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GEOLOGIC MAP OF THE AREA AROUND THE NEBO ANNEX, MARINE CORPS LOGISTICS BASE, BARSTOW, CALIFORNIA

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(Accompanied by map sheet)

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SUMMARY

This map and report present the results of a new geologic field survey of the area surrounding the Nebo Annex of the Marine Corps Logistics Base, near Barstow, California. The map provides a detailed geologic framework that will assist geotechnical and hydrologic operations at the base. The report describes the geologic materials and structures that are shown on the map and explains their significance in terms of regional geologic history.

Certain results of the geologic survey have special practical significance for the Nebo Annex. In particular, we found that the Marine base is traversed by several northwest-trending faults of the Camp Rock-Harper Lake system (faults A-E on the map). Fault C is especially noteworthy because it obstructs the flow of shallow ground water; moreover, it probably has moved during Holocene time and should be considered a potential source of earthquake hazards. The major characteristics of this important group of faults are described more fully near the end of this summary.

The Nebo Annex is constructed mainly upon Quaternary-age alluvial deposits that have accumulated on the sandy bed of the Mojave River and on gravelly alluvial-fans that flank the south side of the river. Older rocks and sediments are exposed in neighboring hills of the southern Mitchell Range that frame the north side of the river. The oldest rock units in these hills include granitoid rocks (quartz diorite) of probable Jurassic or Cretaceous age. In addition, our survey revealed a previously overlooked sizable body of slightly metamorphosed volcanic rocks directly northwest of Elephant Mountain. The latter rocks consist mainly of silicic flows and ash-flow tuff accompanied by minor amounts of andesitic or basaltic rocks. We correlate these rocks with Upper Triassic-Lower Jurassic metavolcanic rocks that are widespread in neighboring mountain ranges south of Barstow.

The Mesozoic granitoid and metavolcanic rocks of the southern Mitchell Range are overlain by a thick succession of Tertiary-age sedimentary and volcanic rocks. These rocks include a discontinuous thin basal unit of red conglomerate and sandstone, which we correlate with the upper Oligocene or lower Miocene Jackhammer Formation of neighboring mountain ranges. The overlying greater thickness of the Tertiary succession consists of interlayered sedimentary and volcanic rocks that we correlate with the lower Miocene Pickhandle Formation of the same nearby ranges. This sequence is remarkably heterogeneous, consisting of felsite flows, silicic tuff and tuff breccia, lacustrine limestone, fluvial sandstone and conglomerate, and coarse sedimentary breccia. Outcrops directly north of the area of our map also include flows of andesite.

The lower Miocene strata are intruded by rare dikes and sills of felsite, several plugs of andesite, and numerous dikes and sills of diabase and basalt. Most of these intrusive bodies probably formed contemporaneously with lower Miocene lava flows of the stratified sequence. However, large intrusions of rhyodacite at Elephant Mountain appear to be significantly younger, possibly middle Miocene. The rhyodacite forms several plugs and domes that intrude cogenetic deposits of rhyodacitic breccia and sandstone.

The lower Miocene sedimentary and volcanic strata of the southern Mitchell Range are unconformably overlain by coarse-grained gravel and conglomerate of presumed late Miocene to early Pleistocene age. These deposits are deeply dissected by erosion, forming scenic bluffs north of the Mojave River and prominent ridges at the south edge of the Nebo Annex and throughout the adjacent Marine Corps Firing Range. Judging from their detrital composition, paleocurrent patterns, and broad areal distribution, the deposits accumulated on large alluvial-fans that sloped southward and northward toward the present-day location of

the Mojave River. This implies that an east-trending trough ancestral to the Mojave River Valley lay at the feet of the old alluvial-fans.

Geologic structures near the Nebo Annex reflect several episodes of crustal deformation during Mesozoic and Cenozoic time. Mesozoic metavolcanic rocks northwest of Elephant Mountain contain steeply-dipping compositional layering, tectonic cleavage, and localized narrow mylonite zones. These structures signify crustal shortening and shearing during Jurassic or Cretaceous time. They probably were reoriented by early Miocene crustal rifting, as explained below.

During the early Miocene, about 23-19 million years ago, the crust of southeastern California was pulled apart in a northeast-southwest direction, creating a complex rift zone in the central Mojave Desert. Rifting was accomplished mainly by large-scale (30-50 km) displacement on a northeast-dipping master shear zone--the Waterman Hills detachment fault. Mid-crustal rocks beneath the detachment fault were pulled southwestward, out from beneath upper-crustal rocks that lay above the fault. This fault is exposed nearby in the hills north of Barstow, and it probably extends southeastward at shallow depths beneath the area of this survey.

Many of the rocks and structures exposed in the southern Mitchell Range, directly north and east of the Nebo Annex, evolved during the early Miocene episode of crustal rifting. The thick sequence of interlayered sedimentary and volcanic strata in this range accumulated in a tectonic depression during rifting, as the wedge of upper-crustal rocks above the detachment fault broke into fault-bounded blocks that subsided differentially. As rifting continued, the fault blocks tilted and pivoted, extensively deforming the overlying lower Miocene strata. Southwest-trending folds and faults were produced during the initial stages of deformation. Subsequently, these early structures were broken and tilted southwestward by displacements on northwest-trending normal faults. Upper-crustal blocks also typically were rotated about a vertical axis during rifting. We infer clockwise rotation of about 50-90° in the southern Mitchell Range on the basis of anomalous northeast-trending layering and cleavage in metavolcanic rocks near Elephant Mountain. Outside the zone of rifted crust, comparable structures in correlative metavolcanic rocks typically trend northwest or north-northwest.

The episode of early Miocene crustal rifting was followed by a period of relative tectonic stability in the late early Miocene and middle Miocene. During this period the tilted blocks of lower Miocene strata were beveled by erosion and then intruded by the plugs and domes of rhyodacite that form Elephant Mountain.

In the late Miocene a new pattern of crustal deformation began in response to north-south compression in the Mojave Desert region. Two main groups of structures evolved concurrently under this new tectonic regime: (1) east-trending folds and reverse faults and (2) northwest-trending strike-slip faults. The widespread ridge-forming deposits of coarse gravel and conglomerate in the study area were a local byproduct of the folding and reverse faulting. These old alluvial-fan deposits accumulated in a broad east-trending trough astride the site of the Nebo Annex. The rock detritus in the alluvial-fans was eroded from basement-cored anticlinal or domal uplifts that rose directly north and south of the study area, near the present sites of Lead Mountain and Daggett Ridge.

Like the great San Andreas fault not far to the southwest, the lesser northwest-trending strike-slip faults of the Mojave Desert region are characterized by right-lateral slip that reflects the persistent northward drift of southwestern California with respect to the continental interior. Several faults of this system pass through the Nebo Annex and adjacent Marine Corps Firing Range (faults A-E on the map). Based on an offset geophysical anomaly, we estimate that the combined long-term lateral displacement on faults B and C alone is about 2.4 km. A 90-m-high east-facing scarp on the Firing Range apparently was produced as lateral slip on these two faults gradually offset a former north-sloping piedmont surface.

Fault C is especially significant to the Nebo Annex for two reasons. First, it forms a ground-water barrier in shallow alluvial deposits near the north edge of the Nebo Annex. This barrier should be considered in the design of toxic waste cleanup operations and the management of ground-water resources. Second, fault C apparently last moved fairly recently, sometime within the past 11,000 years, for it once formed a low topographic scarp within young alluvial-fan deposits directly south of the Mojave River. This scarp, visible on old aerial photographs, was leveled by construction of sewage ponds in about 1950.

Because it appears to be active, fault C deserves further evaluation as a potential source of earthquake hazards, including ground shaking as well as ground rupture by faulting, fracturing, and liquifaction. Faults A, B, D, and E apparently have not moved so recently as fault C and do not seem to affect the flow of shallow ground water. Their movement histories and possible hydrologic effects are poorly known, however. Further studies are warranted to determine the frequency and recency of past movements and to assess whether these faults influence the flow of ground water within deeper aquifers.

INTRODUCTION

The Nebo Annex of the Marine Corps Logistics Base (MCLB) spans the Mojave River 3-7 km southeast of Barstow, California. A geologic map of the area surrounding the Nebo Annex, presented herein, was prepared at the request of the Department of the Navy, represented by the Southwest Division, Naval Facilities Engineering Command. In addition to the Nebo Annex, the map area includes much of the neighboring Marine Corps Firing Range, south of Interstate Highway 40 (I-40), and extends northward to cover the hills between the Mojave River and Interstate Highway 15 (I-15). The new geologic map provides a framework that will assist ongoing and future geotechnical and hydrologic studies at the MCLB.

Methods

Fieldwork was performed mainly during April-August, 1992. Geologic mapping was done concurrently with hydrologic and electrical resistivity investigations, which also were conducted by the U.S. Geological Survey (USGS). The map was compiled at a scale of 1:12,000 using field data recorded on 1:10,000-scale color aerial photographs that were flown on July 2, 1991. Data were transferred from the aerial photographs to a topographic base map using a Kern PG-2 stereo plotter.

Much of our work was concentrated in the hilly areas surrounding the Nebo Annex, where rock units and geologic structures are relatively clearly exposed. During the past half century, civilian and military construction projects and agriculture have obscured primary geologic features in many low-lying areas of the map that are underlain by Quaternary alluvial deposits; such disturbed areas cover a large part of the Nebo Annex. We did not map lithologic units within these areas because, where disturbed, the several different alluvial units generally are indistinguishable on the 1991 aerial photographs. We did map faults within the disturbed areas, however. This involved two steps. First, we identified faults that are well exposed on undisturbed hilly ground north and south of the Nebo Annex. Then we projected these faults across disturbed or alluviated areas on the basis of hydrologic and geophysical evidence, and by consulting older aerial photographs.

Previous Studies

Three previous maps show geologic features near the Nebo Annex. A map of the Daggett 15-minute quadrangle (Dibblee, 1970) shows the broad geologic setting of the base. The hills directly north of the base, commonly termed the southern Mitchell Range, were first mapped by McCulloh (1965) and later by Lambert (1987).

Organization of Report

This report contains three main sections and two appendices. The first section concisely reviews the geologic setting of the Nebo Annex. The second section, termed stratigraphy, summarizes the general physical characteristics, contact relations, and origins of rock units shown on the map. The third section describes geologic structures such as faults and folds and interprets them in terms of regional tectonic history. Appendix 1 provides detailed physical descriptions for each map unit. Appendix 2 consists of a chart that explains the geologic age terms used in the report.

General Conclusions Regarding Young Faults

Our geologic map expands on the previous maps by providing a greater level of detail for all geologic features, but particularly a more comprehensive survey of faults. We identified five northwest-trending faults that cross the Nebo Annex (labeled A-E on the map). Faults B and C pass beneath heavily developed parts of the base. Fault C has distinct hydrologic effects, forming a ground-water barrier where it crosses the Mojave River. It appears to be a northwestward extension of the Camp Rock fault, which ruptured during the June 28, 1992, Landers earthquake. The trace of fault C originally was well defined across part of the Nebo Annex, consisting of a low scarp about 700 m long on the south bank of the Mojave River. This scarp is no longer available for study, having been leveled by construction of sewage ponds in about 1950. However, it appears youthful and uneroded on old aerial photographs, which strongly suggests that fault C last moved during Holocene time. The northwest-trending faults clearly warrant further study to determine their hydrologic effects, their locations where concealed by alluvium, and their significance as a potential source of earthquake hazards to the MCLB and the nearby city of Barstow.

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At the USGS, Jerusha Dahm served as geologic mapping assistant, Edward Gil set up aerial photographs on the Kern PG-2 stereo plotter, and word processing was done by Louise King. Critical data supporting our analysis of faulting within and south of the Mojave River were obtained from three sources in the USGS: Peter Martin provided well logs and other hydrologic information, Adel Zohdy shared his preliminary interpretations from an ongoing direct-current resistivity study, and Andrew Griscom advised us regarding interpretation of pre-existing aeromagnetic data. Peter Martin and Gary Dixon represented USGS interests in numerous communications with the MCLB and Department of the Navy. Jonathan Matti provided a thorough technical review of a previous draft of this report.

GEOLOGIC SETTING

The Nebo Annex of the MCLB is located on Quaternary sand and gravel deposited by intermittent streamflow within the through-going regional channel of the Mojave River and by ephemeral flow of subsidiary streams on alluvial fans flanking the Mojave River. Deeply eroded old alluvial-fan gravel and conglomerate of presumed late Miocene to early Pleistocene age are exposed in the hills north and south of the base. North of the base, in the southern Mitchell Range, these old alluvial-fan deposits overlie a thick Tertiary sequence of upper Oligocene(?) and lower Miocene sedimentary and volcanic rocks; similar rocks presumably extend southward at depth beneath the Nebo Annex. The Tertiary sequence is locally invaded by Miocene volcanic intrusions, including several large bodies of rhyodacite that form Elephant Mountain. The Tertiary strata were deposited on Mesozoic granitic and metavolcanic rocks that are exposed locally near the north edge of the map area.

Geologic structures near the Nebo Annex reflect at least three significant episodes of regional crustal deformation. First, metavolcanic rocks near Elephant Mountain, newly identified during this study, contain structures produced by a Mesozoic episode of crustal shortening. Second, Tertiary sedimentary and volcanic rocks north of the Mojave River were faulted, folded, and tilted as a result of crustal rifting that affected the central Mojave Desert during the early Miocene. A third episode of crustal deformation produced several faults that cross the Mojave River within and near the Nebo Annex. These faults are part of a regional system of northwest-trending strike-slip faults that traverses the central Mojave Desert. This fault system probably originated during late Miocene time, and it remains active today, as illustrated by the Landers earthquake of June 28, 1992, which occurred on this system.

STRATIGRAPHY

Metavolcanic Rocks

Metavolcanic strata (unit Mzv) that are probably the oldest rocks within the map area form a thick sequence of northeast-striking, steeply dipping beds at the northwest foot of Elephant Mountain. These strata consist of silicic extrusive rocks and pyroclastic rocks, including abundant ash-flow tuff. They also include flows or sills of andesitic or basaltic rocks and rare beds of indurated siltstone, sandstone, and conglomerate. Many of the rocks are greenish and appear slightly metamorphosed, although we have not yet obtained any petrographic details. They have a weak to prominent tectonic cleavage and locally are cut by thick veins of white quartz. The rocks are intensely fractured and contain irregular zones of argillic and limonitic alteration.

Distinctive rocks near the northwest end of the body appear relatively homogeneous, consisting chiefly of light-gray ash-flow tuff. These rocks are faulted against rocks that form the main part of the unit. They generally appear less metamorphosed and altered than the other rocks, but they locally are more deformed, containing a narrow steeply dipping mylonitic shear zone.

Although previous workers grouped them with the local Tertiary volcanic assemblage (see maps of McCulloh, 1965; Dibblee, 1970; Lambert, 1987), several features of the metavolcanic rocks indicate that they are considerably older and genetically unrelated to overlying Tertiary volcanic rocks. Tertiary volcanic rocks in the Mojave Desert generally are not metamorphosed and do not contain a tectonic cleavage or thick quartz veins. Moreover, the metavolcanic rocks near Elephant Mountain are overlain with pronounced angular unconformity by sedimentary and volcanic rocks that we correlate with the oldest Tertiary rock units of neighboring mountain ranges, namely, the Oligocene or lower Miocene Jackhammer Formation and the lower Miocene Pickhandle Formation. We suspect that the metavolcanic rocks are closely related to volcanic rocks of Late Triassic to Early Jurassic age that are broadly distributed in neighboring ranges south of Barstow, including Iron Mountain, Sidewinder Mountain, Stoddard Ridge, and the Ord Mountains (Bortugno and Spittler, 1986). Originally grouped within the Sidewinder volcanic series and Hodge volcanic series of Bowen (1954), these rocks include great thicknesses of silicic ash-flow tuff that is deformed and metamorphosed to varying degrees. Narrow steeply dipping mylonitic shear zones are found within the metavolcanic rocks in at least two ranges (Karish and others, 1987; Boettcher and Walker, 1990), indicating another similarity with the rocks near Elephant Mountain.

Quartz Diorite

Pre-Tertiary granitic rocks (unit KJqd) crop out near the boundary of the map area due north of the Nebo Annex, in NE1/4 sec. 2, T9N, R1W. These rocks are heterogeneous, consisting largely of quartz diorite, with lesser amounts of quartz monzonite, tonalite, and granodiorite. Judging from relations elsewhere in the central Mojave Desert, these granitic rocks are Jurassic or Cretaceous in age, and they probably are younger than the metavolcanic rocks near Elephant Mountain.

Red Conglomerate and Sandstone

The basal unit of the local Tertiary stratigraphic succession is exposed in north-central and northeastern areas of the map, where stream-deposited reddish conglomerate and sandstone (unit Trc) rest depositionally on pre-Tertiary quartz diorite and metavolcanic rocks. In neighboring ranges to the north, similar conglomeratic and sandy red beds have been assigned to the Jackhammer Formation, which is known to be early Miocene or older based on isotopic ages obtained from overlying volcanic rocks (Dibblee, 1967, 1968; Burke and others, 1982). In the map area, the contact between the basal red beds and an overlying sequence of sedimentary and volcanic rocks appears conformable. Furthermore, some clasts in the conglomeratic red beds resemble felsitic volcanic rocks in the local Tertiary succession. This suggests that the red conglomerate and sandstone were deposited after the onset of mid-Tertiary volcanism in the Mojave Desert region, which is generally assigned to latest Oligocene or earliest Miocene time. Based on these considerations, we assign the unit a late Oligocene or early Miocene age. The conglomerate and sandstone and directly underlying pre-Tertiary rocks locally are strongly weathered to a clayey grus-like material. This weathered zone reflects a mid-Tertiary episode of relative tectonic quiescence and landscape stability that ended during or directly following deposition of the red beds.

Sedimentary and Volcanic Rocks

A thick, areally extensive, and remarkably heterogeneous sequence of interlayered sedimentary and volcanic rocks conformably overlies the basal red beds. These rocks were previously termed the Daggett Ridge formation by McCulloh (1965) and the Lead Mountain formation by Lambert (1987). The sequence contains the following four parts, listed in ascending order: (1) an interval of pyroclastic and extrusive volcanic rocks, consisting of a discontinuous basal unit of interlayered tuff breccia and felsite flows (Tstb), one or more overlying thick and laterally extensive felsite flows (Tsfr, Tsft), and a discontinuous capping unit of ash tuff (Tst); (2) an interval of interlayered limestone (Tsl), red felsite (Tsfr), and ash tuff (Tst); (3) an interval dominated by three westward-thickening units of sedimentary breccia (Tsb), separated by units of limestone (Tsl), sandstone (Tss), interbedded limestone and sandstone (Tssl), and red felsite (Tsfr); and (4) a thick interval of interbedded conglomerate, sandstone, and sedimentary breccia (Tsc).

The basal sequence of silicic extrusive and pyroclastic rocks was erupted from a nearby volcanic center. The source vents apparently lay toward the east, because the basal unit of tuff breccia and felsite flows pinches out westward by lapping onto metavolcanic rocks about 1.5 km northwest of Elephant Mountain. In keeping with previous work, we have distinguished the overlying thick unit of red felsite (Tsfr) from a thick unit of tan felsite (Tsft) that crops out in the north-central part of the map area. However, the two units grade laterally into one another and the difference in coloration is only superficial. The zone of transition between the two units consists of tan felsite containing local, irregular zones of red felsite. Apparently, the felsite was initially reddish and has been unevenly altered to a tan color by weathering.

The units of red felsite and tan felsite were previously interpreted as intrusive (McCulloh, 1965; Lambert, 1987). We generally favor an extrusive origin for most Tertiary felsite bodies within the map area, however, because interbedded sandstone contains abundant angular felsitic detritus that probably was eroded from coeval extrusive rocks. Furthermore, the thicker felsite bodies are locally vesicular near their tops, and they occupy a constant stratigraphic position throughout a broad outcrop belt extending well beyond the northern border of the map. Finally, laminar foliation and platy cleavage typically are inclined to the upper and lower contacts, implying large-scale flow-folding under conditions of unconfined surface flow.

Abundant deposits of lacustrine limestone constitute one of the most distinctive rock types in the sequence of sedimentary and volcanic rocks. The limestone is most abundant in the central part of the sequence, forming a thick unit that overlies the basal felsite body, and several overlying thinner units that are interbedded with fluvial sandstone, sedimentary breccia, and felsite. The limestone was deposited in a perennial lake, implying a former climate substantially more humid than that of the present day. The existence of lake deposits indicates that a large tectonic depression subsided within and near the northern part of the map area following extrusion of the basal felsite. From the repetitive interlayering of limestone, sandstone, and sedimentary breccia, we conclude that the map area lies near one of the margins of the former lake, where a fluctuating shoreline produced intertonguing of lacustrine and alluvial-fan deposits.

Three units of structureless coarse-grained sedimentary breccia are interlayered with some of the uppermost limestone beds and associated fluvial sandstone deposits. Much of the breccia is monolithologic, consisting solely of debris from silicic to intermediate volcanic rocks, but granitic debris is abundant locally. These units were termed "tuff breccia" by Lambert (1987), but the locally intermixed granitic debris is inconsistent with a pyroclastic origin. The uppermost unit of breccia consists largely of shattered volcanic rocks with little or no matrix between interlocking clasts; this unit probably was deposited by a large landslide or rock avalanche. By contrast, breccia within the lower two units commonly contains a pebbly sandstone matrix and probably consists of interlayered debris-flow deposits and landslide or avalanche deposits. In all three units, breccia clasts are mainly composed of very hard, gray or greenish-gray, epidote-bearing silicic volcanic rocks, including abundant ash-flow tuff. Similar rocks are present in Mesozoic volcanic sequences that crop out locally within the southern Mitchell Range and more extensively in neighboring ranges 10-30 km south of the Mojave River (Bortugno and Spittler, 1986). We suspect that the source area for the breccia lay toward the south and that the debris flows, landslides, and rock avalanches flowed northward into the southern part of the depositional basin.

A thick, relatively homogeneous unit of interbedded conglomerate and sandstone (Tsc) forms the uppermost part of the sequence of sedimentary and volcanic rocks. These rocks consist mostly of fluvial deposits, but they locally include intercalated tuff beds, debris-flow deposits, and lenticular bodies of landslide or avalanche breccia; discontinuous thin beds of limestone are present locally near the base of the unit. Unlike fluvial sandstones lower in the sequence, which contain abundant felsite detritus, the sandstone, conglomerate, and sedimentary breccia in this uppermost unit all consist primarily of detritus from granitic rocks, including granite, quartz monzonite, and granodiorite. The deposits accumulated on a large alluvial fan that developed relatively late in the history of the Tertiary basin, probably reflecting accelerated tectonic subsidence of the basin or uplift of its margins.

The sequence of sedimentary and volcanic rocks is early Miocene in age, as indicated by relations with other rock units and by a single isotopic age. The sequence is younger than the underlying unit of red conglomerate and sandstone, for which we deduce a late Oligocene or early Miocene age; it is older than the early to middle Miocene Barstow Formation, which either overlies the sequence or is faulted down against it on the north side of Lead Mountain, about 2.5 km north of the area mapped for this report (McCulloh, 1965; Dibblee, 1970; Lambert, 1987; Bortugno and Spittler, 1986). These stratigraphic relations indicate the sequence is early Miocene in age and is correlative with sedimentary and volcanic rocks mapped as the Pickhandle Formation in neighboring ranges to the north (Dibblee, 1967, 1968; Burke and others, 1982). A confirmatory early Miocene isotopic age of 21.0 ± 0.8 Ma has been reported for the thick felsite unit at the base of the section (Dokka and others, 1991; R.K. Dokka, oral commun., 1992; Ar^{40}-Ar^{39} method; sample site on south slope of Lead Mountain, near north edge sec. 36, T10N, R1W). This age supercedes a whole-rock K-Ar age of 25.6 ± 0.8 Ma previously reported for the same sample (Lambert, 1987).

Rhyodacitic Breccia and Sandstone

On the flanks of Elephant Mountain, the previously described sequence of lower Miocene sedimentary and volcanic rocks is overlain with angular unconformity by rhyodacitic breccia and sandstone (unit Trb). These volcaniclastic deposits are texturally diverse but compositionally homogeneous, ranging from crudely bedded breccia to well bedded sandstone, all composed exclusively of fragments of biotite-hornblende rhyodacite. They and the underlying lower Miocene sequence are intruded by the rhyodacite of Elephant Mountain, which consists of identical biotite-hornblende rhyodacite. Apparently, debris from pyroclastic eruptions was deposited adjacent to a vent, reworked by fluvial and mass movement processes, then intruded by upwelling magma that filled the vent. The breccia and sandstone are undated but presumably are early or middle Miocene in age.

Gravel and Conglomerate

Deeply dissected deposits of coarse-grained gravel and conglomerate (unit QTg) form ridges both north and south of the Mojave River near the Nebo Annex. North of the river, in the southern Mitchell Range, these deposits rest with pronounced angular unconformity on an irregular erosion surface cut across the sequence of lower Miocene sedimentary and volcanic rocks. This angular unconformity presumably also extends south of the Mojave River, but there the base of the unit is not exposed. The gravel and conglomerate consist of locally-derived, angular, bouldery to pebbly detritus deposited by torrential stream floods and debris flows. South of the Mojave River the detritus consists of Tertiary volcanic rocks and Mesozoic volcanic rocks intermixed in nearly equal amounts; much of this detritus probably was derived from lower Miocene conglomerate, sedimentary breccia, and volcanic rocks that crop out extensively on Daggett Ridge and adjacent hills directly south of the map area (see Dibblee, 1970). North of the Mojave River, detritus of mylonite and gneissic plutonic rocks is abundant south of the junction of I-15 and State Highway 58. This detritus probably was eroded from the Waterman gneiss, which crops out nearby in the northern Mitchell Range, about 2-8 km to the north. The debris of mylonite and gneiss gives way eastward to detritus of limestone, felsite, and diabase derived from the lower Miocene rocks of the southern Mitchell Range. Locally, north of the Mojave River but south of the Harper Lake fault, the stratigraphically lowest exposures of the gravel and conglomerate unit (subunit Tga) consist of fluvial gravel with abundant clasts of Miocene(?) andesite, interlayered with landslide breccia composed of andesite, limestone, and granitic rocks.

The gravel and conglomerate accumulated on a series of coalescing old alluvial fans. We reconstructed the paleoslope directions of these fans from the previously described areal patterns of detrital composition, supplemented by sparse paleocurrent measurements. The evidence indicates two separate paleoslopes: fans in the northern half of the map area sloped southward, while those in the southern half sloped toward the north. The fans converged somewhere near the present-day channel of the Mojave River. This implies that an east-trending trough ancestral to the Mojave River Valley already existed during deposition of the old alluvial fans.

The gravel and conglomerate unit is poorly dated, but substantial antiquity is implied by deep erosional dissection and by localized strong warping and faulting, especially along segments of the Harper Lake-Camp Rock fault system. Furthermore, abundant buried soils within the unit indicate that deposition was drawn out over an extended period of time. About 2-3 km north and south of the map area, the unit unconformably overlies fine-grained clastic deposits and limestone that we correlate with the lower to middle Miocene Barstow Formation. In the absence of more detailed geochronologic evidence, we tentatively infer a late Miocene to early Pleistocene age for the bulk of the unit and a late Miocene or Pliocene age for the subunit of andesitic gravel and monolithologic breccia (Tga) at the base of the section south of the Harper Lake fault.

Alluvial Deposits

The deformed and eroded gravel and conglomerate unit is unconformably overlain by younger alluvium representing two distinct depositional regimes: (1) the through-going regional channel of the Mojave River, and (2) alluvial fans thay flank the river. The alluvial fans form an extensive piedmont south of the river and a discontinuous fringe of piedmont and canyon-filling deposits in the hills north of the river. The alluvial-fan deposits consist predominantly of fluvial sandy gravel locally interbedded with debris-flow breccia, both containing angular pebbles, cobbles, and sparse boulders derived from nearby sources.

The alluvial-fan deposits are subdivided into four map units. The oldest unit (QTa_1) crops out sparsely, forming ridge-capping remnants of Pleistocene and Pliocene(?) gravel in the hills north of the Mojave River (unit QTa). Significantly younger, less eroded, deposits of Pleistocene gravel (unit Qa_2), which retain varnished pavements and conspicuous soil development, are common on both sides of the river. The third map unit consists of unweathered or slightly weathered deposits of inferred late Pleistocene and Holocene age (unit Qa_3), which are subdivided into older (Qa_{3a}) and younger (Qa_{3b}) subunits. A fourth unit consisting exclusively of active Holocene alluvium (Qa_4) is locally recognized within large alluvial-fan stream channels.

By contrast to the alluvial-fan deposits, the far-travelled alluvium of the Mojave River is relatively fine grained and compositionally homogeneous, consisting of sand and minor pebble gravel composed largely of granitic detritus. Most of the detritus probably originated far to the south in the western San Bernardino Mountains, where the headwaters of the Mojave River are located. The river deposits are subdivided into deposits of low stream terraces with moderate plant cover (Qm_1) and unvegetated deposits on the floor of the active river channel (Qm_2). The unvegetated sandy alluvium is periodically eroded and redeposited by southwesterly winds, resulting in a nearly continuous narrow belt of sand dunes (unit Qs) along the north side of the active river channel.

The alluvial-fan deposits near the Nebo Annex form a nested series of inset terraces and channel-filling deposits that generally reflects progressive downcutting by streams, alternating with brief aggradational cycles. The relative importance of climatic and tectonic factors in determining the local erosional and alluvial history warrants further study. It is likely, however, that local alluvial-fan sedimentation was controlled partly by aggradation and erosion within the channel of the Mojave River, as is illustrated in the following example.

During the Pleistocene, the flow of the Mojave River was temporarily ponded within Mojave Valley east of Yermo, resulting in former Lake Manix. The creation of the lake probably initiated a cycle of fluvio-deltaic sedimentation that may have backfilled the Mojave River channel westward to Barstow. Backfilling of the river in turn must have caused tributary streams to aggrade, which could account for extensive Pleistocene alluvial-fan deposits and channel fills north and south of the river (unit Qa_2). Erosional downcutting by the Mojave River and flanking alluvial-fan streams resumed following the draining of Lake Manix in the late Pleistocene, about 14,000 years ago (Meek, 1989).

INTRUSIVE VOLCANIC ROCKS

We have mapped four distinct varieties of intrusive volcanic rocks in the hills north of the Mojave River. These intrusive units span a broad compositional range, including rhyodacite, andesite, and basalt. None of the units has been dated isotopically, but local relations with stratified rocks, and supporting evidence from regional geologic relations, suggest that units of intrusive felsite, basalt, and andesite are early Miocene in age, and that the rhyodacite of Elephant Mountain is early or middle Miocene. The geometric style of intrusion varies systematically with age. The oldest intrusions, consisting of felsite and basalt, tend to form concordant sill-like bodies, whereas younger bodies of andesite and rhyodacite form discordant plugs and domes. As was mentioned previously, we conclude that thick bodies of felsite near the base of the local Tertiary section (units Tsft and Tsfr) consist mainly or entirely of flows; we dispute the intrusive origin for these rocks proposed by McCulloh (1965) and Lambert (1987).

Intrusive Felsite

A small body of silicic felsite (unit Tfi) intrudes the sequence of lower Miocene sedimentary and volcanic rocks at the north edge of the Mojave River, directly opposite the Nebo Annex (E1/2 sec. 11, T9N, R1W). The main mass of the felsite body intrudes landslide breccia, whereas its southern part intrudes upsection and forms a sill-like apophysis along the upper contact of the breccia unit. We have not determined the composition of the felsite, but it probably falls in the range of rhyolite to dacite. It may be genetically related to several more extensive tabular bodies of similar felsite that are intercalated at broad intervals within the lower Miocene sequence, probably mostly as flows (units Tsfr and Tsft). The intrusion lies at a stratigraphic level slightly higher than the uppermost tabular felsite body and apparently lacks an extrusive counterpart. Nevertheless, we infer an early Miocene age based on a close lithologic resemblance to the extrusive felsite found lower in the stratigraphic section (including the thick basal felsite unit).

Intrusive Basalt

Olivine-bearing basalt and diabase (unit Tbi) intrudes stratified lower Miocene sedimentary and volcanic rocks at three localities in the northwestern and north-central parts of the map area. These mafic intrusive rocks are nonresistant, typically weathering to low relief. At each locality contacts are mostly concordant with layering in the host rocks. Throughout the western two localities (S1/2 sec. 2 and E1/2 sec. 3, T9N, R1W) the intrusions consist of nonvesicular diabase. The diabase typically has a medium-grained or coarse-grained ophitic texture, which indicates it was intruded at a great enough depth to allow relatively slow cooling. By contrast, the eastern locality (E1/2 sec. 11 and W1/2 sec. 12, T9N, R1W) consists of fine-grained vesicular or amygdaloidal basalt that must have cooled rapidly at very shallow depth. Although definite intrusive relations were observed in several places, it is possible that the basalt includes flows as well as shallow intrusions.

Based on the foregoing evidence of rapid cooling at shallow depth, the basalt at the eastern locality apparently was emplaced before much of the overlying thick unit of lower Miocene conglomerate and sandstone (unit Tsc) was deposited. This implies that the basalt also is early Miocene in age. This conclusion is reinforced by relations at the westernmost locality (E1/2 sec. 3, T9N, R1W), where plug-like bodies of andesite appear to intrude the diabase. As explained in the following section, the andesite plugs presumably are coeval with lower Miocene lava flows observed directly north of the map area; if so, the diabase must also be early Miocene.

Intrusive Andesite

Small bodies of porphyritic andesite (unit Tai) are found at two localities just north of the Mojave River. The andesite forms prominent knobs, circular to elliptical in plan view, that project above surrounding rocks. At the western locality (E1/2 sec. 3, T9N, R1W), the andesite forms three bodies that are largely surrounded by coarse-grained intrusive diabase. The andesite has an aphanitic groundmass, and the smallest body is chilled against the diabase. These relations indicate that the andesite intrudes the diabase. At the eastern locality (near NW corner, sec. 18, T9N, R1E), a single body of andesite intrudes conglomerate and sandstone that constitute the uppermost unit in the local lower Miocene sequence (unit Tsc). At both localities the andesite bodies have nearly vertical margins, and they cut across lower Miocene strata that dip as steeply as 50-55°. These relations suggest that the andesite was emplaced as vertical plugs following the tilting of the adjacent lower Miocene rocks.

Directly north of the map area (near NW corner, sec. 1 and NE corner, sec. 2, T9N, R1W, but south of I-15), thick flows of brecciated andesite are interlayered with arkosic sandstone that may correlate with unit Tsc. We suspect that the andesite plugs within the map area may have served as feeders for these andesite flows within the lower Miocene section. This would imply that the andesite plugs also are early Miocene in age and not much younger than the diabase and sedimentary strata that they intrude.

Rhyodacite of Elephant Mountain

Resistant biotite-hornblende rhyodacite (unit Tre) forms a north-trending cluster of buttes at Elephant Mountain, near the eastern border of the map area. The same rock type also crops out as a small east-trending dike about 1 km west of Elephant Mountain (NE1/4 sec. 18, T9N, R1E). The buttes comprise at least four rhyodacite bodies. A large composite body made up of two, or possibly three, coalescing intrusions forms the main ridge of Elephant Mountain and an adjacent circular butte to the southeast. Two smaller bodies form the northern tip of Elephant Mountain and a neighboring outlier. Deposits of rhyodacitic breccia and sandstone (unit Trb) enclose the northern part of the composite body and are intruded by it and the adjacent small body to the north. As described in the stratigraphy section of this report, the rock detritus in these flanking clastic deposits apparently was reworked from pyroclastic material produced by early eruptions of the rhyodacite magma; the breccia and sandstone were subsequently intruded when the magma welled up into the vent.

The foregoing intrusive relations with cogenetic sedimentary rocks indicate that the rhyodacite rose to a very shallow level and probably breached the ground surface. Inward-dipping flow foliations were observed near the margins of the composite rhyodacite body, especially in its central part, near hill 2509. The magma apparently ascended through north-trending fissures and flared out at shallow depths to form several volcanic plugs and domes. Compelling evidence of domal expansion is displayed in a small outlier at the southeast foot of Elephant Mountain (near NE corner, sec. 17, T9N, R1E). There, quarry excavations expose a nearly horizontal contact that juxtaposes rhyodacite above sandstone, pebbly sandstone, and claystone of the lower Miocene sequence (unit Tsc). Drag folds above the contact in flow foliated rhyodacite and below the contact in the sedimentary rocks indicate eastward-directed nearly horizontal emplacement of the rhyodacite over the clastic rocks.

The rhyodacite can be assigned an approximate age on the basis of local contact relations and regional magmatic history. Like the much smaller plugs of andesite (unit Tia) that we have mapped west of Elephant Mountain, the rhyodacite was intruded relatively late, after the local sequence of lower Miocene sedimentary and volcanic rocks had been tilted. The rhyodacite may be coeval with similar butte-forming intrusive bodies in the southern Calico Mountains, 6-12 km northeast of Elephant Mountain (Dibblee, 1970; his unit Tai). The latter bodies intrude sandstone and shale correlated with the lower to middle Miocene Barstow Formation (Bortugno and Spittler, 1986). From this evidence we infer that the rhyodacite is early or middle Miocene in age; a younger age is unlikely, because few if any post-middle Miocene isotopic ages have been reported for silicic to intermediate intrusions and flows in the central Mojave Desert region.

GEOLOGIC STRUCTURE

Overview of Regional Tectonic History

The geologic history of the central Mojave Desert near Barstow includes several major episodes of crustal deformation during Mesozoic and Cenozoic time. Here we summarize these tectonic episodes to provide a basis for understanding the structural features described in the latter part of this section.

The earliest tectonic events recognizable within the area of our study occurred in the middle to late Mesozoic, during the same broad period of time when large granitic plutons intruded the crust of the Mojave Desert and adjacent Sierra Nevada. These events included one or more episodes of crustal shortening and ductile shearing that produced folds, cleavage, and localized narrow mylonite zones in metamorphosed Upper Triassic or Lower Jurassic volcanic rocks that are widely distributed in neighboring mountain ranges of the southern Mojave Desert (Miller, 1981; Karish and others, 1987; Boettcher and Walker, 1990; Schermer, 1993). During our geologic survey, a northern outlier of this belt of deformed metavolcanic rocks was discovered in the southern Mitchell Range near Elephant Mountain.

The next regional tectonic event for which there is adequate structural evidence took place in the early Miocene, about 23-19 Ma, when the Mojave Desert was pulled apart in a northeast-southwest direction to form a broad east-trending rift zone that passed through the Barstow region (Dokka, 1986, 1989; Dokka and others, 1988, 1991; Glazner and others, 1989; Walker and others, 1990). Many of the rocks and structures of the southern Mitchell

Range and neighboring ranges were formed at this time. The rift zone opened through large-scale displacement on a northeast-dipping low-angle fault--the Waterman Hills detachment fault. This fault is exposed in the Waterman Hills and northern Mitchell Range, about 10-13 km northwest of the Nebo Annex, where it juxtaposes lower Miocene volcanic and sedimentary rocks on top of deformed Paleozoic and Mesozoic rocks of the Waterman gneiss. During rifting, the gneissic rocks were extracted from mid-crustal depths, pulled about 30-50 km southwestward and out from beneath upper-crustal rocks that lay above the detachment fault (Glazner and others, 1989; Walker and others, 1990; Bartley and others, 1990a).

Outcrops of the Waterman Hills detachment fault are restricted to a relatively small area north of Barstow. The fault is not exposed in the southern Mitchell Range and neighboring areas east of Barstow, where it presumably lies at some unspecified depth beneath the present-day ground surface. In these areas the former rift zone is manifested by thick sequences of lower Miocene volcanic and sedimentary strata and by swarms of early Miocene volcanic dikes. The stratigraphic sequences were deposited and deformed upon fault blocks that differentially subsided, fragmented, and tilted within the upper plate of the active detachment fault. Some of the diverse consequences of upper-plate deformation are illustrated by two sets of structures in the southern Mitchell Range: (1) southwest-trending folds and faults, and (2) northwest-trending normal faults.

Paleomagnetic studies conducted in many parts of the former rift zone show that, in addition to being faulted, folded, and tilted, the upper-plate rocks commonly were rotated about a vertical axis (Ross and others, 1989; Valentine and others, 1993). Within the area of our study, Mesozoic metavolcanic rocks near Elephant Mountain contain anomalous structural trends that suggest they were rotated clockwise roughly 50-90°, presumably during the early Miocene extensional event. In neighboring ranges to the south, tilted and rotated sequences of lower Miocene strata are unconformably overlain by a flat-lying unit of ash-flow tuff that is not rotated (Wells and Hillhouse, 1989). The age of this tuff is late early Miocene, about 18.5 Ma (Nielson and others, 1990), which indicates that block tilting, rotation, and other structural consequences of regional extension were mainly or entirely completed during early Miocene time.

The most recent regional tectonic episode involves the development of a system of strike-slip faults that spans the Mojave Desert between the Transverse Ranges and the Garlock fault. Like the nearby San Andreas fault, the strike-slip faults of the Mojave Desert primarily trend northwest and are characterized by right-lateral slip, reflecting the northward drift of southwestern California with respect to interior parts of North America (Dokka and Travis, 1990). The development of this strike-slip fault system seems to have been accompanied by significant north-south shortening of the Mojave Desert region, as indicated by widespread east-trending folds and reverse faults within upper Cenozoic deposits (Bartley and others, 1990b). The onset of strike-slip faulting and associated contractional deformation is poorly dated but probably was in the late Miocene. The fault system remains active today, as demonstrated by northwest-trending faults in the southern Mojave Desert that shifted during the June 28, 1992, Landers earthquake (Hart and others, 1993).

During the present study we identified several northwest-trending faults that cross the Nebo Annex (faults A-E on the map). These newly recognized segments of the regional strike-slip fault system are locally significant because they influence the flow of ground water beneath the Nebo Annex and are a potential source of earthquake hazards. A group of minor north-trending left-lateral strike-slip faults in the southern Mitchell Range apparently represents a conjugate fault set that developed contemporaneously with the northwest-trending strike-slip faults.

Structural features indicative of Late Cenozoic north-south crustal shortening were not observed within the study area. However, basement-cored uplifts nearby to the south and north may be products of such contractional deformation. These include an east-trending arch near Daggett Ridge (Dibblee, 1970; Dokka, 1986; Bartley and others, 1990b, fig. 1, loc. 19) and a complex domal structure near Lead Mountain (McCulloh, 1965; Dibblee, 1970; Lambert, 1987). The ridge-forming unit of alluvial-fan gravel and conglomerate that crops out extensively near the Nebo Annex (unit QTg of this report) seems to have accumulated in an east-trending structural trough that lay between these basement uplifts; thus this unit, of presumed late Miocene to early Pleistocene age, appears to be an incidental product of crustal shortening.

Structure of Pre-Tertiary Rocks

Pre-Tertiary rocks within the map area contain a limited record of Mesozoic and Cenozoic crustal deformation. Here we emphasize structures of Mesozoic age, because Cenozoic structures are more clearly developed in overlying Tertiary and Quaternary strata. Quartz diorite exposed near the boundary of the map area due north of the Nebo Annex is extensively fractured and is cut by Cenozoic high-angle faults, but it lacks obvious signs of pre-Tertiary penetrative deformation. It may have been intruded subsequent to Mesozoic regional deformation, or it may merely be too resistant or homogeneous to have recorded low to moderate amounts of ductile crustal strain. Significant evidence of pre-Tertiary deformation can be found, however, within the body of metavolcanic rocks northwest of Elephant Mountain. These extrusive and pyroclastic rocks contain a subtle to conspicuous tectonic cleavage that is approximately parallel to northeast-striking steeply dipping compositional layering. In addition, a localized narrow zone of ductile mylonitic shearing cuts ash-flow tuff near the northwest end of the body. Foliation planes in the mylonite strike northeast and dip steeply southeast, roughly parallel to layering and cleavage in the surrounding rocks.

From the nearly parallel cleavage and compositional layering, we infer that the metavolcanic rocks were tightly folded and thereby obtained an axial-planar cleavage and subparallel steeply-dipping layering. Because the foliation within the mylonitic shear zone is essentially parallel to layering and cleavage in adjacent metavolcanic rocks, the mylonite zone may have developed during folding. Alternatively, it may have formed later, exploiting bedding and cleavage as pre-existing planes of weakness. A profound angular unconformity separates the steeply-dipping metavolcanic rocks from depositionally overlying lower Miocene rocks. This indicates that the subvertical bedding, cleavage, and the mylonitic shear zone all developed before the early Miocene.

Based on previous studies of similar rocks in neighboring areas, we infer that the tectonic cleavage and mylonite zone formed sometime in the middle to late Mesozoic. Folded metavolcanic rocks with steeply dipping axial-planar cleavage or foliation have been reported in mountain ranges south and west of Barstow (Miller, 1981; Boettcher and Walker, 1990; Schermer, 1993). The folding has been attributed to contractile deformation of the Mojave Desert during the Middle to Late Jurassic (Karish and others, 1987; Boettcher and Walker, 1990) or the Cretaceous (Schermer, 1993). Rare steeply dipping mylonite zones that cut the metavolcanic rocks in these other ranges are thought to have formed during the Late Jurassic or Cretaceous, in conjunction with the contractile deformation or as part of a separate tectonic episode (Boettcher and Walker, 1990; Schermer, 1993).

The metavolcanic rocks also are cut by numerous northwest-trending and northeast-trending faults that are bordered by crushed or brecciated rocks, indicating brittle failure. In addition, the rocks contain abundant minor fractures of diverse orientation, which gives outcrops a shattered appearance. Several of the northwest-trending faults cut lower Miocene strata and thus are demonstrably late Cenozoic in age. These faults are addressed in a later section on northwest-trending normal faults; we suspect that they, and possibly also the pervasive fractures in the metavolcanic rocks, were products of early Miocene crustal rifting. Three northeast-trending faults clearly are older, possibly early Cenozoic, because they are depositionally overlain by basal units of the lower Miocene stratal sequence. A segment of one northeast-trending fault, in SE1/4 sec. 6, T9N, R1E, was reactivated during the late Cenozoic, moving in combination with two northwest-trending normal faults that bound the northeast side of the metavolcanic rocks.

Southwest-trending Folds and Faults

Lower Miocene sedimentary and volcanic rocks of the southern Mitchell Range contain numerous southwest-trending folds and several southwest-trending faults. Two large map-scale flexures are found within the area of our study: a synclinal hinge west of Elephant Mountain in NE1/4 sec. 7, T9N, R1E, and an anticlinal hinge concealed beneath gravel and conglomerate (unit QTg) north of the Nebo Annex near the NE corner of sec. 11, T9N, R1W. These folds have steep to vertical axial surfaces, and their axes plunge gently to moderately southwest. The folds are gentle, with rounded crests and interlimb angles of 125-140°. Small-scale to outcrop-scale parasitic folds are distributed along the limbs of the large folds. These smaller folds are best exposed within thick units of limestone. They commonly have complex noncylindrical shapes.

Some of the folds developed in concert with southwest-trending faults. For example, a subsidiary map-scale anticline and adjacent syncline are developed in the thick basal limestone unit in E1/2 sec. 2, T9N, R1W. These folds seem to have formed by drag accompanying down-to-south displacement on a well-exposed, southwest-trending, high-angle normal fault. Another southwest-trending fault lies near the axial trace of the large synclinal flexure in sec. 7, T9N, R1E. As recognized by Lambert (1987), this fault is concealed beneath deposits of gravel and conglomerate (unit QTg), but its presence can be inferred from left-lateral separation of Miocene rock units that form the limbs of the syncline. The fault is restricted to the middle and upper parts of the lower Miocene stratal sequence, terminating northeastward before reaching units near the base of the sequence. The large syncline may have formed in concert with rotational slip on this concealed fault. A third southwest-trending fault with minor left-lateral separation and presumed down-to-south displacement lies about 2 km east of the concealed fault, near the SW corner of sec. 8, T9N, R1E.

From their relations with stratigraphic units and intrusions, it appears that the southwest-trending folds and faults developed during the early Miocene. They are depositionally overlain by the gravel and conglomerate unit, which is poorly dated but possibly is as old as late Miocene. Near NW corner sec. 18, T9N, R1E, a small plug of andesite intrudes moderately dipping beds near the axial trace of the large syncline. Judging from its nearly vertical orientation, the plug apparently has not been tilted and probably was intruded after the surrounding strata were folded. Similarly, plugs and domes of rhyodacite at Elephant Mountain were emplaced following tilting and folding of adjacent lower Miocene strata. Finally, north of I-15, just outside the northern boundary of this map, previous workers have mapped large southwest-plunging folds that apparently are cross-cut by diabase intrusions (McCulloh, 1965; Dibblee, 1970; Lambert, 1987).

None of the cross-cutting intrusive bodies have been dated radiometrically, but we suspect that the rhyodacite is early or middle Miocene in age and that the andesite and diabase are early Miocene. Thus, the southwest-trending folds and faults most likely developed during the early Miocene. Similar relations have been reported in the Waterman Hills north of Barstow, where sedimentary and volcanic rocks correlated with the lower Miocene Pickhandle Formation form a large southwest-plunging syncline that is intruded by rhyolite plugs and truncated below by the early Miocene Waterman Hills detachment fault (Walker and others, 1990). Therefore, southwest-plunging folds like those in the map area originally may have formed a belt at least 15 km wide, between Elephant Mountain and the Waterman Hills.

The upper crust of the central Mojave Desert was profoundly extended during the early Miocene (Dokka, 1986, 1989; Dokka and others, 1988; Glazner and others, 1989; Walker and others, 1990; Bartley and others, 1990a). Therefore, the southwest-trending folds and faults in the southern Mitchell Range apparently formed within the context of regional extension. They probably were produced by jostling of fault blocks in the upper plate of the Waterman Hills detachment fault, which is presumed to extend southeastward beneath the southern Mitchell Range (Lambert, 1987; Dokka, 1989; Bartley and Glazner, 1991). The present southwest trend of the folds and faults may be primary, which implies an origin roughly parallel to the northeast-southwest slip direction of the detachment fault. Alternatively, the folds and faults may originally have trended northwest, perpendicular to the axis of regional extension, and they may have been realigned by large-scale rotation of upper-crustal blocks during early Miocene rifting (evidence for vertical-axis rotation is discussed in a following section).

Northwest-trending Normal Faults

The lower Miocene stratigraphic succession north of the Mojave River is locally repeated across a series of northwest-trending faults. The faults with largest displacements are down to the north, although some minor faults show the opposite sense of slip. One of the most prominent faults intersects the northern boundary of the map area near the east edge of sec. 2, T9N, R1W. This fault lies mainly outside the map area, in neighboring sec. 1 and NE 1/4 sec. 2. Several faults near the SE corner of sec. 1 may represent the southeastward extension of the same zone of faulting. Directly north of the map area on the north side of this fault (in NE 1/4 sec. 2) are arkosic sandstone, granitic avalanche breccia, and andesite flows that locally form the uppermost part of the lower Miocene succession (correlated with unit Tsc). These rocks are juxtaposed against granitic basement that forms the south side of the fault, which indicates the north side has been dropped down, probably by at least several hundred meters; according to previous estimates, the throw, or vertical component of displacement, is about 550-600 m (Dibblee, 1970, section B-B'; Lambert, 1987, sec. A-A'). Shear planes along the fault (observed north of the map area) dip northeastward about 40-45°. Therefore, the fault appears to be a normal fault produced by crustal extension. The fault is overlain by thick, unfaulted, old alluvial-fan deposits of unit QTg, but it appears to truncate, and therefore post-date, faults of the southwest-trending set described in the preceding section.

Other northwest-trending faults juxtapose lower Miocene rocks against the northeast side of a body of Mesozoic metavolcanic rocks (unit Mzv) directly northwest of Elephant Mountain. These faults also are northeast-dipping normal faults. In general, the trend and apparent sense of displacement shown by the northwest-trending faults is consistent with northeast-directed crustal extension. We interpret them to be normal faults that formed during the final stages of early Miocene rifting. The southwestward plunge of fold axes in the southern Mitchell Range probably can be attributed to tilting of blocks bounded by this set of faults.

Evidence for Vertical-axis Rotation

The northeast-striking cleavage and layering in Mesozoic metavolcanic rocks near Elephant Mountain are oblique or perpendicular to the dominant structural trends of correlative rocks in the southern Mojave Desert, and we suspect they were reoriented by rotation about a vertical axis during the early Miocene episode of crustal rifting. In several mountain ranges of the southern Mojave Desert that lie directly south of the extensional belt, cleavage and layering in Mesozoic metavolcanic rocks mainly strike northwest or north-northwest (Bortugno and Spittler, 1986). Assuming that the structures near Elephant Mountain originally had a similar trend, their present anomalous orientation suggests they have been rotated clockwise in the range of 50-90°.

Clockwise rotations of this magnitude have been demonstrated for lower Miocene volcanic rocks in nearby mountain ranges on the basis of paleomagnetic studies. About 12 km southwest of Elephant Mountain, lower Miocene strata of Daggett Ridge appear to have been rotated clockwise about 50-60° (Valentine and others, 1993, their sites 95-96). Similarly, a mean clockwise rotation of about 70-75° was determined for lower Miocene rocks of the Newberry Mountains, about 15-30 km southeast of Elephant Mountain (Ross and others, 1989). These large rotations are known to have occurred during the early Miocene, shortly after the volcanic rocks were erupted, because a late early Miocene-age (18.5-Ma) unit of ash-flow tuff in the same mountain ranges is not rotated (Wells and Hillhouse, 1989). Because the Newberry Mountains and Daggett Ridge lie within the early Miocene extensional belt, the rotational deformation in these ranges has been attributed to pivoting of upper-crustal blocks during rifting (Ross and others, 1989; Bartley and Glazner, 1991).

The anomalous structural trends in the metavolcanic rocks near Elephant Mountain are consistent with the cited paleomagnetic studies that indicate large clockwise rotations in neighboring ranges to the south. Therefore, we propose that the metavolcanic rocks rotated clockwise 50-90° during the early Miocene rifting event. This hypothesis could be tested through paleomagnetic studies of the lower Miocene strata in the southern Mitchell Range, which presumably were rotated along with the underlying metavolcanic rocks. Although this work has not yet been done, paleomagnetic data have been obtained for a post-extensional intrusive unit, the rhyodacite of Elephant Mountain (Valentine and others, 1993, their site 62). The rhyodacite has not been rotated, which confirms that the rotation of the metavolcanic rocks, if valid, occurred before middle Miocene time.

Previous Caldera Model Disputed

The most recent previous workers to study the hills north of the Nebo Annex concluded that the area was largely unaffected by early Miocene crustal rifting; instead, they proposed that many structural features can be related to the development of a volcanic caldera (Lambert, 1987; Dokka and others, 1991). To the contrary, we have shown that the southwest-trending folds and faults and northwest-trending normal faults in this area can be explained in terms of regional extension, and that anomalous northeast-trending structures in the metavolcanic rocks near Elephant Mountain may reflect strong clockwise rotation comparable to what has been observed in neighboring areas of the extensional belt.

Although Miocene volcanism produced numerous intrusive and extrusive bodies within the map area, we found no evidence that it culminated with the development of a caldera structure. Lambert (1987) cited several features in support of his caldera model. For example, he inferred that thick felsite units near the base of the lower Miocene sequence consist of intrusions fed by ring dikes of a caldera. By contrast, our work indicates that these felsite units consist mostly or entirely of flows. Units of breccia within the middle part of the lower Miocene sequence were thought by Lambert (1987) to consist of caldera-filling tuff breccia (his units Tlmm and Tlmu), but our findings show that the breccia is composed of epiclastic detritus from Mesozoic volcanic rocks, and that it was deposited by landslides, rock avalanches, and debris flows. Neither could we confirm the existence of Tertiary ash-flow tuff inferred by Lambert (1987). Finally, a concentric arrangement of Tertiary rock units near Lead Mountain, about 1-2 km north of I-15, apparently was produced by folding and faulting, not by development of a caldera.

North-trending Strike-slip Faults

Several approximately north-trending strike-slip faults were mapped in the southern Mitchell Range. The best exposures are found due north of the Nebo Annex in E1/2 sec. 2, T9N, R1W. There, several faults that are well exposed in rock quarries and road cuts produce small left-lateral separations where they intersect an older southwest-trending fault. These faults consistently exhibit nearly horizontal fault-plane striations and therefore appear to be left-lateral strike-slip faults. At least two of them cut the gravel and conglomerate unit, which confirms that they are younger than the previously described sets of southwest-trending and northwest-trending faults. Two other north-trending faults produce left-lateral separations within lower Miocene strata near SE corner sec. 7, T9N, R1E. The north-trending faults apparently represent a minor conjugate fault set that developed contemporaneously with the more important set of northwest-trending strike-slip faults that is described in the following section.

Northwest-trending Strike-slip Faults

Several northwest-trending faults cross the Mojave River at the site of the Nebo Annex (see faults labelled A-E on the map). These structures were identified during the present study from a combination of geologic, hydrologic, and geophysical evidence. The faults are part of a regional system of young right-lateral strike-slip faults that crosses the central Mojave Desert region (Morton and others, 1980; Bortugno, 1986; Jennings, 1992). The regional system consists of four major faults and numerous subsidiary faults in a zone about 45 km wide centered on Barstow. From west to east, the four major structures are the Helendale, Lenwood, Camp Rock-Harper Lake, and Calico faults. The youthful nature of the fault system was underscored by the June 28, 1992, Landers earthquake, which produced ruptures along the Camp Rock and associated faults in the southern Mojave Desert region (Hart and others, 1993). The newly recognized faults that pass beneath the Nebo Annex are strands of the Camp Rock-Harper Lake fault system that lie northwest of the fault segments that ruptured during the Landers earthquake. The southeastern segment of the Harper Lake fault near Barstow was originally called the Waterman thrust (Bowen, 1954), and a derivative term, the Waterman fault, is occasionally still used. The latter term should be avoided, however, because it can be confused with the name for a different structure, the Waterman Hills detachment fault.

Recent regional geologic maps show a 12-km-long gap in mapped faults between the Camp Rock fault, southeast of the area mapped for this report, and the Harper Lake fault, which lies directly north of the Mojave River and approximately on line with the Camp Rock fault (Bortugno and Spittler, 1986; Bortugno, 1986; Jennings, 1992). However, older maps show one or two speculative faults crossing the Mojave River along the trend of the Harper Lake fault; these faults were thought to be buried by pre-Holocene alluvium and therefore were considered inactive (Rogers, 1967; Dibblee, 1970, section C-C'; Jennings, 1975). Our mapping indicates that as many as five fault strands cross the Mojave River, linking the Harper Lake fault with the Camp Rock fault. These faults form a zone that is about 2 km wide where it intersects the intensively developed eastern part of the Nebo Annex. Several minor northwest-trending faults were mapped locally on either side of the main fault zone.

Of the five major fault strands that cross the Mojave River, only faults C and D appear to directly link the Harper Lake and Camp Rock faults. Faults A and B may be continuous with the Camp Rock fault south of the map area, but they seem to merge near the north edge of the Mojave River and continue northwest of the map area as a single strand that lies west of and parallel to the Harper Lake fault. Fault E splays off from the Harper Lake fault near the north boundary of the map area and apparently passes east-southeastward across the Mojave River, diverging from the other strands and eventually terminating on the north slope of the Newberry Mountains 9-10 km southeast of the area of this map (B.F. Cox, unpublished mapping). Each of the five strands cuts poorly dated old gravel and conglomerate of unit QTg. Fault C also cuts younger alluvial-fan deposits and probably has moved during Holocene time. The individual faults are described in detail below, proceeding northeastward across the fault zone.

Fault A

We initially identified fault A on aerial photographs as a faint but nearly continuous northwest-trending lineament that crosses hilly terrain directly south of the Nebo Annex. Subsequent field observations demonstrated that the lineament coincides with a fault that cuts ancient gravel and conglomerate (unit QTg) and slightly disturbs overlying Pleistocene alluvium (unit Qa_2). Younger alluvial deposits (units Qa_3 and Qa_4) do not appear to be affected. Shear planes observed at several localities mainly dip steeply (80-85°) northeast.

The most conspicuous geomorphic evidence of faulting is found in NE1/4 sec. 23, T9N, R1W. This segment of the fault is marked by several notched ridges. Topographic profiles across the fault in this area indicate a highly eroded southwest-facing scarp, with the southwest side apparently thrown down as much as 2-3 m. Ridges and ravines do not appear to be laterally offset by the fault. The fault cuts deposits of Pleistocene alluvium (unit Qa_2), but most of the vertical offset of topographic surfaces predates a varnished pavement that is developed across the top of unit Qa_2. There is no evidence of significant Holocene displacement.

Directly south of the map area fault A curves slightly to form an arc concave toward the northeast. Part of this arc, near the east edge of sec. 36, T9N, R1W, coincides with an eroded northeast-facing scarp about 15-20 m high. The southeast end of the arc points toward a fault in S1/2 sec. 10, T8N, R1E, that was previously mapped as one of two terminal splays of the Camp Rock fault (Dibblee, 1970). We suspect that the arcuate fault segment continues southeastward to join the Camp Rock fault via this splay. Continuity of the faults is uncertain, however, because of an extensive cover of Holocene and Pleistocene alluvial deposits.

The northwestward extension of fault A across the Mojave River is deduced from a recent direct-current resistivity survey conducted along the active channel of the Mojave River (A. Zohdy, written commun., 1992). This survey indicates a lateral discontinuity in resistivity at depths greater than about 150 m near E1/2 sec. 10, T9N, R1W. The fault presumably has a right-lateral component of slip, but we currently do not have any evidence by which to determine the amount of lateral displacement. Neither do we have any data by which to locate the position of the fault northwest of sec. 10, T9N, R1W. As previously mentioned, fault A presumably merges northwestward with fault B near the north boundary of the map area.

Fault B

Fault B is marked by a faint air-photo lineament within deposits of the gravel and conglomerate unit (QTg) in the hills southeast of the Nebo Annex. Our attempts to locate the fault by field inspection were unsuccessful owing to poor exposure. Pleistocene alluvium (unit Qa_2) that locally overlies unit QTg seems to be unaffected, and ravines and ridges are not laterally offset by the fault. Thus, like fault A, fault B appears to have moved entirely before Holocene time. Here, adjacent to the Marine Corps Firing Range, fault B lies parallel to and only 40-80 m west of fault C, but the two faults diverge northwestward across the Mojave River, where fault C merges with fault D and fault B presumably merges with fault A.

The location of fault B beneath the active channel of the Mojave River near the west edge of sec. 11, T9N, R1W, was inferred from a lateral discontinuity in electrical resistivity detected both along a surface transect (A. Zohdy, written commun., 1992) and within wells spudded at intervals along the river bed (P. Martin, written commun., 1992). The surface resistivity measurements suggest that deep rocks are dropped downward as much as 300 m on the southwest side of the fault. The resistivity logs from the wells indicate that this stratigraphic discontinuity across the fault can be traced to within about 100 m of the ground surface, but alluvial deposits shallower than this apparently are not faulted.

Geophysical data indicate that large right-lateral strike-slip displacement has occurred on fault B or fault C. A regional aeromagnetic survey (U.S. Geological Survey, 1987) shows that a west-southwest-trending aeromagnetic ridge more than 9 km long is abruptly truncated at its west end where it is intersected by faults B and C. The site of the truncation is on the Marine Corps Firing Range near the north edge of sec. 30, T9N, R1E. The aeromagnetic ridge presumably is caused by a body of relatively magnetic Tertiary volcanic rocks buried beneath unit QTg (A. Griscom, oral commun., 1992). The offset westward extension of the ridge reappears about 2.4 km to the northwest, suggesting there has been this amount of combined right-lateral displacement on faults B and C. As will be shown, geologic data north of the Mojave River indicate that fault C has displaced unit QTg right-laterally no more than 0.85 km. If there was no earlier displacement on fault C before unit QTg was deposited, the right-lateral slip on fault B alone amounts to at least 1.55 km.

The traces of faults B and C southeast of the Nebo Annex are parallel to and approximately halfway up a 90-m-high east-facing topographic escarpment that forms an effective backstop for the Firing Range. This escarpment is dissected by deep ravines, which suggests that it is old, possibly early or middle Pleistocene. From the close spatial association between the escarpment and the two faults, we infer that the scarp was produced by deformation accompanying faulting.

The scarp may have been produced in large part by simple strike-slip offset of a sloping land surface. Our observations of conglomerate clast composition and sedimentary structures near the Firing Range indicate that unit QTg in this area was deposited on a northward-sloping alluvial fan. Simple geometric considerations show that a northeast-facing scarp will be produced when a northward-inclined surface is broken by a northwest-trending right-lateral strike-slip fault. If we assume that the gradient of the old alluvial-fan surface was comparable to that of present-day active fan surfaces in neighboring areas south of the Mojave River (2-3 degrees), then it follows that a combined right-lateral slip of 2.4 km on faults B and C would produce a hypothetical scarp approximately 65-85 m high, which compares well with the 90-m-high scarp observed near the Firing Range.

Strata within unit QTg near the Firing Range commonly dip as steeply as 15-30°, and dips of 60-70° are found in one locality adjacent to fault C near NW corner sec. 30, T9N, R1E. Tilting probably occurred in conjunction with movements on faults B and C and may have contributed to the development of the east-facing scarp. We have not determined the detailed pattern of tilting or folding in unit QTg near the Firing Range, but the few bedding attitudes that we have measured are not consistent with a simple northwest-trending anticline as was mapped in this area by Dibblee (1970).

Fault C

Of the five fault strands that cross the Mojave River, fault C is best exposed and has the most conspicuous geomorphic and hydrologic expression. Southeast of the Nebo Annex, near the Marine Corps Firing Range, it forms a prominent air-photo lineament that cuts across Pleistocene alluvium (unit Qa_2) as well as across underlying deposits of gravel and conglomerate (unit QTg). Where it crosses minor ridges, the lineament coincides with degraded low scarps facing both northeast and southwest; deposits of unit Qa_2 show vertical separations of as much as several meters across some of these scarps. Several minor ridges and ravines are offset where intersected by the fault. The best examples of this are found near the south side of I-40 directly west of the Nebo Street underpass, where two adjacent north-trending ridges are each offset right-laterally about 50-60 m. Shear planes observed along the fault at several localities south of I-40 dip steeply (75°-90°) to the northeast and southwest.

We found geologic and hydrologic evidence that suggest Holocene movement on fault C at three localities between I-40 and the Mojave River. The fault is exposed in a gravel quarry directly southeast of the Nebo Annex, in W1/2 sec. 13, T9N, R1W. There, on the south wall of the quarry, shear planes cut alluvial-fan deposits including upper Pleistocene or Holocene deposits of unit Qa_3. The shear planes strike about 340° and dip steeply (65°-80°) southwest.

The second locality with evidence of Holocene displacement on fault C lies between the tracks of the Santa Fe Railroad and the active channel of the Mojave River, near SW corner sec. 12, T9N, R1W. Aerial photographs taken before 1950 show a northwest-trending lineament about 700 m long that extends from the railroad tracks to the south bank of the river. The lineament is manifested mainly as a low northeast-facing scarp within upper Pleistocene or Holocene alluvium of unit Qa_3. The lineament probably originally was longer, but its presumed extension south of the railroad tracks was destroyed by construction of the Nebo Annex sometime in the early 1940's. The segment of the lineament between the tracks and the river was obliterated in about 1950 by construction of sewage treatment ponds. By interpolating between the air-photo lineament on the north and the quarry exposure on the south, we have determined approximately where fault C intersects base facilities near the east end of the Nebo Annex. As shown on the map, the fault apparently passes beneath several buildings including a large warehouse.

Additional evidence of Holocene movement on fault C is found beneath the active channel of the Mojave River. The fault forms a ground-water barrier in unconsolidated alluvial deposits lying as little as 6 m beneath the river bed (P. Martin, written commun., 1992). The water table is deeper and slopes more steeply on the northeast side of the fault. Recent measurements indicate that the depth to water increases about 3 m crossing the fault. The other northwest-trending faults near the Nebo Annex apparently do not influence the flow of shallow ground water where they cross the Mojave River. This hydrologic evidence supports the previously cited geologic evidence that indicates fault C has moved more recently than the other faults and may be the only fault that is technically active, having moved sometime during the past 11,000 years.

North of the Mojave River, fault C merges with fault D. The geomorphic expression of the resulting compound fault is similar to that of fault C near the Firing Range; there is a prominent air-photo lineament, low scarps are present within Pleistocene alluvium (unit Qa_2), and several ridges and ravines appear to be offset in a right-lateral sense. The compound fault juxtaposes a narrow sliver of steeply-dipping lower Miocene sedimentary and volcanic rocks, lying northeast of the fault, against gravel and conglomerate (unit QTg) that form the southwest wall of the fault. Shear planes observed at various places along the fault dip steeply (65-85°) northeastward. A component of down-to-south reverse slip is reflected by layering in unit QTg, which is tilted gently to moderately toward the southwest. The surface resistivity survey conducted nearby along the Mojave River (A. Zohdy, written commun., 1992) suggests that, beneath the surface layer of unconsolidated alluvium, rocks on the southwest side of fault C have dropped as much as 150 m relative to adjacent rocks on the northeast side of the fault. Vertical displacements of equal or greater magnitude probably occur north of the Mojave River where faults C and D merge.

Also north of the Mojave River, limits can be placed on the total combined lateral displacement of faults C, D, and E, thus indicating the maximum possible lateral slip of fault C. Northeast of the fault sliver of lower Miocene rocks, gravel and conglomerate of unit QTg locally contain abundant clasts of mylonite and gneiss. These deposits grade eastward fairly abruptly into gravel and conglomerate that contain abundant clasts of Miocene limestone and volcanic rocks. On the southwest side of the fault sliver, a similar lateral change in the detrital composition of unit QTg is displaced about 850 m to the west. On this basis we infer that the combined lateral displacement of faults C, D, and E has been no greater than about 850 m since deposition of unit QTg. Evidence described shortly indicates there has been little displacement on fault E, so that most of the lateral displacement across the fault sliver probably was produced by movement on faults C and D. We suspect that the greatest amount of displacement occurred on fault C, because the previously mentioned west-southwest-trending aeromagnetic ridge near the Marine Corps Firing Range does not appear to be significantly offset where it is intersected by fault D.

Fault D

Fault D splays off from fault C directly north of the Mojave River, in NE1/4 NW1/4 sec. 11, T9N, R1W. Southeast of this point, fault D is only approximately located. We have extended it to the southeastern border of the map on the basis of a direct-current resistivity survey conducted along Ord Mountain Road directly southeast of the map area (A. Zohdy, written commun., 1992). Based on this survey, there appears to be a major lateral discontinuity in rock types at depths greater than about 400 m. This apparent structural break is not precisely located but lies somewhere beneath N1/2 sec. 29, T9N, R1E. Additional evidence for the continuation of fault D southeast of the area of the map includes a northwest-trending air-photo lineament southeast of Ord Mountain Road, in NW1/4 sec. 33, T9N, R1E. This lineament appears to be a fault that cuts deposits of the gravel and conglomerate unit (QTg) but does not disturb younger alluvial deposits correlated with units Qa_2 and Qa_3. We have not found any evidence of Holocene displacement on fault D.

Fault E

As was mentioned previously, fault E bounds the northeast side of the faulted sliver of early Miocene rocks north of the Mojave River. The orientation of the fault plane is quite variable, dipping alternately to the southwest and northeast at moderate to steep angles (56-90°). Map patterns suggest that the fault has minimal lateral and vertical displacement north of the Mojave River. For example, a diabase intrusion (unit Tbi) near the north edge of the map apparently is not significantly offset by the fault, and units of limestone and sedimentary breccia within the fault sliver probably correlate with nearby rocks on the east side of the fault. Gently dipping beds of gravel and conglomerate (unit QTg) on the northeast side of the fault have dropped a small amount, probably less than 100 m, relative to the rocks of the fault sliver. Northeast-dipping strata within unit QTg tend to steepen southwestward approaching the fault, which may reflect drag folding caused by down-to-east vertical slip on the fault. The fault apparently is overlain by undisturbed Pleistocene alluvium (unit Qa2) directly north of the Mojave River, which suggests that its displacements occurred during or before Pleistocene time.

The location of fault E is poorly constrained along the Mojave River southeastward from the fault sliver. Its position south of the river, at the east edge of the map area, is inferred from resistivity data (A. Zohdy, written commun., 1992) and aeromagnetic data (U. S. Geological Survey, 1987). These data suggest that the southwest side of the fault has dropped relative to the northeast side. The contour patterns on the aeromagnetic map allow for only a minor amount of right-lateral displacement, not exceeding about 150-175 m. What may be the same fault crops out again 6-9 km southeast of Daggett, in sec. 6, T8N, R2E, where it offsets several ridges of gravel and conglomerate (correlated with unit QTg) about 150 m in a right-lateral sense.

Minor Faults

Several minor northwest-trending faults were mapped locally on either side of the zone of through-going faults. Two closely spaced right-lateral faults lie southwest of the Nebo Annex, in N1/2 sec. 22, T9N, R1W. These faults offset the crest of a small ridge of gravel and conglomerate (unit QTg) about 30 m and 55 m, respectively, indicating a combined right-lateral displacement of about 85 m. The age of displacement could be either Holocene or late Pleistocene.

Five northwest-trending faults cut lower Miocene rocks north of the Mojave River in NW1/4 sec. 12, T9N, R1W, near the northeast corner of the Nebo Annex. From west to east, the faults show right-lateral strike separations of about 30 m, 100 m, 125 m, 35 m, and 10 m, amounting to an aggregate separation of about 300 m. These faults generally resemble the other northwest-trending faults, dipping steeply (65-90°) to both the northeast and southwest. We suspect they are strike-slip faults and genetically related to the other faults. They apparently are older than the other faults, however, because they do not cut unit QTg. They seem to represent the earliest local strike-slip faulting and may help to date the initiation of the regional strike-slip fault zone once the age of unit QTg is better established.

A fault that dips moderately to steeply southward and trends northwestward through the center of sec. 2 T9N, R1W, due north of the Nebo Annex, may represent the northwest continuation of this relatively old zone of strike-slip faulting. Like its counterparts to the southeast, this fault is buried by unit QTg. Thick west-dipping units of limestone and felsite are repeated across the fault. The observed stratigraphic offsets could have been produced either by right-lateral strike slip or by down-to-north reverse slip on the fault.

Aggregate Slip on the Fault Zone

The total amount of right-lateral shear across the entire zone of northwest-trending strike-slip faults can be estimated by summing the displacements determined for individual faults. As we have shown, two of the five major strands, faults B and C, jointly account for about 2.4 km of lateral slip, as inferred from an offset aeromagnetic anomaly. Offset ridges along fault E southeast of the map area indicate a lateral slip of 0.15 km. Minor faults mapped east and west of the main fault zone account for an additional 0.38 km of lateral slip. The sum of these individual measurements is about 2.9 km. The total lateral slip probably is greater than this, however, because we have not been able to estimate the lateral slip on faults A and D.

Nevertheless, the observed aggregate slip of 2.9 km probably represents as much as 70 to 75 percent of the total slip across the fault zone, judging from estimates that have been given for the slip of the Camp Rock fault and Harper Lake fault on opposite sides of the map area. In the western Newberry Mountains and Rodman Mountains, 10-30 km southeast of the Nebo Annex, the total lateral displacement on the Camp Rock fault has been estimated to be approximately 4.0-4.5 km (Dokka, 1983, table 1; Cox and others, 1987, p. 19-22). Other workers have estimated about 3-4 km of lateral slip on the Harper Lake fault north of Barstow (Bartley and others, 1992). The full displacements determined in these neighboring areas to the southeast and northwest presumably are translated across the Mojave River, which requires the total lateral displacement near the Nebo Annex to be about 4 km.

Summary and Conclusions Regarding Northwest-trending Faults

In summary, our work shows that the Harper Lake and Camp Rock faults are linked by several newly recognized fault segments that cross the Mojave River at the MCLB Nebo Annex. These faults are mainly characterized by right-lateral strike-slip displacement. The cumulative lateral slip across the entire zone is at least 2.9 km and may be as great as 4 km. Most of the faults also show evidence of vertical displacement. In particular, faults B, C, D, and E show significant vertical offsets along the north side of the Mojave River. An older, largely buried, fault slightly farther north, passing through the center of sec. 2, T9N, R1W, may also have a significant vertical component of slip. Vertical displacements on these faults probably were produced by local convergence (transpression) that results where fault segments locally trend west-northwest, counterclockwise of the northwest regional trend of the larger fault zone. As a result of such vertical movements, gravel and conglomerate of unit QTg are dropped on both sides of a narrow sliver of lower Miocene rocks on the north side of the Mojave River. A 90-m-high east-facing escarpment near the Marine Corps Firing Range apparently formed in conjunction with displacements on faults B and C. The topographic relief across this feature can be attributed to horizontal offset of a north-sloping alluvial surface, combined with warping of unit QTg adjacent to the faults.

Our studies indicate that strike-slip faulting began prior to deposition of unit QTg, perhaps as early as late Miocene time, and has continued into the Holocene. Most of the fault strands crossing the Mojave River probably were last active during the Pleistocene. The most recent displacements have occurred on fault C. This fault is technically active, having moved during Holocene time.

Several of the faults, particularly strands A, B, and C, pass beneath buildings and other man-made structures on the Nebo Annex. Any of the faults could produce damaging ground ruptures and strong shaking if reactivated during a future earthquake. Because it has moved most recently, fault C presumably poses the greatest risk of such earthquake hazards. Fault C also warrants special consideration in the context of toxic waste cleanup operations and other geotechnical activities, because it affects the flow of shallow ground water beneath the Nebo

Annex. Some of the other faults may influence water quality and flow patterns within deeper aquifers. New studies planned for 1993, including geologic mapping, resistivity surveys, and fault-trenching, will provide more detailed information about the history of faulting and will yield more precise locations for fault segments that are concealed by alluvium.

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APPENDIX 1

DESCRIPTION OF MAP UNITS

Qs — Sand dunes (Holocene)--fine sand and silt of eolian origin; deposits located along north edge of active Mojave River channel.

Alluvium of Mojave River (Holocene)--Light-gray fluvial sand and pebble gravel. Composed predominantly of far-travelled granitic detritus. Locally derived debris of Mesozoic and Tertiary volcanic rocks present in lesser amounts. Divided into:

Qm2 — Unit 2--Alluvial deposits with little or no plant cover, forming floor of active river channel.

Qm1 — Unit 1--Alluvial deposits with moderate plant cover, forming sand bars and low stream terraces that lie less than 2 m above the floor of active river channel.

Alluvial-fan deposits (Holocene to Pliocene)--Sand and gravel of alluvial-fans and associated stream channels. Fluvial deposits are dominant, locally interbedded with debris-flow deposits. Color ranges from light gray to light brown. Gravel typically is compositionally heterogeneous, containing clasts of volcanic, plutonic, metamorphic, and sedimentary rocks that generally resemble Mesozoic and Tertiary rocks exposed within and near the area of this map. The alluvial-fan deposits are assigned to the following several units on the basis of geomorphic expression and degree of weathering:

Qa4 — Unit 4 (Holocene)--Alluvium of active stream channels and adjacent low-lying areas. Deposits are unweathered, lacking obvious soil development, desert pavements, or varnish on exposed clasts.

Qa3 — Unit 3 (Holocene and Pleistocene)--Undissected to slightly dissected alluvial deposits mostly lying < 1-2 m above the floors of active stream channels. Deposits are moderately to well covered by shrubs and exhibit coarse bar-and-swale texture where coarse alluvium is available. Generally unweathered, but oldest deposits locally show incipient soil development and thin coatings of varnish on clasts. Includes Qa4 alluvium where active channels are too small to map separately. Locally divided into:

Qa3b — Subunit 3b--Alluvial deposits with coarse bar-and-swale texture; subject to sporadic flooding; no conspicuous soil development or varnish on exposed clasts.

Qa3a — Subunit 3a--Alluvial deposits with coarse bar-and-swale texture; rarely flooded, standing higher above active washes than deposits of subunit 3b; weak to moderate soil development and varnish on exposed clasts.

Qa2 — Unit 2 (Pleistocene)--Moderately dissected deposits of stream terraces and inactive areas of alluvial-fans, lying about 1-6 m above active stream channels; locally grades laterally into alluvial and colluvial aprons on adjacent hill slopes. Sparsely covered with shrubs. Upper surface of deposits exhibits tight pavement of moderately to well varnished clasts. Conspicuous soil development includes vesicular A horizon as much as 3 cm thick, and argillic B horizon.

[QTa1] Unit 1 (Pleistocene and Pliocene?)--Strongly dissected alluvial deposits lying about 5-10 m above active stream channels. Soils and pavements spotty or absent, having been largely stripped off by erosion. Surface clasts locally are weakly varnished.

[QTg] Gravel and conglomerate (Pleistocene? to Miocene?)--Profoundly dissected thick deposits of slightly to moderately indurated gravel and conglomerate lying as much as 75 m above the floors of active stream channels. Consists of interbedded fluvial and debris-flow deposits. Matrix of grayish-orange to grayish-orange-pink pebbly sand. Clast compositions variable, commonly include Tertiary limestone and volcanic rocks and Mesozoic plutonic and volcanic rocks. Clasts of gneiss and mylonitized plutonic rocks are abundant locally in the northwest part of the map area. Abundant buried soils within the unit are represented by thick petrocalcic horizons. Ridge crests commonly retain remnants of a formerly widespread pediment surface marked by moderately varnished pavements. The deposits have been conspicuously deformed; they are cut by faults and locally tilted as much as 60-70 degrees. Locally divided into:

[Tga] Andesitic gravel and monolithologic breccia (Pliocene? or Miocene?)--Polymict gravel and conglomerate containing abundant clasts of brownish-gray to olive-brown porphyritic andesite, probably derived from Miocene rocks. Matrix consists of grayish-orange-pink pebbly sand. Locally includes lenses of monolithologic breccia composed of blocks of andesite, limestone, or granodiorite; restricted to a small area north of the Mojave River and southwest of the Harper Lake fault, where it apparently is conformably overlain by the main part of the gravel and conglomerate unit.

[Tre] Rhyodacite of Elephant Mountain (Miocene)--Pale-red to gray porphyritic rhyodacite, containing small phenocrysts of plagioclase, hornblende, and biotite in an aphanitic groundmass. Forms large irregularly shaped shallow intrusive bodies (plugs and domes) near northeast corner of map area, and a small dike in the central part of the map area.

[Trb] Rhyodacitic breccia and sandstone (Miocene)--Crudely bedded to well-bedded breccia and sandstone composed entirely of fragments of porphyritic rhyodacite identical to the rhyodacite of Elephant Mountain, which is intrusive into the breccia and sandstone. The breccia and sandstone apparently were derived from pyroclastic equivalents of the rhyodacite of Elephant Mountain that were reworked by fluvial and mass-wasting processes.

[Tai] Intrusive andesite (Miocene)--Brownish-gray or olive-gray porphyritic andesite with aphanitic groundmass; locally brecciated. Forms several small dikes and plugs.

Tbi — Intrusive basalt (Miocene)--Dark-gray to olive-gray olivine-bearing basalt and diabase; fine to coarse grained; mainly structureless and dense, but locally vesicular or amygdaloidal. Extensively weathered to soft grayish-orange or grayish-olive-green earthy material containing isolated cores of fresh basalt or diabase. Forms numerous dikes and sills that intrude other Miocene rock units in the hills north of Mojave River; may include extrusive basalt locally, in E1/2 sec. 11 and W1/2 sec. 12, T9N, R1W.

Tfi — Intrusive felsite (Miocene)--Grayish-red-purple to pale-red-purple aphanitic silicic volcanic rock containing sparse small flakes of biotite. Pervasively laminated and autobrecciated. Composition not determined, but probably in range of rhyolite to dacite. Locally hydrothermally altered to very light gray montmorillonitic clay. Forms small body that intrudes limestone and sedimentary breccia in SE1/4 NE1/4 sec. 11, T9N, R1W.

Sedimentary and volcanic rocks (Miocene)--A thick sequence of terrestrial sedimentary and volcanic rocks, including fluvial and lacustrine deposits, debris-flow and landslide breccia, tuff, and silicic volcanic rocks. Divided into:

Tsc — Conglomerate and sandstone--Interbedded reddish-brown to pinkish-gray conglomerate, breccia, sandstone, and minor siltstone and claystone. Consists mostly of fluvial and debris-flow deposits. Locally includes lenticular bodies of granitic landslide or avalanche breccia, sparse thin beds of tuff breccia, and rare thin limestone beds. Sandstone is arkosic; conglomerate clasts dominantly granitic with subordinate amounts of Mesozoic volcanic and metamorphic rocks, diabase, and vein quartz; clasts in some beds dominated by Mesozoic volcanic rocks.

Tsl — Limestone--Thin-bedded to thick-bedded micritic limestone, locally grading into calcareous sandstone, silty marlstone, and carbonaceous siltstone. Limestone typically is yellowish brown or brownish gray on fresh surfaces, and weathers yellowish gray or grayish orange; commonly contains chert lenses; algal laminations present locally. Much of the limestone consists of resistant, ridge-forming bodies with slabby or blocky structure; locally nonresistant with shaly or flaggy cleavage.

Tss — Sandstone--Well-bedded fine-grained to coarse-grained sandstone and subordinate siltstone and claystone; locally pebbly. Weakly to moderately indurated; generally nonresistant. Dominant rock type is grayish-orange or yellowish-gray volcaniclastic sandstone containing abundant grains of felsite. Subordinate biotite-rich arkosic sandstone shows a broad range of colors, including yellowish gray, pinkish gray, reddish brown, and greenish gray. Tuffaceous sandstone present locally. Deposits have fluvial lamination, cross-lamination, and channeling.

Tssl — Sandstone and limestone--Deposits of interbedded sandstone and limestone. Rock types same as those mapped separately in the sandstone and limestone units.

Tst — Tuff--Mainly ash tuff, but locally abundant tuff breccia; locally contains moderate amounts of interlayered tuffaceous sandstone. Most deposits are white or yellowish gray; locally pinkish gray, purplish gray, or greenish gray. Biotite flakes commonly present in small amounts. The tuff ranges from structureless to prominently laminated; probably includes air-fall tuff and reworked stream-deposited tuff.

Tsb — Sedimentary breccia--Structureless or very thick bedded deposits composed of angular, pebble- to boulder-size clasts with very sparse to abundant matrix. Where abundant, matrix consists of reddish-brown to reddish-orange pebbly sandstone composed of same material as larger clasts. Breccia forms lenticular bodies as much as several tens of meters thick that are typically composed of a single clast type or very limited range of clast types. Most are composed of debris from gray or greenish-gray silicic to intermediate volcanic rocks; clasts of granitic rocks are abundant locally. Volcanic and plutonic clasts resemble Mesozoic rocks exposed in mountain ranges 10-30 km south of the Mojave River. Matrix-poor deposits probably represent large landslides or rock avalanches; matrix-rich breccia was deposited as debris flows.

Tsfr — Red felsite--Grayish-red-purple to pale-red-purple aphanitic silicic volcanic rocks; typically flow-laminated and extensively autobrecciated. Aphyric to slightly porphyritic. Where porphyritic, contains sparse small phenocrysts of plagioclase and biotite. Composition not determined, but probably in range of rhyolite to dacite. Forms several tabular or lenticular bodies within the lower and central parts of the local Miocene succession; locally interlayered with deposits of ash tuff. May include sills as well as flows.

Tsft — Tan felsite--Grayish-orange to very pale orange and pale-pink aphanitic silicic volcanic rocks of inferred rhyolite to dacite composition. Forms tabular to lenticular bodies that are texturally, structurally, and mineralogically identical to rocks of the red felsite subunit, but are more altered; locally contains irregular zones of red-purple felsite from which the tan felsite was apparently formed by weathering.

Tstb — Tuff breccia and felsite flows--Interbedded tuff breccia, autobrecciated felsite flows, and minor amounts of ash tuff and felsitic debris-flow breccia. Coloration generally pale, ranging from medium or light gray to pinkish gray to pale red-purple.

Trc — Red conglomerate and sandstone (Miocene or Oligocene)--Well bedded fluvial conglomerate, sandstone, and minor siltstone; slightly to moderately indurated. Unit crops out in two separate areas: eastern outcrops northwest of Elephant Mountain consist of discontinuous thin deposits of lithic sandstone and pebbly lithic sandstone that rest on metavolcanic rocks; western outcrops due north of the Nebo Annex consist of thicker deposits of interlayered arkosic sandstone and cobble conglomerate that overlie quartz diorite in NE 1/4 sec. 2, T9N, R1W. Sandstone and sandy matrix of conglomerate are mainly pale red to grayish red, locally with light-gray or light-greenish-gray streaks and mottles. Conglomerate contains subangular to well rounded pebbles, cobbles, and sparse small boulders as much as 50 cm in diameter.

Polymict clast assemblage includes grayish-red-purple felsite that resembles Miocene rocks mapped here as the red felsite unit. Equally abundant are clasts of plutonic rocks and diverse porphyritic volcanic rocks; these igneous clast types resemble Mesozoic rocks that are widespread in the central and southern Mojave Desert. The deposits are moderately to intensely weathered. The most pronounced weathering is found within the eastern outcrop area, where lithic sandstone is strongly altered to clay. Quartz diorite and metavolcanic rocks that directly underlie the clastic rocks are locally weathered to grayish-red grus.

KJqd Quartz diorite (Cretaceous or Jurassic)--Medium-grained to coarse-grained biotite quartz diorite, locally grading into quartz monzonite, tonalite, and granodiorite. Typical rock is medium gray, hypidiomorphic granular, with 10-15 percent quartz and 15-20 percent biotite. Locally contains large inclusions of dark-gray plutonic rock that is relatively rich in mafic minerals.

Mzv Metavolcanic rocks (Mesozoic)--Extrusive and pyroclastic rocks, including abundant silicic flows and ash-flow tuff, interlayered with sparse flows or sills of andesite or basalt. Indurated siltstone, sandstone, and conglomerate locally present in minor amounts. A weak to prominent tectonic cleavage generally lies nearly parallel to steeply dipping lithologic layering. Some rocks are seriticized; many others may contain metamorphic epidote and chlorite, judging from their greenish coloration; sparse veins of white quartz as much as 5 cm thick are present locally. The unit is shattered by abundant faults and fractures and contains numerous irregular zones of argillic and limonitic alteration. Mylonitic rocks locally present within narrow, northeast-trending steeply dipping shear zone near northwest end of outcrops.

APPENDIX 2

GEOLOGIC TIME CHART

EON	ERA	PERIOD		EPOCH	AGE ESTIMATES OF BOUNDARIES (in Ma)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	~570[1]
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				(3800 ?)
pre-Archean[2]					4550

[1]Rocks older than 570 Ma also called Precambrian, a time term without specific rank.

[2]Informal time term without specific rank.