A Field Guide to the Cenozoic Crustal Structure of the Mojave Desert

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INTRODUCTION

Welcome to the Mojave Desert! The purpose of this trip is to acquaint you with aspects of the Cenozoic structural, sedimentary, igneous, paleogeographic, and biologic evolution of the region. Our objectives are to provide you with a crustal-scale view of the Mojave Desert as well as a synthesis of the Cenozoic tectonic evolution of the region.

We would like to take this opportunity to thank a number of institutions and individuals for their support during the years. The Crustal Structure and Tectonics Program (Dr. Thomas O. Wright, Director) of the National Science Foundation has generously supplied moral and financial support to RKD over the past seven years (Grants EAR-8107524 and EAR-8407136). Additional support was provided by an Arco Junior Faculty award. EGF and DO wish to express their appreciation to the Continental Lithosphere Program at NSF (Dr. Leonard Johnson, Director) for support of the California Consortium For Crustal Studies (CALCRUST). MM gratefully acknowledges the support from the National Science Foundation (EAR 78-16413 awarded to A. Boettcher) and the Geological Society of America (Penrose Grant #2494-79). MOM would like to acknowledge the support of the Academic Senate of the University of California, Riverside. We would also like to thank Phillips, Exxon, Chevron, Texaco, Amoco, Arco, CGG, and Buckhorn for making available seismic and related geophysical data. Finally, very little could have been accomplished without the sharing and caring of the following geo-friends: A. K. Baksi, J. Bartley, A. Boettcher, J. Brem, B. Casey, B. Cox, J. C. Crowell, N. Dakota, III, G. A. Davis, G. H. Davis, T. W. Dibblee, Jr., A. Glazner, B. Hanson, G. Henzel, T. Henyey, K. Howard, J. Lambert, R. Larson, B. Luyendyk, R. Mathis, B. McFaddon, R. McPherron, R. H.

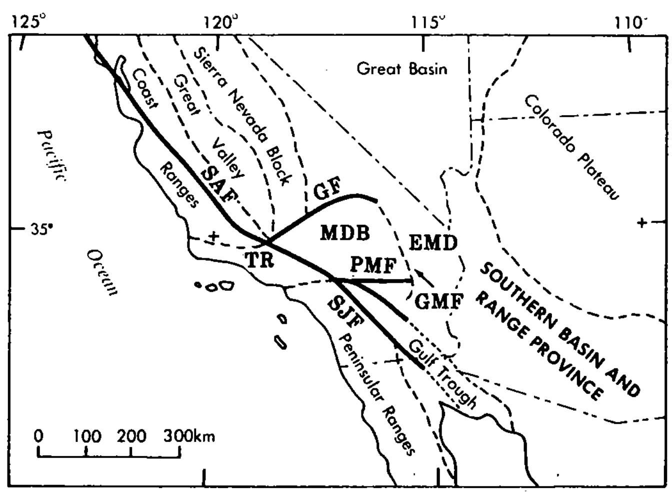


Figure 1. Index map of the Mojave Desert region. MDB=Mojave Desert block; EMD=Eastern Mojave Desert; GMF=Granite Mountains fault; SAF=San Andreas fault; GF=Garlock fault; PMF=Pinto Mountain fault; TR=Transverse Ranges; SJF=San Jacinto fault.

Merriam, D. Miller, S. T. Miller, B. Murray, D. Musselwhite, N. Opdyke, T. Ross, F. Southcott, and J. Southcott.

GEOLOGIC SETTING OF THE MOJAVE DESERT

General Relations

There has always been some confusion among students of the region as to the meaning of the term, ***Mojave Desert*** (see Thompson [1929] for discussion). Although its original meaning relates to a physiographic province (Baker, 1911), some workers have used the term to designate a tectonic domain (Hewett, 1954; Garfunkel, 1974; Dokka, 1983a). Because the Cenozoic tectonic evolution of the Mojave involves the superposition of several different tectonic regimes, great care must be exercised. For discussion purposes here, we will refer to the region west of the Granite Mountains fault as the ***Mojave Desert block*** and the area to the east as the ***Eastern Mojave Desert*** (Fig. 1).

Mojave Desert Block

The Mojave Desert block is bounded by the Garlock fault to the north and the San Andreas and Pinto Mountain fault systems to the south. Its eastern limit is the Granite Mountains fault; the fault coincides with a NNW-trending line defined by geophysical studies (Dokka, 1980, 1983a).

The greater Mojave Desert area is composed of the following lithological assemblages: (1) Precambrian crystalline complex (metamorphic and igneous rocks) ranging in age from 1.87 Ga to 1.2 Ga (Burchfiel and Davis, 1980); (2) Upper Precambrian-Paleozoic sequence of miogeoclinal and platform rocks (Stewart and Poole, 1975; Burchfiel and Davis, 1980); (3) Mesozoic backarc and intraarc shallow marine and continental sequences (Burchfiel and Davis, 1980); (4) Mesozoic batholithic rocks and associated (?) volcanic cover (Kistler, 1974); Burchfiel and Davis, 1980); (5) lower Miocene calc-alkaline and bimodal volcanic sequences and continental sedimentary rocks (Dibblee, 1967a; Armstrong and Higgins, 1973; Woodburne and others, 1982); (6) middle Miocene and younger continental sedimentary rocks and intermediate to silicic volcanic rocks (Dibblee, 1967a; Woodburne and others, 1982; Woodburne and Tedford, 1982); and (7) Quaternary alkalic volcanic rocks (Wise, 1969) and unconsolidated sediments.

The Mojave Desert block was affected by at least four tectonic events during the Cenozoic. The first disturbance was a broad uplift of the entire block that occurred at some time prior to the Miocene. Little is known about this event because of the paucity of lower Cenozoic rocks. It seems likely, however, that regional uplift was the result of Late Mesozoic tectonic thickening of North America caused by thrusting and intrusion. Hewett (1954) estimated that approximately 4.5 km of erosion may have occurred in association with this uplift as evidenced by the absence of sedimentary rocks that were probably deposited across the entire Mojave region during the Late Precambrian, Paleozoic, and Mesozoic (Stewart and Poole, 1975; Burchfiel and Davis, 1980). At the beginning of the Miocene, the western and central Mojave Desert underwent a profound change in physiography, structure, magmatism, and sedimentation patterns as a result of a short, but intense interval of crustal extension (Dokka, 1979, 1980, 1986, in prep.). Work to date suggests that the location, style, and timing of early Miocene extensional tectonism in the Mojave Desert was concentrated in an E-W belt, termed the ***Mojave Rift*** (Fig. 2; Dokka, 1986a, in prep.). Extension of the Mojave Rift was accomplished by low-angle normal faulting (crustal-scale low-angle, normal sense simple shear), high-angle normal faulting, and extension fracturing accompanied by intermediate to silicic composition intrusion (Dokka, 1979, 1980, 1986ab, in prep.). Major extension occurred between 22 and 20 Ma and was followed in time by a less intense interval of heterogeneous extension (local high-angle normal faulting and dike emplacement) between 19 and 17 Ma. Several different domains of extension are recognized within the Mojave Rift based on similarities in faulting style, fault geometry, and associated stratal tilt pattern (Fig. 2a). Extension is partitioned into at least three structural domains; strike-slip faults separate two of the domains. In order of occurrence from northwest to southeast, the terranes are named, Waterman, Daggett, and Bullion (Figs. 2 through 4).

Late Cenozoic tectonics of the Mojave Desert block have been dominated by right-slip faulting that was probably related to Pacific-North American plate interaction (Fig. 2a; Dibblee, 1961; Garfunkel, 1974; Dokka, 1983a). Much of the physiography of the region is controlled by strike-slip faulting (i.e., transtensional basins and transpressional uplifts; Dokka, 1987). Dokka (1983a, 1987, in prep.) has documented that these strike-slip faults possess the following characteristics: (1) the faults are young (< 13 Ma) and are in an early stage of strike-slip development; (2) the faults are discontinuous, with none spanning the entire Mojave Desert; (3) cumulative net slip on faults of the Mojave Desert block is less than 50 km (excluding slip on the Granite Mountains fault); (4) none of the NW-striking faults of the Mojave Desert block can be traced into the Garlock fault; (5) there is a discrepancy in cumulative net slip between faults north and south of a E-W line passing through Barstow; (6) faults of both the northern and southern groups end in transpressive zones along this E-W belt. This zone of convergence is the site of significant Plio-Pleistocene uplift, seismic activity, and deformation.

ROADLOG

DAY 1

Please refer to Figure 5 for locations of stops to be made today. Because portions of today's excursion involve travel on unimproved roads and on stream beds, we have included odometer readings in the text to assist you in

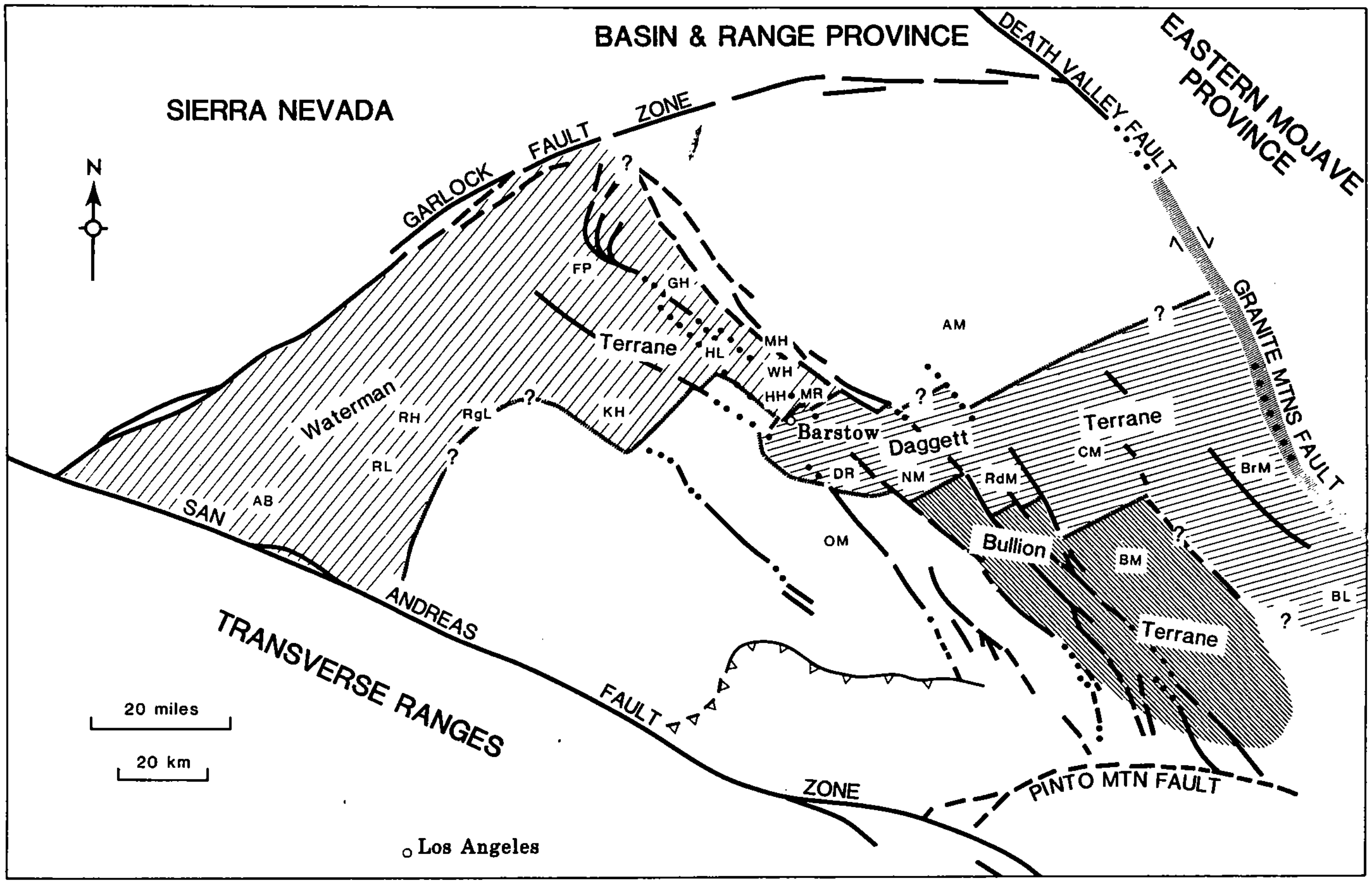


Figure 2. The Mojave Rift of Southern California (Dokka, in prep.). AV=Alvord Mountains; AB=Antelope Buttes; BM=Bullion Mountains; BrM=Bristol Mountains; BL=Bristol Lake; CM=Cady Mountains; DR=Daggett Ridge; FP=Fremont Peak; GH=Gravel Hills; HL=Harper Lake; HH=Hinkley Hills; KH=Kramer Hills; MR=Mitchell Range; MH=Mud Hills; NM=Newberry Mountains; OM=Ord Mountains; RdM=Rodman Mountains; RgL=Rodgers Dry Lake; RH=Rosamond Hills; RL=Rosamond Dry Lake; WH=Waterman Hills.

finding the stops. Be aware that many of these roads are locally sandy or extremely rugged. Four-wheel drive is recommended.

Begin trip at intersection of Interstate 15 and Main Street, Barstow. Continue south on Main Street, following signs for Interstate 40 to Needles. Enter I-40 and proceed ~7 mi to Daggett exit. Turn right and drive 1 block to Camp Rock Rd. Turn left on Camp Rock Rd. and drive 7.1 mi (the road forks after 3.9 mi, take left fork) and turn left onto the unimproved jeep trail. Proceed 1.2 mi east to Beauty Canyon and park at crest of topographic saddle.

* *

STOP #1 -- NEWBERRY MOUNTAINS DETACHMENT FAULT

Objectives

1. To observe the Newberry Mountains detachment fault.
2. To discuss the structure of the Daggett terrane.

A geologic map of the Newberry Mountains is shown in Figure 6. The Newberry Mountains detachment fault (NMDF) is a regional low-angle normal fault that separates a rotated and extended upper-plate from a non-metamorphosed and relatively undeformed lower plate (Fig. 6). Although considered to be a buttress unconformity of colossal proportions by Dibblee (1971), stratigraphic relations and fault-plane features leave no doubt as to the dislocational nature of this contact. For example, sedimentary and volcanic rocks juxtaposed across this zone do not contain any clasts of adjacent lower plate rocks (i. e., cataclasized Mesozoic granite-quartz monzonite or Mesozoic volcanic rocks (Sidewinder Volcanic Series), nor do the strata onlap the basement as might be expected if this surface were one of deposition as suggested by Dibblee (1971). Instead, this contact is marked by a zone of extreme shearing and shattering of lower plate rocks, comminution of materials near the fault, development of fault-plane features and kinematic indicators (slickensides, striations, fibrous mineral growths), and the abrupt truncation of bedding and foliations. Mapping of this surface strongly suggests that it once continuously underlay the Newberry Mountains. Although the NMDF does not crop out in other ranges in the Daggett terrane, its presence in the subsurface is suspected because of the

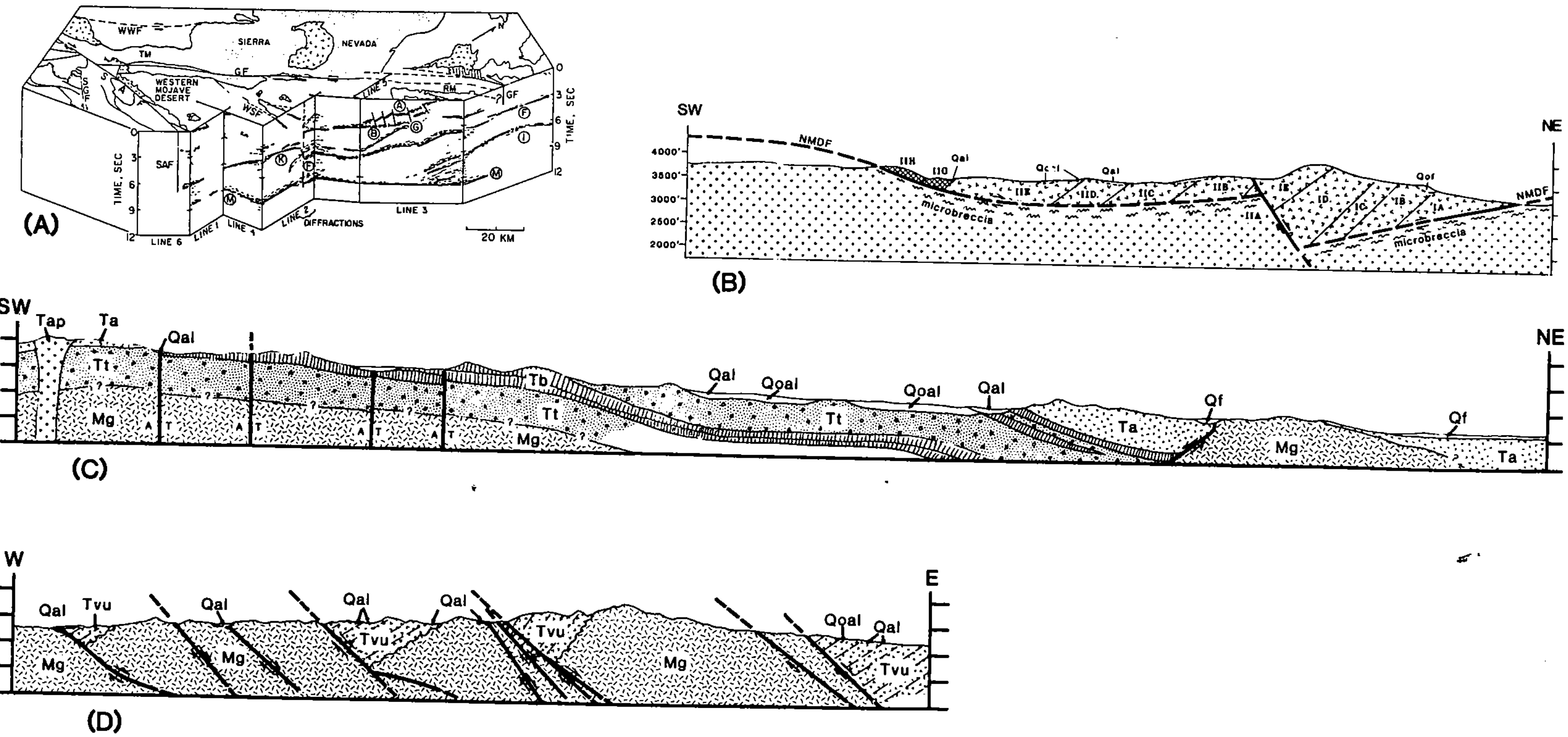
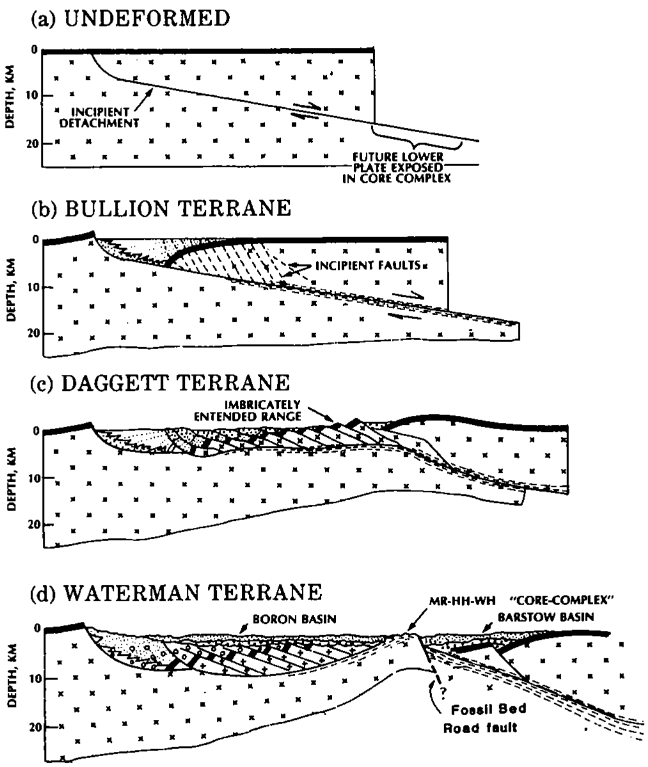


Figure 3. Examples of the architecture of extensional domains of the Mojave Rift. (A) Block diagram of the western Mojave Desert (Waterman terrane) based on COCORP seismic reflection data (Cheadle and others, 1986). Note reflection B and the inferred high-angle normal faults that lie above it. Reflection B is interpreted to be a detachment fault. This fault projects to the surface at STOP #5. (B) Structure section across the north-central Newberry Mountains (Daggett terrane)(based on map presented in Dokka [1986]). (C) Structure section across the Bullion Mountains (Bullion terrane)(after Dibblee, 1967). (D) W-E cross-section of of the central Cady Mountains (Daggett terrane)(from Mathis, 1986).



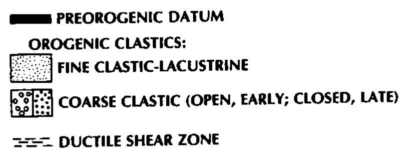
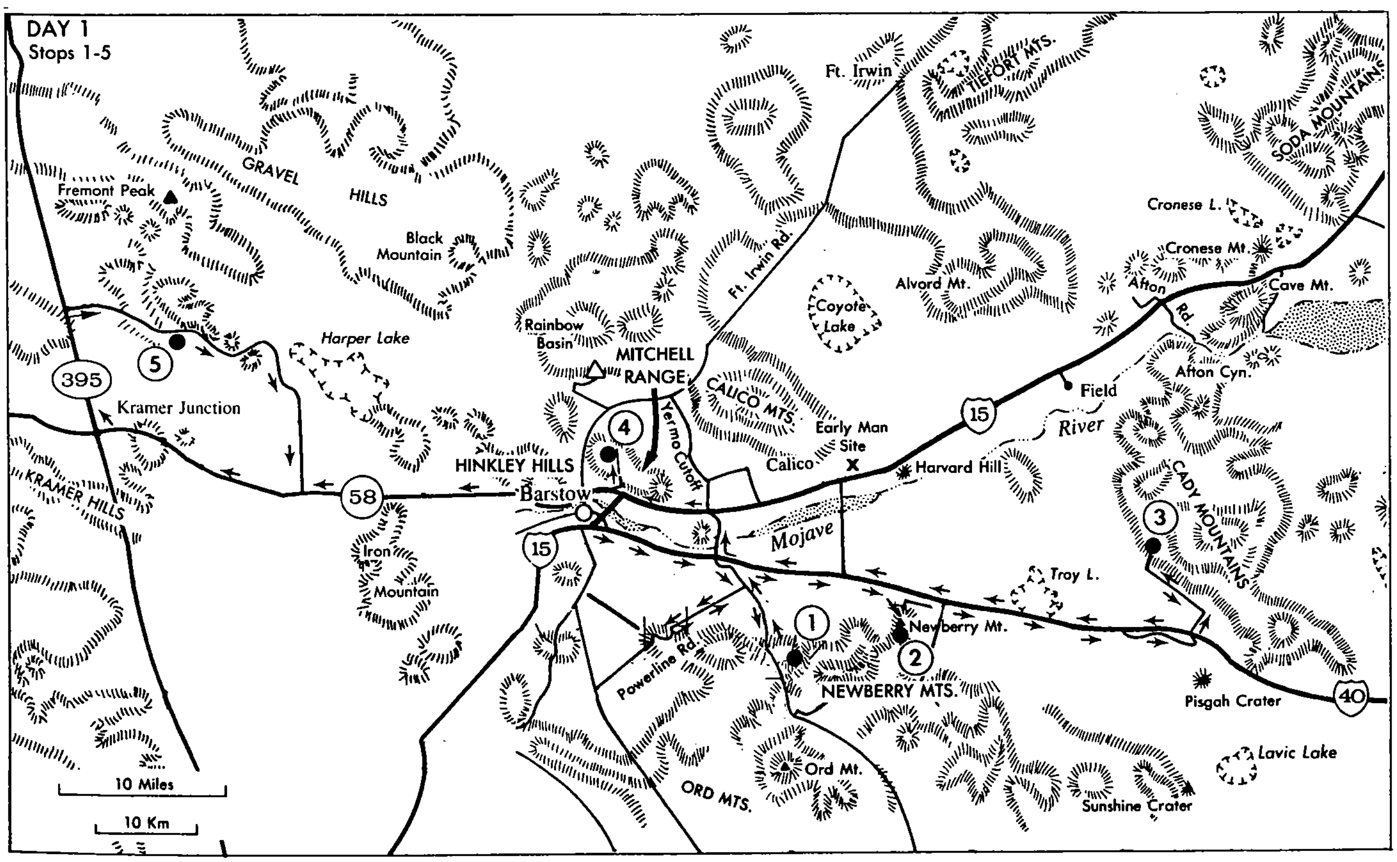


Figure 4. Generalized structure of extensional domains of the Mojave Rift (concept modified from Wernicke, 1985). MR-HH-WH=Mitchell Range-Hinkley Hills-Waterman Hills core complex uplift.

Figure 5. Route for Day 1.



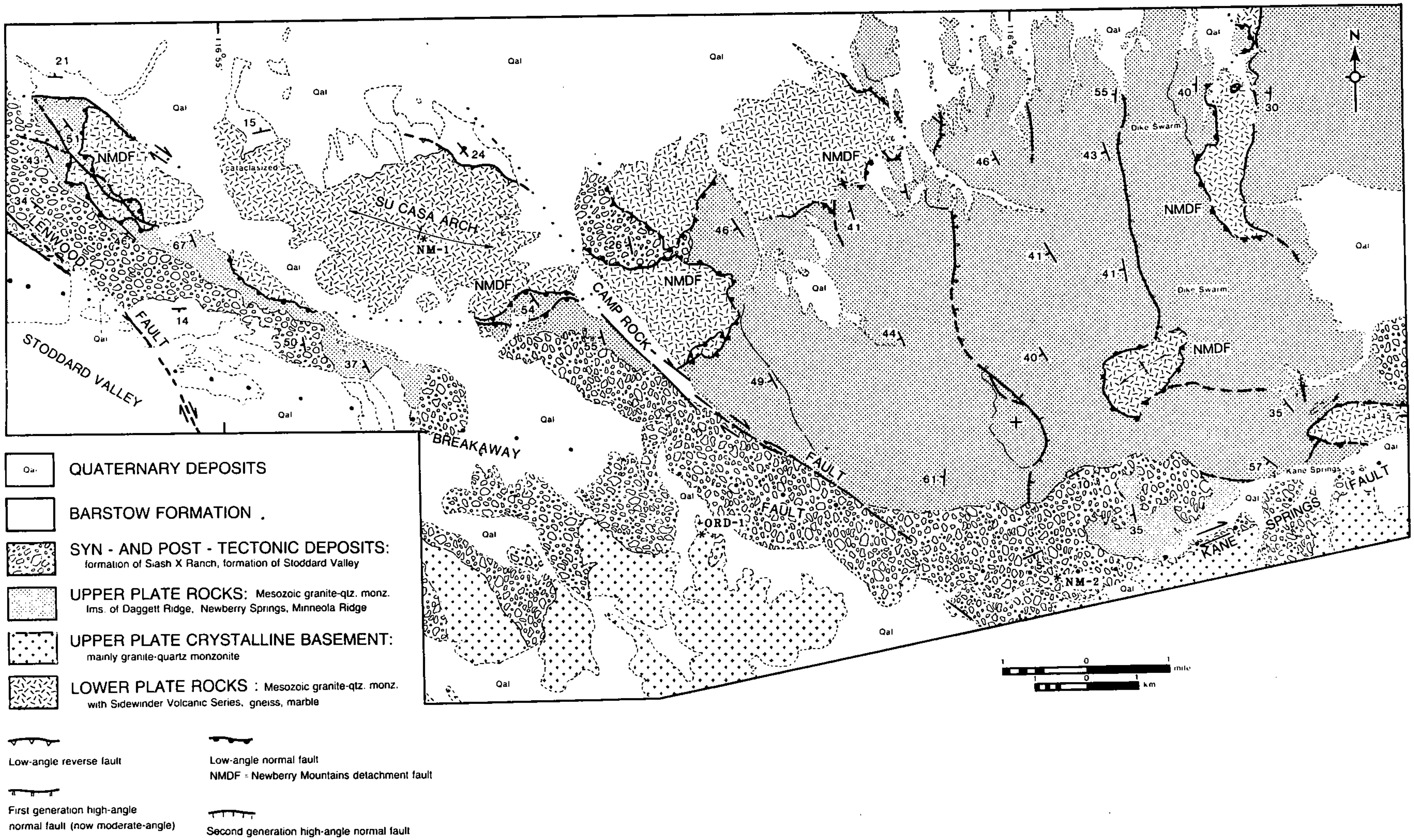


Figure 6. Generalized geologic map of the Newberry Mountains highlighting the locations of the Newberry Mountains detachment (NMDF), Kane Springs fault, upper plate normal faults, and the breakaway.

similarity of upper-plate structure (tilted and extended lower Miocene strata and basement rocks). Because of disruption by later faulting and doming, the NMDF now occurs as a series of smaller sheets. Individual fault segments strike northwest and dip gently (0°-20°) to the southwest. Near Su Casa dome, the fault has been upwarped into an E-W-trending, doubly plunging antiform (Fig. 6) that may be analogous to arches associated with middle Tertiary extensional terranes of the Colorado River trough (Spencer, 1984). The timing of doming at Su Casa has been bracketed between 22 and 16 Ma based on stratigraphic relations. Map relations and cross-sections indicate that the NMDF is locally fluted (i.e., downdip profiles of the fault are curviplanar or step-like). The best example of this is found near the Azucar Mine where the NMDF changes orientation from subhorizontal to northeast-striking and moderately southwest-dipping (Dokka, 1986a). Inasmuch as the nearby strata are not folded, upwarping by later doming cannot alone be invoked to explain the curvature of the this portion of the fault. The NMDF must have initially formed as a curved surface.

The NMDF crops out discontinuously along its trace and is generally marked by a resistant ledge of cataclasized rock and gouge that caps a variably thick (5-100 m and perhaps more) zone of coherent microbreccia and cataclasite (nomenclature after Higgins, 1971). These rocks are considered to be related to the NMDF because: (1) the zone of cataclasis only occurs adjacent to the NMDF; and (2) the unit contains shear zones that are geometrically and kinematically similar to the NMDF.

Timing of movement on the NMDF can be constrained on the basis of well-dated cross-cutting relationships. The lower limit is established by the age of the youngest rock that has been displaced along the NMDF. Nason and others(1979) presented a K-Ar date of 23.1±2.0 Ma on a dacite flow that lies in tectonic contact with the detachment in the northeastern Newberry Mountains. The upper limit is based on the age of the oldest post-tectonic sedimentary rocks that rest directly on the detachment. Near Su Casa, the base of the Middle Miocene Barstow Formation unconformably overlies the cataclasized lower plate granite. The Barstow Formation was deposited between 16 and 13 Ma ago (Burke and others, 1982). These data bracket the timing of movement along the NMDF to 23-16 Ma. The upper age constraint must be considered loose because it also includes the time during which the detachment was domed and exhumed.

This stop also affords a good view of the Camp Rock fault, one of the family of young (<13 Ma; perhaps <5 Ma), NW-striking, right-slip faults that are responsible for present-day tectonism and much of the physiography of the western and central Mojave. The fault displays 1.6 km of right slip (Dokka, 1983a). The fault terminates to the north into zone of transpression in the Gem Mine area.

* *

Retrace your steps to the Camp Rock Rd. Turn right and return to I-40. Proceed east on I-40 to the Newberry Springs offramp. Exit and turn right on to National Trails Highway. Drive 0.1 mi to Quarry Rd. and turn right. Continue west 0.5 mi to paved mine road. You need permission from McKee Products Co. (subsidiary of Santa Fe and Southern Pacific) in order to go to the next stop. Proceed 1.7 mi up the road to the mine office and park.

* *

STOP #2 -- THE NMDF NEAR NEWBERRY SPRINGS

Objectives

1. To observe a low-angle normal fault (presumed to be the NMDF).
2. To observe rotated upper-plate fault blocks lying above the detachment.

The geology of this area was described and mapped by Dokka (1980, 1986a) and is depicted on Figure 6. The low-angle fault that is so spectacularly exposed on the north wall of this canyon separates an upper-plate of lower Miocene volcanic rocks (vent deposits, viscous flows, and feeder dikes) from a sheared and altered lower plate (Cretaceous-Jurassic granite-quartz monzonite, Mesozoic Sidewinder Volcanic Series). Note also the first-generation, rotated, upper-plate normal faults that merge with the detachment. The upper-plate rocks have been informally designated as the formation of Newberry Springs (Dokka, 1980). Approximately 2.1 km of the section is exposed.

A second-generation, high-angle, E-dipping normal fault passes through the saddle. This major N-striking fault traverses the range and steps the NMDF down a minimum of 1 km to the east. Measurement of fault plane kinematic indicators suggest dip-slip along an axis that trends ENE. Three members of the formation of Newberry Springs can be seen at this locality. The lowest (oldest) member consists of white tuff breccia and lapilli tuff. These rocks contain xenoliths of granite that were ripped out of the volcanic conduit. The middle member that constitutes much of the hill above the low-angle fault is a sequence of pale purple hornblende-biotite dacite flows. An irregular pattern of flow foliations suggests that the unit experienced locally intense churning during viscous flow. Lying on top of this unit is a sequence of massive dacites and tuffs that were deposited as viscous flows and ash-flow tuffs, respectively. This upper member is volumetrically the most important unit in the eastern Newberry Mountains and constitutes most of the rugged mountainside to the east. This is the unit that McKee Products is quarrying for ballast and roadbed. Offset (by late Cenozoic strike-slip faulting) equivalents of these rocks occur in the eastern Rodman Mountains.

* *

Return to intersection of National Trails Highways and Quarry Rd. Proceed east ~3 mi along National Trails Highways to Fort Cady Rd. (east-bound onramp to I-40). Drive ~14 mi to Hector Rd. **Exit** at Hector Rd. offramp, then left under freeway, and continue along dirt road toward Hector siding (railroad tracks). Reset your odometer to zero now. After **0.5 mi,** bear right. At **1.2 mi** turn left and then right at **1.3 mi** to find crossing point of railroad tracks. After crossing tracks, turn left toward "Hector" siding sign. At **1.6 mi** mark, make sharp right turn onto secondary road, and then an immediate left turn onto the track that can be seen leading northward into the distance. If you can't find all of this, the objective is to get onto the track that can be seen leading northward into the distance. At **1.7 mi** mark continue north across the fence-line (please close the gate) to the distant western flanks of Cady Mountains. You will cross dirt track coming in from east at **2.8 mi** mark; continue on the center of the three tracks that impinge here (the eastern track originates from the powerline road to the east which can be accessed from the freeway at the next exit east from Hector Rd; in the event that the railroad crossing at Hector is inoperative you can follow the freeway to the next exit, continue under the freeway, past the power station, across the railroad tracks, and enter the then west-leading dirt track to join with the one we now are on. This is very tedious, however). At **4.1 mi,** you will encounter a wash that may obliterate the track which should continue across it to the north. Don't take the northeast-trending track from here. Continue north. At **5.1 mi,** turn northeast through the narrow canyon into the type area of the Hector Formation, and carry on (do not take the first steam bed to the right). At **5.3 mi,** keep right next to alluvium-capped scarp and follow the canyon obliquely left toward the next alluvium-capped point with light-colored Hector Formation unconformably below. Stay to the right of this point. Take the right-hand fork in stream at **5.4 mi** mark and continue for 0.5 mi to the next very narrow canyon. This is passable by vehicles. We will park here, however, as we will return from our hike down the canyon that is now on our left.

* *

STOP #3 -- GEOLOGY AT THE TYPE SECTION OF THE HECTOR FORMATION

Objectives

1. To discuss the geologic relationships of the Hector Formation at its type section.
2. To discuss the structure of the underlying upper-plate tilted fault blocks of the Daggett terrane.
3. To discuss regional Cenozoic stratigraphic relations.

As shown in Figures 7, 8, and 9, the Hector Formation (Woodburne and others, 1974) unconformably overlies a tilted pre-Hector terrane of 25 to 22 Ma andesitic to rhyodacitic flows and breccias. We will walk up the canyon that displays this contact and pass downsection into the pre-Hector Formation terrane. As we wind through this canyon, a basalt flow will be visible that postdates the pre-Hector terrane and - as we will see - is interbedded with Hector Formation sediments. This basalt is yet undated, but certainly pre-dates a tuff dated at 21.6 Ma (see Figs 7 and 8). Fossil mammals pertaining to the Black Butte Mine Fauna have been recovered from this part of the section.

We will climb up the ridge to the north, composed essentially of the pre-Hector rocks, and once standing on top of the ridge we will be able to see the (in-part) fault-bounded graben in which the sediments of the type Hector Formation are preserved. The sequence is on the order of 500 m thick and preserves a largely volcaniclastic debris-flow basal interval that dips steeply to the west. This is gradationally overlain by a finer grained, dominantly tuffaceous, progressively less tilted interval. The younger interval preserves the Logan Mine Local Fauna noted on Figure 9. Note that tuffaceous deposits also occur at the base of the formation as exposed here.

As we walk down the ridge face and then turn right up-canyon for a few meters we will traverse the pre-Hector/Hector contact and observe the basalt that interfingers with early Hector deposits. Chemical analyses have yet to be obtained from this basalt.

Now follow the canyon westward to the vehicles observing the general fining of the stratigraphic sequence both in a down-dip and up-section orientation.

* *

Return to the vehicles and to I-40. Proceed west-bound to Daggett Rd. and exit. Turn right (north) on Daggett Rd. and continue across the valley to I-15. Enter I-15 toward Barstow (west). Exit interstate at California 58 (to Bakersfield) and drive 1.0 mi and turn right on to dirt road. Drive via a maze of jeep trails 1.8 mi to base of Mitchell Range and park.

* *

STOP # 4 -- MITCHELL DETACHMENT FAULT, NORTHERN MITCHELL RANGE

Objectives

1. To observe the rocks and structures of the Waterman terrane, including the Mitchell detachment.
2. To discuss thermochronologic data from the Mitchell detachment.
3. To review the evidence presented today for early Miocene extension of the Mojave Desert.

The geology of the Mitchell Range is shown on Figure 10. The contact that we are standing on is the Mitchell detachment, a brittle-ductile, low-angle, normal-sense shear zone. Brittlely extended and rotated upper-plate fault blocks overlie the shear zone. The upper-plate consists of Lower Miocene and older sedimentary and volcanic rocks that rest unconformably on Mesozoic granitoids and older metasedimentary and metavolcanic rocks. The structure of the Mitchell detachment is virtually identical to the NMDF except that its lower plate records an additional deformational interval where ductile flow was dominant (mylonitic rocks overprinted by

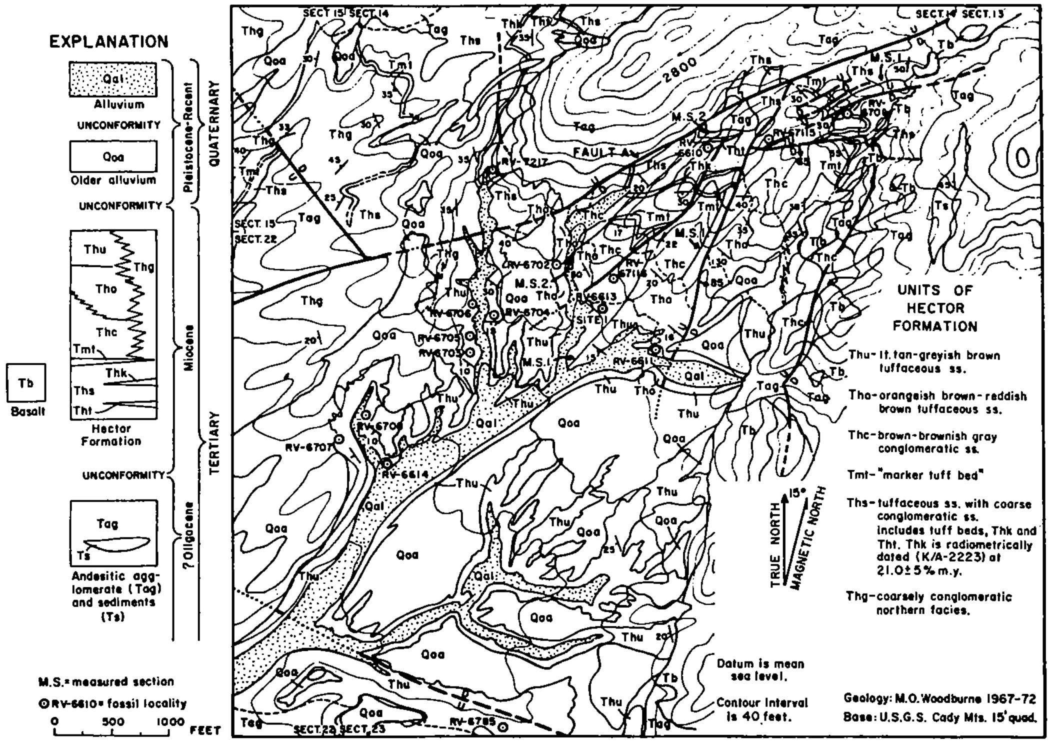


Figure 7. Geologic map of a portion of the central Cady Mountains at the type section of the Hector Formation (from Woodburne and others, 1974).

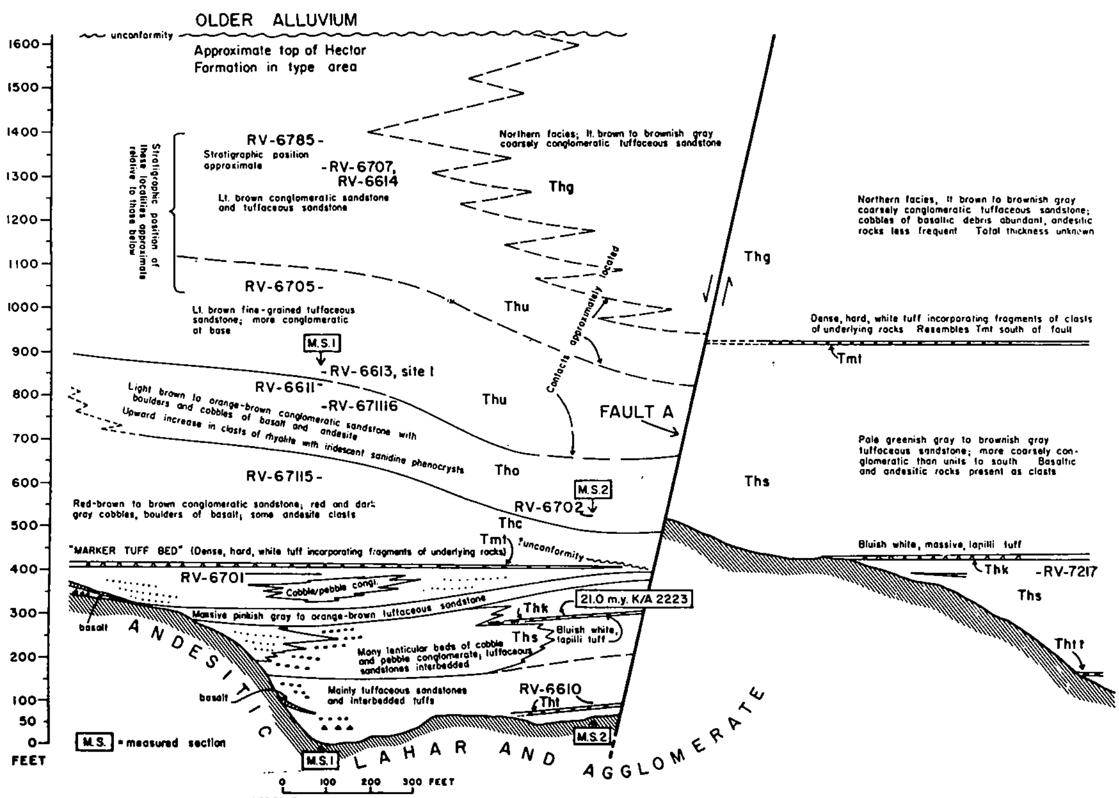


Figure 8. Stratigraphic relations at the type section of the Hector Formation (from Woodburne and others, 1974).

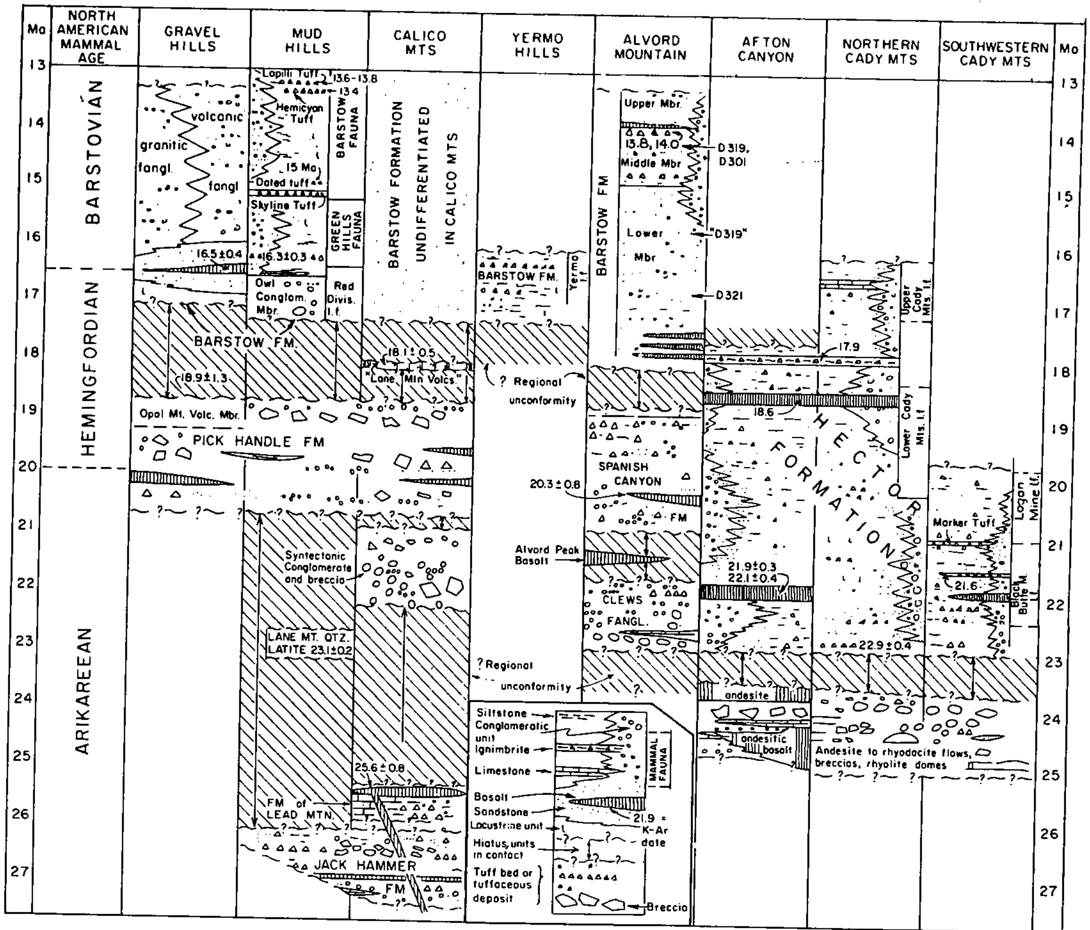


Figure 9. Regional correlation chart of Early and Medial Miocene stratified rocks of the central Mojave Desert (from Dokka and Woodburne, 1986).

brittle structures). These rocks are interpreted as forming at a deeper level of a crustal-scale, normal-sense zone of simple shear such as originally proposed by Wernicke (1981). This range and the Waterman Hills, the Hinkley Hills, and the hills near the hamlet of Lockhart constitute what is commonly referred to as a "metamorphic core complex" (cf. Davis and Coney, 1979).

The Waterman gneiss contains a wide variety of mylonitic rocks, namely mylonitic gneiss, carbonate mylonite, and quartz-mica mylonite. Many of these rocks can be classified as Type II S-C mylonites, using the nomenclature of Lister and Snoke (1984). Strain studies in the Hinkley Hills (Weiss, 1954), Waterman Hills (Dokka and Woodburne, 1986; Bartley and Glazner, 1987), and the Mitchell Range (McCabe and Dokka, in prep.) indicate that the rocks are L- and L-S tectonites. These rocks are thought to form in zones of non-coaxial laminar flow that form during conditions of decreasing pressure and temperature. Typical microstructure of type II S-C mylonites are mica "fish" produced by boudinage and microfaulting of pre-existing (white) mica grains. Dokka and cohorts (Steven Jones, John Lambert, and Riley Milner) have studied most of outcrops of the Waterman mylonitic rocks in the Mojave Desert in terms of their S-C deformational fabric relations for the purpose of ascertaining the sense of shear and "transport" direction. In nearly every case, the structures indicate that upper levels have been transported to the northeast relative to lower levels. This sense of shear is similar to the movement pattern determined for the upper-plate. Similar relations have been reported by Bartley and Glazner (1987) in the Waterman Hills. $^{40}Ar-^{39}Ar$ and fission track studies of both the Waterman Hills and the Mitchell Range indicate that major tectonic denudation associated with detachment faulting occurred near 20 Ma (Dokka and Baksi, in prep.)

* *

Return to California 58 headed west toward the town of Mojave. Proceed to Kramer Junction (intersection of California 58 and U.S. 395; ~26 mi from STOP #4). At Kramer Junction, turn right (north) on U.S. 395 and drive approximately 6.5 mi to intersection with graded road heading east. Turn onto this road and continue 3.1 mi to the junction with a major dry (hopefully!) gulch; before entering, prepare your vehicle for 4-wheel operation. Follow the well-worn trail ~4 mi to the top of the Harper Lake detachment.

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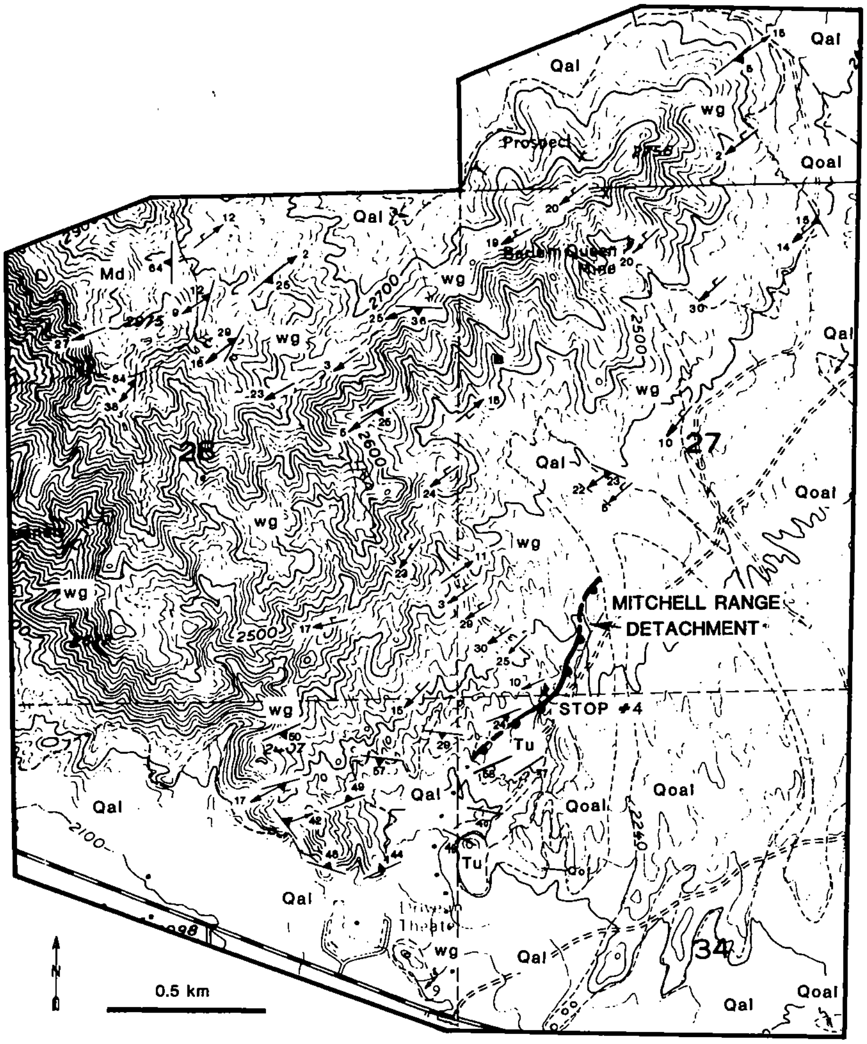

Figure 10. Geologic map of a portion of the northern Mitchell Range. wg=Waterman Gneiss (lower plate of Mitchell Detachment [MD]); Tu=Lower Miocene tuff, sandstone, and conglomerate [upper plate]; Qoal=older alluvium; Qal=alluvium.

STOP # 5 -- HARPER LAKE DETACHMENT FAULT, SMALL HILLS WEST OF LOCKHART

Objectives

1. To observe the structure and petrology of the Harper Lake detachment.
2. To observe the effects of cataclasis at the base of rotated upper-plate fault blocks.
3. To discuss the relationship of outcrop relations of the Harper Lake detachment with reflections seen in seismic data.

Discovery of the structural relations at this locality have greatly influenced thinking on the regional tectonics of the western Mojave Desert. Dokka (1986; in prep.) has recently proposed that the structures seen in outcrop in this district are the updip equivalents of reflections observed in seismic sections to the west (Cheadle and others, 1986ab; Serpa and Dokka, 1988). A geologic map of this region is shown on Figure 11.

Our route from Kramer Junction to this point has passed through a complete section of the upper-plate of the Waterman terrane. The detachment in this region is very shallowly dipping (~5°-10° southwest). The upper-plate consists of tilted lower Miocene volcanic and sedimentary strata that sit unconformably on Cretaceous and/ or Jurassic granitic rocks and roof pendants of older rocks. Upper-plate strata are exposed at the surface in the Kramer Hills and are known in the subsurface near Kramer Junction (Benda and others, 1960; Dibblee, 1967). The great borate deposits at Boron are post-tectonic sediments within the Mojave Rift. A few mi before we turned off U.S. 395, upper-plate granitic rocks were encountered. Beginning a short distance from the intersection of U.S. 395 and the graded road to this stop, we drove through the sheared lower portion of the upper-plate.

The mylonitic rocks at this stop are equivalent to the Waterman complex seen at the last stop. Sense of shear determined at outcrop and microscopic scale shows that upper levels moved northeast relative to lower levels.

* *

Our return via the hamlet of Lockhart (group of farm houses) is catch-as-catch-can. Sufficient daylight is needed in order to find our way through the maze of jeep trails and dry gulches. If it is near nightfall, we will retrace our steps to U.S. 395 and to Barstow.

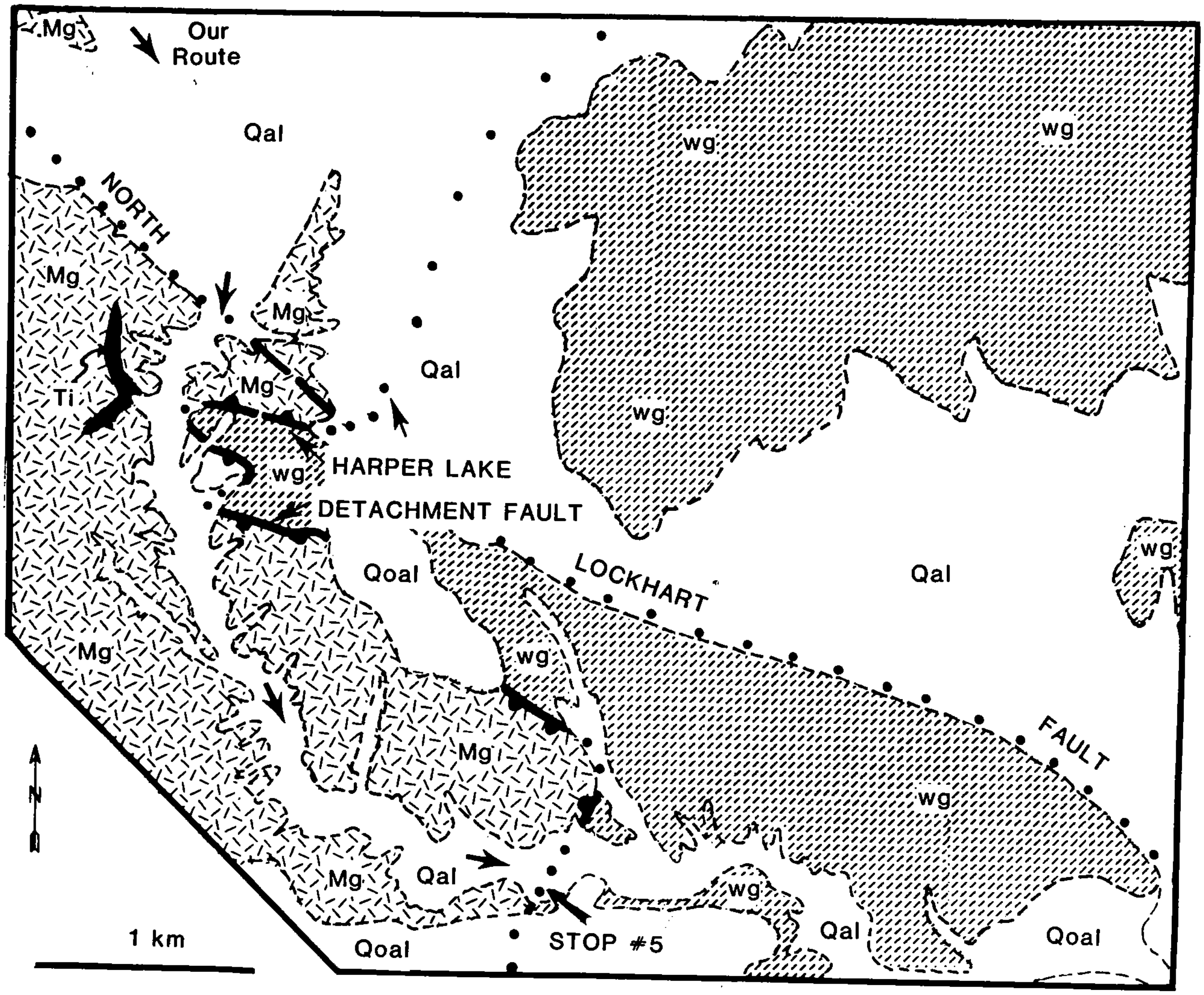

Figure 11. Geologic map of the hills west of Harper Lake. wg=Waterman Gneiss (lower plate of Harper Lake Detachment [HLD]); Mg=Mesozoic granitoids (upper plate; cataclasized near detachment); Qoal=older alluvium; Qal=alluvium.

Otherwise return to the vans and proceed east following the drainage to the first north-south graded road you encounter. Turn right and make your way back to Lockhart. Continue along paved road to California 58. Turn left and head for Barstow for dinner and motel.

END OF DAY ONE.

* *

DAY 2

Today, we will concentrate on the sedimentology, stratigraphy, magnetic properties, and paleontology of sedimentary rocks that were deposited within and at the perimeter of the Mojave Rift. Our route is shown on Figure 12. Our journey will begin at the intersection of I-15 and Main Street in Barstow. Reset your odometer as you enter the interstate (eastbound). Proceed ~46 mi to Basin Road Exit. Turn right onto Basin Rd. and continue to **0.2 mi** mark where you will turn right onto dirt track. Follow it southward **2.3 mi** to where the road forks. Take the left fork and continue **2.8 mi** to another fork. Take the left fork. At **3.9 mi** mark you will encounter the main channel of Mojave River; note wooden post. If variable, this track will lead to railroad crossing. Otherwise, make a short detour right and drive up the berm for about 0.9 mi to crossing at railroad tracks. At **5.0 mi,** cross tracks and turn left, closely adjacent to railroad tracks. At **5.5 mi** cross siding tracks, follow along closely adjacent to tracks, then take farthest right dirt track across flats. At **6.3 mi** mark take left of two tracks. Now enter main drainage of Northern Cady Mountains district at **7.5 mi mark**. Dark-colored hill in near distance to oblique left contains mylonitic clasts of unknown derivation. At **8.5 mi** mark, note fault-line scarp along west side of valley. No map shows this as a fault. Structures seen farther south in the Northern Cady Mountains project to this scarp. Take right fork in track at **9.0 mi** mark, or veer in that direction if is not found. At **9.5 mi,** take left fork or veer in that

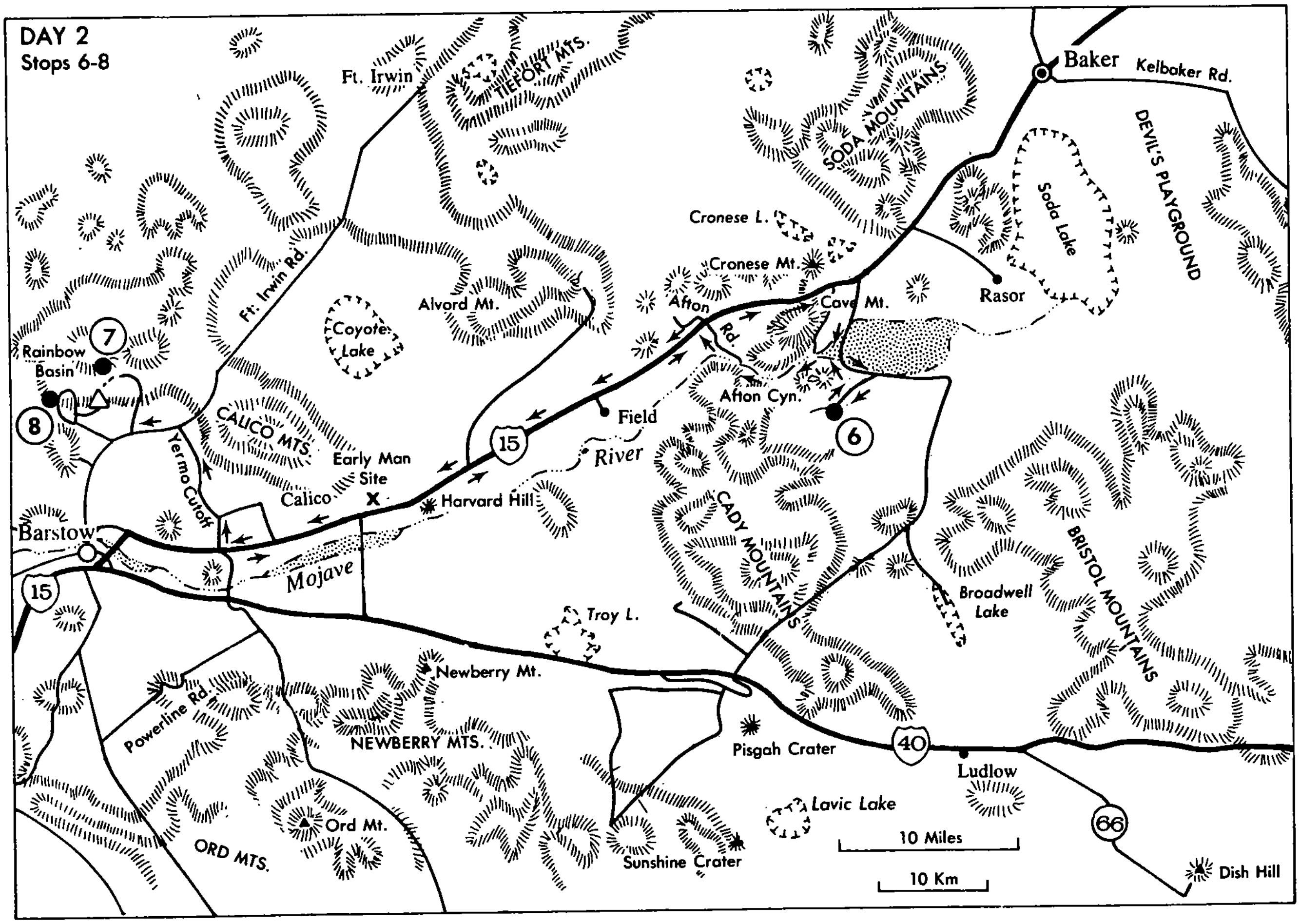

Figure 12. Route for Day 2.

direction. Veer sharply left of isolated berm in center of drainage at **9.7 mi** mark. Entrance to proper drainage is about 200 yds downstream of the berm. You are trying to get to the obvious basaltic outcrop to the oblique left. STOP #6 is located at **10.1 mi** mark.

* *

STOP #6 -- GEOLOGY OF THE NORTHERN CADY MOUNTAINS DISTRICT

Objective

1. To discuss the geology of the northern Cady Mountains District.

Based on mapping by S. Miller (1980), Moseley (1978), and Williamson (1980) (Fig. 13), the sediments seen here are unconformably underlain by a sequence of calk-alkalic rocks that ranges in composition from basaltic andesite to rhyodacite. These rocks are extensively exposed in the eastern Cady Mountains (Williamson, 1980), but also can be found in the Afton Canyon District to the north (Moseley, 1978). As in the southwestern Cady Mountains (STOP #3), these rocks are separated by an unconformity from the overlying volcaniclastic, basaltic, and tuffaceous Hector Formation.

In contrast to the stratigraphically lowest Hector sediments of the southwestern Cady Mountains, the deposits we are looking at are relatively undeformed. They occur in a gentle, E-W trending synform with a shallow eastern plunge, and are composed of finer grained, more distinctly and finely bedded, strata. Clasts found in these sediments in more southeastern (and stratigraphically lower) locations appear to have been derived from pre-Hector vocanic rocks, suggesting that the core of the Cady Mountains was emergent (Woodburne and others, 1974; Williamson, 1980; Dokka, 1986a; Mathis, 1986). Minor amounts of granitic and metasedimentary clasts also occur in these rocks, as well as in stratigraphically higher parts of the Hector Formation. These relations, along with paleocurrent data, suggest that these deposits were derived from the core of the Cady Mountains. Dokka (1986a) and Mathis and Dokka (1986) have proposed that the central Cady Mountains were arched in the early Miocene. Some of these granitoid and metasedimentary clasts may have been reworked; Williamson (1980) and Dokka (1986a) have described local patches of arkosic sediment stratigraphically between the pre-Hector volcanic terrane and Cady Mountain basement rock, analogous to descriptively similar sediments in the Alvord

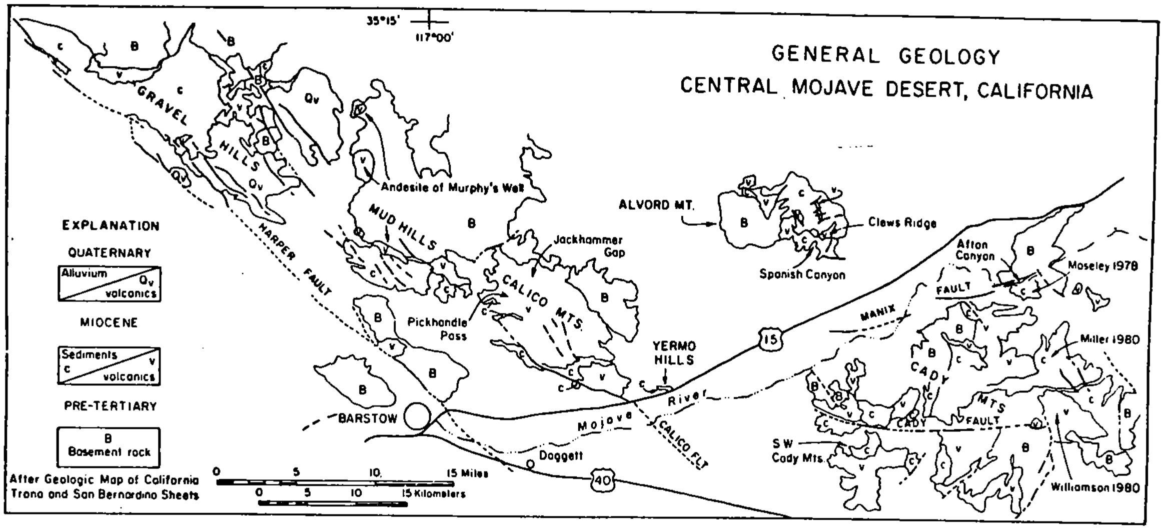

Figure 13. Generalized geologic map of the central Mojave Desert (from Woodburne and others, 1974).

Mountains (Byers, 1960). Clasts of muscovite schist, and minor amounts of granitoid and metavolcanic rocks and marble in the Afton Canyon District (Moseley, 1978) suggest, on the other hand, that a source of that composition was near-by to the north. If both interpretations are correct, the Northern Cady Mountains and Afton Canyon Hector Formation sequences formed in an essentially spatially continuous depositional basin with elevated, but arguably active northern and southern rims.

It seems almost inescapable that the laharic and volcanigenic sequence of the Eastern Cady Mountains (Williamson, 1980) is part of the pre-Hector terrane (dated at about 24 Ma; Dokka, 1986a). This terrane is overlain with strong hiatus by the uppermost part of the Hector Formation described by S. Miller (1980), dated paleontologically and radioisotopically at about 17-15 Ma. The district described by Williamson (1980) is only removed by a short distance (<1 mi) from that described by S. Miller (1980). Thus, unless modified by a somewhat complex pattern of uplift and crustal shortening, the N-S separation of these two areas indicates that the basin margin, which lay to the south of the major Hector Formation depocenter, was narrowly proscribed. Inasmuch as the Hector Formation sediments described by S. Miller (1980) can be said to reflect derivation from a largely volcanic source terrane, the presence of limited amounts of plutonic and metasedimentary clasts in these deposits may be best resolved by their having been part of a previously deposited erosional sequence that pre-dated the extrusions and eruption of the pre-Hector volcanic terrane. In any case, a certain amount of uplift of the "Central Cady Mountains" is implied. At the same time, both S. Miller (1980) and Williamson (1980) show that another phase of major unroofing of the "Central Cady Mountains" followed the deposition of the Hector Formation. These younger sediments, with major amounts of plutonic and metamorphic clasts, are undated, but most likely are of latest Tertiary/early Quaternary age.

The basalt seen at this outcrop has been dated at 18.6 Ma and caps the lower part of the Hector Formation in this area. This basalt has been correlated to a unit found in the Afton Canyon sequence, as well (e.g., Fig. 9). Tuffs in the lower part of the Hector Formation about 1 mi west of here have yielded K-Ar dates of about 23 Ma and are not appreciably tilted (20° SE). Dokka considers these volcanic rocks to lie just north of the northern boundary of the Daggett terrane (Baxter Wash fault; Fig. 2; Dokka and Woodburne, 1986). Delineation of this fault is based on the abrupt termination of structures (moderately tilted upper-plate fault blocks of the Daggett terrane) along its proposed trace. We propose that the Hector formation represents syntectonic and in post-tectonic in-filling of extensional basins.

As we drive you up the canyon, we will encounter the middle part of the northern Cady Mountains sequence of the Hector Formation: largely thin-bedded, fine-grained white to light green-colored tuffaceous sediments of plausibly lacustrine origin. These sediments are contemporaneous in part with the predominantly tuffaceous succession exposed in the upper part of the type Hector Formation we saw at STOP #3. Again, somewhat coarser grained facies in the Afton Canyon District appear to be coeval with the rocks we are now seeing, and to reflect a near-by northern boundary to the Hector depositional basin.

We now will drive 1 mi up the canyon to stop at outcroppings of a pink to bluish gray ignimibrite that caps the middle part of the Hector Formation, both in this area and in the Afton Canyon District. Note the eutaxitic textures; the unit is not extensively welded, however, as demonstrated by the occasional large pumice fragments.

* *

We now will retrace our steps and travel westward along Interstate 15 back to Barstow. Exit at turn off for California 58 and continue to Camp Irwin Rd. Turn right and continue 4.3 mi to Barstow-Randsburg Rd. (graded road). Turn left and proceed 5.4 mi to crest of Mud Hills. Turn left at improved dirt road and continue 1.7 mi to west. Turn left 0.1 mi before reaching tracking station entrance and follow Owl Canyon (downhill) to overlook. Park vehicles and proceed to basement-Jackhammer Formation contact. Note: We will walk down the canyon to Owl Canyon Campground where the vehicles will meet us. If you come back later, you are advised to begin and end this leg of the trip at Owl Canyon Campground. Beware of rattlesnakes !!

* *

STOP #7 -- BARSTOW BASIN SEQUENCE AT OWL CANYON, MUD HILLS

Objectives

1. To observe excellent exposures of the Jackhammer Formation (Oligocene or older), Pickhandle Formation (Lower Miocene), and Barstow Formation (Middle Miocene).
2. To discuss the petrology, magnetostratigraphy, and biostratigraphy of rocks of the Barstow Basin.

The Mud Hills have been studied by Dibblee (1967, 1968), Woodburne and others (1982) and McFaddon and others (1988). The Jackhammer Formation consists of probable low gradient fluvial deposits that were deposited at some time in the early Cenozoic (Fig. 9). The Barstow Formation (post-tectonic with respect to Mojave Rift extension) and the underlying Pickhandle Formation (syntectonic) were deposited in the half-graben of the Fossil Bed Road fault, a large NE-dipping normal fault that lies along the northeast side of the Mitchell Range (seen to the southeast). This fault displays a minimum stratigraphic throw of 1 km.

* *

Return to vans and proceed 1.7 mi to Rainbow Basin Rd. Turn right and enter Rainbow Basin.

* *

STOP #8 -- RAINBOW BASIN, MUD HILLS

Objectives

1. To observe folds and faults associated with post-middle Miocene right-slip faulting.
2. To discuss results and implications of paleomagnetic studies of the Barstow Formation.

The structure of the Rainbow Basin area is the result of transpression developed within the Calico fault, a northwest-striking, right-slip fault (Dibblee, 1967a).

* *

Follow well-graded road back to the highway and return to Barstow for dinner and motel.

END OF DAY 2

* *

DAY 3

Please refer to Figure 14 for our route today. Begin Day 3 at intersection of Main Street and Interstate 40. Proceed approximately 50 mi to Kel-Baker Rd. offramp. Exit and park.

STOP #9 -- GRANITE MOUNTAINS FAULT OVERVIEW

Objective

1. To discuss the nature of the boundary between the Mojave Desert block and the Eastern Mojave Desert.

* *

Return to I-40 heading eastbound. Drive approximately 20 mi to the Essex offramp. Proceed north on the paved road to Mitchell Caverns State Park (16 mi).

* *

STOP #10 -- GEOLOGIC OVERVIEW OF THE PROVIDENCE - WOODS MOUNTAINS AREA

Objectives

1. To discuss the geologic setting of the Providence Mountains-Woods Mountains area, and to compare and contrast the Tertiary volcanic and tectonic evolution of this area with the Mojave Desert block.
2. To observe a deeply eroded early Miocene paleotopography that was buried by the Peach Springs and Wild Horse Mesa ash-flow tuffs.

The principal theme today is to illustrate features of a part of the Eastern Mojave Desert that is characterized by weak Miocene upper crustal extension, and by a style of volcanism that is unique in the Mojave Desert but that occurs in some other weakly extended continental terrains. We are located roughly equidistant between the Mojave Rift and the extended terranes of the Colorado River (cf., Anderson, 1971; Davis and others, 1980; Spencer, 1985). Exposures in this area are dominantly of early Proterozoic gneiss and granitic rocks, Paleozoic sedimentary rocks, Jurassic and Cretaceous granitic rocks, and middle Miocene volcanic rocks (Hewett, 1956; Hazzard, 1954; Goldfarb and others, in press). Pre-Tertiary rocks are exposed in deeply incised, north to northwest-trending ranges that are separated by wide alluviated valleys. These rocks were deeply eroded, and formed a topographically rugged terrain over which the Miocene volcanic rocks were deposited. Beginning at about 16.4 Ma and continuing until 15.8 Ma, volcanism was dominated by the extrusion of trachyte and mildly peralkaline rhyolite from a volcanic center located in the Woods Mountains area (McCurry, 1985; McCurry, in prep.). Erosional remnants of a rhyolite ash-flow tuff that was derived from this center extend from the Blind Hills on the south, to the New York Mountains on the north, and from the northern Providence Mountains on the west to Hackberry Mountain on the east.

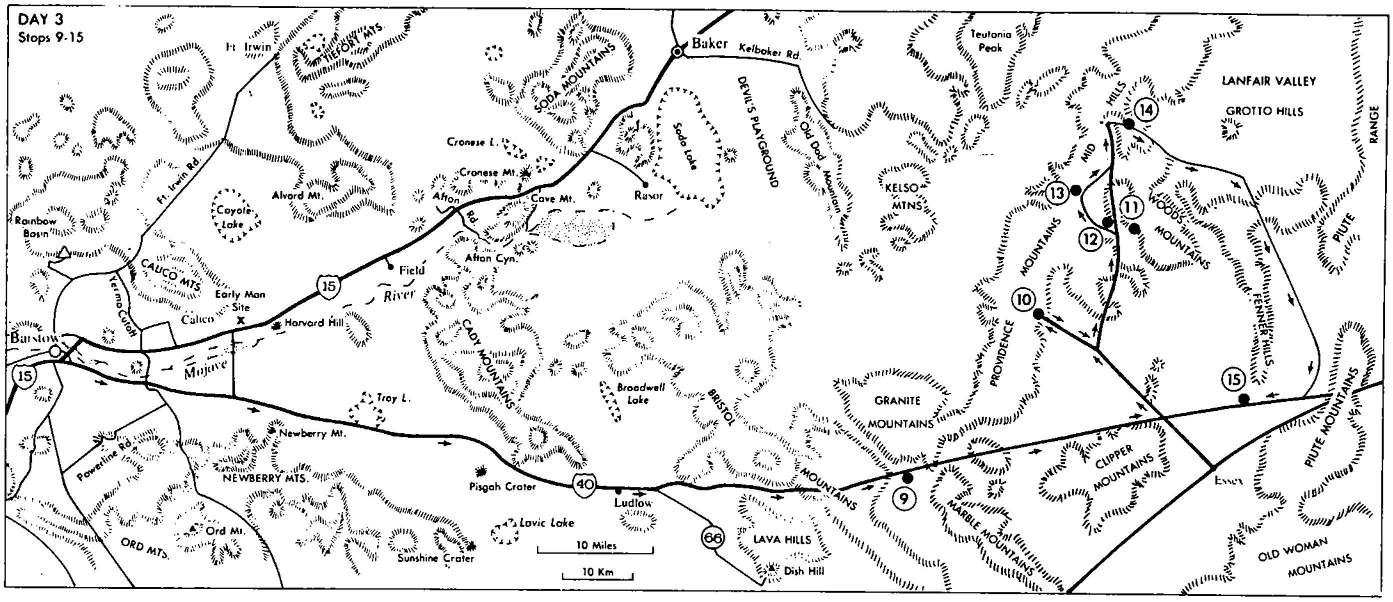

Figure 14. Route for Day 3.

These rocks are overlain in some areas by small amounts of middle Miocene andesite, basalt, and alkali basalt flows. Middle Miocene rocks are weakly faulted in a pattern suggesting minor NW-SE extension.

We are standing on early Proterozoic rocks on the east flank of the northern Providence Mountains (Fig. 14). The northern Providence Mountains are an east tilted fault block of Paleozoic and early Mesozoic clastic and carbonate continental shelf sedimentary rocks (Hazzard, 1954; Goldfarb and others, in press). Four sets of normal faults are recognized (Goldfarb and others, in press; Hazzard, 1954). The absolute ages of these faults are poorly constrained. Following Goldfarb and others (in press), the oldest normal faults strike north-northwest, and dip steeply east. East striking faults drop strata down to the north. A more continuous set of N-NE striking faults vary from steeply east to vertical to steeply west dipping, and cuts the east-striking faults. Low angle, west-dipping faults are the last phase of normal faults in the Providence Mountains. Prominent reddish rocks that make up the high peaks to the east of Mitchell Caverns State Park are part of a large biotite rhyolite plug. The plug, named the Fountain Peak Rhyolite by Hazzard (1954) was intruded during or after the first three sets of faults. Although it may be Tertiary, Goldfarb and others (in press) note similarities between dikes extending from the intrusion, and Jurassic dikes in the southern Providence Mountains, and suggest that it is Jurassic. The eastern structural border of the northern Providence Mountains is bounded by the north-striking East Providence Fault. This major, east dipping reverse fault juxtaposes Paleozoic rocks against early Proterozoic rocks, and has 2.3 km of displacement (Hazzard, 1954). The fault bifurcates to the north. The easternmost segment is near vertical, cuts middle Miocene volcanic rocks, downfaulting rocks to the east by 100 to 150 m. Similar volcanic rocks form scattered exposures just north of Mitchell Caverns State Park suggesting that part of the East Providence Fault was reactivated in the opposite sense of the earlier reverse faulting, during the Miocene.

Prominent mesas to the northeast of the Mitchell Caverns State Park are of nearly flat-lying Wild Horse Mesa Tuff, a metaluminous to peralkaline ash-flow tuff that was derived from vents located in the western Woods Mountains. The 15.8 Ma tuff fills prominent paleovalleys that were eroded into Jurassic and early Proterozoic rocks. The paleovalleys have a relief of at least 160 m (McCurry, 1985) and can be seen from here, where the Colten Hills merge to the north into Wild Horse Mesa.

* *

Proceed east on the Mitchell Caverns road, back towards Interstate 40, for 6.1 mi (Note the Bureau of Land Management sign for Mid Hills and Hole-in-the-Wall Campgrounds). Turn north on Black Canyon Road; proceed north for 9.2 mi. Look for an unimproved dirt road and turn right (east). There are two similar looking dirt roads close together here (as of October, 1987). The first is at 8.8 mi and only proceeds east from Black Canyon Road, the correct road at 9.2 mi proceeds both east and west off of Black Canyon Road. You will know if you've gone too far because the Mid Hills Campground is only another 0.7 mi further north on Black Canyon Road.

Reset mileage to zero. Proceed east on the unimproved dirt road (normally, this road is easy to traverse with a 2-wheel drive vehicle). The road forks at 0.8 mi; take the left (northerly) fork. Continue along the road to a gate at 1.1 mi. The road forks on the east side of the gate; take the right (easterly) fork. Continue along the road towards some basalt cliffs, normally the road is washed out at about mi 1.95. Find a place to park.

* *

STOP #11 - THE WOODS MOUNTAINS VOLCANIC CENTER

Objectives

1. To summarize the evolution of a volcanic center that is petrologically and structurally unusual in the eastern Mojave Desert.
2. To observe the proximal facies of a middle Miocene peralkaline ash-flow sheet, caldera structures, and intracaldera lava flows.
3. To discuss the implications of peralkaline volcanism for the magmatic-tectonic evolution of the eastern Mojave Desert.

The Woods Mountains Volcanic Center is a middle Miocene silicic caldera complex. It consists of a trachyte-trachydacite-rhyolite-peralkaline rhyolite association of lava flows, domes, plugs, pyroclastic rocks, and epiclastic breccia. Volcanism began at about 16.4 Ma, near the end of a local flare-up of felsic to intermediate magmatism and associated crustal extension. Numerous metaluminous high-K trachyte, trachydacite, and rhyolite lava flows, domes, and pyroclastic deposits accumulated from vents scattered over an area of 200 km^2 forming a broad volcanic field with an initial volume of about 10 km^3 (Fig. 15a). At 15.8 Ma about 80 km^3 of metaluminous to mildly peralkaline high-K rhyolite ash flows were extruded from vents in the western part of the field in three closely spaced pulses resulting in the formation of a trap-door caldera 10 km in diameter (Fig. 15b). The ash flows formed the Wild Horse Mesa Tuff, a compositionally zoned ash-flow sheet that originally covered an area of about 600 km^2 to a maximum thickness of at least 320 meters. High-K trachyte pumice lapilli, some of which are intimately banded with rhyolite, were extruded late in the later two of the eruptions. Intracaldera volcanism from widely distributed vents rapidly filled the caldera with about 10 km^3 of high-K, mildly peralkaline, high-silica rhyolite lava flows and pyroclastic deposits. These are interlayered with breccia derived from the caldera scarp (Fig. 15c). They are intruded by numerous compositionally similar plugs, some of which structurally uplifted and fractured the center of the caldera. After a hiatus of 5 to 6 m.y. several mafic lava flows were extruded from dikes located near the western margin of the caldera (Fig. 15d). The oldest, a sparsely porphyritic olivine bearing andesite, has a K-Ar whole rock date of 10±0.6 Ma. It is unconformably overlain by basalt and alkali basalt flows.

The Woods Mountains Volcanic Center is one of the most distinctive centers of Miocene magmatism in the Mojave Desert area. It is distinguished in two principal ways. First, it is apparently the only center in the region in which a large volume of peralkaline high-silica rhyolite magma was extruded. Secondly, it is distinguished by an unusually low intensity of middle to late Miocene faulting. This is despite its location about midway between two highly extended regions to the west and east. Is there a genetic connection between the two most distinctive features of the center? One possible explanation for at least some of the features has been suggested by D. Miller (personal communication, 1984) in reference to the apparent paucity of calderas in the region. Intense detachment faulting could be expected to inhibit the formation of upper crustal magma chambers by highly fracturing the upper crust. If highly differentiated, peralkaline rhyolite magmas require significant residence times in the upper crust in which to form then these types of magmas, as well as genetically related calderas and large-volume ash-flow tuffs would be favored in areas of less extension. Mahood (1984) points out that peralkaline volcanic centers are conspicuously absent from areas of rapid mid-Tertiary extension in the western United States. The idea that the Woods Mountains area underwent less extension during the middle Miocene than some surrounding areas

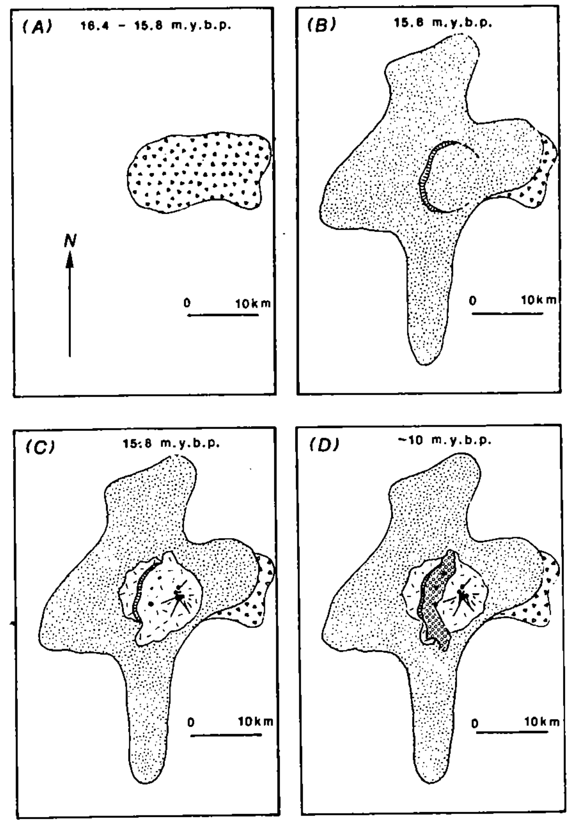

Figure 15. Evolution of the Woods Mountains volcanic center. Triangle pattern - Hackberry Spring Volcanics; dot pattern - Wild Horse Mesa Tuff; stipple pattern - lava flows, tephra, and caldera scarp breccia of the Tortoise Shell Mountain Rhyolite; solid black - rhyolite plugs of the Tortoise Shell Mountain Rhyolite; small circle pattern - interbedded andesite, alkali basalt and basalt lava flows.

is consistent with regional bouguer gravity data (K. Mickus, unpublished data, 1987) and seismic data (Fuis, 1980) that suggest that this area is underlain by thicker crust than in surrounding areas. Additionally, the absence of an exposed detachment fault in the area, near horizontal attitudes of the rocks, and the paucity of high angle faults that cut the Miocene rocks are also suggestive of weak extension. The unique aspects of the center may therefore be understood in terms of the unique tectonic evolution of the area.

We are located on the western margin of the Woods Mountains caldera (Fig. 16). At this location the caldera is characterized by a wide zone of high angle faults. Most of the faults are east-side-up. The next descriptions refer to locations on Figure 16.

Location 1: The numerous petroglyphs are on a very sparsely porphyritic olivine-bearing andesite that has yielded a K/Ar whole-rock date of 10.0±0.6 Ma. The basalt was extruded from a system of north trending dikes that are very well exposed several kilometers to the north (McCurry, 1985). The flow is overlain by several meters of weakly indurated epiclastic sedimentary rocks. Both the andesite and epiclastic sediments were eroded and then overlain by a distinctive, porphyritic alkali basalt. The alkali basalt contains large phenocrysts of augite (≤1 cm across), partially iddingsitized olivine (≤5 mm), and sparse, rounded plagioclase (≤1 cm). Some anastomosing dikes that probably served as source vents for the flow occur near location 2.

Location 2: Contact between the upper member of the Wild Horse Mesa Tuff, and a comagmatic lava flow. Note the prominent large brown pumices of trachyte that occur at and near the top of the peralkaline, high-silica rhyolite ash-flow tuff. Some of the pumices consist of interbanded rhyolite-trachyte.

Location 3: A coarse co-ignimbrite lag-fall deposit is exposed at the base of this flow unit located at the top of the middle member of the Wild Horse Mesa Tuff. Lithics include a variety of accessory volcanic fragments as well as fragments of granitic rocks that resemble the Mid-Hills adamellite and Proterozoic metamorphic rocks exposed in surrounding areas. The largest fragments are > 5 m across. Overlying parts of the ash-flow unit contain lithic segregation features that were formed by strong degassing of the deposit.

Location 4: An overview of the western margin of the Woods Mountains caldera. Viewed to the north, outflow units of the Wild Horse Mesa Tuff and overlying rhyolite lava flows are juxtaposed against intracaldera epiclastic breccia deposits, and lava flows.

* *

Proceed back to Black Canyon Road by retracing the route taken in getting to this locality. Turn right (north) onto Black Canyon Road and proceed 0.5 mi up the road to the entrance to Hole-in-the-Wall Campground; enter the campground and find a convenient parking place. Picnic tables, and facilities are available at the campground.

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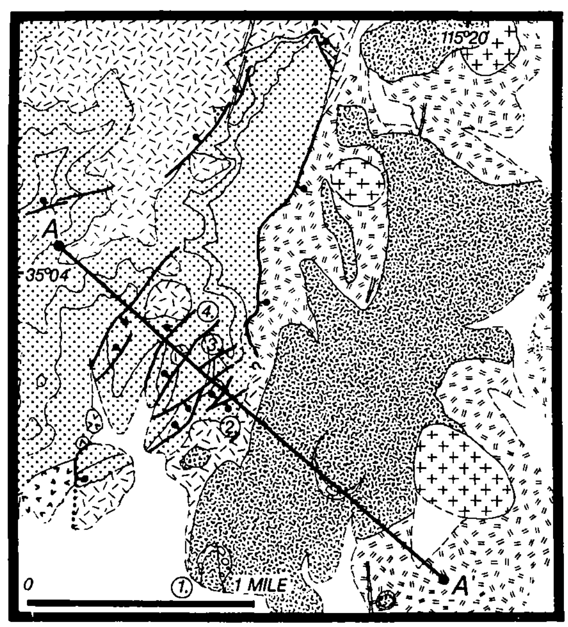

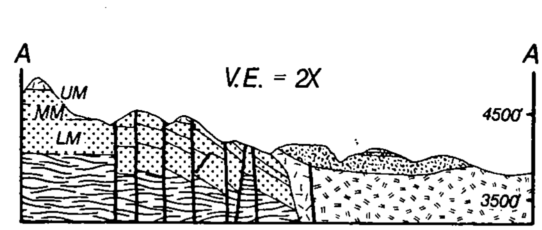

Figure 16. Simplified geologic map of the western Woods Mountains (after McCurry, 1985). In stratigraphic order the units are: undifferentiated pre-Tertiary rocks - heavy line pattern; Hackberry Spring Volcanics - v-pattern (16.4 - 15.8 Ma); Wild Horse Mesa Tuff (divided into lower (LM), middle (MM), and upper (UM) members) - dot pattern (15.8 Ma); early phase of the Tortoise Shell Mountain Rhyolite consisting of interbedded rhyolite lava flows and tephra - stippled pattern; later phase of the Tortoise Shell Mountain Rhyolite consisting of interbedded rhyolite lava flows, tephra, and caldera scarp breccia - double dash pattern; last phase of the Tortoise Shell Mountain Rhyolite consisting of rhyolite plugs - plus pattern (15.8 Ma); interlayered andesite, basalt, and alkali basalt flows - mottled pattern (~10 Ma), and epiclastic sediments - gravel symbol; alluvium - no symbol. Circled numbers refer to stops described in the text.

STOP #12 -- HOLE-IN-THE-WALL CAMPGROUND

Objectives

1. To discuss the stratigraphy of the Wild Horse Mesa Tuff.
2. To observe the lower member of the Wild Horse Mesa Tuff.

The Wild Horse Mesa Tuff is a comagmatic sequence of dominantly rhyolitic ash-flow tuffs that form a large group of mesas over an area of 600 km^2. Stratigraphic characteristics of the tuff are illustrated in Figure 17. Exposures of the horizontal to gently SE - dipping deposits vary from 20 to 320 m thick, and they have a distinctive layer-cake appearance that results from welding and devitrification zonation. The tuff is divided into lower, middle and upper members on the basis of stratigraphically coincident discontinuities in devitrification and welding zonations, phenocryst assemblage and abundance, and whole-rock chemical composition (McCurry, 1985; McCurry, in prep.). Each member is a cooling unit that consists of multiple flow units (cf., Fisher and Schmincke, 1985), many of which are well characterized by depositional bedforms of the "standard ignimbrite unit" (cf., Sparks and others, 1973). Contacts between units are primarily distinguished by moderately sorted tuff at the base a few centimeters thick (layer 2a), that grades upward into a nonsorted zone from a few centimeters to a few meters thick that is enriched by about a factor of ten or more in lithic fragments (L - zones). Ash cloud deposits (layer 3) occur at the tops, and ground surge deposits (layer 1) occur at the base of some of the flow units. However, layers of air-fall tephra are absent except between the members. Each member is interpreted to have been emplaced in what was essentially a single major eruption.

Exposures at Hole-in-the-Wall Campground are of the lower member of the Wild Horse Mesa Tuff (Fig. 17). The deposits dip approximately 3° to the southeast. Anastomosing zones of buff colored vapor phase alteration and devitrification cut across the weakly welded to nonwelded, glassy, medium gray ash-flow tuff. Near horizontal lensoid lithic fragment segregations occur in some parts of the tuff. Weak, laterally discontinuous zones of stratification can also be found in some areas. The spectacular cliffs, and cavernous weathering patterns at this locality are apparently a result of differential weathering of altered and nonaltered parts of the tuff, and weathering along joints, and around lithic fragments.

Take a break during lunch and wander down the Hole-in-the-Wall. Follow the campground road north to a large parking lot. You will find a concrete observation overlook; a little further to the north you can climb down a steep split in the rocks along a series of metal rings. Numerous depositional and vapor-phase alteration features of the lower member of the Wild Horse Canyon Tuff are beautifully exposed.

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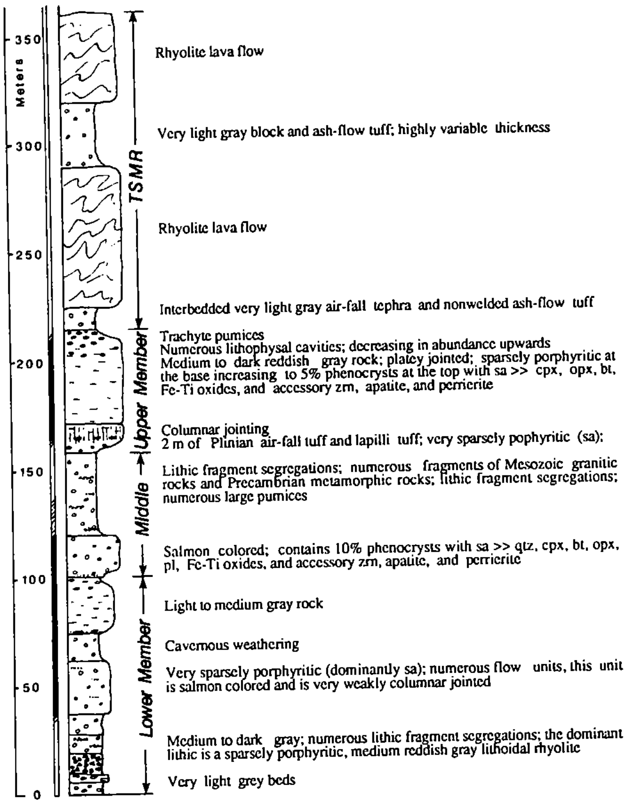

Figure 17. Simplified stratigraphic section of the Wild Horse Mesa Tuff based on a measured stratigraphic section in the northwestern corner of the Woods Mountains (after McCurry, 1985). Bar to the left of the column indicates intense devitrification - solid, partial devitrification - diagonal lines; glassy - no pattern; pattern on the column indicates dense welding - dash; moderate welding - ellipses; no welding - circles.

Turn right out of the Hole-in-the-Wall Campground and proceed south on the Black Canyon Road for 0.2 mi. Turn right (west) onto the Wild Horse Canyon Road. Proceed 4.6 mi to the first prominent outcrops of pre-Tertiary rocks along the road.

On route to STOP #13 the road passes between Wild Horse Mesa (to the south and west) and Barber (north). The mesas consist entirely of Wild Horse Mesa Tuff. The base of the tuff is not exposed, and top is partially eroded away, indicating that the mesas set a lower limit of 320 m for the original thickness of the tuff.

A little further up the road (2.7 mi from STOP #13) the road cuts through an exposure of a moderately porphyritic rhyolite dome. The dome is overlain on the south side by the Wild Horse Mesa Tuff. Crumble breccia from the dome is overlain on the north flank of the dome by lacustrine sedimentary rocks (Fig. 18).

Excellent exposures of Peach Springs Tuff occur about 0.25 mi east of the road at mi 3.6 (Fig. 18). At this locality the tuff overlies weakly consolidated arkosic alluvium. The

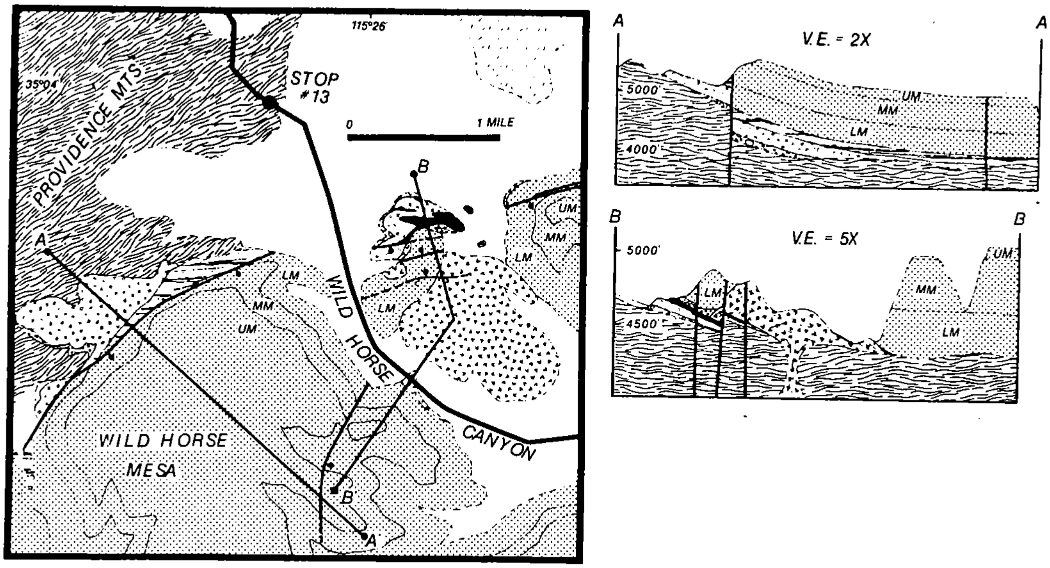

Figure 18. Simplified geologic map of the northern Wild Horse Canyon area (after McCurry, 1985). In stratigraphic order the units are: early Proterozoic metamorphic rocks (oldest) - heavy line pattern; Cretaceous Mid Hills adamellite - stippled pattern; Tertiary alluvial deposits - gravel pattern; Peach Springs Tuff (~18 Ma) - double dash pattern; a basaltic lava flow - black; an endogenous rhyolite dome and associated, flanking crumble breccia - v-pattern; lacustrine rocks - fine line pattern; Wild Horse Mesa Tuff - dot pattern; alluvium - no pattern. The Wild Horse Mesa Tuff is divided into lower (LM), middle (MM), and upper (UM) members.

alluvium is several meters thick, and is deposited on Mid Hills adamellite (cf., Beckerman and others, 1982). The tuff is in turn overlain by a sparsely porphyritic olivine-bearing basalt flow, rhyolite crumble breccia, lacustrine sedimentary rocks, and the Wild Horse Mesa Tuff. The lacustrine rocks in this area are locally strongly silicified. Some multicolored pockets (generally green) of chalcedony have been quarried. Numerous fragments of petrified wood occur within some parts of the lacustrine rocks. Note the steeply northward dipping fault below the prominent castle shaped peak east of the road. Vertical offset is about 30 m (north side down). It is one of several northward dipping normal faults that are peculiar to this area. Barber and Wild Horse mesas are bounded on the north ends by high angle faults in which the north side is up relative to the south by approximately 100 to 150 m.

Peach Springs Tuff also underlies the prominent southward dipping mesa to the west (Fig. 18). A sanidine phenocryst separate from correlative rocks located 3 km to the southwest of that area has been dated using the K-Ar method at 18.0±0.2 Ma (McCurry, 1985).

* *

STOP #13 -- PRE-TERTIARY GEOLOGY AND LATE TERTIARY FAULTING

Objectives

1. To observe Precambrian gneiss and a Mesozoic intrusive breccia.
2. To discuss late Tertiary extensional faulting.

A short stop to take a look at strongly foliated early Proterozoic biotite gneiss. The best exposures occur on the west side of the road. According to Goldfarb and others (in press) the early Proterozoic rocks exposed in the Providence Mountains area consist mostly of medium-grained biotite granite to granodiorite, in some areas with garnets to 1 cm across, and a lithologically variable gneiss that includes garnet biotite gneiss, interspersed with lenses, several meters wide, of biotite and amphibole schists. At this locality the foliation dips 35°NW, and strikes N45°E. Goldfarb and others (in press) indicate that the foliation generally strikes N to NE, and that it forms broad folds spaced approximately 3 km apart that have nearly horizontal fold axes.

Exposures on the east side of the road are of a plutonic breccia. Angular fragments of gneiss and hornblende schist up to 1 m across occur in a matrix of medium to coarse grained granitic rock, probably the Cretaceous Mid Hills adamellite of Beckerman and others (1982).

The north ends of large mesas to the south are bounded by a system of high-angle normal faults (McCurry, 1985). The sense of faulting is north-side up (from approximately 100 to 150 m), therefore there has been a strong reversal of the topography, apparently because of the high erosional resistance of the densely welded upper member of the Wild Horse Mesa Tuff. This system of faults are the only significant faults that cut the Tertiary rocks in this area, and they are briefly described below.

Tertiary volcanic and sedimentary rocks are cut by a system of laterally discontinuous, near vertical fault segments apparently splays from a reactivated segment of the East Providence Fault (Fig. 18). The system of faults trends to the north along the east flank of the Providence Mountains, and extends through Barber Canyon, it then curves to the northeast around Wild Horse Mesa, and then to the west, bounding the northern flanks of Barber and Woods Mountains. The fault zone terminates in the Woods Mountains against the boundary of the Woods Mountains caldera.

The dip-slip component on faults of this system varies from 100 to 150 m (N side up). Slip occurs along one or several subparallel fault segments in a zone that varies from a few meters to 100 meters wide. Fault gouge and breccia commonly occur along the faults in a zone from 1 to 5 m wide. The gouge and breccia are moderately to strongly silicified in many areas, and, where they are silicified they are erosionally resistant and show prominent relief. The lithology of the fragments is the same as that on either side of the fault. Grooved and polished surfaces occur in many areas. The orientation of the linear features generally indicates that they were formed by dip-slip movement along the fault.

In the northern Providence Mountains and Wild Horse Mesa areas, the rocks on the eastern and northern sides, respectively, have been rotated downward into the fault plane by 10°-15° whereas rocks south of the fault have been rotated upward by about 5°. The net effect of the faulting, folding, and rotation of the rocks in this area has been a relative, post-Wild Horse Mesa Tuff uplift of the northern Providence Mountains, with respect to the Colten Hills-Black Canyon areas, of at least 300 meters, and as much as 500 m.

Because the faults cut the 15.8 Ma Wild Horse Mesa Tuff, and because of the extensive erosion up the up-thrown blocks the age of the faulting is inferred to be late Miocene. The arcuate pattern of faulting suggests that the late Miocene faulting resulted from weak NW-SE oriented extension.

* *

Proceed north for 7.1 mi; you will pass the entrance to Mid Hills Campground after 5.1 mi (this is a great place to camp; picnic tables, water, and facilities are available). The Wild Horse Canyon road reconnects with the Black Canyon road at 7.1 mi. Turn left (north) onto the Black Canyon Road. Proceed for 2.9 mi to the intersection with Cedar Canyon Road. Turn right (east) onto the Cedar Canyon Road and proceed 4.6 mi to a small, unimproved dirt road. The road is on the left (north) side of Cedar Canyon Road, and is located just to the east of a cattle guard. Proceed north on the road towards Cedar Canyon as far as you can. The road is generally passable for 2-wheel drive vehicles for about 0.2 mi.

* *

STOP #14: PEACH SPRINGS TUFF AND MIDDLE TO LATE MIOCENE STRATIGRAPHY OF THE EASTERN MOJAVE DESERT

Objectives

1. To discuss the implications of the Peach Springs Tuff for the Miocene structural evolution of the Mojave Desert.
2. To observe the Peach Springs Tuff, lacustrine rocks, and the Wild Horse Mesa Tuff.

We are located on the south side of Pinto Mountain (Fig. 14). Approximately 250 m of Tertiary volcanic, lacustrine, and epiclastic rocks dip gently NE and overlie Mid Hills adamellite or Rock Spring monzondiorite (Beckerman and others, 1982). Stratigraphy of the deposits is illustrated in Figure 19. The lowermost Tertiary unit is the Peach Springs Tuff.

The Peach Springs Tuff is a particularly important volcanic unit because it may have been regionally extensive. Glazner and others (1986) have correlated the tuff from Peach Springs on the east, 320 km to the west to near Barstow. Lively debate is expected at this point! Although we are located near the middle of the tuff unit, there is no direct evidence for a source caldera in the Providence Mountains, Woods Mountains, or Hackberry Mountains area. The tuff is the subject of ongoing detailed petrological and volcanological studies by Buesch and Valentine (e.g., Buesch and Valentine, 1986).

At this locality the Peach Springs Tuff is about 40 m thick. Some of the "typical" features of the Peach Springs Tuff that are observed here are an abundance of sanidine phenocrysts, locally with a bluish chatoyance, and a distinctive salmon color.

The Peach Springs Tuff is conformably overlain by about 12 m of massive and laminated carbonate lacustrine sedimentary rocks. No fossils were observed in the sedimentary rocks here. However, fragments of petrified wood occur in similar lacustrine

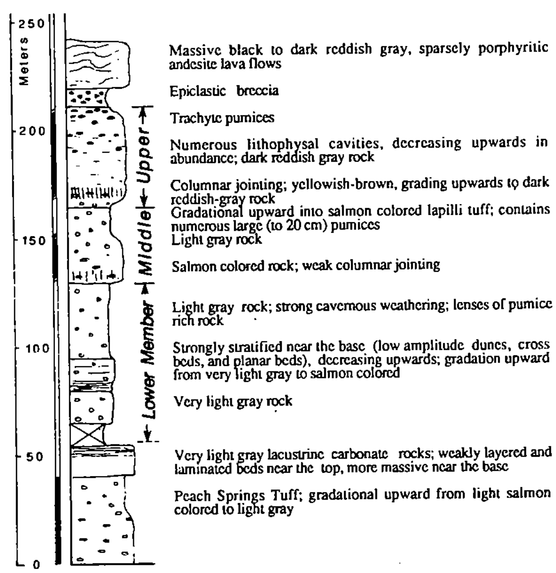

Figure 19. Simplified stratigraphic section of Pinto Mountain (after McCurry, 1985). Symbols are as indicated in Figure 17.

sedimentary rocks that overlie the Peach Springs Tuff in the northern Providence Mountains (McCurry, 1985).

Lacustrine sedimentary rocks are conformably overlain by the Wild Horse Mesa Tuff. Part of the lower member of the tuff is strongly stratified, a feature that is common for the distal facies of some ash-flow tuff sheets (Fisher and Schmincke, 1984). The upper member is conformably overlain by several meters of a breccia that consists of angular to subangular fragments of quartz monzonite, diorite, gneiss, and mylonitic granitoid rock in a fine-grained tuffaceous matrix. The largest clasts are approximately 1 m across, and the tuffaceous matrix of the deposit resembles the upper part of the underlying ash-flow unit. The breccia is probably a remnant of an alluvial fan that was derived from a source to the north. It is overlain by two andesite lava flows.

* *

STOP #15: OVERVIEW OF CRUSTAL STRUCTURE OF SOUTHEASTERN CALIFORNIA

Objectives

1. To discuss the implications of seismic reflection data for the crustal structure and tectonic evolution of southeastern California.
2. To summarize the relationships seen on the trip.

At this last stop, we will have the opportunity to see seismic reflection data from the ranges off to the southeast. These data clearly show the influence Tertiary tectonic events have had in the shaping of crust of Southern California. These relationships are shown in Figure 20.

END OF DAY THREE.

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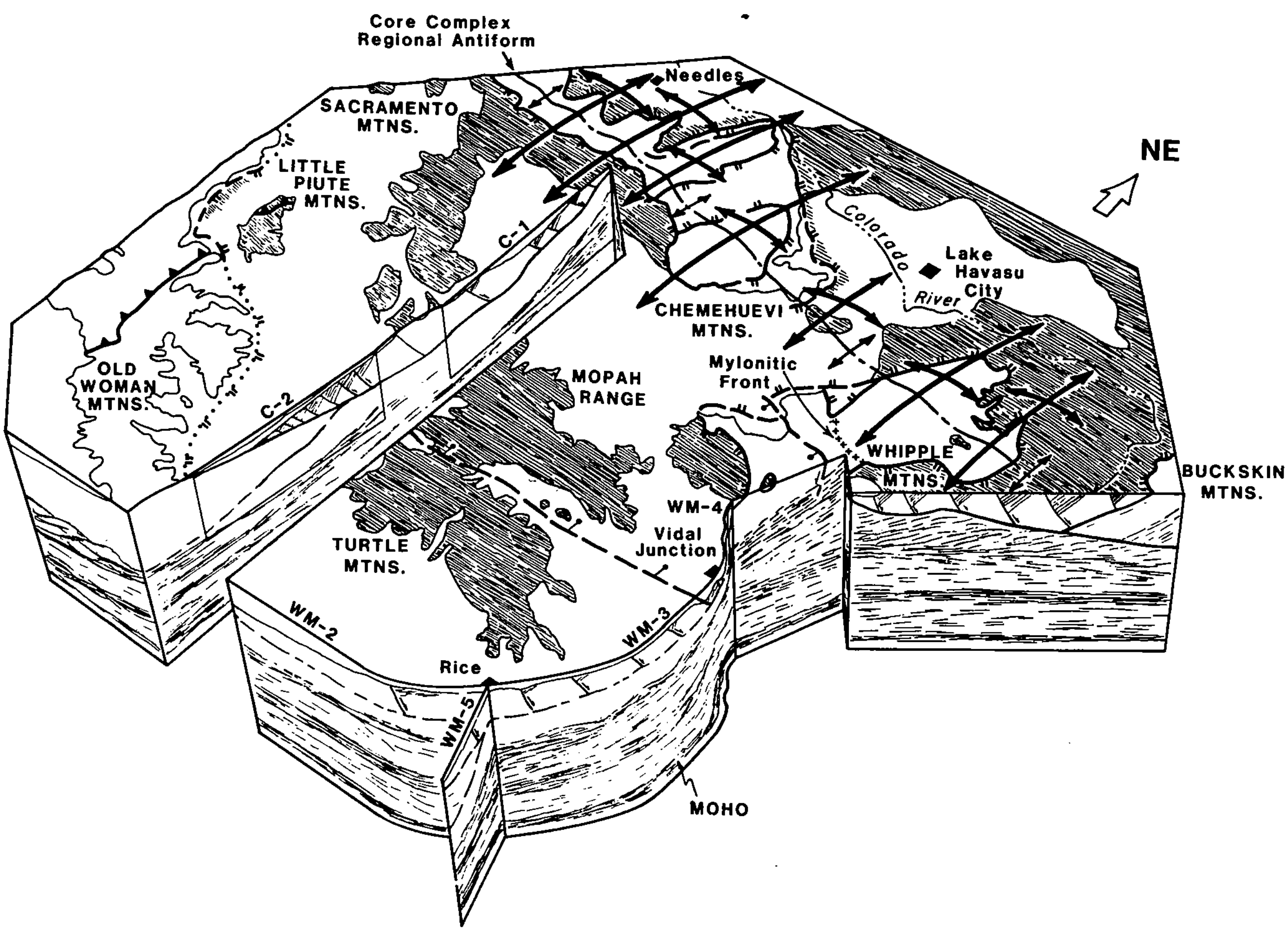

Figure 20. Block diagram of a portion of southeastern California based on CALCRUST and industry seismic lines. Strongly reflective crust dips gently to the southwest away from its apparent exposure as a structural window in the Whipple, Chemehuevi, and Buckskin Mountains (Frost and Okaya, in prep.).

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