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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.

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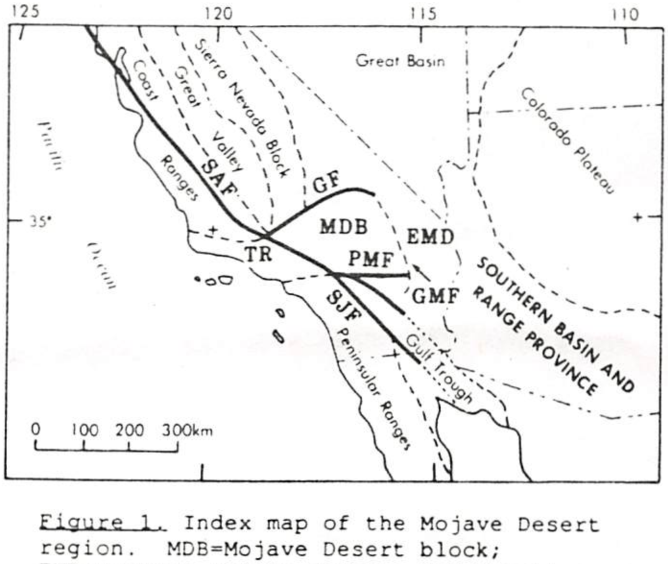

Figure 1. Index map of the Mojave Desert region. MDB=Mojave Desert block; EMD=Eastern Mojave Desert; GMF=Granite Mountains fault; SAF=San Andreas fault; GF=Garlock fault; PMF=Pinto Mountain fault; TR=Transverse Ranges; SJF=San Jacinto fault.

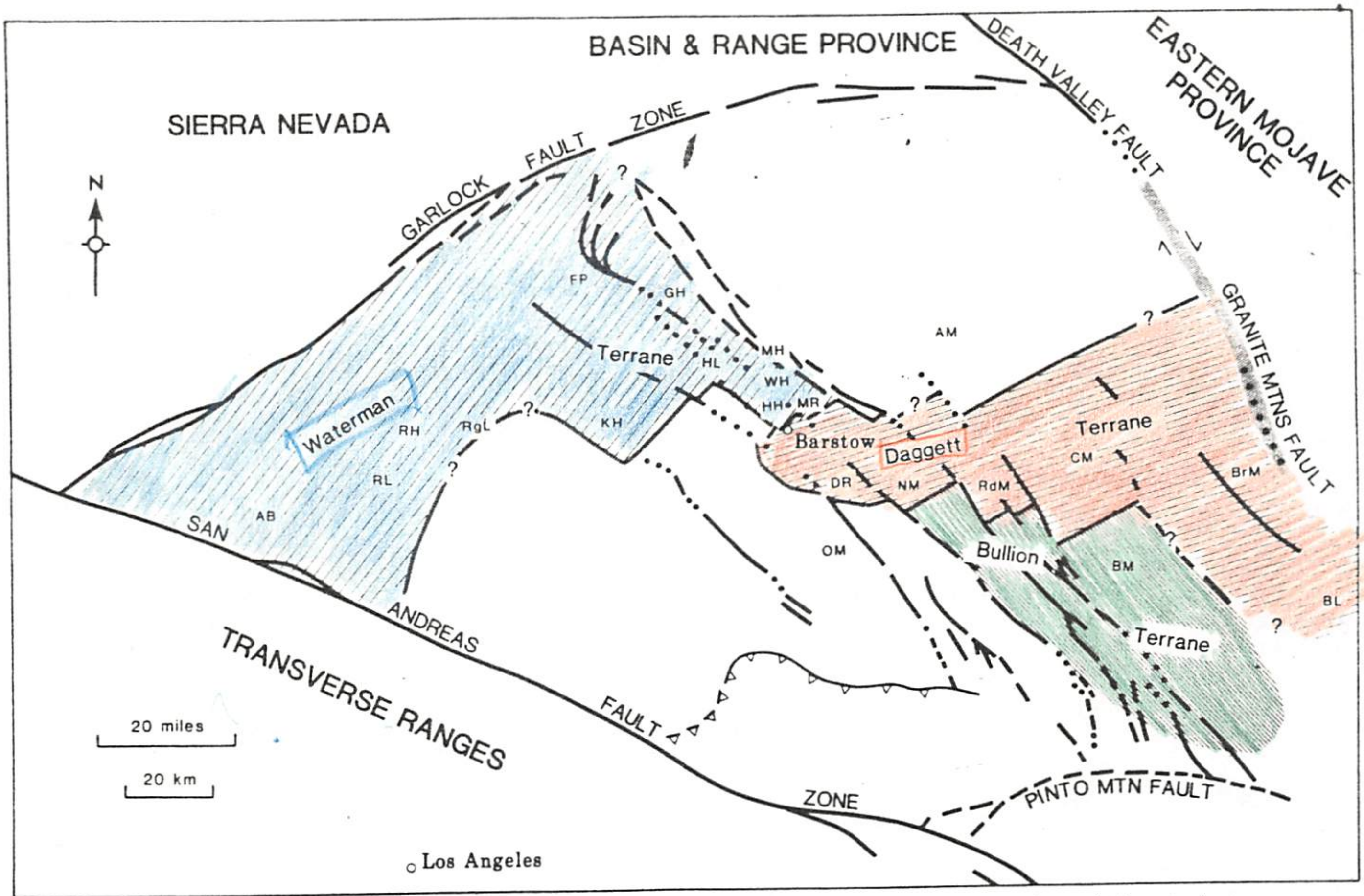

Figure 2. The Mojave Rift of Southern California (Dokka, in prep.). AV=Alvord Mountains; AB=Antelope Buttes; BM=Bullion Mountains; BrM=Bristol Mountains; BL=Bristol Lake; CM=Cady Mountains; DR=Daggett Ridge; FP=Fremont Peak; GH=Gravel Hills; HL=Harper Lake; HH=Hinkley Hills; KH=Kramer Hills; MR=Mitchell 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.

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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 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.

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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.

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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 predates 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.

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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

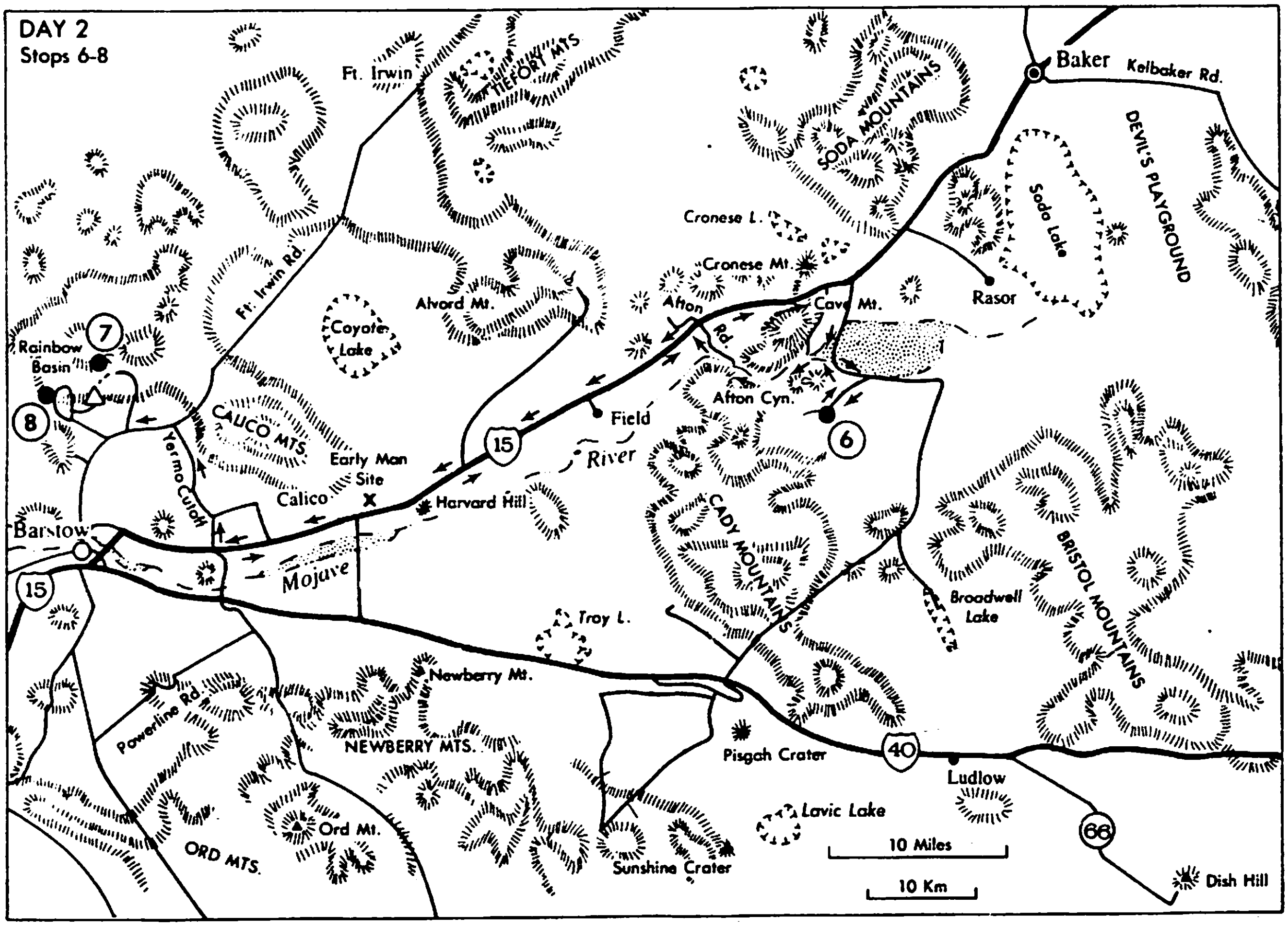

Figure 12. Route for Day 2.

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.

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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

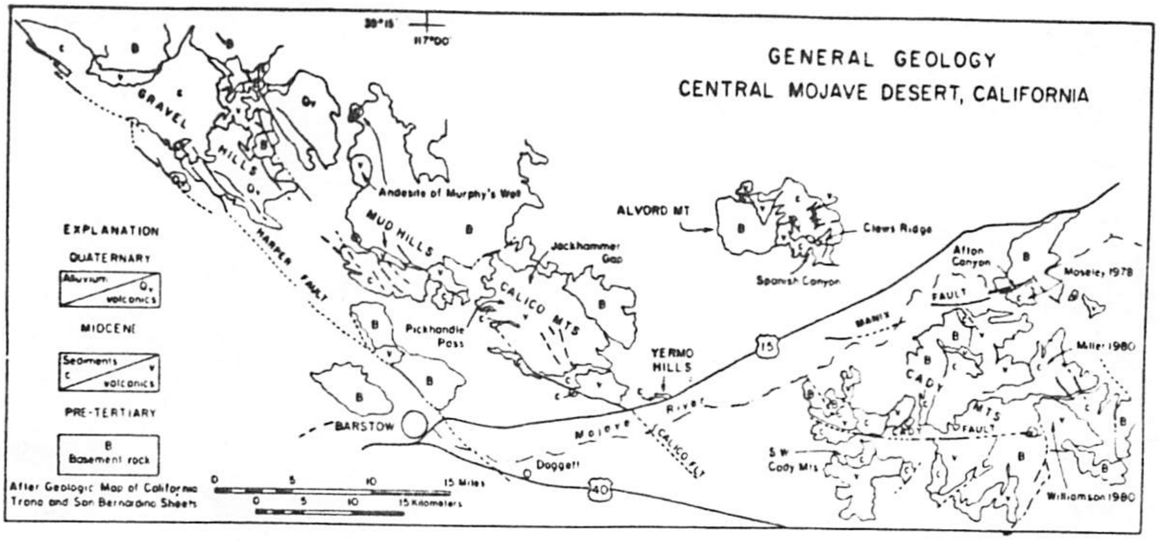

Figure 13. Generalized geologic map of the central Mojave Desert (from Woodburne and others, 1974).

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 ignimbrite 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.

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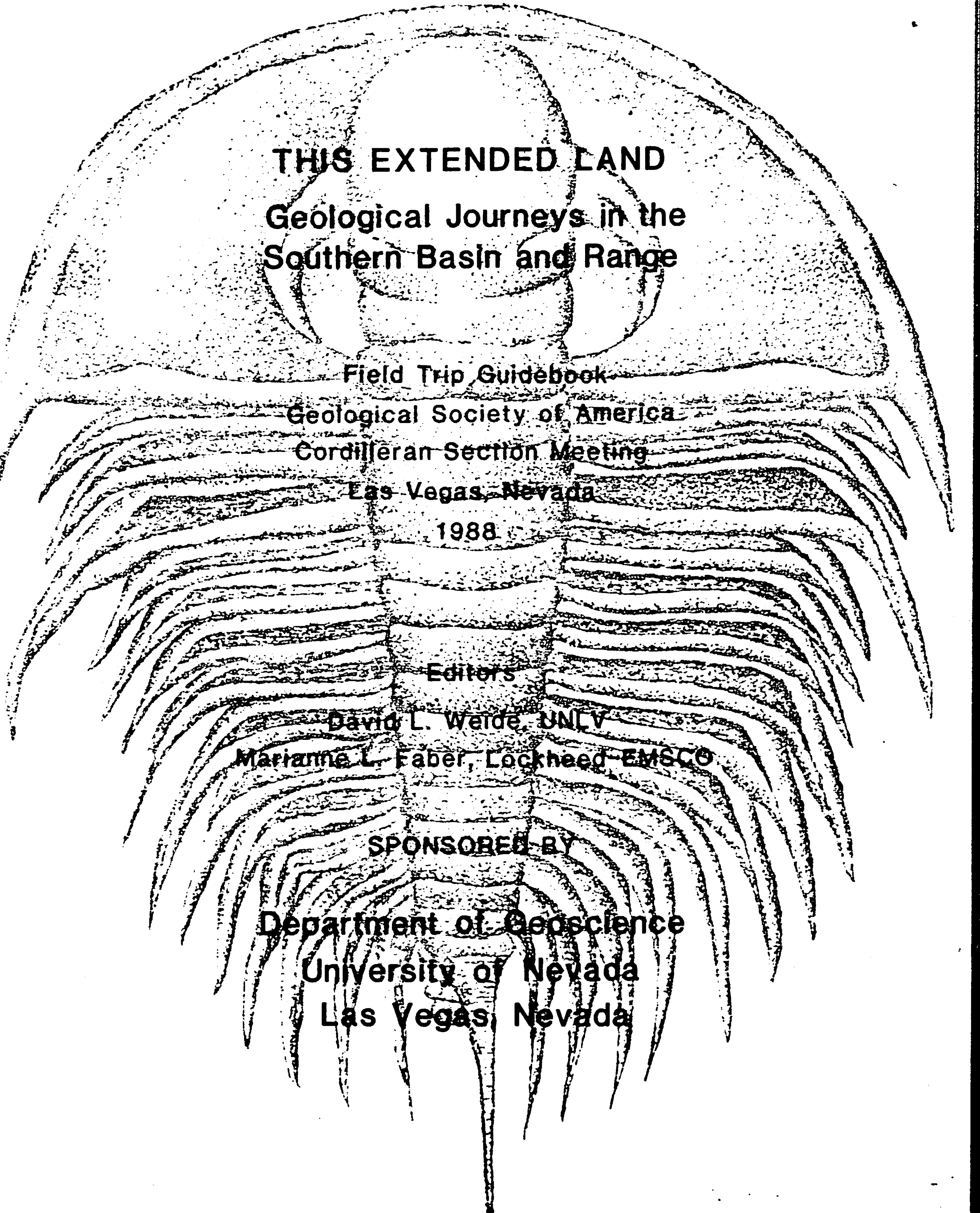

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