

**GEOLOGIC MAP OF THE EL PASO MOUNTAINS WILDERNESS STUDY AREA,
KERN COUNTY, CALIFORNIA**

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STUDIES RELATED TO WILDERNESS

Bureau of Land Management Wilderness Study Areas

The Federal Land Policy and Management Act (Public Law 94-579, October 21, 1976) requires the U.S. Geological Survey and the U.S. Bureau of Mines to conduct mineral surveys on certain areas to determine the mineral values, if any, that may be present. Results must be made available to the public and be submitted to the President and the Congress. This report presents the results of a geologic survey of the El Paso Mountains Wilderness Study Area (CDCA-164), California Desert Conservation Area, Kern County, California.

ABSTRACT

The El Paso Mountains Wilderness Study Area (CDCA-164) encompasses 13,252 acres of mountainous desert land located approximately 10 mi southwest of Ridgecrest, Calif. A geologic survey of the study area included new geologic mapping, radiometric dating, and geochemical studies. The area is underlain by Cenozoic sedimentary and volcanic rock units ranging from Paleocene to Holocene in age. In ascending order these rock units are: the Paleocene and Eocene Goler Formation; the Miocene Ricardo Formation of Dibblee (1952); the Miocene Black Mountain Basalt; and Quaternary alluvium and landslide deposits. These rock units preserve an extensive record of tectonism, volcanism, and sedimentation near the southwest corner of the Basin and Range province. This record shows that the structural boundary between the southwestern Basin and Range and Mojave Desert, now occupied by the Garlock fault zone, has been an important tectonic boundary throughout the Cenozoic Era. Vertical movements predominated on this boundary throughout most of the Cenozoic, whereas the strike-slip regime of the modern Garlock fault zone apparently did not develop until late Miocene time.

The sedimentary basin of the Goler Formation, containing as much as 13,050 ft of continental sediments, subsided astride the structural zone during Paleocene and Eocene time. Pronounced tectonic subsidence of the basin ultimately resulted in a marine incursion and deposition of fossiliferous mudstone near the top of the formation. The Goler Formation was tilted northward and eroded to a nearly featureless plain before early Miocene time, probably in concert with major uplift of the Mojave Desert block on the south side of the structural zone.

During Miocene time, the Ricardo Formation of Dibblee (1952) and the Black Mountain Basalt were deposited in a new basin that subsided on the north side of the structural zone. The Ricardo Formation consists of three lithostratigraphic units of potential formational rank that are herein informally designated the lower, middle, and upper parts of the Ricardo Formation. Deposition of the lower part of the Ricardo Formation began before or during early Miocene time when coarse-grained alluvial-fan deposits (the conglomerate unit of Bonanza Gulch) were shed northward from the Mojave Desert block. This basal conglomerate unit is overlain by subalkaline volcanic rocks, including basalt, andesite, dacite, and silicic tuff, that have yielded radiometric ages of 18.1 ± 1.2 m.y. (andesite breccia unit) and 17.2 ± 0.8 m.y. (andesite flows unit). The Black Mountain Basalt, formerly considered to be Pleistocene in age, is determined to be Miocene on the basis of its stratigraphic relations with the Ricardo Formation; this

age assignment is confirmed by four potassium-argon ages ranging from 15.1 ± 0.5 m.y. to 17.9 ± 1.6 m.y. The Black Mountain Basalt is chemically distinctive, consisting of potassium-poor high-alumina basalt that is transitional between tholeiitic basalt and alkali-olivine basalt. The basalt was erupted mostly from east-west fissures, reflecting north-south extension between the Mojave Desert block and southwestern Basin and Range during early and middle Miocene time.

The middle part of the Ricardo Formation was deposited disconformably upon the Black Mountain Basalt and the lower part of the Ricardo Formation during middle and late Miocene time. The deposits are composed of granitic and volcanoclastic detritus derived from the Mojave Desert block. Lacustrine mudstone is predominant within the area of the map but gives way to alluvial-fan sandstone and conglomerate southwest of the map area. The upper part of the Ricardo Formation consists of granitic alluvial-fan deposits that were shed eastward from the southern Sierra Nevada, beginning about 8 m.y. ago during late Miocene time. These deposits are correlated temporally with the Kern River Formation on the west side of the southern Sierra Nevada. They indicate uplift of the Sierra Nevada along its eastern frontal fault, and thus are the first clear record of east-west extension near the southwest corner of the Basin and Range province.

East-west extension north of the Garlock fault continued from late Miocene to Quaternary time and is represented by down-faulted Miocene strata west and east of Black Mountain and by westward dipping Miocene strata and eastward-dipping low-angle faults near the southwest corner of the map area. Deep erosion along the margins of the Black Hills during Quaternary time has promoted numerous landslides, including large blocks of strata and sheets of monolithologic rubble that have slid parallel to bedding.

INTRODUCTION

Location and Physiography

The El Paso Mountains Wilderness Study Area (CDCA-164) is located on the north flank of the El Paso Mountains between California Highway 14 and U.S. Highway 395 approximately 10 mi southwest of Ridgecrest, Calif. (see index map). Lowlying areas adjacent to the study area are accessible by infrequently maintained dirt roads and jeep trails, but no roads or trails extend into the interior. The study area encompasses 13,252 acres of sparsely vegetated mountainous terrain, including Black Mountain and most of the Black Hills. Elevations range from approximately 2,800 ft in Little Dixie Wash at the north edge of the study area to 5,244 ft at Black Mountain. The Black Hills consist of gently sloping tableland dissected by narrow canyons that drain mostly toward the north and west. Areas of lower elevation include deeply gullied badlands east of the Black Hills and small alluvial fans along the northwest foot of the Black Hills.

Geologic Setting

The El Paso Mountains lie in the southwest corner of the Basin and Range Province, between the Garlock and Sierra Nevada faults. The El Paso fault, a high-angle normal fault that merges eastward with the Garlock fault, uplifted

the range relative to Fremont Valley. The Garlock fault is a major regional strike-slip fault with a cumulative Cenozoic left-lateral displacement of 30 to 40 mi (Smith, 1962; Smith and Ketner, 1970). Much of this displacement may have occurred during the past 5.5 m.y. (Carter, 1982). Late Cenozoic movements on the Sierra Nevada fault uplifted the southern Sierra Nevada relative to the El Paso Mountains.

Pre-Tertiary plutonic and metamorphic rock units, which form the core of the El Paso Mountains, lie immediately southeast of the study area. One of these units, the Garlock assemblage (Carr and others, 1984), extends into the southeast corner of the map area. The Garlock assemblage consists of Ordovician to Permian eugeoclinal sedimentary and volcanic rocks that have been intensely folded, faulted, and metamorphosed to the greenschist facies. Outside the map area, Permian and Triassic as well as younger Mesozoic plutons intrude the Garlock assemblage.

Tertiary sedimentary and volcanic rocks and Quaternary alluvial deposits unconformably overlie the pre-Tertiary rocks to the south and cover the entire study area. Three Tertiary rock units are present: the Goler Formation of Paleocene and Eocene age; the Ricardo Formation of Dibblee (1952) of Miocene age; and the Black Mountain Basalt, also of Miocene age. Quaternary deposits include large alluvial fans that extend eastward from the Sierra Nevada and smaller alluvial and landslide deposits that radiate outward from Black Mountain and the Black Hills.

Previous Studies

Dibblee (1952, 1959) mapped two 15-minute quadrangles that encompass the area of this map; his quadrangle maps have been incorporated in small-scale geologic maps of the Trona 1° by 2° quadrangle (Jennings and others, 1962) and western Mojave Desert (Dibblee, 1967). The local geology is also shown on reconnaissance maps accompanying water-resource reports (Moyle, 1963; Kunkle and Chase, 1969). Cox (1982a, pl. 1) mapped southern and eastern parts of the map area in detail as part of an investigation of the Goler Formation; this mapping has been revised and incorporated in the present map.

Conventions

Field and petrographic classification of plutonic and volcanic rocks conforms to the recommendations of the International Union of Geological Sciences Subcommittee on the Systematics of Igneous Rocks, as follows: plutonic rocks--Streckeisen (1976); volcanic rocks--Streckeisen (1979); pyroclastic rocks--Schmid (1981). Chemical classification of volcanic rocks follows the system of Irvine and Baragar (1971). Potassium-argon ages originally calculated with old constants are herein recalculated with new constants using Table 2 of Dalrymple (1979).

Acknowledgements

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STRATIGRAPHY

Five major lithostratigraphic units separated by unconformities are present in the map area (rock-unit symbols used in this pamphlet refer to large map on accompanying sheet). These units are the Paleozoic Garlock assemblage, Paleocene and Eocene Goler Formation, Miocene

Ricardo Formation of Dibblee (1952), Miocene Black Mountain Basalt, and Quaternary deposits.

Garlock Assemblage

The Garlock assemblage (Carr and others, 1984), which comprises the Mesquite Schist and Garlock Formation of former usage (Dibblee, 1952, 1967), consists of eugeoclinal metasedimentary and metavolcanic rocks that form the main ridge of the central El Paso Mountains. The unit has been folded isoclinally, metamorphosed to the greenschist facies, and tilted to form a northeast-dipping structural homocline. The Garlock assemblage ranges in age from Ordovician to Permian. The unit has many members (Dibblee, 1952, 1967; Christiansen 1961, 1962; Carr and others, 1984), but these were not mapped during the present investigation, which focuses on the overlying Cenozoic rock units.

Goler Formation

The Goler Formation consists predominantly of non-marine clastic sedimentary rocks, including cobble and boulder conglomerate, pebbly sandstone, siltstone, and minor amounts of sedimentary breccia; in addition, deposits of marine mudstone occur near the top of the formation. The Goler Formation overlies an irregular, deeply channelled erosion surface cut into pre-Tertiary rocks. The formation dips gently toward the north and northwest.

Dibblee (1952) named the Goler Formation after Goler Gulch, which is located near the southeast corner of the map area (see index map). He divided the formation into two informal members 1 and 2, and he designated a type section that extends northward from Goler Gulch to the east side of the Black Hills. Cox (1982a) conducted a more detailed study of the Goler Formation, which is the basis for the seven informally designated units shown on the map and for the following general description of the formation.

The Goler Formation is approximately 13,050 ft thick as measured from the deepest part of its channelled base near Last Chance Canyon (southwest of map area), but it thins northeastward to about 7,900 ft as measured from the base near Goler Gulch (thicknesses revised from those of Cox, 1982a). There apparently are no significant unconformities within the formation. The Goler Formation consists of two major lithostratigraphic sequences: (1) a lower upward-fining sequence derived mostly from granitoid rocks and eugeoclinal metasedimentary rocks; and (2) an overlying westward-fining sequence derived from silicic metavolcanic rocks, quartzite, and granitoid rocks. The boundary between these two sequences is stratigraphically higher than the contact between Dibblee's (1952) members 1 and 2. The lower sequence consists of the sedimentary breccia unit of Holland Camp (Tgh, equivalent to part of Dibblee's member 1), the lower sandstone and siltstone unit (Tgsl, equivalent to the lower part of Dibblee's member 2), and additional units south of the map area. The upper sequence consists of the conglomerate and sandstone unit of Sheep Spring, the upper sandstone and siltstone unit, and the conglomerate unit of Black Hills (Tgs, Tgsu, and Tgb, respectively, which together are equivalent to the upper part of Dibblee's member 2).

The two lithostratigraphic sequences accumulated on separate fluvial paleoslopes that occupied different regions of the Goler sedimentary basin. The lower sequence consists of fluvial channel deposits, floodplain deposits, and minor debris-flow deposits that accumulated on alluvial plains, alluvial fans, and canyon-mouth embayments that formed a southward-sloping piedmont adjacent to the mountainous northern margin of the basin. The upper sequence consists of channel and floodplain deposits of a westward-flowing braided river that occupied the axial region of the basin directly south of the piedmont slope. The superposition of the two sequences indicates that the braided-river plain expanded northward across part of the piedmont slope as the basin subsided. Layers of cobble conglomerate (subunit Tgslc) in the lower sandstone and siltstone unit represent brief northward excursions of the braided-river plain predating this

major northward expansion. Deposits of distinctive pale-yellowish-gray mudstone (subunit Tgbm) that are intercalated within the conglomerate unit of Black Hills were originally interpreted to be lake deposits (Cox, 1982a, p. 139), but are now known to be marine on the basis of microfossils and a pelecypod fossil found during the present study. The mudstone was deposited in an arm of the ancestral Pacific Ocean that temporarily flooded the braided-river valley as basin subsidence climaxed late in Goler time.

The aforementioned facies and paleocurrent patterns suggest that the east-west-trending axis of the Goler sedimentary basin lay south of the El Paso Mountains and that the basin subsided astride an area now occupied by the Garlock fault zone (Cox, 1982a, p. 104-106). Correlative sedimentary strata have not been located south of the fault zone, however; such strata deposited on the south side of the Goler basin presumably were eroded away during uplift of the Mojave Desert block between Eocene and Miocene time.

Fossils discovered within the past three decades indicate that the middle part of the Goler Formation is Paleocene and that the uppermost part is Eocene. Bones and teeth of middle Paleocene (Torrejonian) mammals have been found in the middle part of the Goler Formation (McKenna, 1955, 1960; West, 1970). The fossil mammals, specifically multituberculates and condylarths, occur together with chelonian and crocodylian remains in the conglomerate and sandstone unit of Sheep Spring and in the upper sandstone and siltstone unit. During the present study, marine dinoflagellates, foraminifers, and a pelecypod were found near the top of the Goler Formation, all occurring in the mudstone subunit within the conglomerate unit of Black Hills. The dinoflagellates, reported by Cox and Edwards (1984), consist predominantly of *Deflandrea* cf. *dartmooria*, a form that is particularly common in the Paleocene but which has also been reported in the early Eocene (Williams and Bujak, 1977). A single poorly preserved pelecypod fossil resembles the genus *Lucinoma*, whose oldest recorded occurrence is late Eocene (E. J. Moore, written commun., 1984). Benthic foraminifers indicate an early Eocene (Penutian) age for the mudstone subunit (K.A. McDougall, written commun., 1985), and planktic foraminifers likewise indicate an early Eocene age (foraminifer zone P8 or P9) for a sample collected near the base of the mudstone subunit (G. Keller, oral commun., 1985). The combined fossil evidence indicates that the mudstone subunit is Eocene in age, rather than Paleocene as suggested earlier (Cox and Edwards, 1984).

The lower part of the Goler Formation, comprising the lower sandstone and siltstone unit and underlying units, is poorly dated. An Eocene age was originally proposed on the basis of fossil leaves in the lower sandstone and siltstone unit at Colorado Camp (F. H. Knowlton, cited by Fairbanks, 1896; Axelrod, 1949), but this age was proven too young when Paleocene mammals were found higher in the formation. We presume that all of the lower part of the Goler Formation is Paleocene in age; however, we cannot rule out the possibility that latest Cretaceous deposits might be present near the base of the formation.

The Goler Formation may be temporally correlative with the lower Tertiary Witnet Formation, which crops out at several places in the southern Sierra Nevada and northern Tehachapi Mountains approximately 20 to 40 mi southwest of the map area. The Witnet Formation consists of poorly dated nonmarine sandstone and conglomerate that rest nonconformably upon Mesozoic plutonic rocks and that are in turn unconformably overlain by pyroclastic deposits of the middle Miocene Kinnick Formation (Dibblee, 1967; Dibblee and Louke, 1970). Potential correlation of the Goler and Witnet Formations is suggested by lithologic similarity, proximity, and analogous structural setting directly northwest of the Garlock fault.

Ricardo Formation of Dibblee (1952)

The Ricardo Formation of Dibblee (1952) is a heterogeneous unit of nonmarine sedimentary and volcanic rocks which consists of conglomerate and sandstone, mudstone, tuff, and intermediate and mafic flows. The

Ricardo Formation forms a broad west-dipping homocline that extends from the El Paso Mountains to the Sierra Nevada fault. An angular unconformity separates the Ricardo Formation from underlying north-dipping strata of the Goler Formation. The unconformity is approximately parallel to bedding in the Ricardo Formation.

Merriam (1913, 1919) casually applied the terms "Ricardo beds", "Ricardo Formation", and "Ricardo Group" to deposits located in Red Rock Canyon near the now long-abandoned townsite of Ricardo, approximately 6 mi southwest of the map area of this report (see index map). Dibblee (1952, 1954, 1967) published the first comprehensive descriptions of the Ricardo Formation. He divided the formation into eight informal members and designated a type section extending from Last Chance Canyon westward across Red Rock Canyon to the Sierra Nevada. The thickness of this section was originally estimated to be approximately 7,000 ft (Dibblee, 1952), but was later revised to 5,700 ft (Dibblee, 1967).

Eleven informal units and subunits were mapped within the Ricardo Formation during the present investigation. Each of these can be correlated with greater or less certainty to a particular member or unmapped subunit denoted by Dibblee (1952), as indicated in the accompanying unit descriptions. The present investigation, in combination with other recent studies (Whistler, 1969; Cox, 1982a; Loomis and others, 1983; Loomis, 1984), indicates that the eleven units and subunits can be grouped into three major stratigraphic subdivisions that are herein termed the lower, middle, and upper parts of the Ricardo Formation. Each of these three subdivisions is represented by deposits in the map area. Differences in age and lithology between the three subdivisions provide reasonable criteria for eventual partitioning of the Ricardo Formation into new formal rock units; however, pending completion of ongoing stratigraphic studies southwest of the map area, the name Ricardo Formation is applied to all three subdivisions in this report.

The lower part of the Ricardo Formation, equivalent to Dibblee's members 1 and 2, consists of the conglomerate unit of Bonanza Gulch (Trbg) and an overlying volcanic sequence. The coarse-grained angular rock detritus that constitutes the conglomerate unit of Bonanza Gulch was deposited by north-west-flowing streams. The unit probably formed as alluvial fans that grew in response to strong relative uplift of a mountainous region located southeast of the map area. The Goler Formation and pre-Tertiary rocks resembling those presently exposed in the El Paso Mountains contributed some of the detritus in the conglomerate unit of Bonanza Gulch, but the abundant granitic detritus in the unit was derived largely from an unidentified bedrock source terrane that probably was located south of the El Paso Mountains in the Mojave Desert region. This source terrane probably was uplifted relative to the El Paso Mountains along an ancient structural zone located near the present position of the Garlock fault zone.

The volcanic sequence that overlies the conglomerate unit of Bonanza Gulch consists of the following four main units, listed in ascending stratigraphic order: a lower tuff unit (Trtl); an andesite breccia unit (Trab); an upper tuff unit (Trtu); and a capping andesite flows unit (Tra). The lower and upper tuff units both consist mostly of silicic ash-flow tuff that forms layers as much as 100 ft thick; air-fall tuff and tuffaceous sandstone are present in lesser amounts. In addition, the upper tuff unit contains a local thin basalt flow subunit (Trtub) that crops out about 1 mi northwest of Black Mountain. The andesite breccia unit consists of unstratified flow breccia and related volcanoclastic deposits, all composed of andesite and dacite; thick deposits of flow breccia are present at the southwest corner of the map area, whereas outcrops on Black Mountain and throughout the Black Hills typically consist of relatively thin deposits of debris-flow breccia and pebbly sandstone. The andesite flows unit at the top of the volcanic sequence consists mostly of unbrecciated platy andesite. In combination with the Black Mountain Basalt, the volcanic rocks in the lower part of the Ricardo Formation constitute a transitional subalkaline assemblage that has both tholeiitic and calcalkaline affinities (geochemistry of volcanic rocks is discussed in a later section).

The volcanic sequence in the lower part of the Ricardo Formation was erupted from both nearby and distant sources. An andesite dike (Trad) at the west edge of the Black Hills (on structure-section line A-A') apparently was a feeder for the andesite flows unit. Thickness and facies patterns suggest that the eruptive center for the andesite breccia unit was located south of the map area. No conduit or related dikes have been identified in the El Paso Mountains region, however, so that the andesite breccia unit may have been erupted south of the El Paso Mountains in the Mojave Desert region. A small felsic dike (Trfd) composed of pumiceous rhyolite or dacite cuts the lower tuff unit near the southwest corner of the map area (near SE corner of sec. 32, T. 28 S., R. 38 E.). This dike indicates that some silicic magma originated beneath the El Paso Mountains region. However, the main sources of the voluminous ash-flow tuff, air-fall tuff, and tuffaceous sandstone in the volcanic sequence were more distant, and possibly were located south of the map area in the Mojave Desert region.

Radiometric ages (table 1) for the andesite breccia unit (sample EP208A, 18.1 ± 1.2 m.y.) and andesite flows unit (sample EP103A, 17.2 ± 0.8 m.y.) indicate that the volcanic sequence in the lower part of the Ricardo Formation was deposited in early Miocene time; a second radiometric age for the andesite flows unit (sample G48B, 14.0 ± 0.4 m.y.) is anomalously young and probably is unreliable. The volcanic sequence is approximately correlative with pyroclastic deposits of the Kinnick Formation in the southernmost Sierra Nevada (Dibblee, 1967; Dibblee and Louke, 1970), which have yielded a potassium-argon age of 17.6 m.y. (Evernden and others, 1964, sample KA 478). The underlying conglomerate unit of Bonanza Gulch may be early Miocene in age. However, a clay-rich zone near the top of this unit may represent weathering and thus a possible depositional hiatus; the conglomerate unit of Bonanza Gulch therefore may be older than Miocene.

The middle part of the Ricardo Formation, equivalent to Dibblee's members 3 through 7, disconformably overlies the lower part of the Ricardo Formation and is represented in the map area by a basal lacustrine unit of cherty mudstone (Trm) and by two fluvial units of conglomerate (Trc) and sandstone (Trs) whose exact stratigraphic positions are obscured by faulting and Quaternary alluvium. These three units are exposed along the west flank of the Black Hills but are absent farther east, probably owing to removal by erosion. Each of the units consists of granitic detritus mixed and interlayered with abundant volcanoclastic detritus including layers of ash tuff and tuffaceous sandstone. Southwest of the map area, near Red Rock Canyon, the middle part of the Ricardo Formation also contains two basalt flows and a layer of ash-flow tuff.

The sandstone and conglomerate in the middle part of the Ricardo Formation were deposited on alluvial fans by northwest-flowing streams that originated in the western Mojave Desert region (Whistler, 1969; Loomis and others, 1983; Loomis, 1984). The stream deposits interfinger northward into, and probably prograde northward across, lacustrine strata of the cherty mudstone unit, which accumulated near the center of the depositional basin. Recent paleomagnetic studies southwest of the map area suggest that the basin was rotated counterclockwise 15 to 20 degrees about 7 to 10 m.y. ago, during deposition of the middle part of the Ricardo Formation (D. W. Burbank, oral commun., 1985).

A middle and late Miocene age is indicated for the middle part of the Ricardo Formation on the basis of the following evidence: (1) middle and late Miocene (Clarendonian) vertebrate fossils that are distributed throughout Dibblee's members 4 through 7 (Merriam, 1919; Whistler, 1969; D. P. Whistler, oral commun., 1984); (2) a potassium-argon age of 10.3 m.y. on biotite from a bed of ash tuff in his member 4 (Evernden and others, 1964, sample KA 453); and (3) zircon fission-track ages of 10.4 ± 1.6 m.y. and 8.4 ± 1.8 m.y. for two tuff beds located near the base of Dibblee's member 6 and in the upper half of his member 7, respectively (C. W. Naeser, written commun., 1985). Paleomagnetic data (Burbank and Whistler, 1985; D. W. Burbank, oral commun., 1985) suggest that the middle part of the Ricardo Formation is as old as 13.5 m.y. near its base 4 mi southwest of the map

area (base of Dibblee's member 3 near Last Chance Canyon) and is approximately 8 m.y. old near its top about 4 to 8 mi southwest of the map area (top of Dibblee's member 7 near California Highway 14). The 8-m.y. paleomagnetic age is corroborated by a latest Miocene (Hemphillian) vertebrate fossil recently collected near the top of Dibblee's member 7 (D. P. Whistler, oral commun., 1985).

In combination with new radiometric ages reported herein (table 1), the foregoing data suggest that the lower and middle parts of the Ricardo Formation are separated by a hiatus of 3 to 4 m.y. (approximately 17.2 to 13.5 m.y. ago). This hiatus probably reflects a combination of nondeposition and erosion. Erosion of the upper tuff and andesite flows units along the top of the lower part of the Ricardo Formation is locally apparent near the southwest corner of the map area and is somewhat more pronounced farther south near Last Chance Canyon.

Two erosional remnants composed of the conglomerate and sandstone unit (Trcs) located east of the northern Black Hills (0.2 to 0.7 mi south of secs. 31 and 32, T. 27 S., R. 39 E.) are herein interpreted to be outliers of the upper part of the Ricardo Formation, which is equivalent to Dibblee's member 8. Like the main body of his member 8, located 10 mi to the southwest, the outliers in the map area consist mainly of weakly indurated granitic conglomerate and arkosic sandstone. However, the main body and the outliers have distinctly different stratigraphic settings. The main deposits of Dibblee's member 8 overlie conglomerate and sandstone of his member 7 along a gradational contact (Whistler, 1969, p. 33; B. F. Cox, unpub. mapping, 1984). By contrast, the outliers unconformably overlie the Goler Formation and faulted tuff of the lower part of the Ricardo Formation. Therefore, deposition of the upper part of the Ricardo Formation apparently was preceded by faulting and erosion in the Black Hills, whereas deposition of the middle and upper parts of the Ricardo Formation continued uninterrupted in more central parts of the depositional basin located southwest of the Black Hills.

Neither the outliers nor the main body of the upper part of the Ricardo Formation are well dated, but the aforementioned gradational contact suggests that, near its base, the main body is only slightly younger than Dibblee's member 7, that is, latest Miocene; preliminary paleomagnetic data (D. W. Burbank, oral commun., 1985) suggest an age of 8 m.y., or slightly less, for the lowest strata. The change from a mixed arkosic-volcanoclastic sediment composition in the middle part of the Ricardo Formation to a predominantly arkosic composition in the upper part of the formation indicates a major change in sedimentary provenance. Fluvial sedimentary structures in the western outlier in the map area suggest that the arkosic detritus was shed eastward from sources in the southern Sierra Nevada, as previously inferred by Whistler (1969). The Kern River Formation in the southeastern San Joaquin Valley (Bartow and Pittman, 1983) may be temporally correlative and tectonically analogous to the upper part of the Ricardo Formation, for the Kern River Formation similarly consists of a nonmarine wedge of arkosic detritus that was deposited during and following latest Miocene time, probably in response to major uplift of the southern Sierra Nevada. Limited geochronologic evidence supports this correlation. A vertebrate fauna collected near the base of the Kern River Formation (Kern River local fauna) has been correlated with a late Miocene (early Hemphillian) vertebrate fauna from the Mehrten Formation (Siphon Canal local fauna), which occurs 12 ft below a layer of biotite-rich tuff that has been potassium-argon dated at 8.19 ± 0.16 m.y. (H. M. Wagner, 1981, p. 69, 92, 94; J. A. Bartow, oral commun., 1985).

Black Mountain Basalt

The Black Mountain Basalt, originally named by Baker (1912) for exposures on Black Mountain, is the most conspicuous rock unit in the map area. The unit consists of numerous flows of subalkaline olivine-augite basalt that cap summit areas atop Black Mountain, throughout the Black Hills, and on buttes near the east margin of the map area. Alluvium and

landslide deposits composed of basalt rubble extend far beyond the basalt outcrops, extensively obscuring underlying Tertiary rocks. Structural relations indicate that the Black Mountain Basalt disconformably overlies the upper tuff unit of the Ricardo Formation. This disconformity is evident in two locations where steeply dipping faults offset the upper tuff unit but do not offset the base of the overlying basalt; one of these is shown in structure section A-A'. However, despite this structural evidence of an erosional hiatus, there is no obvious channeling along the contact.

Dibblee (1952, 1967) inferred a Pleistocene age for the Black Mountain Basalt, mainly on the basis of an apparent absence of superjacent strata. However, detailed mapping for the present study has revealed that the basalt is disconformably overlain by the middle part of the Ricardo Formation (cherty mudstone unit) at one location, 2.7 mi northwest of the east summit of Black Mountain; elsewhere superjacent strata have been stripped away by erosion. Thus bracketed by Miocene strata of the Ricardo Formation, the basalt must also be Miocene in age. Four potassium-argon ages (table 1) for the basalt confirm this assignment; they range from 17.9 ± 1.6 m.y. (sample EP302A) near the base to 15.1 ± 0.5 m.y. (sample G49C) near the top, indicating that the age of the Black Mountain Basalt is early and middle Miocene.

Two workers have incorrectly extended the name Black Mountain Basalt to post-Miocene basalt in the western Mojave Desert. Hulin (1925) applied the name Black Mountain Basalt to intrusions and flows in the Summit Range 8 mi east of the map area. Subsequently, Dibblee (1968) applied the name to basalt flows in the Fremont Peak and Opal Mountain quadrangles 35 mi southeast of the map area, where there happens to be another peak named Black Mountain. The rock in the Summit Range consists of quartz-bearing augite-hornblende basalt that intrudes and overlies andesite of probable Pliocene age (Hulin, 1925; Dibblee, 1967, p. 108); this basalt is clearly unlike the type Black Mountain Basalt in both lithology and age. The basalt in the Fremont Peak and Opal Mountain quadrangles bears some lithological and chemical similarity to the type Black Mountain Basalt (Dibblee, 1968; Wise, 1969, p. 54-55, samples 8 and 9), but it is much younger, having yielded a late Pliocene potassium-argon age of 2.55 ± 0.58 m.y. (Burke and others, 1982). Rocks designated as the Black Mountain Basalt in the Summit Range and in the Fremont Peak and Opal Mountain quadrangles are thus much younger than the type Black Mountain Basalt. Based on these data, Diggles and others (1985) geographically restricted the name Black Mountain Basalt to the original usage of Baker (1912), signifying flows near Black Mountain on the north flank of the El Paso Mountains.

The Black Mountain Basalt occupies approximately the same vertical stratigraphic position as the andesite flows unit of the Ricardo Formation; that is, between the upper tuff and cherty mudstone units of the Ricardo Formation. Furthermore, the Black Mountain Basalt and the andesite flows unit have yielded comparable radiometric ages (table 1). The two units do not interfinger or overlap, even though they crop out less than 4000 ft apart for 3 mi along the southwest edge of the Black Hills. The distinct lateral distributions of basalt and andesite probably mainly reflect spatial segregation of source vents but may also have been reinforced by a low north-trending paleotopographic barrier near the southwest edge of the Black Hills. In this regard, it is noteworthy that basal flows of the Black Mountain Basalt at Black Mountain may be older than basal flows of the same unit in the southwestern Black Hills (17.9 ± 1.6 m.y. for sample EP302A versus 16.6 ± 1.9 m.y. for sample EP301B). Perhaps the basalt flows ponded against the east side of a low north-trending ridge. The andesite flows unit may have been confined to the west side of this hypothetical barrier.

Judging from the present distribution of basalt dikes (unit Tbd), the Black Mountain Basalt apparently flowed from numerous fissures located in southwestern and northern parts of the Black Hills and in other sites southwest of the map area. A large basalt dike located approximately 1.5 mi southwest of the map area yielded a radiometric age of 17.3 ± 0.5 m.y. (table 1, sample EP111A). Contrary to a previous interpretation (Baker, 1912), a closed depression

located southwest of the east summit of Black Mountain is related to landslide activity and is not an eruptive vent of the Black Mountain Basalt.

The Black Mountain Basalt has distinctive chemical attributes (table 2; see section on chemistry of volcanic rocks) that may have significant paleotectonic implications. The unit consists of potassium-poor high-alumina basalt that is chemically transitional between tholeiitic basalt and alkali-olivine basalt. The average K_2O abundance in five samples of the Black Mountain Basalt is only 0.47 percent. Such basalt is atypical of neighboring regions in the Sierra Nevada (Larsen 1979; Moore and Dodge, 1980; Dodge and Moore, 1981) and Basin and Range province (Leeman and Rogers 1970), where basaltic rocks of Miocene to Holocene age consist predominantly of alkali-olivine basalt and related alkalic rocks that contain at least 1 percent K_2O . However, transitional basalt and tholeiitic basalt containing low concentrations of K_2O have been reported in western and central parts of the Mojave Desert (Byers, 1960, table 3; Wise, 1969, table 1; Higgins, 1973, tables 2 and 3) and near the northern and eastern margins of the Basin and Range province (Waters, 1962; Lipman, 1969; Condie and Barsky, 1972; Best and Brimhall, 1974; Hart and others, 1984). In many cases, these basalts erupted concurrently with major high-angle normal faulting. Basaltic magmas are readily enriched in potassium when exposed to felsic minerals that are abundant in continental crust (Watson, 1982). Therefore, low concentrations of K_2O in continental basalts suggest a rapid passage through the crust, and this is most likely to occur during rapid crustal extension along deeply rooted high-angle faults.

Thus, the low abundance of potassium in the Black Mountain Basalt may reflect rapid and deeply rooted crustal extension in the El Paso Mountains region approximately 15 to 18 m.y. ago. Most of the basalt dikes exposed within the map area and in adjacent areas of the El Paso Mountains strike approximately east-west (Cox, 1982a, p. 159, 243), which suggests that extension was along a north-south line and that the inferred broader zone of high-angle faulting and fracturing trended approximately east-west. As noted previously in this report, the paleocurrents and provenance of the conglomerate unit of Bonanza Gulch indicate that, during or before early Miocene time, the El Paso Mountains region was strongly depressed relative to the Mojave Desert block along an ancestral structural zone that locally coincided with the present position of the Garlock fault zone. It therefore seems likely that the crustal extension inferred from the Black Mountain Basalt and related dikes reflects a continuation or renewal of tectonism along this same structural boundary.

Quaternary Deposits

Quaternary deposits within the map area consist mainly of alluvial deposits in lowlying areas near the margins of the map area and landslide deposits that are abundant on slopes throughout the Black Hills. The alluvial deposits consist of sand and gravel in modern washes, in alluvial fans, and in elevated pediment veneers and stream terrace deposits. They are divided into an older alluvium unit consisting of weathered and deeply eroded deposits, and a younger alluvium unit consisting of relatively unweathered and uneroded deposits. The alluvial deposits locally grade laterally into colluvium, which is more extensive than shown on the map. Within the Black Hills and adjacent parts of the El Paso Mountains, the older and younger alluvium units form a nested series of deposits that reflect a long history of Quaternary erosion punctuated by intermittent episodes of sedimentation. Net erosion in these mountainous areas has been accompanied by more continuous sedimentation in neighboring Fremont and Indian Wells Valleys, which constitute the local base levels for streams that originate in the El Paso Mountains.

Landslide deposits have developed in concert with vigorous downcutting and headward erosion by streams in the Black Hills region. Most of the landsliding has occurred where incompetent tuffaceous units (Trtu and Trtl) of the Ricardo Formation underlie thick deposits of the Black

Mountain Basalt. Two types of landslide deposits are distinguished by separate symbols on the map (landslide terminology after Varnes, 1978): (1) rock-slump landslides are denoted by double arrows and unornamented bounding contacts; and (2) bedding-parallel rock-block landslide sheets and (or) lateral-spread landslide sheets are denoted by bold single arrows and hachured bounding contacts. Rock-slump landslide deposits are abundant on the steep flanks of Black Mountain; the larger masses shown on the map actually consist of multiple nested slump deposits. Many of the slumps have uneroded scarps and undrained head depressions that indicate recent movement; other slump deposits are deeply eroded and may be Pleistocene or early Holocene in age.

An extensive landslide sheet underlies a 7-mi² area of low hills and gently sloping mesas at the north end of the Black Hills. The sheet is bounded on its southwest side by a structurally complex zone of northwest-trending faults located approximately 0.5 to 1.5 mi south of sec. 34, T. 27 S., R. 38 E.; additional high-angle faults disrupt the sheet along the south side of Little Dixie Wash. The structure and internal stratigraphy of the landslide sheet is best exposed where it is cut by a deep canyon in sec. 36, T. 27 S., R. 38 E. In ascending order, the landslide sheet contains the lower tuff unit (Trtl), andesite breccia unit (Trab), upper tuff unit (Trtu), and Black Mountain Basalt (Tb).

There has been minimal churning or mixing, so that stratigraphic contacts generally are mappable throughout the landslide sheet. However, the Black Mountain Basalt has been thoroughly fragmented to loose boulder rubble and the underlying tuff units are sheared and brecciated and apparently have been thinned significantly by abrasion or extension; large blocks within the tuff units locally are tilted toward the south and southeast. The most extreme attenuation of the lower and upper tuff units occurs in secs. 30 and 31, T. 27 S., R. 39 E., where the two units have an aggregate thickness of only 40 to 60 ft, or approximately one-third their aggregate thickness in nearby undisturbed stratigraphic sections. In this area, limitations of the map scale required that the lower and upper tuff units be consolidated into a single unit of undivided tuffaceous rocks (Trt).

Two principal dislocation surfaces are present within and beneath the landslide sheet, as shown by hachured lines on the map; these occur at the base of the Black Mountain Basalt and at the base of the lower tuff unit. The slip surface at the base of the basalt is apparent because it locally cuts discordantly across underlying units of tuff and andesite breccia. The slip surface at the base of the lower tuff unit is marked by intense brittle shearing. The thorough fragmentation of the basalt and the apparent mechanical thinning of the underlying tuff units suggest that slip on the principal dislocation surfaces was supplemented by lateral flowage of the landslide mass in the manner of the lateral-spread type of landslide described by Varnes (1978).

The transport direction of the landslide sheet is inferred to be approximately the same as both the general slope direction of the present ground surface and the dip direction of the basalt-tuff contact; transport is inferred to be approximately opposite to the dip direction of tilted blocks of tuff within the landslide sheet. On this basis, two domains having nearly orthogonal movement directions are apparent, as shown by bold arrows on the map: (1) a southwestern domain that moved northwestward; and (2) a northeastern domain that moved northeastward. The amount of movement in either part of the landslide sheet is uncertain. Basalt and tuff have overridden deposits of the older alluvium unit at two locations near the northeast edge of the Black Hills, locally indicating northeastward or eastward landslide movement of at least 500 feet. However, this movement may represent later superficial slumping along the eroded northeast edge of the landslide sheet, rather than primary large-scale displacement of the entire sheet.

Development of the landslide sheet was facilitated by the following conditions: (1) the presence of incompetent tuffaceous rocks beneath a thick section of basalt; (2) orientation of bedding planes parallel to a sloping ground surface; and (3) removal of lateral support by erosion around the northern margin of the Black Hills. The age of the main

movements of the landslide sheet is uncertain. Initial movement of the sheet may have occurred during the Pleistocene, possibly in response to saturation of incompetent tuff units by groundwater under a climate more humid than that of the present day. Subsequently, the landslide sheet was disrupted by numerous high-angle normal faults, was eroded by streams that formed the deep canyon in sec. 36, T. 27 S., R. 38 E., and was locally overlain by deposits of the older alluvium unit. Parts of the landslide sheet may have been reactivated during Holocene time; renewed movement is suggested by a low northwest-facing scarp that cuts the southwest part of the sheet, and by a large poorly drained depression in the center of sec. 35, T. 27 S., R. 38 E.

STRUCTURE OF CENOZOIC ROCKS

The geologic structure of Cenozoic rocks in the map area is dominated by the following features: (1) a north-dipping homocline in the Goler Formation; (2) a west-dipping homocline in the Ricardo Formation; and (3) normal and oblique-slip faults with a variety of trends.

Homocline in the Goler Formation

The most prominent of the above-listed structural features is the north-ward tilt of the Goler Formation (map sheet, structure section B-B'). The homoclinal dips mostly range between 10° and 30°, and average about 15° or 20°; dips as low as 5° to 10° are locally common near the north end of the Black Hills. The tilting may have resulted from major uplift of the northwest Mojave Desert along a structural zone that was approximately coincident with the modern Garlock fault zone (Cox, 1982a p. 182, 1982b). The homoclinal tilting occurred after deposition of the Paleocene and Eocene strata of the Goler Formation but before eruption of early Miocene volcanic rocks of the lower part of the Ricardo Formation that have yielded radiometric ages as old as 18.1±1.2 m.y. (table 1).

Homocline in the Ricardo Formation of Dibblee (19°2)

The Ricardo Formation of Dibblee (1952) dips consistently toward the west or west-northwest in most outcrops southwest of the map area (Dibblee, 1952, 1967). Dip angles in that part of the homocline are mostly 10° to 20°, and the angular discordance with underlying strata of the Goler Formation generally ranges from 10° to 35°. The homoclinal structure of the Ricardo Formation is also recognizable at the south end of the Black Hills, although dip directions are more variable, ranging from west to north. The dip decreases to nearly horizontal in the east-central part of the Black Hills and at the east edge of the map area, indicating that the homocline terminates eastward or northeastward either by faulting or by flexure. The homocline in the Ricardo Formation formed during late Miocene or Pliocene time, probably by east-west extension of the region between the El Paso Mountains and the southern Sierra Nevada (Cox, 1982a p. 159-160).

Faults

The Goler and Ricardo Formations are cut by numerous faults with small to moderate displacements. With few exceptions, the faults are moderate- to high-angle normal faults and oblique-slip faults with vertical components of slip ranging from less than 100 ft to at least 500 ft. North-striking faults predominate but northwest-, northeast-, and east-striking faults are also common, especially in the north half of the map area. Several early Miocene faults are mapped in the west and northeast parts of the Black Hills (for example, see map sheet, structure section A-A'); these faults cut the lower part of the Ricardo Formation but are overlain by the Black Mountain Basalt or by the upper part of the Ricardo Formation. Many other faults are post-middle

Miocene in age, for they cut the Black Mountain Basalt. Quaternary displacements are indicated for several faults that form low scarps in the older alluvium unit along the west and north edges of the Black Hills, and are inferred for several other faults that cut the extensive Pleistocene(?) landslide sheet near the north end of the Black Hills.

The principal effect of faulting has been to elevate a structural block near Black Mountain relative to downfaulted blocks west, north, and east of Black Mountain. This effect is most conspicuous west and north of Black Mountain, where the Black Mountain Basalt and units in the lower part of the Ricardo Formation descend stepwise toward Indian Wells Valley (map sheet, structure sections A-A', B-B'). Relative downward movement east of Black Mountain is recorded by outcrops of the Black Mountain Basalt at the east edge of the map area, which are situated approximately 1000 ft lower than the basalt outcrops on Black Mountain.

There are several noteworthy complications in the pattern of faulting. North-trending faults along the west edge of the Black Hills bound narrow horsts and grabens that separate gently dipping strata of the Ricardo Formation in the Black Hills from more steeply dipping strata west of the Black Hills (map sheet, structure section A-A'). This faulting apparently represents a concentration of tensional stress caused by local flexure of the Ricardo Formation. North-northeast-trending faults east of Black Mountain that cause large stratigraphic offsets in the Goler Formation are mostly east-dipping oblique-slip faults that have their west sides displaced relatively upward and northward (Cox, 1982a p. 160, 245-246); movement on these faults may be kinematically related to post-Miocene oblique right-lateral displacement on the north-trending part of the Sierra Nevada fault northwest of Inyokern (see Hay, 1976). Three east-dipping low-angle normal faults are located near the southwest corner of the map area, along and west of Bonanza Gulch. These structures may be related to east-west extension and westward tilting of the Ricardo Formation during late Miocene or Pliocene time (Cox, 1982a p. 244-245).

Steeply dipping siliceous and calcareous hydrothermal veins cut the Goler Formation in the east and southeast parts of the map area. These structures are more resistant to erosion than the host rocks and crop out as low wall-like features 2 to 5 ft thick. The trend and mineralogy of the veins changes from north to south. Veins in the east-central part of the map area trend north or north-northeast and consist of chalcedony and opal; veins farther south are more variable in orientation, trending mostly east or east-northeast, and consist of calcite with common drusy voids. The walls of the veins typically show little or no evidence of shear displacement and therefore apparently originated as tensional fractures. The origin of the veins is uncertain; however, basalt dikes (unit Tbd) within and near the map area show a similar north-to-south change in orientation from north-trending to east-trending, which suggests that the veins may have formed during the eruption of the Black Mountain Basalt in early and middle Miocene time. The dikes and veins may both reflect north-south extension across a major crustal boundary that separated the El Paso Mountains region from the Mojave Desert block to the south.

GEOCHEMISTRY OF VOLCANIC ROCKS

Volcanic rocks from the Black Mountain Basalt and the lower part of the Ricardo Formation were analyzed by X-ray fluorescence to determine their major-element compositions (table 2). Previously published geochemical data for Tertiary rocks of the El Paso Mountains are limited to major-element and trace-element analyses on a single sample of the Black Mountain Basalt (Wise, 1969, tables 1 and 2, sample 8). Our geochemical sampling was limited in scope, but the new data indicate some of the essential geochemical features of the volcanic rocks and help to define problems for detailed study.

The volcanic rocks are chemically diverse. Silica (SiO_2) content varies from 48.3 to 72.5 percent (volatiles included), with individual analyses falling within the compositional fields of basalt, andesite, dacite, and rhyolite. All analyses plot within the subalkaline field on the alkalis-silica diagram

of Irvine and Baragar (1971, fig. 3). Total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) increases fairly uniformly with increasing silica content, from approximately 3.5 percent at 49 percent SiO_2 to 8.7 percent at 72.5 percent SiO_2 . Potassium (K_2O) content increases sharply from approximately 0.5 percent to 6 percent over the same range of silica concentrations. The assemblage is intermediate between tholeiitic and calcalkaline magma series as defined by relative abundances of iron, magnesium, and alkalis (AFM diagram of Irvine and Baragar, 1971, fig. 2); however, such characterization is uncertain because of the limited number of analyses and because the assemblage may not be entirely comagmatic. Individual rock units are discussed below in order of increasing silica content.

The four most mafic rock units are the Black Mountain Basalt (Tb), basalt dikes unit (Tbd), basalt flow subunit (Trtub), and the andesite flows unit (Tra). The analyses for these four units form a gradational series that may reflect related origins. The Black Mountain Basalt was studied in the greatest detail (5 analyses); it is given special attention in the following discussion because it probably is the least affected by differentiation or crustal contamination, and because it may have value as a paleotectonic indicator.

The Black Mountain Basalt contains low concentrations of silica (avg 49.0 percent), potassium (avg 0.47 percent), and titanium (avg 1.35 percent TiO_2); low to moderate concentrations of total alkalis (avg 3.46 percent), and moderate to high concentrations of alumina (avg 16.7 percent Al_2O_3). Normative plagioclase composition falls within the range $\text{An}_{54}\text{-An}_{56}$, and both olivine and hypersthene are present in the norm (hypersthene > olivine). Such basalt, chemically intermediate between alkali-olivine basalt and tholeiitic basalt, has been termed high-alumina basalt (Kuno, 1960) or transitional basalt (Bass, 1972). The single sample from the basalt dikes unit (table 2, sample EP-111A) contains less alumina (15.5 percent) but closely resembles the Black Mountain Basalt in other aspects of chemistry and normative mineralogy; this chemical similarity, in combination with comparable radiometric ages (table 1) and modal mineralogy, suggests that the basalt dikes within and near the map area were feeders for the Black Mountain Basalt. The possible paleotectonic implications of the Black Mountain Basalt and associated basalt dikes are discussed in the stratigraphy section of this report.

Like the Black Mountain Basalt, the basalt flow subunit within the upper tuff unit of the Ricardo Formation consists of high-alumina basalt (table 2, sample EP110A). However this thin local basalt flow is significantly richer in silica (53.2 percent) and total alkalis (5 percent) and is relatively depleted in iron (total Fe) magnesium (MgO) and calcium (CaO). A small amount (5 percent) of quartz is present in the norm. The andesite flows unit (samples EP103A, BN-171-3) consists of high-alumina andesite that is yet richer in silica (avg 56.8 percent) and total alkalis (avg 5.8 percent), and more depleted in iron, magnesium, and calcium. A moderate amount (10-12 percent) of quartz is present in the norm. The gradational changes in chemical composition and the spatial association of the andesite flows unit, basalt flows subunit, and Black Mountain Basalt suggest related origins. This is particularly likely for the andesite flows unit, which further resembles the Black Mountain Basalt in stratigraphic position, radiometric age (table 1), and in the occurrence of feeder dikes within the area of the map. Trace-element and isotopic studies are needed to evaluate the magmatic origins of these units, particularly the Black Mountain Basalt.

The three relatively silicic rock units of the volcanic assemblage consist of the lower tuff unit (Trtl), andesite breccia unit (Trab) and upper tuff unit (Trtu). The genetic relation of these three units to the more mafic volcanic rocks discussed above is uncertain because the silicic rocks were erupted an unknown distance outside the area of the map and because geochemical similarities with the mafic rocks are tenuous. The andesite breccia unit is chemically heterogeneous, containing brecciated flows of both andesite and dacite (table 2, samples EP208A and BN-150-3). Both samples are metaluminous (molecular $\text{Na}_2\text{O} + \text{K}_2\text{O} < \text{Al}_2\text{O}_3 < \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$). Pumiceous glass samples from the lower and upper tuff units (table 2, samples BN-164-2 and EP104A) consist of

dacite and rhyolite, respectively. Both samples are rich in potassium but are peraluminous (molecular $Al_2O_3 > Na_2O + K_2O + CaO$) because of their low content of sodium (Na_2O). The peraluminous character probably is not primary, however, inasmuch as the substantial weight loss on ignition (LOI in table 2) suggests that both pumice samples are hydrated; strong leaching of sodium commonly occurs during hydration of silicic volcanic glass (Noble, 1967). Additional major-element analyses are needed to adequately determine the chemical heterogeneity of the andesite breccia unit and the lower and upper tuff units.

SUMMARY OF CENOZOIC GEOLOGIC HISTORY

The stratigraphy and structure of Cenozoic deposits in and near the El Paso Mountains Wilderness Study Area record the following sequence of sedimentary, volcanic, and tectonic events.

1. During Paleocene and Eocene time the Goler Formation was deposited nonconformably upon Paleozoic metasedimentary rocks of the Garlock assemblage. A lower upward-fining sequence of breccia and conglomerate, pebbly sandstone, and siltstone, consisting of the sedimentary breccia unit of Holland Camp, the lower sandstone and siltstone unit, and additional units south of the map area, accumulated on a southward-sloping piedmont along the north margin of the Goler sedimentary basin. An overlying westward-fining sequence of cobble conglomerate, pebbly sandstone, and siltstone, which comprises the conglomerate and sandstone unit of Sheep Spring, the upper sandstone and siltstone unit, and the conglomerate unit of Black Hills, accumulated on the plain of a westward-flowing braided river that occupied the axial region of the sedimentary basin. The braided-river valley straddled an area now occupied by the Garlock fault zone and probably extended westward across the southern Sierra Nevada, reaching the ancestral Pacific Ocean in the southeast part of the San Joaquin Valley. Major tectonic subsidence of the Goler sedimentary basin resulted in deposition of as much as 13,050 ft of mostly nonmarine sediments, and climaxed during Eocene time with a marine incursion and deposition of marine mudstone near the top of the Goler Formation.

2. Sometime between Eocene and early Miocene time, the Goler Formation was tilted northward and then was eroded to a plain of low relief. Tilting may have been contemporaneous with major uplift of the western Mojave Desert region along an ancestral structural zone lying near the present position of the Garlock fault zone (Cox, 1982a, p. 182-185).

3. During Miocene time, nonmarine clastic rocks and volcanic rocks of the Ricardo Formation of Dibblee (1952) and the Black Mountain Basalt were deposited with angular unconformity on the Goler Formation in a new sedimentary basin that subsided north of the present site of the Garlock fault. The Black Hills probably lay near the northeast end of the basin. Deposition of the Ricardo Formation spanned an interval of at least 10 m.y.; during this interval, sedimentation and volcanism were punctuated by recurrent tectonism that is recorded by intraformational disconformities, buried faults, volcanic dikes and hydrothermal veins, and changes in sedimentary provenance.

The conglomerate unit of Bonanza Gulch at the base of the Ricardo Formation is poorly dated but was deposited during or before early Miocene time, possibly before the onset of regional volcanism. This unit of coarse-grained alluvial fan deposits indicates renewed uplift of the Mojave Desert block along the structural zone located directly south of the El Paso Mountains region. The overlying assemblage of subalkaline volcanic rocks, comprising the Black Mountain Basalt and extrusive and pyroclastic rocks of the lower part of the Ricardo Formation, was deposited during early and middle Miocene time. Most of the volcanic deposits in the lower part of the Ricardo Formation, including the lower tuff unit, the andesite breccia unit, and the upper tuff unit, were erupted from vents located somewhere outside the area of the map, possibly in the Mojave Desert region south of the present site of the Garlock fault. The upper tuff unit and

underlying rock units were broken by faults and eroded before the Black Mountain Basalt and the approximately contemporaneous andesite flows unit of the Ricardo Formation were erupted from pipes and fissures in and near the map area. The low-potassium composition of the Black Mountain Basalt may reflect contemporaneous rapid north-south crustal extension and deeply rooted high-angle normal faulting between the Mojave Desert block and the El Paso Mountains region during these eruptions.

The middle part of the Ricardo Formation was laid down disconformably upon the Black Mountain Basalt and the lower part of the Ricardo Formation during middle and late Miocene time, beginning about 13.5 m.y. ago. The middle part of the Ricardo Formation consists largely of clastic sedimentary rocks that are represented at the west side of the map area by the cherty mudstone, conglomerate, and sandstone units. Each of these three rock units consists of a mixture of epiclastic detritus derived from granitoid rocks and Tertiary volcanic rocks, as well as contemporaneous pyroclastic debris including layers of ash tuff and tuffaceous sandstone. The epiclastic volcanic detritus probably was eroded from lower and middle Miocene volcanic rocks correlative with those that constitute the lower part of the Ricardo Formation. The epiclastic and pyroclastic deposits accumulated on alluvial fans and playas that lay north of a source region in the western Mojave Desert. Southwest of the map area, the sedimentary basin was rotated counterclockwise approximately 15 to 20 degrees during deposition of the middle part of the Ricardo Formation; this rotation may record the onset of left-lateral displacement on the Garlock fault zone about 10 m.y. ago (Burbank and Whistler, 1985). The onset of lateral movement on the Garlock fault in turn probably reflects the initiation of east-west extension in the southwestern Basin and Range province north of the fault.

The upper part of the Ricardo Formation, which consists largely of granitic detritus, was shed eastward on alluvial fans that emanated from the southern Sierra Nevada, most likely beginning about 8 m.y. ago during latest Miocene time. The shift in paleocurrents and provenance relative to those of the middle part of the Ricardo Formation may reflect major uplift of the southern Sierra Nevada along the Sierra Nevada fault, which apparently began shortly following the onset of lateral movement on the Garlock fault. The wedge of alluvial-fan deposits may originally have extended eastward beyond the northeast edge of the Black Hills, if isolated erosional remnants mapped herein as the conglomerate and sandstone unit of the Ricardo Formation indeed correlate with the upper part of the Ricardo Formation (unit 8 of Dibblee, 1952). The unconformity separating the conglomerate and sandstone unit from underlying faulted deposits of the lower tuff unit suggests that the time of transition between the middle and upper parts of the Ricardo Formation was marked by tectonism along the east side of the Ricardo basin; whereas sedimentation apparently proceeded without major interruption in the center of the basin.

4. During latest Miocene or Pliocene time, that part of the Ricardo Formation located southwest of the Black Hills was tilted westward, extended along eastward-dipping low-angle faults, and dropped down along the Sierra Nevada fault. At about the same time, a structural block centered near Black Mountain was faulted upward relative to surrounding areas to the west, north, and east. These structural developments reflect intensified east-west extension north of the Garlock fault and may correspond to accelerated uplift of the Sierra Nevada along its eastern frontal fault beginning about 4.5 m.y. ago (Hay, 1976).

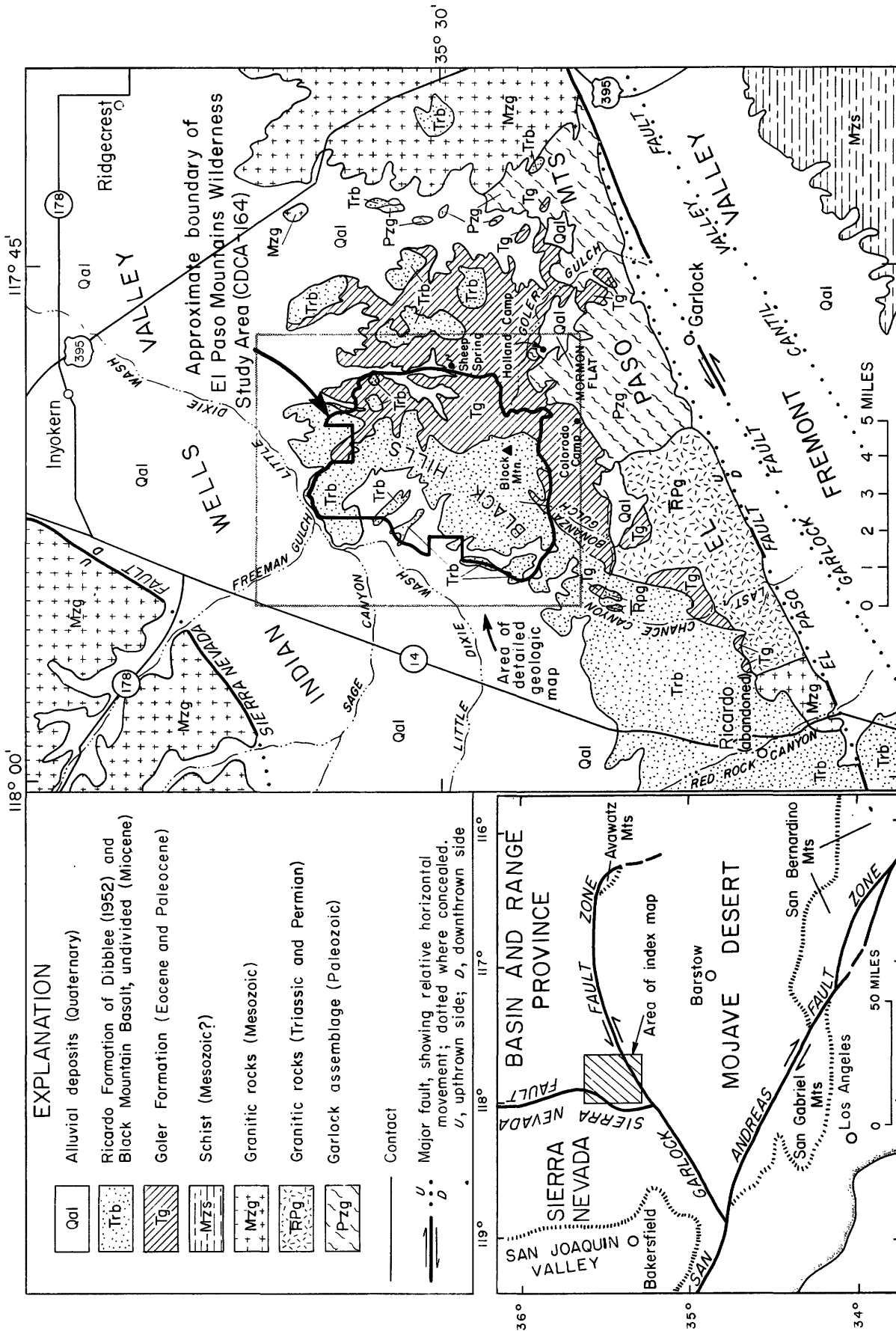
5. During Quaternary time, net erosion of the Black Hills has been punctuated by intermittent sedimentation, resulting in the present patchy distribution of alluvial deposits that now form erosional remnants perched at various topographic levels in the map area. Sedimentation has proceeded more continuously in neighboring lowlying areas located north, west, and south of the Black Hills, owing to relative uplift of the southern Sierra Nevada west of the map area and to relative subsidence of Indian Wells Valley and Fremont Valley north and south of the map area. Unstable

slopes produced by deep erosion of the Black Hills region have promoted extensive Quaternary landslide activity, which is manifested as rock slumps on the flanks of Black Mountain and as large rock-block or lateral-spread landslides near the north end of the Black Hills. Tectonism has continued during Quaternary time, as is indicated by faults that cut the extensive Pleistocene(?) landslide sheet near the north end of the Black Hills and by other faults that cut deposits of the older alluvium unit at the west and north edges of the Black Hills.

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Index map showing location and geologic setting of the El Paso Mountains Wilderness Study Area (CDCA-164), Kern County, California. Generalized geology adapted from Jennings and others (1962), Cox (1982a, pl. 1), and this report. Inset map shows location of the index map area with respect to regional physiographic provinces and major fault zones.

Table 1. -- Potassium-argon analyses and calculated ages of volcanic rocks from the El Paso Mountains, California

(Ages are calculated using the following constants (Steiger and Jager, 1977): $\lambda_B = 4.962 \times 10^{-10} \text{ yr}^{-1}$; $\lambda_C + \lambda_E = 0.581 \times 10^{-10} \text{ yr}^{-1}$; $40K_{\text{total}}K = 1.167 \times 10^{-4} \text{ mol/mol}$. Materials analyzed: BAS = whole-rock basalt; AND = whole-rock andesite; PLAG = plagioclase mineral separate. Potassium analyses on I.L. flame photometer using lithium internal standard (Ingramells, 1970). Potassium analysts: B. Lai (samples G49A, G49C); P. R. Klock and S. T. Neil (all other samples). Argon analyses by standard techniques of isotope dilution (Dalrymple and Lanphere, 1969). Argon analysts: J. L. Morton and M. Gilzean (samples G49A, G49C); M. F. Diggles (all other samples))

Map unit (pl. 1)	Map location No.	Sample field No.	Geographic coordinates		Material	K ₂ O (wt pct)	40Ar _{rad} (10 ⁻¹¹ mol/g)	40Ar _{rad} (percent)	Calculated age (m.y.)
			Lat N.	Long W.					
Tb	KA-1	G49A	35°28.54'	117°50.47'	BAS	0.483 0.489	1.202	46	² 17.1±0.5
Tb	KA-2	G49C	35°28.53'	117°50.50'	BAS	1.049 1.044	2.281	68	² 15.1±0.5
Tb	KA-3	EP302A	35°28.56'	117°50.50'	BAS	0.180 0.169	0.452	48.1	17.9±1.6
Tb	KA-4	EP301B	35°29.38'	117°51.84'	BAS	0.311 0.284	0.715	13.3	16.6±1.9
Tra	KA-5	EP103A	35°27.50'	117°53.84'	AND	1.744 1.787	4.384	25.8	17.2±0.8
Tra	(1)	G48B	35°25.13'	117°55.45'	PLAG	0.658 0.657	1.335	5.4	14.0±0.4
Trab	KA-6	EP208A	35°27.54'	117°53.63'	AND	2.775 2.887	7.414	50.4	18.1±1.2
Tbd	(1)	EP111A	35°25.55'	117°54.42'	BAS	0.741	1.852	22.6	17.3±0.5

¹ Absence of location number indicates that sample site is located outside area of the map.

² Ages for samples G49A and G49C were calculated by J. L. Morton and were reported previously by Cox (1982a, 1982b); all other ages were calculated by M. F. Diggles.

Table 2. -- Major-element analyses (weight percent of oxides) of volcanic rocks from the El Paso Mountains, California

[Analysis by wavelength-dispersive X-ray fluorescence spectroscopy. Analysts: A.J. Bartel, K.C. Stewart, J.E. Taggart, Jr., and D. Hopping.
Data for sample EP-2 courtesy of C.R. Bacon (unpublished data, 1978)]

Map unit (pl.1)	Trtl	Trab	Trab	Titu	Tritub	Tra	Tra	Tb	Tb	Tb	Tb	Tb	Tb	Tbd
Sample field NO.	BN-164-2	EP208A	EP104A	EP104A	EP110A	EP103A	BN-171-3	G49A	EP301B	EP302A	EP301B	EP-2	EP111A ¹	
Lab No.	M-161769	M-160653	M-161770	M-160648	M-160652	M-160650	M-160660	M-160661	M-160650	M-160651	M-160650	M-135091	M-160649	
Latitude N.	35°28.03'	35°28.34'	35°27.50'	35°28.98'	35°27.50'	35°29.12'	35°28.54'	35°28.54'	35°28.56'	35°28.38'	35°29.38'	35°32.13'	35°25.55'	
Longitude W.	117°52.60'	117°53.20'	117°53.82'	117°51.46'	117°53.84'	117°53.62'	117°50.47'	117°50.50'	117°50.50'	117°50.50'	117°51.84'	117°53.18'	117°54.42'	
Material	pumice	andesite	pumice	basalt	basalt	andesite	andesite	basalt	basalt	basalt	basalt	basalt	basalt	basalt
SiO ₂	69.8	59.9	72.5	53.2	56.6	57.1	48.5	49.5	48.3	49.1	49.1	49.6	49.1	
Al ₂ O ₃	13.1	16.0	12.0	16.6	17.1	17.3	16.4	16.2	17.0	16.8	16.8	16.9	15.5	
2Fe ₂ O ₃	1.27	6.69	1.78	10.9	8.56	7.72	11.7	10.9	12.3	12.0	11.6	11.6	11.4	
MgO	0.64	0.69	0.24	4.03	2.03	2.15	6.88	6.66	5.66	6.45	7.73	7.73	7.68	
CaO	0.97	4.36	0.50	7.24	5.77	6.03	9.84	10.6	9.78	10.1	9.92	9.92	9.51	
Na ₂ O	2.40	4.02	2.72	3.47	4.26	4.00	3.00	2.88	2.95	3.01	3.09	3.09	2.75	
K ₂ O	4.23	3.52	5.99	1.51	1.70	1.63	0.43	1.01	0.23	0.35	0.31	0.31	0.69	
TiO ₂	<0.05	0.81	0.09	1.82	1.56	1.55	1.34	1.44	1.41	1.33	1.25	1.25	1.52	
P ₂ O ₅	<0.05	0.32	<0.05	0.32	0.31	0.34	0.16	0.33	0.16	0.17	0.16	0.16	0.20	
MnO	0.03	0.10	<0.02	0.16	0.15	0.15	0.17	0.16	0.17	0.17	0.17	0.16	0.17	
LOI ³	7.52	1.50	4.06	0.09	1.63	1.63	1.85	0.66	1.98	0.75	0.99	0.99	1.51	
Total	99.99	100.04	99.88	99.34	99.67	99.60	100.27	100.34	99.94	100.23	101.71	100.71	100.03	

¹ Sample site located outside area of the map.

² Total Fe as Fe₂O₃.

³ Weight loss on ignition.

1

2

3

4