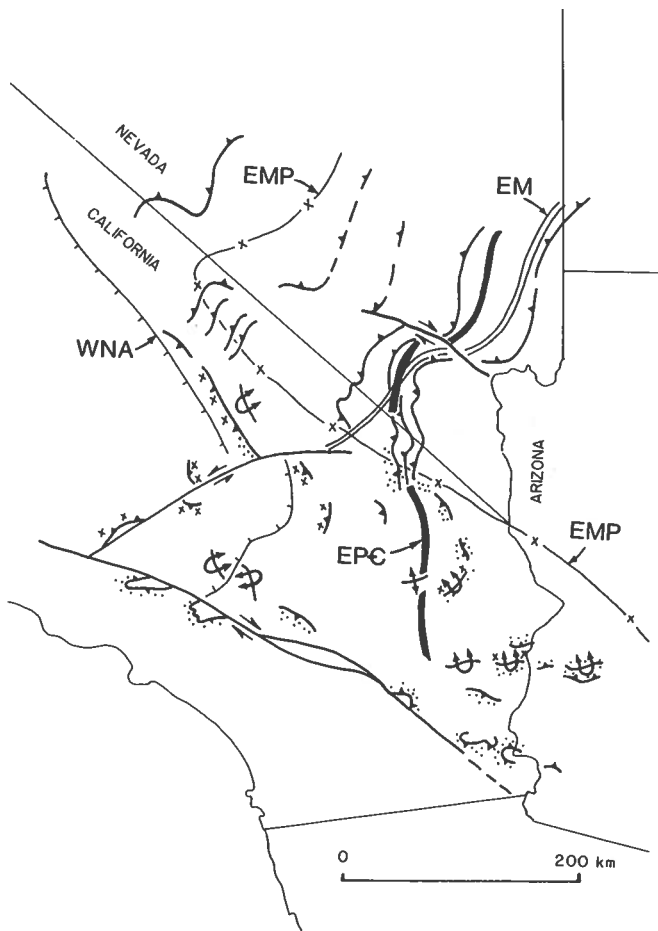
Figure 2. Schematic tectonic map of the southwestern part of the Cordilleran orogen showing relations between major structural and paleogeographic elements. Structures that involve Precambrian crystalline rocks and Mesozoic plutonic rocks are decorated by stippled and crossed patterns respectively. The 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.
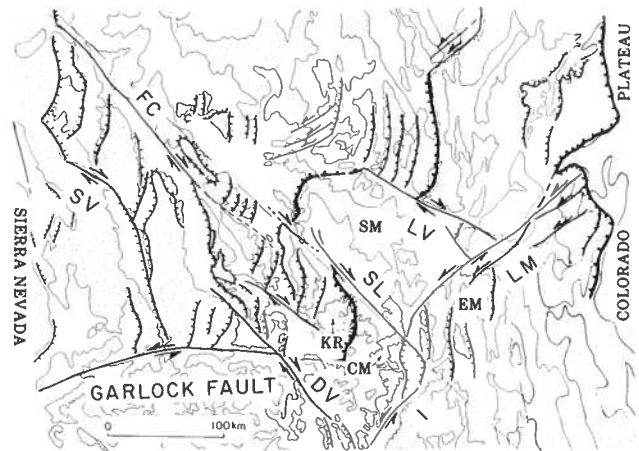

Figure 3. Schematic map of the major structures formed during Cenozoic extension. Normal faults are shown with hatchured lines and strike-slip faults with relative motion arrows. Major breakaway faults for extended terranes are shown with heavy hatchured lines. Major strike-slip fault zones: Lake Mead (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.

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,
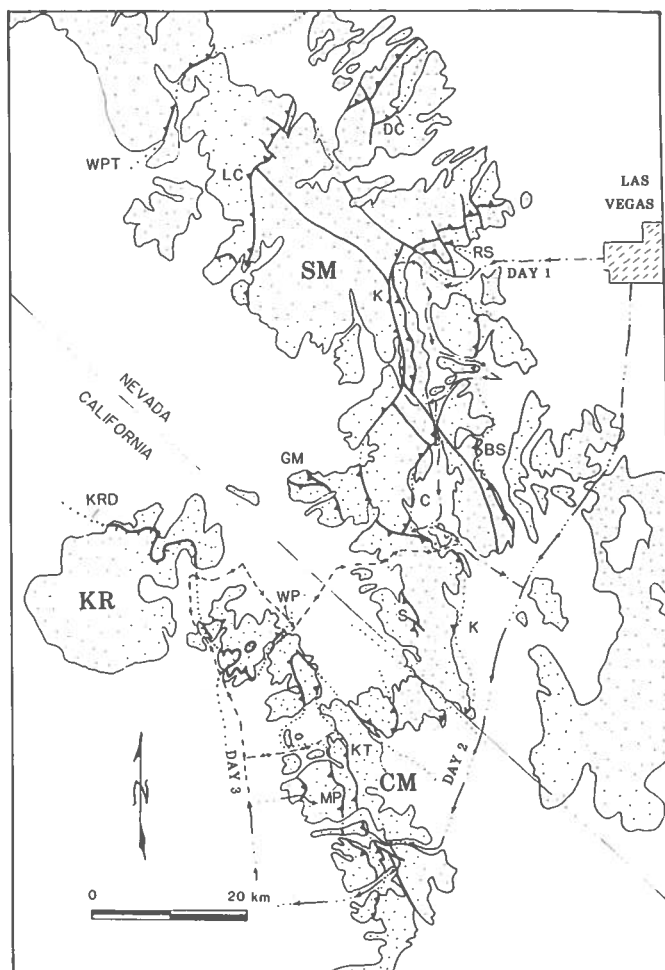

Figure 4. Generalized map of the field trip region showing the location of major structural features relevant to the field trip. The field trip routes for each day are shown: day 1 (—.—.—); day 2 (—···—); day 3 (————). Major thrust faults (from north to south): Red Spring (RS); Keystone (K); Bird Spring (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.
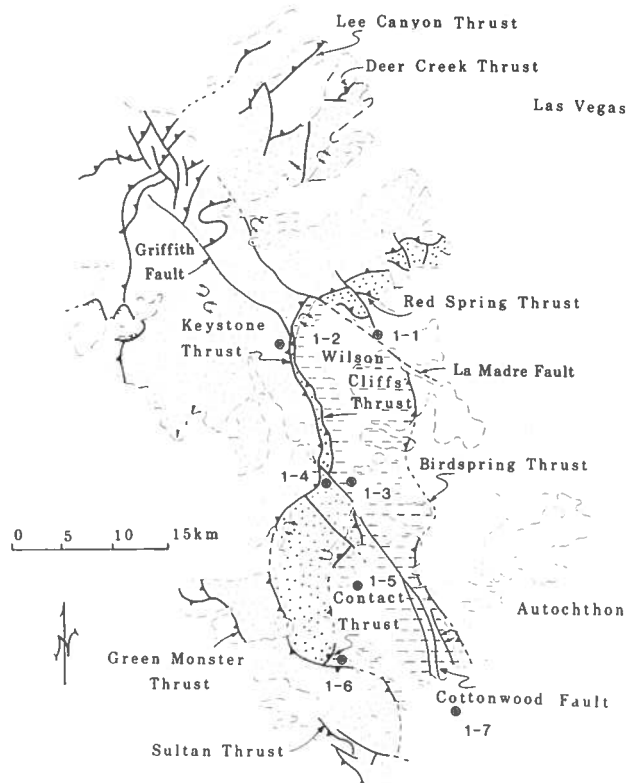

Figure 6. Major structural units in the eastern Spring Mountains. Locations of stops for the first day are indicated.
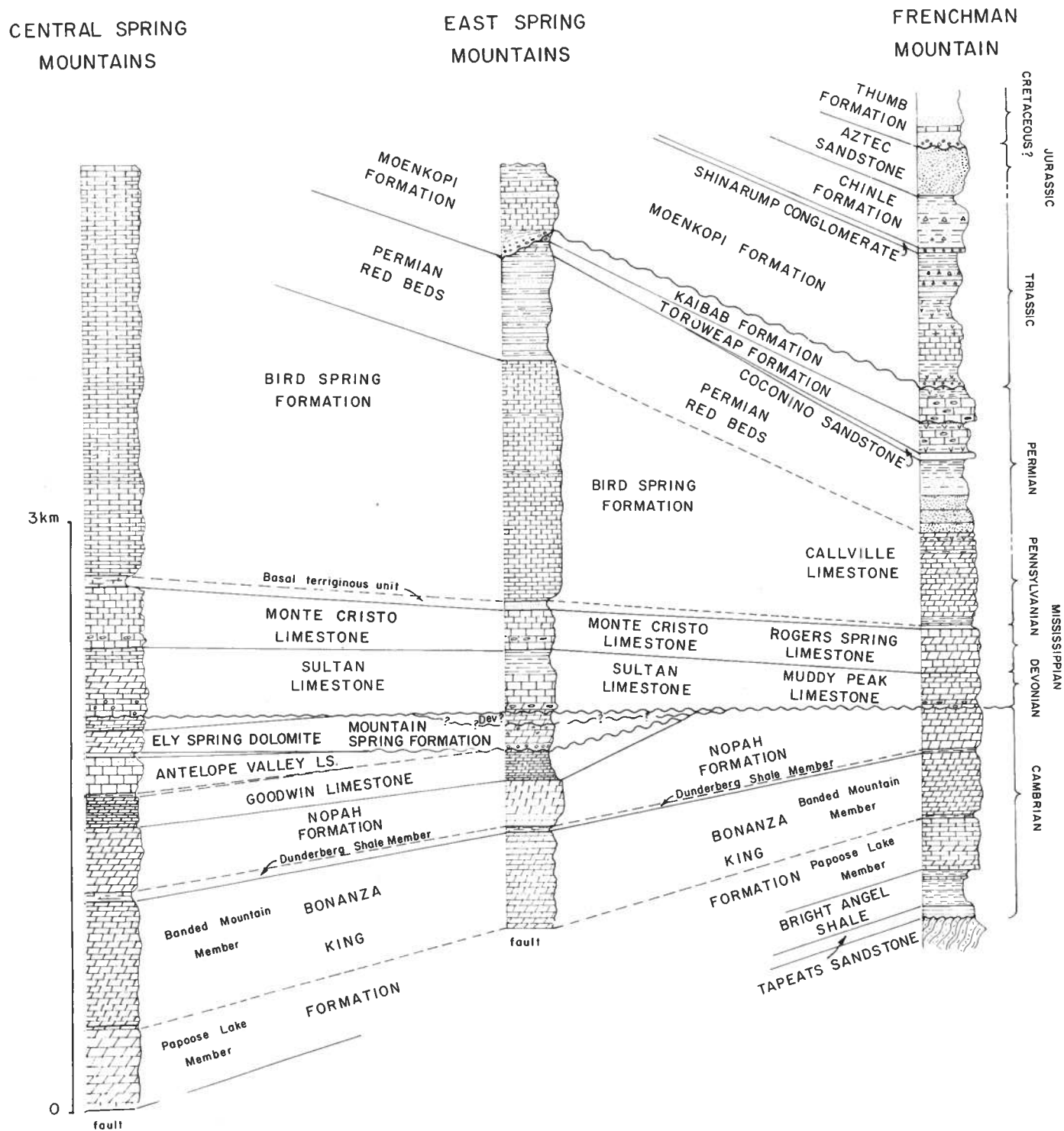
Figure 5. Generalized stratigraphic sections in the Frenchman and Spring Mountains areas.

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
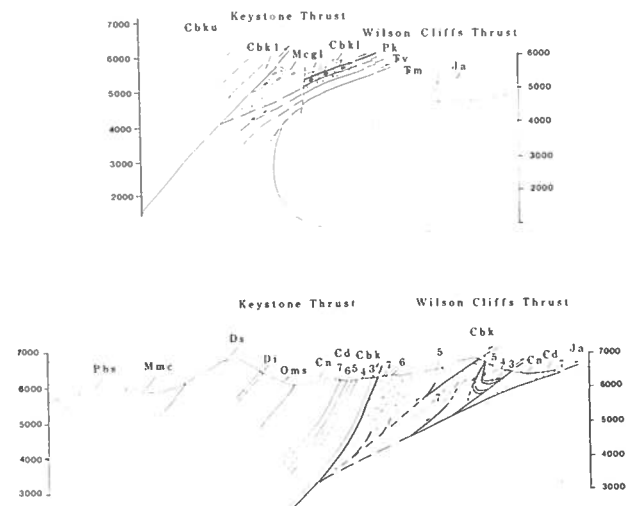

Figure 7. Cross-sections of the Keystone and Wilson Cliffs thrust plates.

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 (€d); Nopah Formation (€n); Mountains Springs Formation (Oms); Ironside Dolomite (Di); Sultan Formation (Ds); Monte Cristo Formation (Mmc); Birdspring Formation (Pbs).

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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).
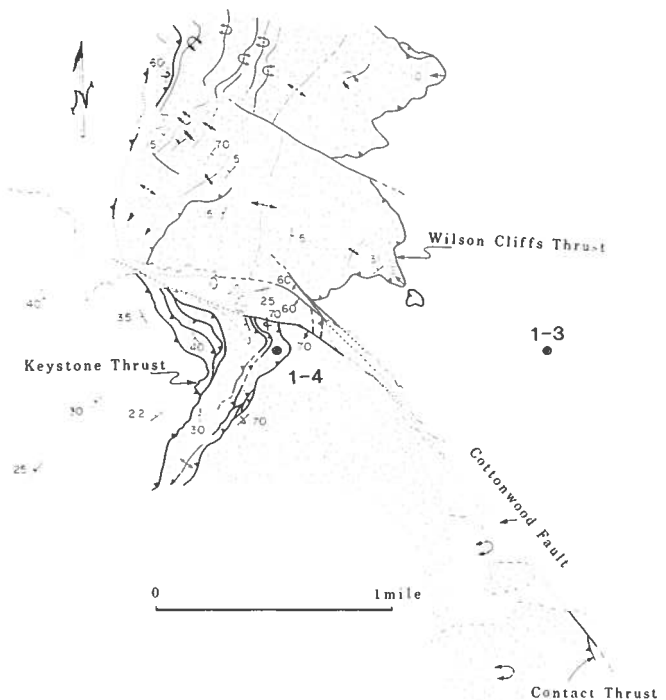

Figure 8. Geologic map along the Cottonwood fault at Mountain Springs Pass, Spring Mountains. Mapping indicates that the Wilson Cliffs and Contact thrust plates (stippled) are equivalent. The Keystone plate lies above the Wilson Cliffs/Contact plate. It has been warped by displacement on the Cottonwood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

Fieldtrip Stops

Leaving Las Vegas, we will drive west on Charleston Blvd. toward Red Rock 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 strata. 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 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
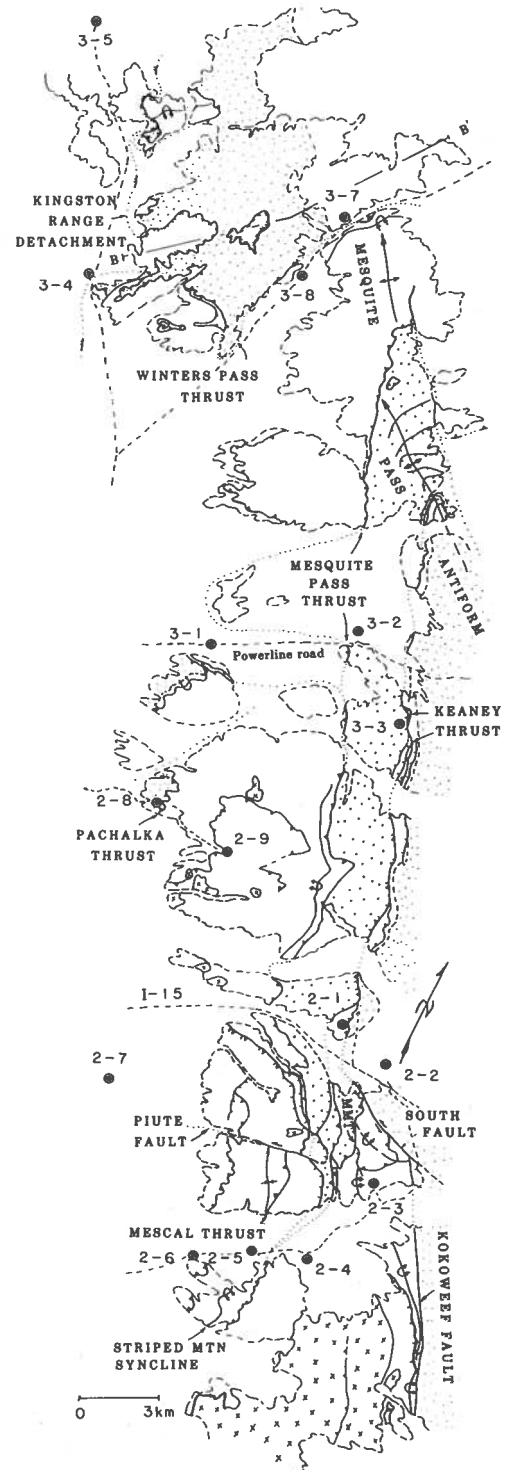formations in the or cratonal sequence of the

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).
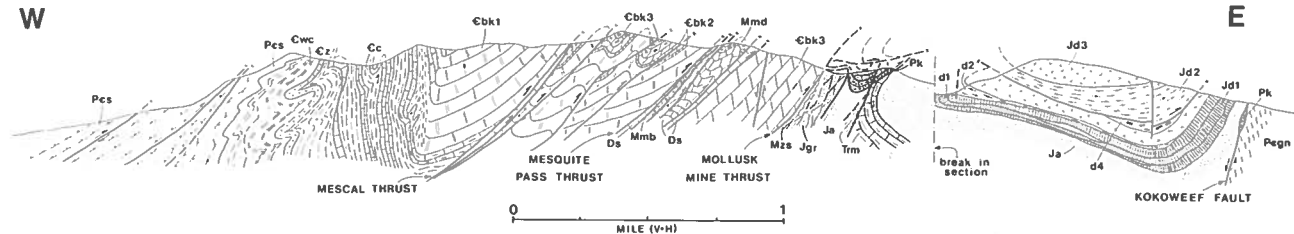
Figure 10. Cross-section through the southern Mescal Range (south of Piute fault, Fig. 9) of the Clark Mountain thrust complex. Various parts of this section will be seen at stops 2-3, 4, 5, and 6. Rock units from west to east: Stirling Quartzite (P€s); Wood Canyon Formation (€wc); Zabriskie Quartzite (€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 (Pegn).

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.

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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.
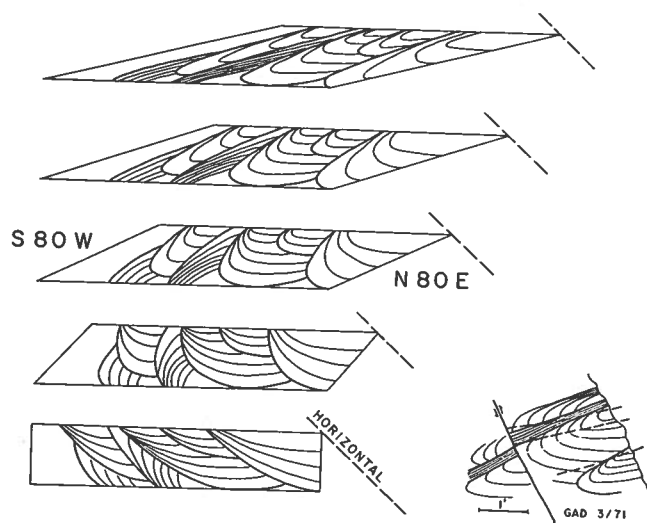

Figure 11. Lower right corner: field sketch, parallel to a prominent stretching lineation, illustrating the geometry of distorted, overturned cross beds in Stirling Quartzite mylonitic tectonites, southwestern Striped Mountain. The five sections illustrate progressive deformation by homogeneous simple 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.]
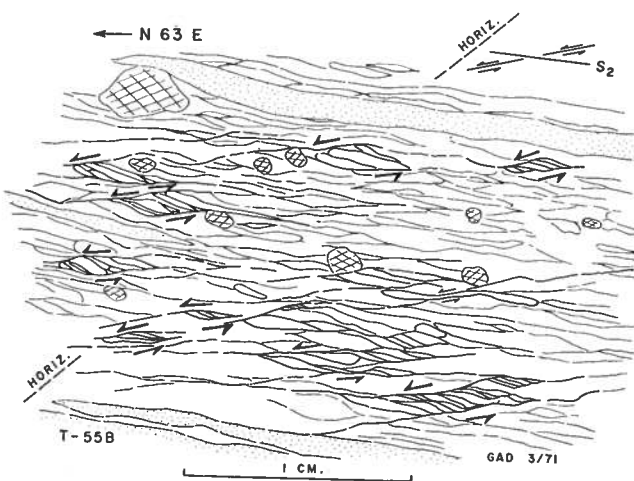

Figure 12. S-C fabric relationships within a thin-section of a Stirling mylonitic quartzite, from the southwestern corner of Striped Mountain. The section is cut parallel to a prominent stretching lineation. The foliation (S2 = S) is transected by shear surfaces (= C) with a geometry that indicates a 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 wheteher 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).
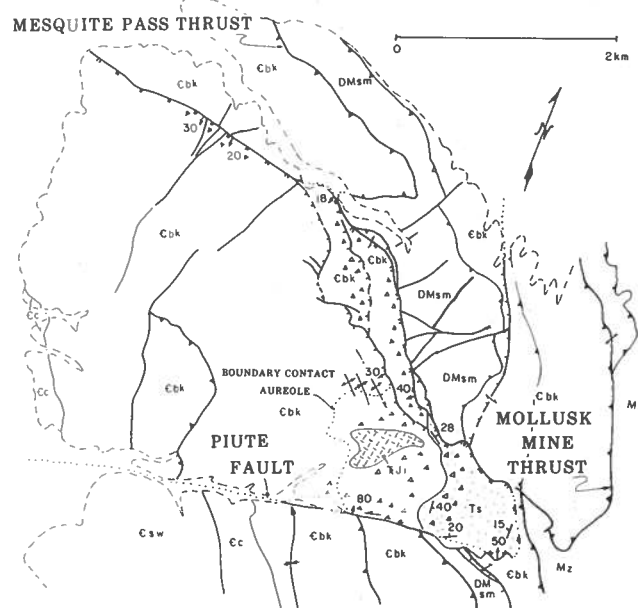

Figure 13. Highly simplified tectonic map of northern Mescal Range, Clark Mountains thrust complex. Interstate Highway 15 lies directly north of the map area (cf. Fig. 9). Most of map area lies within an extensional Cenozoic allochthon that has developed across the Mesozoic thrust belt. The allochthon 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 overridden 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 uncomfortable 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). 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 Cenozic 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
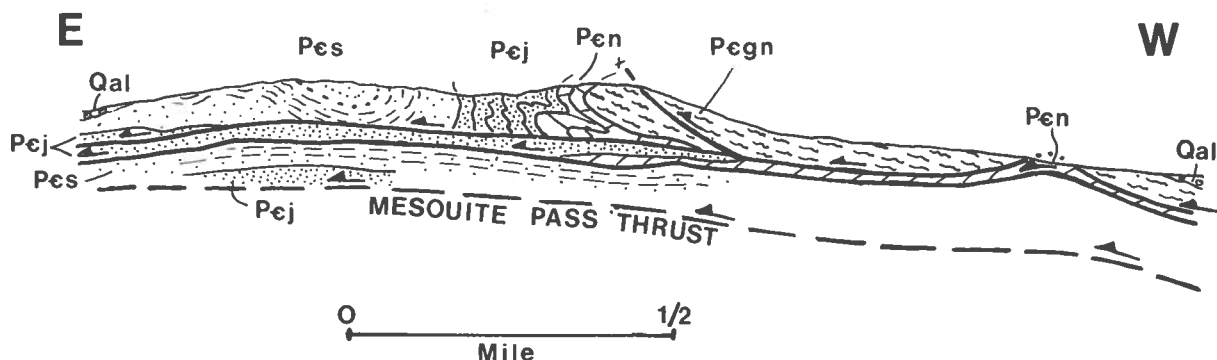

Figure 14. Cross-section through the Mesquite Pass thrust plate, hill south of powerline road (cf. Fig. 9), illustrating involvement of basement crystalline rocks in the thrust belt. Geologic relationships are explained at stop 3-1. Rock units (oldest first): Precambrian gneisses (Pcgn); Noonday Dolomite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

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
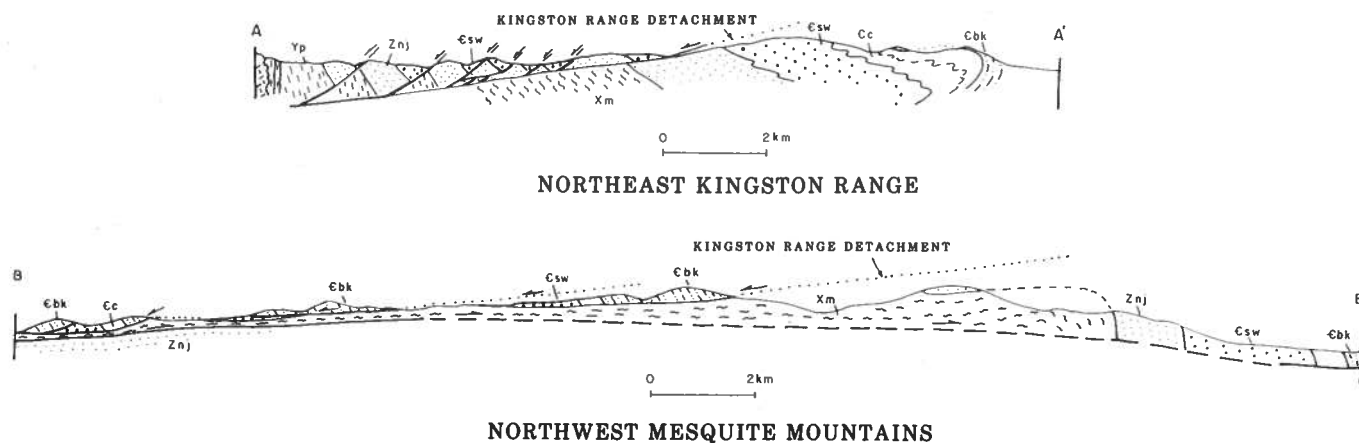

NORTHWEST MESQUITE MOUNTAINS

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.
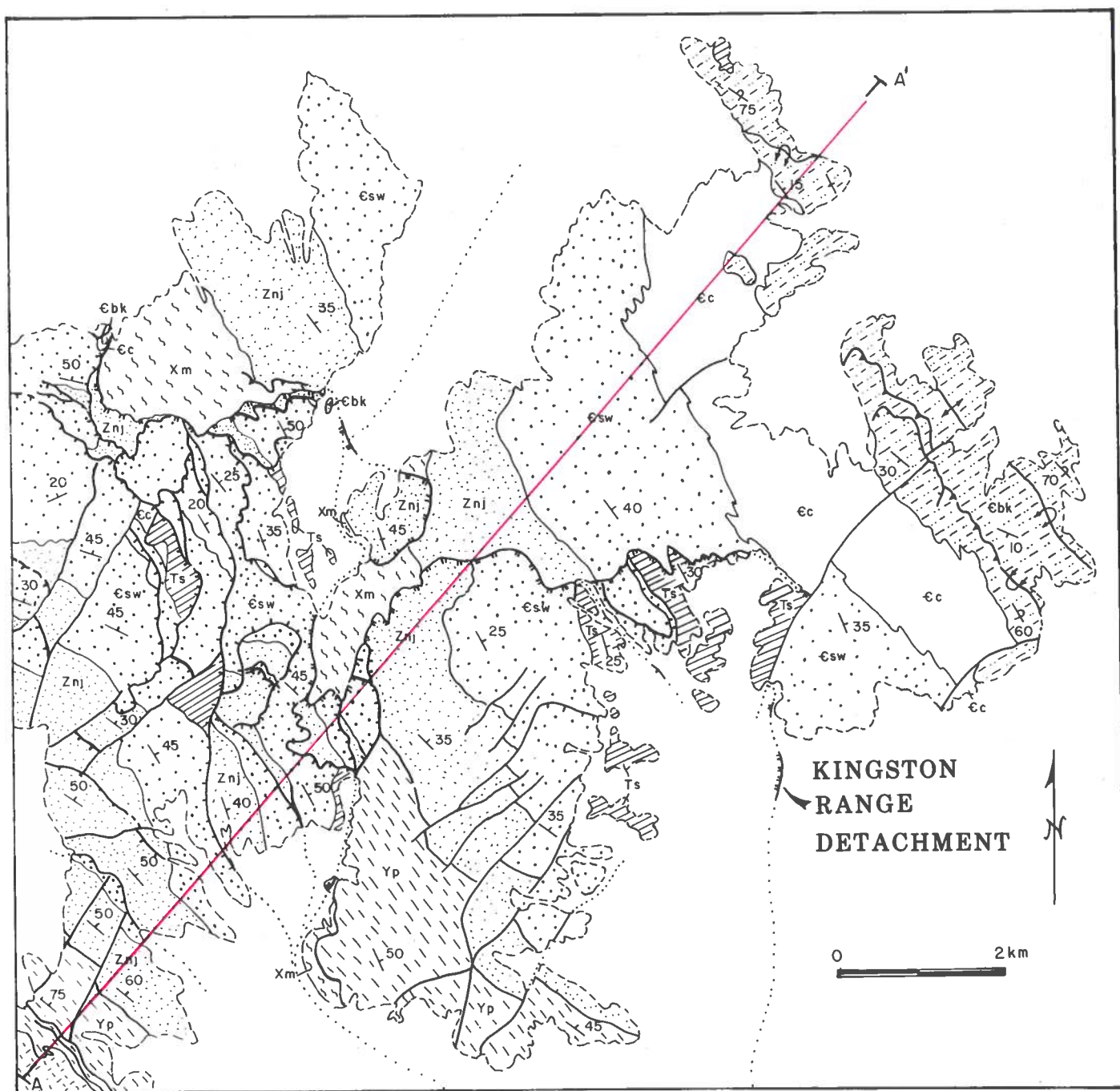
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Figure 16. Simplified geologic map of the northeastern Kingston Range (cf. Fig. 4) showing location of the Kingston Range detachment fault and its upper-plate structure. The unlabeled patterned unit at the southwestern corner of the figure is the Miocene 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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