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GEOLOGY OF THE DEVIL'S PLAYGROUND AREA
EASTERN MOJAVE DESERT, CALIFORNIA

by

George Charles Dunne

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

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INTRODUCTION

Purpose of Study.

Few areas within the southern Cordillera of the southwestern United States appear to be as geologically complex as the eastern Mojave Desert of California (Fig. 1). Attempts at regional geologic synthesis of this region have been frustrated both by the limited exposure of pre-Cenozoic stratified rocks and by the paucity of accurate, small-scale geologic maps. The present report which describes the geology of the Devil's Playground area represents a small contribution toward the solution of this latter problem. This area was chosen for study because reconnaissance maps indicated the presence of a variety of pre-Cenozoic rock units as well as fault structures of possible regional significance.

In addition to providing a general geologic report and map of the Devil's Playground, emphasis was placed on determining answers to the following questions:

1) Is there any evidence that some or all of the Precambrian metamorphic rocks in the study area are allochthonous?

2) Are Eocambrian and Early Cambrian detrital strata in the study area autochthonous relative to coeval strata in adjacent areas?

3) How much of the Paleozoic carbonate strata in the study area is allochthonous, how far has it traveled, and in what direction?

4) Do Mesozoic strata in the study area resemble the predominantly volcanic Mesozoic units of the central Mojave or non-volcanic Mesozoic strata of southern Nevada?
5) How many periods of Mesozoic deformation occurred in this area, and what was the style of each deformation?

6) What was the nature of Tertiary deformation in the study area?

It is hoped that the answers given to these questions will provide useful information for and constraints upon future syntheses of the geologic history of the Mojave Desert.

Geographic Setting

The Devil's Playground area lies at the southern end of the greater Death Valley depression within the Mojave Desert physiographic province and the Basin-Range geologic province (Fig. 1). Boundaries of and within the Mojave Desert used in this report partially conform with those shown by Jahns (1955, p. 11, Fig. 4). In this usage, the Mojave Desert is bounded on the west and southwest by the San Andreas fault, on the north by the Garlock fault and the northern slopes of the Kingston Range, and on the east by the Colorado River. Within the Mojave Desert, north-south lines on the west side of the Soda Mountains (lat. 116°15' west) and at Barstow (lat. 117°00' west) are used herein to separate the eastern from central and central from western portions of the Mojave Desert, respectively.

Terrain within the Playground is typical of desert regions of the southwest, consisting of steep-sloped, mountainous tracts separated by broad, low-lying alluviated areas, portions of which are covered by sheets and dunes of sand. Elevations within the map area range from 980 feet at the edge of Soda (dry) Lake to 4764 feet on the top of Kelso Peak.

Climate and flora of this area can be typified as rigorous and sparse, respectively. Hot summers (105° - 115° daytime
Figure 1. Index map of the Mojave Desert, showing relation of study area to other localities mentioned in the text.
temperatures), mild winters, and little rainfall (3-5 inches annual precipitation) characterize the climate. At lower altitudes, only a few hardy varieties of desert shrubs, grasses, and cacti manage to survive while the somewhat milder temperatures and greater rainfall above 3000 feet elevation allow relatively luxurious growths of Joshua, yucca, and creosote.

Access roads to and within the Playground are shown in Figure 2. Dirt roads in various states of repair lead southward to the area from Baker, the principal supply center in the region, and northward to the area from the railroad settlement of Kelso. The several dirt roads within the study area provide easy access to most outcrop areas.

Most geographic names used in this report are those found on the U.S. Geological Survey topographic maps of this area. The canyons which bound the north and south ends of Old Dad Mountain are referred to informally as Iron Mine and Powerline Canyons, respectively (Fig. 2). The term Old Dad Mountain block refers to the entire high area bounded on the east side by the Old Dad fault and which extends from Iron Mine canyon on the north to the south edge of the map area.

Letter-number combinations such as R-27 which are found through the text refer to the letters and numbers along the bottom and right side of Plate 1. These are used as a reference grid to help the reader locate geographic and geologic features on the map plate.

Previous Investigations

Three published geologic maps cover part or all of the present study area. Hewett's (1956) reconnaissance map of the one degree Ivanpah quadrangle was the first modern geologic map of much of the eastern Mojave Desert, and includes
Figure 2. Index map of the Devil's Playground area showing roads and principal geographic features.
most of the present study area. More recently, Barca (1962) reported on the geology of the northern half of the Old Dad Mountain quadrangle; his 1:62,500-scale map covers a small portion of the northwestern corner of the present study area. That portion of the state geologic map of California (Kingman and Trona sheets) which covers the Devil's Playground was derived from the maps of Hewett and Barca. Unpublished investigations of portions of the Playground have been made by Yelverton (1963) and geologists of the Southern Pacific Land Company.

In addition to these general geologic investigations, Hazzard and others (1937) briefly noted the possible occurrence of Lower Triassic rocks south of Powerline Canyon while Lanev (1945) described the geology of a small iron deposit in Iron Mine Canyon.

Present Study

Geologic mapping was done directly on topographic maps created by enlarging portions of the U.S. Geological Survey 15 minute Kelso, Soda Lake, and Old Dad Mountain quadrangles to a scale of approximately 1:20,000. Most of the mapping was done during the early summer of 1969 and the fall and winter of 1970-71; a total of approximately five months was spent in the field.

Stratigraphic thicknesses reported for the Eocambrian and Early Cambrian units of the Kelso Mountains were measured in the field with the aid of a Jacobs staff. Other thicknesses in this report were determined from map cross sections.

Over 200 thin sections were examined to substantiate and expand upon hand specimen petrologic descriptions. With a few exceptions, at least two specimens from each of the pre-Cenozoic, non-carbonate map units were examined in thin section.
Acknowledgments

Several individuals made substantial contributions to the successful completion of this report. Dr. B.C. Burchfiel suggested and supervised the study, and his continued enthusiasm and guidance during the mapping and the preparation of the manuscript are much appreciated. Drs. D. Baker and F. Fisher reviewed the manuscript and served on the thesis committee. Dr. Avé Lallemant examined several thin sections and clarified several points concerning the metamorphic history of the basement rocks. Thanks are due Mr. C. Jordan for identifying several fusulinid collections, Mr. E. Johnson for his able assistance in the field during the mapping of 1969, and Miss R. Gulliver for editing an early draft of the manuscript. Numerous discussions with Mr. E. Abbott and Miss J. Novitsky concerning the Mesozoic rocks of the Play-ground and adjacent areas were most helpful. Finally, I would like to thank my parents for their continued encouragement and financial support during my seemingly endless college career culminating in this report.

Financial support for the field and laboratory work was provided by National Science Foundation grants GA 1079 and GA 21375 awarded to Dr. Burchfiel. Rice University furnished most of the needed field equipment and laboratory facilities, while San Jose State College, San Jose, California, provided the short-term use of a petrographic microscope and working space. Stipends covering tuition and living expenses were provided by a National Science Foundation Graduate Fellowship (1969-71) and Rice Teaching Fellowships (1968;1972).
REGIONAL GEOLOGIC SETTING

Depositional Setting

The Devil's Playground area lies within the Paleozoic miogeosynclinal facies belt of the Cordilleran geosyncline (Fig. 3). This facies was deposited on a slowly subsiding, shallow continental shelf marginal to a relatively stable continental platform lying to the east. The narrow transition zone between the thinner platform strata on the east and the lithologically similar but significantly thicker miogeosynclinal sequence on the west extends southwest from Las Vegas and appears to have passed not far south of the study area (Stewart 1970, p. 8; Bissell and Chilingar 1968, p. 156). A deeper oceanic or eugeosynclinal facies belt lay to the west and northwest of the miogeosynclinal belt.

Marine sedimentation in the Cordilleran miogeosyncline began in the late Precambrian and continued with only minor interruptions into the Early Triassic. During the initial depositional phase extending from late Precambrian (Eocambrian) to Middle Cambrian time, predominantly detrital rocks were deposited in an essentially conformable sequence. During the remainder of the Paleozoic Era, deposition of predominantly carbonate strata alternated with short periods of nondeposition and/or erosion. At the top of the Paleozoic section, a widespread erosional unconformity is overlain by alternating fine detrital and carbonate strata of the Moenkopi Formation, the lower portions of which are marine whereas the higher strata are of continental origin.

Beginning in mid(?)-Early Triassic time and extending through most of the Mesozoic Era, a more complex depositional picture obtained. A northwest-trending volcanic-plutonic belt developed across the northeast-trending facies and isopach
Figure 3. Depositional setting of the study area. Principal Eocambrian, Paleozoic, and Mesozoic trends shown.
trends of the Paleozoic geosyncline (Fig. 3) (Hamilton, 1969; Burchfiel and Davis, 1972). In the eastern Mojave Desert, subaerial flows and tuffs of the eastern margin of this belt interfinger with non-volcanogenic, continental strata which were being deposited east of the belt. Numerous granitic plutons invaded the belt and its eastern margin during the Mesozoic Era.

During the Cenozoic Era, extensive erosion of uplifted areas exposed wide areas of Precambrian metamorphic rocks in the eastern Mojave Desert; adjacent low-lying areas often contain thousands of feet of subaerial and lacustrine sedimentary and volcanic rocks.

Tectonic Setting

Four periods of tectonic activity marked by linear belts of eastward-moving thrust plates have been delineated in the southern Cordilleran geosyncline (Burchfiel and Davis, 1972). The first two of these, the mid-Paleozoic Antler orogeny and the Permo-Triassic Sonoma orogeny, were confined to the mio-geosynclinal-eugeosynclinal interface and did not directly affect the eastern Mojave Desert; only a disconformity marks these events in the study area.

The two younger periods of deformation affected areas farther to the east within the miogeosyncline of the Cordilleran geosyncline and platform facies to the east. The older of these two deformations is referred to as the Mesocordilleran orogeny (Burchfiel and others, 1970). Thrust plates developed during this orogeny form a poorly delineated belt trending roughly south-southwest through Nevada and into the Mojave Desert (Fig. 4a). These plates were thrust eastward during Triassic and Early Jurassic time. Mesocordilleran thrust faults occur at Clark Mountain, only 30 miles north-
Figure 4. Tectonic setting of the study area; 4a) Approximate location of the early Mesozoic Mesocordilleran orogenic belt; 4b) Location of the late Mesozoic Sevier orogenic belt.
east of the Devil's Playground area. Burchfiel and Davis (1971) report that one of these thrust faults transported a thick plate of Precambrian metamorphic rocks in a northeast direction for a distance possibly as great as 16 miles and perhaps even more.

Younger Mesozoic thrust faults can be grouped into two events which probably represent portions of a continuous period of tectonism. Armstrong (1968) gave the name Sevier orogeny to the older of these two events in the southern Cordilleran orogen. The Sevier orogenic belt trends southwest through Utah and Nevada and into the Mojave Desert; thrust fault activity was greatest during the interval Late Jurassic - Late Cretaceous. Burchfiel and Davis have mapped thrust faults of probable Sevier age at Clark Mountain. Thrusts which developed during the latest Cretaceous and early Tertiary Laramide orogenic event are known to the northeast and southeast of Clark Mountain, but no thrusts within the eastern Mojave Desert have yet been proven to be of Laramide age.

Two points emerge from this brief review of regional tectonics that are of special significance to the present study and to any future mapping projects in the Mojave Desert. First, it must be kept in mind that two orogenic belts characterized by generally eastward-moving thrust plates overlap in southeastern California. Thus greater attention must be given to the determination of ages and sequence of development of various structures. Secondly, the discovery of thrusted Precambrian metamorphic rocks at Clark Mountain suggests that such rocks elsewhere in the eastern Mojave Desert may also be allochthonous, and thus must be investigated for evidence of thrusting as closely as are the sedimentary rocks lying upon them.
STRATIGRAPHY

Introduction

A surprisingly complete collection of rock units ranging in age from Precambrian through Recent ages crop out in the Devil's Playground area. Precambrian metamorphic rocks, Eocambrian through Jurassic stratified units and granitic intrusive rocks have received the greatest attention in this study. Tertiary (?)–Mesozoic (?) hypabyssal rocks and Cenozoic stratified units were not studied in detail, and they will be described only briefly. A compilation and brief description of pre-Cenozoic stratified units is presented in Table 1. These units readily fall into four lithostratigraphic groups which will be described separately; these are Precambrian metamorphic rocks, Eocambrian and Early Cambrian units, Late Cambrian to Permian strata, and Mesozoic units.

Precambrian Metamorphic Rocks

General Statement

Regionally and/or thermally metamorphosed rocks of Precambrian age form the stratigraphic basement of the study area. The bulk of these rocks crop out in three blocks separated by faults, Mesozoic (?) granitic intrusions, or younger sediments. These three blocks are referred to informally as the Kelso Mountains block (centered near H–6), the Powerline Canyon block (centered near L–18 and bounded on the west by the Old Dad fault), and the Iron Mine block (centered near R–25 and bounded on the east by the Old Dad fault). The Kelso Mountains and Iron Mine blocks are overlain unconformably by non-regionally metamorphosed Eocambrian sediments.

Regionally Metamorphosed Rocks

Kelso Mountains block: Slightly-foliate, felsic gneiss
<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
<th>Thickness (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Jurassic</td>
<td>Delfonte Volcanics</td>
<td>Unit 4 Rhyodacite tuff, flow breccia.</td>
<td>2000+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit 3 Quartz latite tuff.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit 2 Andesite, dacite flows, flow breccia.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit 1 Rhyolite, quartz latite tuff, flows.</td>
<td></td>
</tr>
<tr>
<td>Early Jurassic</td>
<td>Aztec Sandstone</td>
<td>Quartz arenite with minor amounts of fine-grained volcanic detritus; pebble to boulder conglomerate lenses near base of formation.</td>
<td>2100+</td>
</tr>
<tr>
<td>Late, Middle Triassic</td>
<td></td>
<td>Predominantly andesite and dacite flow breccia, and tuff with interbedded volcanioclastic, quartzites.</td>
<td>5200+</td>
</tr>
<tr>
<td></td>
<td>Lower Volcanic Unit</td>
<td></td>
<td><strong>basal quartzite</strong> Quarts and volcanic pebble conglomerates and quartzite.</td>
</tr>
<tr>
<td>Early Triassic</td>
<td>Moenkopi(?) Formation</td>
<td>Interbedded marl, siltstone, limestone and shale.</td>
<td>400+</td>
</tr>
<tr>
<td>Permian, Pennsylvanian</td>
<td></td>
<td>Bird Spring Formation</td>
<td>Limestone, silty limestone with minor interbedded shale; chert abundant in lower part. Interbedded quartzite and limestone in Permian-aged strata.</td>
</tr>
<tr>
<td>Mississippian</td>
<td></td>
<td>Yellowpine Formation</td>
<td>Massive dark gray limestone.</td>
</tr>
<tr>
<td></td>
<td>Monte Cristo Limestone</td>
<td></td>
<td>Massive pale gray limestone.</td>
</tr>
<tr>
<td></td>
<td>Bullion Formation</td>
<td>Dark gray limestone w/ abundant chert.</td>
<td></td>
</tr>
<tr>
<td>Devonian</td>
<td>Sultan Limestone</td>
<td>Light gray to cream-colored limestone; porcelain-like texture in upper part.</td>
<td>700+</td>
</tr>
<tr>
<td>Devonian-Middle Cambrian</td>
<td>Goodsprings Dolomite</td>
<td>Mottled and banded dolomite plus limestone; minor amounts of chert in some beds.</td>
<td>600+</td>
</tr>
<tr>
<td>Middle, Early Cambrian</td>
<td>Carrara Formation</td>
<td>Upper member Silty limestone w/ siltstone interbeds</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower member Shale w/ dolomite, quartzite interbeds</td>
<td>75+</td>
</tr>
<tr>
<td>Early Cambrian</td>
<td>Zabriskie Quartzite</td>
<td>Nearly massive quartzite with interbeds of siltstone near middle of unit.</td>
<td>68</td>
</tr>
<tr>
<td>Early Cambrian, Eocambrian</td>
<td>Wood Canyon Formation</td>
<td>Upper</td>
<td>Dark green siltstone and shale with interbedded fine-grained quartzite.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle</td>
<td>Coarse-grained to conglomeratic, cross-bedded quartzite; shale interbeds.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Dark green siltstone, shale.</td>
</tr>
<tr>
<td>Eocambrian</td>
<td>Upper Stirling Quartzite</td>
<td>Medium-grained to pebbly, orange weathering quartzite.</td>
<td>175</td>
</tr>
<tr>
<td>Eocambrian</td>
<td>Lower Stirling Quartzite, Johnnie Formation, undivided</td>
<td>Basal conglomerate overlain by interbedded quartzite, silty argillite, and dolomite.</td>
<td>12-450</td>
</tr>
<tr>
<td>Precambrian</td>
<td></td>
<td>Ortho and paragneiss; minor schist.</td>
<td></td>
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</table>
is the dominant lithology of basement rocks in the Kelso Mountains block. Small, flattened lenses and thin layers of mafic and opaque minerals mark the foliation, reinforced in some areas by flattening of the accompanying felsic minerals. This lithology grades toward both dark mineral-free, non-foliated granofels and, less commonly, to biotite-rich, schistose rocks. Granular to slightly foliated mafic rocks occur as thin, discontinuous layers and lenses parallel with the foliation in surrounding gneisses in a few areas. It is interpreted that these rocks have been derived by the metamorphism of sedimentary strata.

Pegmatitic quartz-feldspar rock cuts all of the above lithologies. Forming irregular patches as well as layers parallel with the foliation of the host gneiss, the pegmatitic rock in most cases displays gradational contacts with its host rock. As the metamorphic grade of the country rocks does not appear to have been very high (see below), these pegmatitic rocks are probably not partial melts formed in situ. It is interpreted that they were injected from greater depths into moderately hot gneiss with which they reacted slightly to form gradational contacts.

Iron Mine block: The principal rock type of the Iron Mine block is moderately well-foliated biotite gneiss. Mineral segregation into felsic and mafic bands is more pronounced than in the Kelso Mountains block while non-foliated felsic granofels are less common. Near R-25 small amounts of foliated quartzite occur within the gneiss indicating a sedimentary origin for these rocks. Tectonized blocks of metamorphosed carbonates are found near the quartzites, but it is not certain whether they were interbedded with the gneiss or faulted into it. Outcrops of foliated and non-foliated granitoid and granitic rocks were found at several places in
the Iron Mine block. Some of these almost certainly represent Precambrian granitic intrusives, but others may be of Mesozoic age. Pegmatitic quartz-feldspar rock similar to that found in the Kelso Mountains block was observed in numerous outcrops in the Iron Mine block. All of the above lithologies have been subjected to variable amounts of hydrothermal alteration including extensive epidotization.

Powerline Canyon block: The Powerline Canyon block is dominated by a body of foliated granitic rock which has invaded paragneiss similar to that described above. One intrusive contact with the paragneiss can be seen near L-17. This intrusive is readily recognized in most outcrops by the presence of mafic xenoliths, usually flattened into the plane of the foliation, and/or large, tabular plagioclase phenocrysts (porphyroclasts). Again, pegmatitic quartz-feldspar material invades these gneisses.

Samples of paragneiss from all three blocks are surprisingly uniform in textures and compositions. The principal mineral assemblages observed in these rocks are as follows (most abundant assemblage first, least abundant assemblage last):

- quartz - microcline - albite - biotite + muscovite
- quartz - microcline - albite - biotite - hornblende + muscovite
- plagioclase - biotite - hornblende (found in mafic layers)

Accessory minerals are magnetite and epidote. Felsic to intermediate gneiss, the most common rock type, has principal mineral abundances in the following ranges:

- quartz 25% - 50%  
- biotite 3% - 10%  
- microcline 25% - 40%  
- hornblende 0% - 5%  
- albite 10% - 25%  
- muscovite 0% - 1%

Textures of these rocks range from granoblastic to well-foliated gneissic. Foliation is produced by slightly undula-
tory trains of opaque and aligned, elongated mafic minerals set in a granoblastic to slightly foliate quartz-feldspar matrix. These trains consist both of continuous layers a few millimeters thick which are spaced 1 centimeter or less apart and as aligned lenses of dark minerals.

Many thin sections show evidence of a small amount of thermal retrograde metamorphism such as recrystallization of larger mafic minerals into numerous smaller grains, replacement of hornblende by biotite or by mixtures of actinolite and chlorite, and the presence of tiny flakes of muscovite in random orientations. Another textural feature which may be the result of this thermal metamorphism is the presence in many samples of tiny, unstrained, round blebs of quartz.

Orthogneiss from the Powerline Canyon block is readily recognized in thin section by the presence of subhedral, tabular grains of plagioclase displaying oscillatory zoning. Diamond-shaped euhedra of sphene also reflect the igneous origin of this rock. These minerals are set in a foliated matrix of K-feldspar, quartz, and biotite. Principal mineral assemblages and modal compositions of this orthogneiss are essentially the same as the paragneiss which it invades. The plagioclase porphyroclasts, however, have an overall composition more calcic than albite due to the relict igneous zoning.

In summary, two periods of metamorphism have affected the foliated precambrian rocks of the study area. An earlier, regional event produced foliation and created principal mineral assemblages which, for the following reasons, appear to indicate a metamorphic grade in the uppermost greenschist facies (possibly the quartz-albite-epidote-almandine subfacies of Winkler, 1967, p. 102):

1) Albite is the dominant plagioclase mineral;
2) Oscillatory zoning in granitic plagioclase has sur-
vived the regional metamorphism;
3) Minerals (or their pseudomorphs) of higher metamorphic grade (e.g., sillimanite, garnet) have not been recognized in these rocks.

Subsequent to this regional metamorphism, a thermal metamorphic event caused slight retrograde recrystallization.

Structures within the Precambrian rocks of the study area appear to be relatively simple. Macroscopic (map scale) folds were not directly observed during the mapping, although mesoscopic foliation data indicate that such folds exist. Lack of marker beds or widespread, distinctive lithologies precludes their direct recognition.

Mesoscopic (scale of outcrop to hand specimen) structures also appear to be relatively simple. The gneissic mineral foliation is the only fabric element present in the majority of outcrops. Poles to this foliation (π diagrams) have been plotted and contoured for each of the three basement blocks (Fig. 5). These diagrams indicate that the foliation has been folded either by one inhomogeneous deformation or two or more times by homogeneous deformations. Two factors preclude a unique interpretation of the deformational history of these rocks. First, and most importantly, penetrative structures other than the one foliation are lacking. Second, the attitudes of strata lying unconformably above these Precambrian metamorphic rocks indicate that they have undergone variable amounts and directions of tilting and/or rotation during Mesozoic and Cenozoic faulting. An attempt was made to subdivide the outcrop blocks into smaller domains of more homogeneous structure using the method of Ramsay (1967, p. 552), but without notable success. Because of these factors, only a few general comments can be made concerning the folding of the foliation.
Figure 5. $\pi$-diagrams for the three principal outcrop areas of Precambrian metamorphic rock. Poles to metamorphic foliation are plotted.
Lack of penetrative mesoscopic structures other than the one foliation as well as the lack of large-scale visible fold closures suggest that the foliation is deformed in broad open folds rather than in tight or isoclinal folds. The simplest $\pi$ diagram is that of the Iron Mine block. The northwest trending foliation is subvertical and may be only very slightly warped about steeply plunging axes. The $\pi$ diagram for the Powerline Canyon block is somewhat more complex. The majority of pole concentrations fall on a partial small-circle girdle. The predominant strike of the foliation remains to the northwest while the dip becomes moderate to steep in a northeast direction. The $\pi$ diagram for the Kelso Mountain block exhibits an extreme scatter of points defining several concentrations. No great or small-circle girdles fitted to the diagram accommodate more than approximately two-thirds of the poles. This scatter may reflect considerable faulting and tilting of areas within this block or perhaps an extra folding episode not found in the other blocks.

A few mesoscopic folds quite different than those reflected in the $\pi$ diagrams were observed in each of the three outcrop blocks. These are small (amplitudes less than one foot), generally isoclinal similar folds with axial surfaces coincident with the foliation of the host rock. With one exception, the material folded is pegmatitic quartz-feldspar rock; the surrounding gneiss does not appear to be deformed. A possible explanation of this phenomenon involves the injection of pegmatitic material into gneiss near the end of the metamorphic event creating the foliation. The last flowage movements partially transposed veins and patches of pegmatitic material into the plane of the foliation, thus creating similar folds.
Gabbroic Dikes

The Powerline Canyon block contains a large number of dark green gabbroic dikes which constitute perhaps 30% of the outcrop area of the entire block. These dikes strike north and northwest and have subvertical dips. They lack foliation and have sharp, intrusive contacts with the rocks they invade. Thus they clearly appear to postdate the regional metamorphic event which gave rise to the foliation in the enclosing gneiss.

In thin section, the mafic hypabyssal rocks consist of thermally (hydrothermally?) altered hornblende, plagioclase of intermediate composition, biotite, magnetite, and epidote, in order of decreasing abundance.

Regional Correlations

Published descriptions of Precambrian geology in surrounding areas in the eastern Mojave Desert are very similar to that presented above for the study area. Radiometric age-dating (Rb-Sr method) of Precambrian rocks in some of these areas reveal that the last regional metamorphism to occur in this region was between 1650 and 1730 m.y.b.p. (Lanphere, 1964, p. 396). The regional metamorphism of sedimentary or meta-sedimentary rocks and the syntectonic emplacement of granitic and pegmatitic magma in the study area is tentatively correlated with this time interval. Unfoliated granites in the Marble Mountains and elsewhere have yielded radiometric ages of approximately 1400 m.y.b.p. The thermal metamorphic event seen in the study area may be related to regional heating during the emplacement of these granite plutons.

Emplacement of mafic hypabyssal rocks during the late Precambrian appears to have been a widespread phenomenon in the southwestern United States (cf. Cloud, 1971, p. 15).
These rocks yield radiometric (Rb-Sr) ages in the range of 1100 - 1200 m.y.b.p. The gabbroic dikes of the Powerline Canyon block probably date to this period.

Eocambrian to Early Cambrian Strata

General Statement

Several partial and complete sections of Eocambrian and Early Cambrian strata crop out on the south flank of the Kelso Mountains where they rest unconformably upon Precambrian metamorphic rocks. Other, smaller outcrops of these strata, disrupted and metamorphosed by intrusives, occur to the north of Kelso Peak and on the north slope of Cowhole Mountain. These strata have been correlated with and named after formations of similar lithology and stratigraphic position found in surrounding areas of the Cordilleran miogeosyncline. The following descriptions are derived from the complete and well-exposed sections lying two miles northwest of Kelso (F-2, H-2). A columnar section of these Eocambrian and Early Cambrian rocks is given in Figure 6.

Lower Stirling Quartzite-Johnnie Formation, undivided

Strata correlative with the lower and middle portions of the Stirling Quartzite and with the Johnnie Formation (both named by Nolan, 1929, p. 463) form the basal unit of the Eocambrian to Early Cambrian sequence. Various exposures on ridges within two miles of each other are quite variable in thickness and lithology; they have been placed in the same unit only because of their equivalent stratigraphic position. This variability may in part reflect infilling of an irregular erosional surface developed on Precambrian gneiss and in part be due to rapid near-shore facies changes. It was at first thought that the one thick section may have been
Figure 6. Columnar section of Eocambrian and Early Cambrian strata of the Devil's Playground area. Lithologic symbols after Compton (1962, p. 338).
thrust into its present position from the north, but close examination of the area revealed no thrust faults. The age of the Stirling-Johnnie unit is late Precambrian. The term Eocambrian is used here because this and immediately overlying units form a conformable sequence with still higher, fossiliferous, Early Cambrian strata. 

Thickness: On one ridge (H-4) the Stirling-Johnnie unit reaches an estimated thickness of 400 to 500 feet. Extensive shearing and alteration in the upper part of the unit preclude a more accurate measure. On ridges to the east and west of this locality, the Stirling-Johnnie unit is only 12 to 70 feet thick. In the Providence Mountains which lie approximately eight miles to the southeast of the Kelso Mountains section, Steward (1970, p.153) reports a thickness of 417 feet for strata equivalent to the Stirling-Johnnie unit while just to the north of the map area these same units total 1100 feet in thickness (Stewart, 1970, p.150-152).

Lithostratigraphy: At the locality containing 400 to 500 feet of Stirling-Johnnie strata (H-4), the unit begins with 150 feet of medium-grained, dark gray- to orange-weathering quartzite at the base of which are several feet of quartz and feldspar pebble conglomerate. Overlying this quartzite unit is a sequence of dark green-gray argillites and slaty shales with occasional interbeds of orange- to brown-weathering dolomite; the total thickness of these strata is approximately 150 feet. Above this sequence the rocks become extensively sheared and mineralized, but appear to consist of interbedded sequences of quartzite, fine clastics, and dolomite. The thinner Stirling-Johnnie sections found on adjacent ridges typically begin with 5 to 20 feet of gray, fine-grained quartzite followed by buff- to orange-weathering dolomite with interbedded fine-grained quartzite
and/or a distinctive green-gray banded siltstone.

Upper Stirling Quartzite

Lying stratigraphically above the Lower Stirling Quartzite-Johnnie Formation, undivided unit is the ridge-forming Upper Stirling Quartzite. Contacts with the underlying unit are sharp and appear to be conformable. The lithology and stratigraphic position of the Upper Stirling clearly indicate that it is correlative with the uppermost or E member of the Stirling Quartzite as defined by Stewart (1970, p. 37). Because it lies within the conformable section below Early Cambrian strata, the upper Stirling Quartzite is Eocambrian in age.

Thickness: In contrast the underlying formation the Upper Stirling has a fairly uniform thickness. Exposures on three ridges average 175 feet in thickness. Stewart (1970, p. 150-152) reports a thickness of 76 feet for the E member of the Stirling in the Providence Mountains while just to the north of the map area (his locality 39), it is 150 feet thick.

Lithostratigraphy: The Upper Stirling consists of massive-looking, pink- to orange-weathering quartzite of medium grain size. Scattered through the unit are a number of quartz grit to quartz pebble layers which are especially abundant near the top. Faint laminae within the quartzite reveal occasional low-angle, sweeping cross-bedding.

Wood Canyon Formation

Strata assigned to the Wood Canyon Formation (named by Nolan, 1929, p. 463) conformably overlie the Upper Stirling Quartzite; the intervening contact is gradational over a few inches. Three lithologically distinct members are present within the formation. The upper and lower members are non-
resistant and crop out in saddles whereas the middle member generally supports a low ridge. The Wood Canyon Formation is considered to be in part Eocambrian and in part Early Cambrian age; the boundary is usually placed in the middle member (cf. Reynolds, 1969, p. 37). The only fossils found during the present study were various tracks, burrows, and tubes which occur in all three members.

Thickness: Measurement of one complete section and several partial sections revealed little variation in thickness; the average thicknesses for the lower, middle, and upper members are 133 feet, 412 feet, and 140 feet, respectively. Stewart (1970, p.153) reports that in the Providence Mountains the lower member is missing and the middle and upper members are 447 feet and 191 feet thick, respectively. In the Salt Spring Hills, 50 miles to the north of the Kelso Mountains section, Stewart (1970, p. 138-139) reports thicknesses (bottom to top) of 43 feet, 720 feet, and 557 feet for the three members.

Lithostratigraphy: The lower member consists of dark-green, micaceous silty shales, siltstones, and fine-grained quartzites in varying proportions. Bedding thicknesses range from 1 to 10 inches. Beds in the siltstones are often laminated, and often contain chips and fragments of the interbedded shale. Bedding surfaces of the finer rocks often have a hummocky appearance apparently caused by extensive bioturbation.

The contact between the lower and middle members of the Wood Canyon Formation is sharp and sometimes has slight irregularities suggestive of a brief period of erosion between the deposition of these two members. Five to 10 feet of vein-quartz and jasper pebble conglomerate occur immediately above the contact, followed by 20 to 50 feet of coarse-grained quartzite containing scattered horizons of similar pebbles.
Above this, and forming the bulk of the middle member, is fine- to medium-grained, cross-bedded quartzite with interbedded siltstone and silty shale. The purple-weathering quartzite occurs in beds 6 inches to 3 feet thick within which laminations display prominent high-angle, festoon cross-bedding. Fragments of the interbedded shale and siltstone are common within the quartzite. The finer-grained interbeds are black to dark green in color, generally very micaceous, and occur in layers one-half inch to 1 foot thick. They constitute about 15 percent of the total thickness of the middle member.

The upper member of the Wood Canyon Formation overlies the middle member with a contact which is gradational over a distance of about 5 feet. This upper member bears a superficial resemblance to the lower member in that it is fine-grained and green in color. A distinctive feature of the upper member, however, is its rhythmic interbedding of laminated, fine-grained, gray-green quartzite with olive green siltstone and silty shale. The quartzite occurs in beds 1 to 2 feet thick while the beds of finer-grained rocks are 1 to 3 feet thick. Microripple marks and hummocky bedding surfaces caused by bioturbation are common in the finer-grained horizons.

Zabriskie Quartzite

The Zabriskie Quartzite (named by Hazzard, 1937; redefined by Wheeler, 1948) conformably overlies the Wood Canyon Formation; the contact between the two units is gradational over a distance of approximately one foot. Like the upper Stirling Quartzite, the Zabriskie Quartzite is a prominent ridge-forming unit. No age-diagnostic fossils have been found in the Zabriskie either during this study or elsewhere.
Because it is underlain and overlain by Early Cambrian strata, the Zabriskie is assigned this age.

Thickness: A constant thickness of 68 to 70 feet is maintained by the Zabriskie throughout its area of outcrop in the Kelso Mountains. Stewart (1970, p. 152) reports a thickness of 70 feet for the Zabriskie in the Providence Mountains while in the Salt Spring Hills it is 187 feet thick (Stewart, 1970, p. 138).

Lithostratigraphy: Fine- to coarse-grained, pale-pink quartzite is the predominant lithology of the Zabriskie. A few thin interbeds of micaceous, platy-fracturing, buff and yellow silty shale occur near the middle of this unit. Although apparently massive in most outcrops, the Zabriskie occasionally reveals beds 1 to 4 feet thick within which faint laminae define low-angle, sweeping cross-bedding. Abundant white-sand-filled, vertical tubes about one-quarter inch in diameter (Scolithus?) occur in some horizons in the upper half of the Zabriskie.

Carrara Formation

The Carrara Formation (named by Cornwall and Kleinhämml, 1961) is an important unit in the Eocambrian to Early Cambrian section because within it occurs the transition from predominantly clastic sediments below the middle of the unit to predominantly carbonate strata above. Only the lower, primarily clastic portion (referred to informally herein as the lower member) of the Carrara is in stratigraphic continuity with underlying units; the silty limestone of the upper half of the Carrara is present only as variably brecciated slide blocks which are described in the section discussing structure of the Kelso Mountains (p.54). The age of the lower member is Early Cambrian based on the presence of diagnostic tri-
lobites, one collection of which was made in the Kelso Mountains outcrops by Hewett (1956, p. 37). Hewett used the name Bright Angel Shale for these strata, a name now restricted to equivalent strata of the platform facies.

Thickness: Measurements of three exposures of the lower member of the Carrara Formation yielded an average thickness of 75 feet. This is a minimum figure because the shales at the top of these sections appear to have undergone tectonic attenuation during movement of the overlying limestone. In the Providence Mountains, equivalent clastic strata are 87 feet thick (Stewart, 1970, p. 153) while in the Silurian Hills to the north of the study area, these same strata are 90 feet thick (Stewart, 1970, p. 143).

Lithostratigraphy: Green and red shale and silty shale make up about 90 percent of the lower member of the Carrara Formation. Near the base of this unit are a few 1 to 3 foot thick beds of medium-grained quartzite similar to the underlying Zabriskie Quartzite. Scattered through the upper half of the member are several 1 to 2 foot thick beds of brown-weathering dolomite. These beds are slightly cherty and contain variable amounts of fossil hash. Casts and molds of trilobites and trilobite fragments are common in some shale horizons while others are quite hummocky due to intense bioturbation.

Regional Correlations

The 1400 feet thick section of Eocambrian and Early Cambrian units in the Kelso Mountains is representative of a widespread group of similar strata which form a southeast-thinning wedge which exceeds 10,000 feet in thickness in northern Death Valley (Hunt and Mabey, 1966). Figure 7 presents comparative sections of these units along a line roughly
Figure 7. Comparative sections of Eocambrian and Early Cambrian strata in the eastern Mojave Desert.
perpendicular to the regional isopach and facies trends. The platform facies exposed in the Marble Mountains contains only a thin sequence of Early Cambrian strata lithologically equivalent to the Carrara, Zabriskie, and upper and middle Wood Canyon units. These thicken progressively northward, and northward-thickening Cambrian units appear below them. As seen in Figure 7, the Kelso Mountains section fits readily into this regional trend.

Late Cambrian to Permian Strata

General Statement

Late Cambrian to Permian strata of the Devil's Playground area are characteristic of the carbonate-dominated, eastern miogeosynclinal facies of the southern Cordilleran geosyncline. A columnar section of these rocks is presented in Figure 8. In the study area these units crop out on Old Dad Mountain and in the Cowhole Mountains; they are interpreted to be entirely allochthonous in both of these areas. In addition, small outcrops of tectonized, thermally metamorphosed carbonate strata near H-20, K-20, and R-4 have tentatively been correlated with the Paleozoic section.

These carbonate units have not provided a great deal of new stratigraphic data because of their deformed state. Only one formation, the Monte Cristo Limestone, displays both upper and lower stratigraphic contacts. In addition to disruption by faulting and folding, these carbonate units have undergone considerable gravity-induced slumping and surficial brecciation.

Goodsprings Dolomite

The Goodsprings Dolomite (named by Hewett, 1931, p.11) crops out over much of southern Nevada and the eastern Mojave
Figure 8. Columnar section of post-Early Cambrian Paleozoic rocks, Devil's Playground area. Lithologic symbols after Compton (1962, p. 338).
Desert. Gans (1970) has shown that within the Goodsprings, several mappable units are present which are lithostratigraphic equivalents to the (bottom to top) Bonanza King, Nopah, Pogonip, and Ely Springs units mapped in other areas in the southern Cordillera. Hewett assigned a Late Cambrian to Devonian age to the Goodsprings. Gans' study revealed that the bulk of the formation is Middle and Late Cambrian. In the study area, one block of Goodsprings crops out on the northwest flank of Old Dad Mountain while several larger outcrops of this unit are present in the northern half of the Cowhole Mountains.

Thickness: Isolated outcrops surrounded by sand near M-35 are the only places where significant thicknesses of stratigraphically coherent Goodsprings Dolomite are present. There, an estimated minimum thickness of 800 feet is present. Hazzard (1954, p. 30) reports a thickness of 2900 feet for strata equivalent to the Goodsprings in the Providence Mountains, while to the north, in Death Valley, as much as 7400 feet of rock were deposited during the time interval represented by the Goodsprings (Hunt and Mabey, 1966).

Lithostratigraphy: Banded and mottled dolomite with subordinate limestone typify the Goodsprings Dolomite in the study area. Banded outcrops generally consist of varying proportions of dark - and light-gray dolomite in alternating layers a few inches to a few feet thick. The very distinctive mottled outcrops consist of irregular, rounded, brown-weathering patches of dolomite in a blue-gray limestone matrix. Small amounts of stringy to nodular chert are present in both rock types of the Goodsprings. While often appearing massive in outcrop, both banded and mottled Goodsprings contain beds ranging in thickness from 1 to 10 feet.
Sultan Limestone

Light-colored limestone lying unconformably above the Goodsprings Dolomite at Goodsprings, Nevada was named the Sultan Limestone by Hewett (1931, p. 31). In the Devil's Playground area, strata assigned to the Sultan Limestone crop out above the Playground thrust on the northwest flank of Old Dad Mountain. Fossil evidence in the type locality and elsewhere place the Sultan in the Middle Devonian.

Thickness: A minimum stratigraphic thickness of 700 feet was determined for the Sultan Limestone on Old Dad Mountain. The lower stratigraphic contact is not exposed, and an indeterminate amount of basal strata are covered. Hazzard (1954, p. 30) reported that the Sultan Limestone is approximately 1000 feet thick in the Providence Mountains while Hunt and Mabey (1966) measured approximately 2000 feet of correlative strata (Lost Burro Formation) in Death Valley.

Lithostratigraphy: Hewett divided the Sultan Limestone into three members at the type locality. These are, from bottom to top, the Ironside Dolomite, Valentine Limestone, and Crystal Pass Limestone. On Old Dad Mountain, strata equivalent to the middle and upper portions of the Valentine and all of the Crystal Pass members appear to be present. Light-gray or brown to cream-colored limestone is the dominant lithology with a few interbeds of darker dolomitic limestone present in the lower part of the exposed section. A few pink-weathering silty zones are also present. Small amounts of stringy chert occur in the Valentine Limestone member. The upper few hundred feet of the Sultan consist of a distinctive porcelain-like, cream-colored limestone correlative with the Crystal Pass member. The uppermost 20 feet of this unit contain numerous silty zones and one horizon of flat-pebble, intraformational conglomerate. Bedding, which is fairly prominent in the Valentine member and rather ob-
scure in the Crystal Pass member, ranges from 2 to 10 feet thick in both members.

Monte Cristo Limestone

The Monte Cristo Limestone was named by Hewett (1931, p.17) from exposures near Goodsprings, Nevada. In the study area, complete sections of the Monte Cristo are exposed on the northwest flank of Old Dad Mountain and are part of the allochthonous Playground thrust plate. Both the upper and lower contacts of the Monte Cristo are disconformities. The age of this unit, based on fossil evidence from several localities in the eastern Mojave Desert, is Early to Middle Mississippian (cf., Hewett, 1956, p. 42; Hazzard, 1955, p. 28).

Thickness: A thickness of 1090 feet was determined for the Monte Cristo Limestone from a cross section through its outcrop near P-26. This compares with 700 to 880 feet measured by Hazzard (1954, p. 28) in the Providence Mountains. About 1000 feet of equivalent strata (Tin Mountain Limestone) are present in Death Valley (Hunt and Mabey, 1966).

Lithostratigraphy: At the type locality, Hewett defined five members within the Monte Cristo Limestone. From base to top, these are the Dawn, Anchor, Bullion, Arrowhead, and Yellowpine Limestones. In the Providence Mountains, Hazzard was not able to identify the Arrowhead Limestone, but did map an additional unit he called the basal sandstone. The Monte Cristo Limestone in the Devil's Playground area is very similar to that in the Providence Mountains with the exception that the Dawn and Anchor members can not be readily separated.

The basal sandstone consists of 5 to 8 feet of fine-grained, silty quartzite with thin interbeds and partings of shale. This sequence becomes very calcareous upward, grading into sandy limestone. The overlying Dawn-Anchor Limestone begins
with medium to dark-gray, banded and mottled limestone with moderately distinctive beds two to three feet thick. Small amounts of stringy to nodular chert and pink-weathering silty zones occur throughout these lower strata. Higher in the section the limestone becomes progressively darker and bedded chert becomes more abundant until it forms up to 50 percent of the unit. This lithology is typical of Hewett's Anchor Limestone member. Both chert and limestone occur in layers which are typically 1 to 10 inches thick, though chert-free limestone layers up to 10 feet thick are present. The limestone is rich in small pelmatozoan columnals.

The Bullion Limestone member conformably overlies the Dawn-Anchor Limestone. The contact zone between these two is 50 to 100 feet thick. Over this distance, the limestone changes color from dark to very light gray and chert decreases in abundance until only a few, scattered horizons of nodular chert remain. The Bullion Limestone is crowded with pelmatozoan columnals. Bedding in this unit is very indistinct, and its outcrops are smooth, steep slopes.

On the cliff face in the vicinity of Q-24.5, the Bullion Limestone is conformably overlain by the Yellowpine Limestone member, the contact between these two being quite sharp. The Yellowpine is about 80 feet thick and consists of nearly-massive, sparsely-fossiliferous, dark-gray limestone which forms a vertical cliff above the Bullion Limestone. On the steep slope just west of P-25, the Yellowpine Limestone is missing and the Bird Spring Formation rests directly on the Bullion Limestone with a somewhat tectonized contact which may mark a thrust fault with a small amount of slip.

Bird Spring Formation

The Bird Spring Formation (named by Hewett, 1931, p. 21)
forms much of the upper plate of the Playground thrust on Old Dad Mountain as well as the Cowhole thrust plate on Cowhole Mountain. Smaller outcrops of Bird Spring are found elsewhere in the Cowhole Mountains. Near Q-24, good exposures of the lower stratigraphic contact reveal 5 to 15 feet of red shale and sandstone between the Monte Cristo Limestone and the lowest limestone of the Bird Spring Formation. These clastics have been included in the Bird Spring on Plate 1. The upper stratigraphic contact of this formation is not exposed in the study area.

In the Providence Mountains, Hazzard (1954, p. 28) has documented Early Pennsylvanian to Middle Permian ages for the Bird Spring. The oldest and youngest fusulinid species present in several fossil collections gathered on Old Dad Mountain were Triticites and Pseudoswagerina, respectively (Jordan, pers. comm.). These indicate a minimum age-range of Late Pennsylvanian to Early Permian for the Bird Spring Formation in the study area.

Thickness: Within the study area, the greatest thickness of Bird Spring strata occurs on Old Dad Mountain where an estimated minimum thickness of 3000 feet is present beneath the highest part of the mountain. In the Providence Mountains, Hazzard (1954, p. 28) reported that 2900 feet of Bird Spring strata are present. Hunt and Mabey (1966, p. 46) measured 5500 feet of age-equivalent strata in Death Valley.

Lithostratigraphy: Both the lithology and bedding characteristics of the Bird Spring Formation are distinctive. Slopes underlain by the Bird Spring have a bedding-controlled cliff-bench appearance which is especially well developed in areas of moderate dip. The bedding, and hence the individual cliff, is generally from 3 to 15 feet thick, though some cliffs consisting of several beds range up to 50 feet high. Inter-
vening benches develop on the less-resistant silty interbeds. In most areas, this cliff-bench topography is modified by gravity-induced slumping and brecciation to which the Bird Spring Formation appears to be particularly susceptible.

The lithology of the Bird Spring Formation is dominated by light- to medium-gray limestone. Buff-to pink-weathering silty to sandy limestone and thin silty shale interbeds are present throughout the exposed section. Lower strata contain bedded and nodular chert which decreases in abundance upward. In small, fault-bounded blocks containing Early Permian strata, the Bird Spring consists of alternating yellow, medium-grained quartzite and silty limestone in beds 1 to 4 feet thick.

Regional Correlations

Although the post-Early Cambrian Paleozoic section within the study area is structurally fragmented and incomplete, the coherent strata which are exposed are very similar to coeval sections found elsewhere along the southeastern margin of the southern Cordilleran miogeosyncline. Representative sections containing the same units, and which occur in about the same position in the miogeosyncline (e.g. Goodsprings, Nevada and the Providence Mountains), are about 7000 to 8000 feet thick. If the greater thickness of the Monte Cristo Limestone is the study area relative to its thickness in the Providence Mountains is representative of a trend throughout the section, then the post-Early Cambrian Paleozoic rocks in the Devil's Playground area may have initially totaled 8000 to 10,000 feet in thickness.

Coeval strata of the platform facies deposited southeast of the Providence Mountains contain unconformities which reduce these sections to thicknesses of 5000 to 6000 feet (cf.,
Miller, 1970). In a northward direction across the miogeosyncline, these unconformities are replaced by continuous or nearly continuous sections which attain a thickness of more than 14,000 feet in Death Valley (Hunt and Mabey, 1966).

**Triassic and Jurassic Strata**

**General Statement**

An estimated 9000 feet of Mesozoic strata crop out in the Devil's Playground area. A composite section containing four map units (Fig. 10) has been created from isolated and/or fault-bounded outcrops in the Cowhole Mountains and the Old Dad Mountain block. A detailed columnar section of these strata is presented in Figure 9. The oldest (Early Triassic) Mesozoic sediments in the study area represent the last geosynclinal deposits in the eastern Mojave Desert. The overlying continental volcanic and non-volcanic strata of Triassic and Jurassic age are representatives of an entirely new depositional and tectonic regime in southeastern California.

**Moenkopi(?) Formation**

Several small outcrops in the Cowhole Mountains and south of Powerline Canyon in the Old Dad Mountain block have been assigned to the Moenkopi(?) Formation (named by Ward, 1901). Neither the upper nor lower stratigraphic contact of this unit is exposed in the study area, nor were fossils discovered in these outcrops. They have been assigned to the Moenkopi(?) Formation partly on the basis of their spatial relationships to outcrops of probable Middle Triassic age and partly because their lithologies are unlike any of the Paleozoic units in the region but somewhat similar to those found in the Moenkopi Formation in the Providence and Soda Mountains. Fossil collections from these other areas indicate that the Moenkopi is
Figure 9. Columnar section of Mesozoic rocks, Devil's playground area. Lithologic symbols after Compton (1962, p. 338).
Early Triassic in age (cf. Grose, 1959, p. 1525).

Thickness: The thickest outcrops of the Moenkope (?) occur south of Powerline Canyon (J-20) where about 400 feet of fault- and alluvium-bounded strata are present. In the Providence Mountains, Hazzard (1954, p. 28) reports a minimum thickness of 1000 feet for the Moenkopi while Grose (1959, p. 1524) measured 1677 feet of an incomplete Moenkopi section in the Soda Mountains.

Lithostratigraphy: Strata assigned to the Moenkopi(?) Formation in the study area consists of fine-grained clastic rocks and limestone. Outcrops near J-35 consist of shale, silty shale, and fine-grained quartzite interbedded with limestone. The clastic rocks are dark green-gray in color, laminated to thin-bedded, and display abundant micrripple marks on bedding surfaces. The interbedded limestone is a medium gray color arranged in slightly lighter and slightly darker bands. Both the limestone and the clastic rocks occur in alternating layers 4 to 6 feet thick.

Moenkopi(?) strata in the vicinity of J-20 consist of pale orange-, green-, and gray weathering silty marl and limestone. The marls are thin-bedded to laminated while the limestone occur as thoroughly tectonized "interbeds" several feet thick.

Lower Volcanic Unit

Mixed volcanic and clastic strata which underlie much of the southern Cowhole Mountains and the southern part of the Old Dad Mountain block have been assigned to one formation which is referred to informally in this report as the Lower Volcanic Unit. Neither the upper nor lower stratigraphic contact is exposed in the study area. No fossils were found in this unit and no published radiometric dates exist for the
volcanic strata. A Middle and Upper Triassic age is suggested for the Lower Volcanic Unit on the basis of regional correlations (see p. 38).

Thickness: An accurate determination of the thickness of the Lower Volcanic Unit is difficult. This unit occurs in numerous isolated outcrops, and no recognized marker horizon is available to determine whether strata are being omitted or repeated from block to block. Furthermore, the internal structure of the various outcrops is not well known. My feeling is that about 4500 to 5500 feet of unrepeated section are exposed in the study area. Grose (1959, p. 1526) mapped a Triassic-Jurassic volcanic and clastic unit in the Soda Mountains which he estimated to be about 7000 feet thick. Regional correlations (again see p. 38) suggest that approximately the lower 4000 feet of Grose's unit are equivalent to the Lower Volcanic Unit. Similar strata do not crop out east of the Devil's Playground area.

Lithostratigraphy: The Lower Volcanic Unit consists of a heterogeneous assemblage of volcanic flows, flow breccia, tuff, volcaniclastic rocks, and quartzite and quartzite-volcanic conglomerate. Two presumably superposed sequences are interpreted to be present within this unit; one, believed to be the lower sequence, crops out south of Old Dad Mountain and is distinguished by the presence of considerable amounts of quartzite while the higher sequence, which crops out in the southern Cowhole Mountains, is quartzite-free. Another possible interpretation is that these sequences are lateral equivalents of one another. Although definite proof of either hypothesis is presently lacking, the superposed hypothesis is accepted in this report.

The oldest exposed rocks within the lower, quartzite-bearing sequence occur near J-20 where they are faulted against Moenkopi (?) strata. The steeply dipping fault separa-
ting these two units appears to have undergone only small amounts of dip-slip movement, and the attitudes of the Moenkopi(?) and Lower Volcanic Unit strata on either side of the fault are concordant. It is interpreted that only a small amount of strata near the contact is missing because of this fault, and that an almost continuous sequence of Moenkopi(?) Formation into Lower Volcanic Unit strata is present.

About 100 feet of quartzite and volcanic pebble conglomerate comprise the lowest exposed strata of the quartzite-bearing sequence. The pebbles are mostly well-rounded, about 1 to 2 inches in diameter, and are set in a matrix of fine-grained quartz sand and silt. This lithology grades upward into pebbly wackes and wackes, then into quartzite and occasional quartz-rick wackes in beds a few inches to about one foot in thickness. A few of these beds contain low-angle cross-bedding. Several thin layers of fine-grained igneous rock are present within this sequence which appear to be hypabyssal intrusives rather than flows. Total thickness of these sedimentary strata is approximately 950 feet. Overlying this section of clastic rock, and forming all of the exposures of Lower Volcanic Unit north and south of the slope centered on J-20, is a series of volcanic and volcaniclastic strata containing perhaps 5 to 10 percent quartzite in the form of discontinuous lenses and layers.

Volcanic rocks of the quartz-bearing sequence and the quartz-free sequence are very similar; both consist of volcanic flows, flow breccia, and tuff in proportions which are estimated to be 50:30:20, respectively. All appear to be of subaerial origin. Flows and tuff are generally porphyritic and occasionally vesicular. Flow breccia consists of abundant, rounded clasts of volcanic material set in a volcanic matrix of very similar composition. Although weathering to
a rather uniform dark green-gray color, fresh surfaces of flows and flow breccia reveal colors of reddish-brown, light gray, and green-gray to nearly black. Tuff layers are usually light gray or reddish-brown on fresh surfaces.

Metasomatism and thermal metamorphism have thoroughly altered all of these volcanic rocks. Virtually all of the original phenocrysts except quartz have been replaced or extensively altered. All plagioclase has been converted to unzoned albite while ferromagnesian minerals have been replaced by aggregates of epidote, chlorite, calcite, and magnetite. Potassium feldspars are now cloudy and flecked with white mica. Admittedly shaky estimates of the proportions and amounts of the original principal minerals indicate that these extrusives ranged from andesite to rhyolite with a preponderance of andesite and dacite. A few specimens of more alkalic rock types such as trachyte and latite were also identified in thin section.

Interbedded with the volcanic rocks of both the upper and lower sequences are lenses and thin layers of volcanic wacke and shale which together constitute perhaps 15 percent of the Lower Volcanic Unit. These sometimes pebbly rocks are thin-bedded to laminated, and occasionally show graded bedding.

Aztec Sandstone

Distinctive, light-colored quartzite cropping out in the northeast Cowhole Mountains and on the west side of Old Dad Mountain has been assigned to the Aztec Sandstone (named by Hewett, 1931, p. 35). On Old Dad Mountain, the Aztec Sandstone is very incomplete, being bounded entirely by faults. Exposure of the Aztec is much more complete in the Cowhole Mountains. There the base of the Aztec is faulted against Paleozoic rocks and intruded by hypabyssal material while the
upper contact is a disconformity overlain by the Delfonte Volcanics. No age-diagnostic fossils have been recovered from the Aztec Sandstone. It is generally believed to be a western extension of the Early Jurassic Navajo Sandstone.

Thickess: The maximum exposed thickness of the Aztec Sandstone in the study area is approximately 2100 feet. A more exact measurement is precluded by the presence of variable amounts of hypabyssal intrusive rock within the formation. Between 2000 and 2500 feet of Aztec Sandstone are present in southern Nevada (Longwell and others, 1965, p. 41).

Lithostratigraphy: Pale yellow- to brick red-weathering quartzite is the dominant lithology of the Aztec Sandstone. Grain size ranges from fine to coarse, and sorting within given horizons is good. The rounded to well-rounded quartz grains are set in a generally sparse matrix of silt sprinkled with magnetite dust. At several horizons in the section, fine-grained, pink to gray volcanic debris is abundant. Throughout the section, bedding is 1 to 6 inches thick. It is planar in the lower half of the section, but small-scale, high-angle cross beds are common in the upper half.

Conglomerates are present in the lower strata of the Aztec Sandstone. In the lowest exposed strata of the northwesternmost outcrop of the Aztec, there is a 2 to 3 foot thick layer of quartz, chert, and jasper pebble conglomerate. The pebbles are generally well-rounded, perhaps having been derived from an older conglomerate (Shinarump?), and they are set in a fine-grained quartz sand matrix. Above this layer at this locality, and scattered through the lower 100 feet of exposed strata elsewhere in Aztec outcrops (including Old Dad Mountain) are lenses of limestone and chert conglomerates with clasts ranging in size from pebbles to boulders up to 3 feet in diameter. These clasts are set in a matrix of typical
Aztec quartzite. They appear to have been derived primarily from the Bird Spring Formation.

Delfonte Volcanics

An east-dipping sequence of volcanic flows, tuffs, and volcaniclastic strata disconformably overlies the Aztec Sandstone in the northeast Cowhole Mountains. This sequence is herein correlated with volcanic strata of similar stratigraphic position cropping out in the Ivanpah Mountains which are informally named the Delfonte Volcanics (cf. Burchfiel and Davis, 1971, p. 6). In the study area, the Delfonte Volcanics are overlain by Quarternary sand while in the Ivanpah Mountains the upper contact is a thrust fault. Preliminary results from a radiometric age determination of a sample from the basal strata of the Delfonte collected in the Ivanpah Mountains indicate that this unit is older than 150 million years (Sutter, oral comm., 1971). In this report, a Middle Jurassic age is tentatively assigned the Delfonte Volcanics.

Thickness: The largest continuous exposure of Delfonte Volcanics in the Cowhole Mountains is approximately 1700 feet thick. If additional, isolated outcrops of this unit lying to the east of the main outcrop are part of a stratigraphically continuous section, then the Delfonte Volcanics have a minimum thickness of 2000 feet. This compares with the thrust-truncated section in the Ivanpah Mountains which is 600 feet thick, and an incomplete, 1000-foot thick section in the Soda Mountains (Abbott, 1971, p. 69).

Lithostratigraphy: Four lithologically distinct members referred to informally as units one through four (base to top) comprise the Delfonte Volcanics in the Cowhole Mountains. Unit one is sporadically distributed at the base of the Delfonte Volcanics due to a period of erosion subsequent to its
deposition. It consists of pink to reddish-brown, very-porphryritic flows and tuffs. Phenocrysts of quartz, K-feldspar, and sodic plagioclase suggest these volcanic rocks are quartz latite and rhyolite. Muscovite, present in amounts less than 1 percent, is the only varietal mineral in this unit.

Unit two forms a large part of the entire Delfonte section. This member rests on the Aztec Sandstone in some places and on unit one in others. Small amounts of volcanic erosional debris are found immediately beneath and within the lowest layer of unit two. Dark-red and dark-purple, slightly-porphyritic andesite, latite, and trachyte(?) appear to be the principal rock types present in unit two, based on phenocryst mineralogy. As in unit one, the only varietal mineral is muscovite, present in trace amounts. Above unit two lie 100 to 200 feet of indistinctly bedded, coarse-grained volcanic wacke indicating another period of erosion.

Unit three presents something of a puzzle because it is not clear either in outcrop or in thin section whether this is an extrusive unit or a hypabyssal intrusive emplaced between units two and four. In thin section, some specimens resemble recrystallized tuffs while others appear to be of hypabyssal origin. The mineralogies of phenocrysts in these rocks are typical of quartz latite and rhyodacite.

Unit four crops out on the eastern tips of east-facing spurs (R-34). It consists of porphyritic, vesicular flow material, flow breccia, and tuff, all of which are rust red in color. The moderately abundant phenocrysts of quartz, plagioclase, and K-feldspar suggest that these rocks are rhyolite and quartz latite with perhaps some trachyte.

Regional Correlations
Two rather different sequences of strata were deposited during Mesozoic time in the region embracing the southern Cordillera and the platform to the east. In southern Nevada and areas farther east, a relatively thin, predominantly non-volcanogenic sequence of shallow marine continental strata was laid down, while to the west in the central and western Mojave Desert, a much thicker sequence of continental, predominantly volcanic strata, was deposited. That portion of the eastern Mojave Desert stretching from the Ivanpah Mountains to the Soda Mountains and including the Devil's Playground area is a stratigraphic transition zone in which formations typical of these eastern and western Mesozoic sequences interfinger. A hypothetical palinspastic cross section of Mesozoic strata drawn along a northeast-trending line through the Playground depicts this transition (Fig. 11).

The volcanic sequence to the west represents the upper portion of a Mesozoic volcano-plutonic belt which trends north-westward through the central and western Mojave Desert. The eastern Mojave Desert transitional sequence lies on the eastern margin of this belt. Burchfiel and Davis (1972) and Hamilton (1969) have discussed the significance of this belt in terms of plate tectonic theory.

Comparative sections of Mesozoic rocks in the eastern and transitional sequences are given in Figure 10. The Moenkopi Formation is the only Mesozoic unit to exhibit relatively uniform stratigraphic characteristics over the entire area, perhaps because the volcano-plutonic belt did not become fully developed until after the Moenkopi was deposited. The lower portions of the Moenkopi are of marine origin whereas the upper part is of continental origin. Small amounts of volcanic tuff and coarser debris found in the upper part of the Moenkopi (Hewett, 1956, p. 47) apparently reflect an early phase of vol-
Figure 10. Correlation of Mesozoic formations in the eastern Mojave Desert.
Figure 11. Hypothetical palinspastic cross section of the eastern Mojave Desert at the end of the Middle Jurassic. Pre-Middle Jurassic thrust faults and granitic plutons are not shown.
canic activity in the central and western Mojave Desert.

The Chinle Formation does not crop out west of the Ivan-pah Mountains, and apparently did not extend as far west as the study area. Volcanic tuff is found throughout the Chinle section (Longwell and others, 1965, p. 40), indicating on-going volcanic activity to the west. The Chinle appears to be entirely of continental origin.

The Devil's Playground area marks the westernmost occurrence of the Aztec Sandstone as a mappable unit. In the Soda Mountains, cross-bedded quartzite correlative with the Aztec occurs as lenses interbedded with volcanic rocks, all of which were placed within the Soda Mountain Formation by Grose (1959, p. 1527).

In the past, most geologists working in southern Nevada considered the Aztec Sandstone to be a classic example of eolian sandstone. More recently Stanley and others (1971, p. 11) have suggested that part of the Aztec may have been deposited in or reworked by marine waters. The presence of limestone and dolomite beds in the upper part of the Aztec in the Ivanpah Mountains (Hewett, 1956, p. 48) supports the idea that a brief marine transgression occurred near the end of the deposition of the Aztec Sandstone.

The Delfonte Volcanics mark the return to continental conditions across the eastern Mojave Desert in Middle Jurassic time. Abbott (1971, p. 69) reported at least 1000 feet of volcanic strata lying above the highest lenses of quartzite correlative with the Aztec Sandstone in the Soda Mountains. Although all of these strata were included in the Soda Mountain Formation by Grose, these uppermost volcanic rocks are probably equivalent to the Delfonte Volcanics.
Cenozoic Strata

General Statement

Two groups of Cenozoic rocks, one of probable late Tertiary age and the other of Quaternary age, crop out in the Devil's Playground area. A profound unconformity separates these strata from underlying deformed rocks of Precambrian to Mesozoic age.

Mio-Pliocene (?) Fanglomerate

Tertiary fanglomerate material containing small amounts of carbonate breccia and volcanic rock forms a group of low hills between Old Dad Mountain and Kelso Peak. A minimum of 1000 feet and perhaps as much as 2000 feet of fanglomerate strata are present in these hills.

The age of this fanglomerate unit is not known with certainty. Its lithology and outcrop appearance are very similar to the Mio-Pliocene Avawatz Formation found in the Soda and Avawatz Mountains (Grose, 1959, p. 1535), thus it is tentatively correlated with and assumed to be age equivalent to the Avawatz Formation.

The bulk of this fanglomerate unit consists of slightly-consolidated, poorly-sorted pebble to boulder conglomerate with a matrix of sand- to clay-sized material. The poor sorting, indistinct bedding, and various channeling features are reminiscent of modern desert alluvial fans, hence the name fanglomerate is applied. Very fine-grained, laminated, gypsiferous strata are found in a few localities within the fanglomerate. These strata are interpreted as lacustrine deposits. Volcanic tuffs and flows occur near the base of the fanglomerate unit at several places just east of the Old Dad Fault. The dark-gray to green-gray, slightly-vesicular flow rocks are designated as andesite and latite based on examination of
two thin sections. The white and pale-gray tuffs contain numerous phenocrysts of quartz and are thought to be rhyolite.

Thin layers, lenses, and a few larger bodies of brecciated carbonate rock occur within fanglomerate outcrops lying within two miles of the Old Dad fault. Most of the carbonate appears to have been derived from the Goodsprings Dolomite. The majority of outcrops consist of poorly- to moderately-sorted, angular to subrounded clasts generally less than 1 foot in diameter which are cemented by calcite and caliche. Contacts between these breccias and the surrounding siliceous clastic material are gradational over a distance of 1 or 2 feet. The three large outcrops centering near locality P-19 are unusual in that they contain large, coherent blocks of Goodsprings Dolomite which are brecciated around their margins, and which are set in a carbonate breccia of the type described above.

Carbonate breccias and blocks similar to those found in the Devil's Playground area are present in younger Tertiary strata throughout the eastern Mojave Desert. They are often thought to have originated directly or indirectly from landslides of carbonate rock from steep mountain fronts at the foot of which were alluvial fans (cf. Longwell, 1951).

Quaternary Alluvium and Sand

Several different varieties of semi-consolidated and unconsolidated alluvium have been placed in one map unit called Quaternary alluvium. These include semi-consolidated alluvial terraces capped by desert pavement, scree and talus deposits near the base of slopes, and alluvium within the youngest fans and channels.

Quaternary sand deposits consist of unconsolidated aeolian
sand found in dunes and sheets which cover much of the region from west of the Cowhole Mountains to the west slope of the Old Dad Mountain block and along the southern border of the map area.
INTRUSIVE ROCKS

Mesozoic (?) Granitic Rocks

General Statement

Seven different granitic bodies, herein called plutons regardless of outcrop area, have been mapped in the Devil's Playground area. For ease of description, informal names have been given those plutons not previously described in the literature. With one exception, these plutons are isolated from one another, hence their relative ages are unknown. They have been arranged on Plate 1 and in the descriptions below in order of decreasing mafic mineral content and decreasing evidence of deformation.

All of these plutons are tentatively assigned to the Mesozoic(?) Era on the basis that with one exception (a Tertiary pluton 40 miles north of the Playground), radiometric age determinations on granitic rocks in the eastern Mojave Desert have yielded Mesozoic ages. Recent radiometric age determinations on one pluton in the study area, the Sands Granite, have confirmed a Mesozoic age for this pluton (see p. 48). These granitic rocks appear to be representatives of the lower, intrusive portion of the volcano-plutonic belt which developed in the Mojave Desert during the Mesozoic Era.

Old Road Pluton

The Old Road pluton is exposed over an area of approximately one-third square mile in the vicinity of D-7. It intrudes Precambrian gneiss and is intruded by the Gravel Wash pluton. The contact between the Old Road pluton and the gneiss is a complex hybrid or mixed rock zone.

In outcrop, the Old Road pluton granitic rock is dark green-gray in color, being variably epidotized and containing numerous mafic inclusions. In thin section, this grani-
tic rock is coarse-grained hypidiomorphic granular in texture with many granulated grain borders as well as warped phenocrysts. Modal mineralogy is that of a hornblende diorite.

Tower Pluton

A small body of granitic rock that is exposed over an area of one-eighth square mile in the vicinity of T-10.5 is referred to in this report as the Tower pluton. The only exposed contact of this pluton with pre-Cenozoic rock is a fault. In outcrop, the distinctive feature of this granitic rock is a foliation created by the alignment of platy feldspar and quartz grains. In the one thin section of this rock which was examined, this foliation was not readily apparent, and it could not be determined whether this foliation was of primary or secondary origin. In thin section, K-feldspar, and quartz form a matrix in which are set aligned grains of feldspar and biotite. The overall modal mineralogy is that of a biotite granite.

Mine Canyon Pluton

The Mine Canyon pluton forms an elongate body exposed over a one-eighth square mile area centered near H-4.5. It intrudes Precambrian gneiss with sharp contacts between the two rock types. Outcrops of this pluton are distinctly rounded and mantled by green-gray gruss slopes. Thin sections of this granitic rock reveal medium-grained hypidiomorphic textures, with biotite being the only varietal mineral. Modal mineralogy of this rock is that of a biotite granodiorite.

Cowhole Mountain Pluton

Granitic rocks exposed over an area of 1¼ square miles in the northwest Cowhole Mountains are given the name Cow-
hole Mountain pluton. This pluton has been described briefly by Barca (1965, p. 4-5) who incorrectly correlated it with the Sands Granite, a distinctly different granitic pluton which crops out 3 miles to the south of the Cowhole Mountain pluton (see p. 47). The Cowhole Mountain pluton intrudes Precambrian gneiss, lower Paleozoic units, and the Lower Volcanic Unit. Contacts with the latter two are generally sharp whereas the contact with the Precambrian gneiss is a mixed rock zone. The Cowhole Mountain pluton itself is intruded by a large number of generally northwest-trending dikes which constitute an estimated 20-25 percent of the total outcrop area depicted on Plate 1 as granitic. Only a few of these dikes are shown on Plate 1.

Hand specimens of this pluton are quite variable in appearance, due in part to variable amounts of epidotization. Textures are generally granular to slightly porphyritic. Outcrops near carbonate wall rocks are often miarolitic. Thin sections reveal variable amounts of hornblende and biotite as the varietal minerals. Overall modal mineralogies are those of quartz monzonite and granodiorite. Estimated percentages of principal mineral constituents are presented in Table 2.

Table 2. Estimated percentages of principle minerals of Cowhole Mountain pluton.

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Kelso Peak Pluton

The Kelso Peak pluton crops out over an area of approximately 10 square miles in the northeast corner of the study area. Hewett (1956) mapped much of this area as Precambrian gneiss. The granitic rocks which he did recognize were included in his Teutonia quartz monzonite unit, a name he applied to numerous bodies of granitic rock that display a considerable range of texture and composition (Hewett, 1956, P. 61-63). The Kelso Peak pluton intrudes Precambrian gneiss with sharp contacts, and in turn is intruded by numerous northwest-trending dikes.

Based on hand specimen textures, there are two facies of the Kelso Peak pluton. Most outcrops consist of medium- to coarse-grained, granular or seriate biotite quartz monzonite that has a somewhat pinkish tint due to the presence of flesh-colored K-feldspar. Along the northeast border of this pluton, this predominant lithology grades into a finer-grained facies which is fine- to medium-grained, pale gray on fresh surfaces, and contains distinctive euhedral booklets of biotite. Thin sections reveal similar ranges of compositions for both facies. In thin section, textures of the coarse facies range from hypidiomorphic granular to hypidiomorphic seriate. A distinctive feature is the poikilitic nature of perthitic K-feldspar grains and phenocrysts. The finer-grained facies is hypidiomorphic granular in texture. Estimated percentages of principal mineral constituents are presented in Table 3.

Gravel Wash Pluton

A body of light-gray, fine-grained granitic rock exposed over a one-quarter square mile area around E-7 is referred to herein as the Gravel Wash pluton. This pluton intrudes both Precambrian gneiss and the Old Road pluton with sharp contacts;
Table 3. Estimated percentages of principal minerals of the Kelso Peak pluton.

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* Finer-grained facies

a few dikes emanating from the Gravel Wash pluton cut these host rocks.

This pluton has an unusual texture in thin section. A fine-grained granulose ( aplitic) matrix of quartz and feldspar encloses small, euhedral phenocrysts of these same minerals as well as biotite and hornblende. Overall modal composition of this pluton is biotite hornblende granodiorite.

Sands Granite

The large body of granite exposed in the southwest portion of the study area was named the Sands Granite by Hewett (1956, p. 49). Outcrops occur as numerous small ridges and hills isolated by Quaternary sand. Present outcrop area is approximately 2 square miles. The Sands Granite is only seen to intrude the Lower Volcanic Unit; the contacts between these two are quite sharp.

The Sands Granite is a distinctive rock both in outcrop and in thin section. Hand specimens are pale pink in color, coarse-grained, leucocratic, and usually display small patches of miarolitic texture. Near E-34 is a small outcrop of what
is interpreted to be a finer-grained facies of the Sands Granite. This rock is fine-grained, pink-gray in color, and contains moderate amounts of mafic minerals and sphene. In thin section, the texture of the coarser Sands Granite is striking. Potassium feldspar occurs as large, subhedral perthitic grains enclosing numerous, vaguely defined patches of sodic plagioclase which formed either by replacement or extensive exsolution or perhaps by simultaneous crystallization of plagioclase and K-feldspar. Quartz that crystallized within the K-feldspar forms a granophytic texture. These textures, as well as the modal compositions of several specimens (presented in Table 4) suggest that the Sands Granite was a vapor-rich magma possibly of near eutectic composition at the time of emplacement. In modal composition, the coarse-grained rocks are true granite while the finer-grained facies is quartz monzonite.

Table 4. Estimated percentages of principal mineral constituents of the Sands Granite.

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<td>accessories</td>
<td>1</td>
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*fine-grained facies; specimen provided by J. Novitsky

Two biotite mineral separates from a specimen of the fine-grained facies Sands Granite have recently been dated by conventional K/Ar methods by J.M. Novitsky of Rice University. The apparent ages of these separates, 80 (± 4.1) and 87 (± 4.5) m.y.b.p., confirm the Mesozoic age tentatively assigned to the Sands Granite.
Tertiary(?)–Mesozoic(?) Hypabyssal Rocks

General Statement

A long and complicated history of hypabyssal intrusion is evident throughout the Devil's Playground. The sequence of intrusion is so complex and the variety of rock types so great that only the most general features of these intrusives can be presented in this report.

The several episodes of hypabyssal intrusion appear to represent a fairly long time-span. Some of these rocks were emplaced in the Cowhole Mountains prior to a period of middle(?) Mesozoic deformation while others post-date all visible structures. The Mio–Pliocene(?) fanglomerate unit post-dates at least two and perhaps all periods of hypabyssal activity. Thus, these intrusives can be dated no more closely than Tertiary(?)–Mesozoic(?) at the present time.

All hypabyssal rocks mapped during this study have been placed in four categories based largely on the color and texture of hand specimens of these rocks. These categories are designated as diabase, melanocratic, leucocratic, and felsite. It should be kept in mind that within each category, hypabyssal rocks of several different ages and/or compositions may be present.

Diabase

Several masses of mafic rock cropping out in the northern Cowhole Mountains are referred to as diabase, the term applied to these rocks by Barca (1965, his map plate). These rocks intrude Paleozoic strata, the Cowhole Mountain pluton, and the Aztec Sandstone, often creating mixed rock zones. The diabase is in turn intruded by melanocratic, leucocratic, and felsitic hypabyssal rocks.

Though quite variable from place to place, the diabase is typically dark to medium green in color on both fresh and
weathered surfaces, and is fine-grained granular to porphyritic in texture. Thin sections reveal a variety of compositions; most primary minerals display considerable amounts of alteration. Plagioclase of intermediate composition, clinopyroxene, hornblende, occasionally biotite, small amounts of interstitial quartz and K-feldspar, and opaque minerals occur in varying amounts. Textures of a few specimens are diabasic, but most display a non-descript hypabyssal texture.

Melanocratic Rocks

Dark-colored, relatively mafic dikes and small pods which occur throughout the study area are placed in the melanocratic group of hypabyssal rocks. Representatives of this group intrude almost all other pre-Cenozoic rock units in the study area.

Although several different rock types are included in this group, two lithologies predominate. The first and probably older of the two consists of dark-to medium-green, mafic porphyries, some of which may be related to the diabase unit. The second sub-group consists of dark-gray porphyritic dikes with basaltic mineralogy which outcrop in the northern Kelso Mountains.

Leucocratic Rocks

Light-colored, fine-grained, occasionally porphyritic hypabyssal rocks have been placed in the leucocratic catagory. They intrude most other pre-Cenozoic rock units in the map area. Numerous dikes and pods of leucocratic rocks in the southern Kelso Mountains have microgranitic textures and compositions in the range quartz monzonite–granodiorite. In other areas, dikes placed in the leucocratic group are somewhat more mafic and finer-grained, but of similar overall
composition.

Felsite

In the northern Cowhole Mountains, lenticular masses, dikes, and sills of an orange-yellow to pale-pink, slightly-porphyritic hypabyssal rock with an aphanitic groundmass were mapped as felsite. At least two generations of felsite intrusion are indicated by cross cutting relations. Some, if not all, of the felsite dikes appear to be the youngest hypabyssal intrusives in the northern Cowhole Mountains. A unique feature of these intrusives is convolute flow-folding observed along the margins of many of these bodies. Phenocrysts of K-feldspar, quartz, and sodic plagioclase suggest that these rocks have an overall composition of rhyolite.

Dikes of very similar appearance to the above intrude Precambrian gneiss just to the east of the Old Dad Mountain block. It is uncertain whether these are correlative with the felsite of the northern Cowhole Mountains.
STRUCTURE

Introduction

Structures of Precambrian, Mesozoic, and Cenozoic age occur in rocks exposed in the Devil's Playground area. No distinct evidence of Paleozoic movements other than those of an epeirogenic nature was found during this study, and none has been reported from elsewhere in the eastern Mojave Desert. Structures found in Precambrian rocks were discussed on pages 13 to 14. Some of the gentle, large-scale folds that affect the metamorphic foliation in these basement rocks may be of Mesozoic age, but lack of continuous exposures of such rocks with folded Paleozoic or Mesozoic strata precludes a direct correlation.

Thrust faults, folds, and a major shear zone, all of which are inferred to be of Mesozoic age, were the most thoroughly studied structures during the investigation. These structures are very tentatively correlated with the two Mesozoic orogenic events known to have affected the eastern Mojave Desert. More speculative aspects of the Mesozoic deformation of the Devil's Playground area are treated in the last section of this chapter.

The presence of northwest-trending, linear highlands separated by broad, low-lying alluviated areas immediately suggests to one familiar with the geology of the Basin and Range province that high-angle normal faults are an important Cenozoic structural feature of the Devil's Playground. One such fault, the Old Dad fault on the east side of Old Dad Mountain, has several thousand feet of dip-slip movement.

Because structures in the three major outcrop blocks are not readily traceable from one block to another, the structural geology of each block will be described separately.
Kelso Mountains

Phanerozoic structures in the Kelso Mountains appear to be relatively simple, involving only dip-slip faulting, tilting and/or rotation of faulted blocks, and some gravity sliding. The Eocambrian-Early Cambrian and the Mio-Pliocene (?) fanglomerate sections are both homoclinal, the former being inclined at moderate to steep dip to the southeast while the latter dips gently eastward. With the exception of minor flexures near faults, folds are not present in these strata.

Numerous steeply dipping faults causing strike separations of 20 feet to a few hundred feet in Eocambrian and Early Cambrian units were mapped in the southeast Kelso Mountains. In the few places where these faults are well-exposed, drag features indicate dip-slip motion. Stata on opposite sides of some of these faults display significantly different dips to the southeast, suggesting a rotational component to some fault movements. Most of these faults trend northwest; a few faults, the existence of which is largely inferred by the presence of anomalously thick sections of Wood Canyon and other units, are thought to have east-west trends. The three major spurs on which these strata occur appear to be offset relative to one another, as can be seen by following the Precambrian gneiss-Eocambrian sediment contact along strike (Plate 1). The faults causing the offset of this contact were not observed in outcrop, and they are shown on Plate 1 as queried, dotted lines trending northwest in washes separating the spurs. These faults could not be located in the Precambrian gneiss to the northwest. However, what may be an exposure of another fault of this type lies just southwest of G-8, where thoroughly brecciated and sheared Early Cambrian strata are faulted against gneiss along a northwest-trending line.
In the southeastern Kelso Mountains several bodies of variably brecciated carbonate rocks derived from upper Carrara and younger units rest with faulted contacts upon Precambrian gneiss and various Eocambrian and Early Cambrian units. These bodies overlie some of the northwest-trending dip-slip faults but are displaced by others. Brecciation is very thorough in some of these bodies while others are less brecciated and retain much of their original bedding. In many aspects these bodies resemble the carbonate breccias found in the Mio-Pliocene (?) fanglomerate unit and they may well have originated in the same manner (see p.41). Three small outcrops of upper Carrara limestone near E-2 lie upon lower Carrara shale with conformable attitudes across contacts that have undergone tectonic flow rather than brecciation. These outcrops are interpreted to be the remnants of relatively thick, parautochthonous blocks of upper Carrara and perhaps younger strata. In sum, all of these carbonate bodies appear to have moved down slope under the influence of gravity, presumably during the tilting of this portion of the Kelso Mountains toward the southeast.

The dip-slip faulting, tilting and rotation of faulted blocks, and gravity sliding which occurred in the southeastern Kelso Mountains may have occurred during Mesozoic and/or Tertiary or perhaps even Quaternary age. In other regions of the eastern Mojave Desert, structures similar to those found in the southeast Kelso Mountains have been related to differential vertical movements on post-Eocene normal faults (Basin and Range faults). On this admittedly tenuous basis, a post-Eocene age is suggested for these structures in the southeastern Kelso Mountains.

Old Dad Mountain Block
Three major structural features occur in the Old Dad Mount-
ain block. These are the Powerline Canyon shear zone and the Playground thrust fault of probable Mesozoic age, and the Old Dad normal fault of late Tertiary age.

Powerline Canyon shear zone: The Powerline Canyon shear zone is exposed over a distance of approximately three-quarters of a mile on the north and south sides of Powerline Canyon. On the north side of the canyon the shear zone lies to the west of the Old Dad fault and extends beneath the Playground thrust fault to the north; on the south side the shear zone intersects the Old Dad fault at a low angle and does not reappear to the east of this fault. On both sides of the canyon the shear zone juxtaposes the Lower Volcanic Unit on the southwest with Precambrian basement to the northeast. Sheared lenses of volcanic and hypabyssal rock, limestone, Sands Granite, and Precambrian basement material are caught up in the shear zone. In many cases these lenses are partially bounded by one or more of the several distinct fault surfaces which run through the shear zone. In sum, the Powerline Canyon shear zone displays characteristics of a strike-slip fault or an oblique-slip fault with a considerable horizontal component of movement.

The strike, dip, and sense of movement of the Powerline Canyon shear zone are largely speculative due to the short distance over which this feature is exposed. The dip appears to be vertical or very steep to the east while the strike is approximately N 35°W to N 45°W. A hypothetical northward extension of the shear zone beneath the Playground thrust fault is shown on Plate 3. The distribution of masses of Sands Granite within the shear zone relative to outcrops of this intrusive on either side of the zone vaguely suggest a right-lateral sense of movement. Movements within the zone post-date the intrusion of the Sands Granite and pre-date the
arrival of the Playground thrust plate; the Sands Granite is known to be Mesozoic (see p.48) and the Playground thrust is inferred to belong to this same Era.

Playground thrust fault: The Playground thrust fault was initially mapped and named by Hewett (1956). His map and the later map of Yelverton (1963) show northern and southern thrust fault segments which placed Paleozoic carbonate strata over Precambrian metamorphic rock. Mapping during the present study has revealed that while the age relations shown by Hewett and Yelverton are correct for the northern thrust segment (exposed east of Q-24), the southern thrust segment (M-21, N-23) placed Paleozoic strata over Mesozoic units as well as some Precambrian rock on the east side of the Powerline Canyon shear zone. These two thrust segments are separated by a down-dropped block of Paleozoic strata within which the thrust surface is not exposed. This latter feature causes considerable ambiguity in the interpretation of the Playground thrust fault.

The northern segment of the thrust surface strikes approximately north-south and dips 40° to 50° to the east. A well-developed mylonitic limestone zone 4 to 10 feet thick occurs at the base of the thrust plate. During thrust movements ductile flow within this zone transposed bedding in the carbonates of the thrust plate into flow-foliation (Fig. 12). At a few places the deformational environment caused chert interbedded with the limestone to behave in a ductile manner; in most instances, however, chert within this zone behaved brittly. Angular to lenticular blocks of non-mylonitized Precambrian rock are enveloped within the mylonitic zone in places (Fig. 12). The base of the plate is nearly planar along some short segments but rather undulatory along others.

The thrust surface cuts to its highest stratigraphic po-
Figure 12. Ductilly folded mylonitic limestone (Bird Spring Fm.) near base of northern Playground thrust fault segment. Fragment of metamorphic rock from lower plate (outlined by broken line) is completely enveloped by limestone. Dark, rounded body to right of hammer is chert nodule.
sition approximately midway along the length of its outcrop (R-24.5); to the north and south of this point, the thrust surface cuts down-section to include older Paleozoic strata within the thrust plate. Because of the obliquity between bedding of the thrust plate and the thrust fault surface, approximately 1400 feet of Paleozoic strata in the thrust plate have been truncated during thrust movements.

A few structural features of mesoscopic scale found within and immediately below the mylonitic zone indicate that thrust movement along this segment of the thrust surface was to the southeast. These include northeast-striking lithologic layering in rocks below the thrust surface which immediately below the thrust surface are clearly overturned to the southeast, as well as chert nodules which in places within the mylonitic zone have been elongated in a northwest-southeast direction.

Several characteristics of the southern thrust segment are markedly different than their counterparts in the northern thrust segment. For example, the southern thrust surface is subhorizontal, with a dip on only 10° to 15° to the east while the strike remains approximately north-south. Near its southeasternmost exposure, the southern thrust surface dips 60° to the north, but this is thought to be a local affect due to post-thrusting deformation. Limestone of the thrust plate was mylonitized at the base of the plate during thrust movements; however, this mylonitic zone is only a few inches to a few feet thick. Unlike the northern thrust surface, the southern thrust exhibits a décollement geometry, its surface being subparallel to bedding within the thrust plate (Fig. 13). The only reliable mesoscopic structural feature indicative of the direction of movement is a nearly recumbent fold measuring approximately 15 feet across which
Figure 13. Southern segment of the Playground thrust fault (marked by broken line) seen looking north across Powerline Canyon. The fault surface dips gently eastward and displays décollement geometry relative to strata in thrust plate. In this view, upper plate is Bird Spring Formation, (Paleozoic), lower plate is Lower Volcanic Unit (Mesozoic).
crops out in the lower portion of the thrust plate along Powerline Canyon just north of L-21.5. The nearly horizontal fold axis trends east-northeast and the fold is overturned toward the southeast, suggesting a southeastward direction of movement for the thrust plate.

Some structures within the Playground thrust plate above the mylonitic zone appear to have formed before or during thrust movement. Strata within the plate are folded into a large, northwest-trending, asymmetric anticline which plunges gently southeast. The west limb contains a gentle synclinal flexure and displays both east and west dips while the east limb of the anticline dips steeply eastward (see section F-F', Plate 2). Superimposed on this east limb are two or three large open flexures with axes trending approximately eastwest and plunging eastward. At the north end of the northern thrust segment, Paleozoic strata of the thrust plate are folded into syncline overturned toward the south; its axis trends and plunges southeast. Most of the overturned limb has been removed by erosion while the base of the hinge zone and part of the lower limb are truncated by the thrust. Several high-angle faults within the upper plate also appear to predate final movements on the Playground thrust. These can be traced downward to the thrust surface where they terminate without offsetting it.

Strata below the thrust surface were also deformed prior to the emplacement of the Playground thrust plate in its present position. The Powerline Canyon shear zone (p.55) appears to be the most important pre-thrust structure. West of Q-24, thermally metamorphosed limestone and chert strata of Paleozoic (?) age underlie the thrust surface. These rocks were faulted against surrounding Precambrian rocks and thermally metamorphosed before the arrival of the Playground thrust.
Minor faults and folds in Mesozoic strata below the thrust surface near N-24 also appear to have formed prior to the arrival of the thrust plate.

In the foregoing descriptions the Playground thrust fault has been treated as one allochthonous thrust plate lying on autochthonous strata. This is the interpretation applied to the Playground thrust fault by Hewett (1956) and supported by Yelverton (1963). However, the presence of Mesozoic strata and a Mesozoic(?) shear zone beneath the southern thrust surface suggest that a more complicated structural history was involved. Two interpretations of the evolution of the Playground thrust are proposed on the basis of data gathered during the present study (Plate 3). In the simplest interpretation, the Precambrian rocks beneath the northern thrust surface and the Mesozoic and Precambrian rocks beneath the southern thrust surface are autochthonous and all of the Paleozoic strata on Old Dad Mountain are part of one allochthonous thrust plate (Plate 3a). This interpretation supposes that at some time after the deposition of the Aztec Sandstone, movement on the Powerline Canyon shear zone juxtaposed Aztec and older Mesozoic strata against Precambrian rocks, following which the Playground thrust plate was emplaced. A deformational sequence similar to this occurred in the Clark Mountain area (Burchfiel and Davis, 1971) where the Keystone thrust plate overrode the Kokoweef fault (see Fig. 16). In the Playground, this interpretation requires that the single thrust surface involved would have a décollement geometry in its southern exposure which must change rapidly northward to non-décollement geometry.

A second interpretation involves the emplacement of two thrust plates and assumes that all of the Paleozoic and Mesozoic strata on Old Dad Mountain are allochthonous. This in-
terpretation supposes that the northern thrust segment represents an older, lower thrust whereas the southern thrust segment is a younger, higher thrust (Plate 3b). The suggested sequence of events leading to the present arrangement of various units is as follows:

1.) At some time during the Mesozoic Era, a thrust plate of Paleozoic and probably overlying Mesozoic strata was emplaced on Precambrian (and near Q-24.5 metamorphosed Paleozoic(?)) strata; see p. 58) rocks. The possibility cannot be excluded that the Mesozoic strata now exposed beneath the southern thrust segment were deposited on this already allochthonous plate of Paleozoic rocks, but the preferred interpretation herein is that these Mesozoic strata were transported with the Paleozoic rocks.

2.) Movement on the Powerline Canyon shear zone juxtaposed autochthonous Precambrian basement rocks against allochthonous Mesozoic strata within the older thrust plate.

3.) Another thrust plate of Paleozoic and possible younger strata was emplaced on the faulted autochthon and lower allochthon.

4.) Tertiary(?) dip-slip faults down-dropped a large block of the upper thrust plate, and placed the lower thrust surface to the north of this block at the same level as the upper thrust surface to the south of the block.

Information gathered during the present study does not favor one of the above hypotheses over another. Cross sections D through G of Plate 2 depict the one-thrust hypothesis only for the sake of simplicity. The two-thrust hypothesis is presented in the super-allochthonous interpretation of the
structural evolution of the Devil's Playground presented on pages 68 to 70.

Geologic evidence on Old Dad Mountain demonstrates that the Playground thrust (or upper thrust if the two-thrust hypotheses is accepted) moved during the interval Early-Jurassic-Mio-Pliocene(?). Hewett (1956) believed that movement on the Playground thrust occurred during a post-early Pliocene orogeny, based on a correlation with supposed late Tertiary thrust klippen in the Shadow Mountains west of Clark Mountain (Hewett, p. 96). These klippen have since been demonstrated to be gravity-slide blocks unrelated to compressive deformation (cf. Wilson, 1966; Bell, 1971). Regional geologic considerations presented on pages 7 to 8 suggest that the Playground thrust developed during the Mesozoic Era.

Old Dad Fault: The Old Dad fault (named by Hewett, 1956) is an important normal fault bounding the east side of the Old Dad Mountain block. The Old Dad fault is interpreted to be one of several probably similar Basin and Range-type normal faults exerting the principal control on the distribution of northwest-trending mountains and intervening valleys in the study area. The Old Dad fault is the only one of these faults presently exposed. It juxtaposesPrecambrian rocks on the east with strata as young as Triassic on the west, indicating an east-side-up sense of movement which is confirmed by the sense of overturn on large drag folds in Paleozoic strata next to the fault north of Powerline Canyon. Stratigraphic throw on this fault is on the order of 15,000 feet.

The Old Dad fault is exposed only in a few small areas north of Powerline Canyon where it appears as a rather sharp contact between Precambrian and Paleozoic strata which is marked by only a few inches of brecciated rock. A strike of N 30°W to N 40°W with a dip of 75° to 85° west is inferred
for the fault from these few outcrops, as well as from the general distribution of Paleozoic and Precambrian rocks on the east side of Old Dad Mountain.

Based on geologic evidence in the study area, movements on the Old Dad fault occurred during the interval Triassic-Mio-Pliocene(?); Triassic rocks are the youngest rocks cut by the fault while Mio-Pliocene(?) fanglomerate south of Powerline Canyon overlaps the projected trace of the fault without apparent offset. Evidence from other areas in the Basin and Range province indicate that movements on similar normal faults commenced in the Oligocene. Thus movement on the Old Dad fault probably occurred during the Oligocene and/or Miocene.

Other structures of probable Tertiary age include cross faults, gravity-slide blocks, and carbonate breccia. Cross faults are those faults the trends of which are oblique or perpendicular to that of the Old Dad Mountain block. The majority of these faults appear to have undergone dip-slip movement; they are thought to represent mechanical adjustments of the Old Dad Mountain block to vertical movements on the Old Dad fault. The Playground thrust fault(s) is offset in three places by such cross faults.

Several blocks of Paleozoic strata north of Powerline Canyon are interpreted herein to have been emplaced in their present positions by gravity-induced sliding during the Tertiary. Some of the larger slide blocks (eg. L-22.5, S-24.5, Q-26) have subhorizontal basal surfaces which give these blocks the appearance of thrust klippen, and these blocks were mapped as such by Yelverton (1963). However, examination of the lower surfaces of these blocks reveal that they were brecciated during movement rather than having undergone ductile flow as did the Playground thrust(s). In addition, the strata on which
these blocks rest resemble paleosols and contain rounded clasts of carbonate (Fig. 14). It is interpreted that these blocks moved down erosional slopes initially generated by vertical movements on the Old Dad fault. Some blocks of Paleozoic carbonate strata apparently moved very rapidly down steep slopes, becoming partially or entirely brecciated, giving rise to bodies of carbonate breccia such as that at N-24.5.
Figure 14. (A) View of base of Tertiary(?) gravity slide block (Paleozoic Bird Spring Formation resting on thoroughly weathered Mesozoic volcanic rocks) near M-23.5. General appearance and age relationships of rocks suggest a thrust fault. (B) Close-up view of same feature showing brecciated nature of carbonate rock of Bird Spring Formation and rounded clasts of same mixed into top layer of volcanic rock.
Cowhole Mountains

Folds and faults visible in the Cowhole Mountains as well as "hidden" faults (see p. 65) of major significance indicate a complex structural history for the western part of the study area. Two periods of folding are evident in the Goodspring Dolomite on Cowhole Mountain. The first deformation, affecting most of the exposed Goodsprings, transposed bedding into a flow-foliation and produced small isoclinal folds of similar style. Fold axes typically trend north and northeast and plunge at low to moderate angles in these directions. Axial surfaces strike generally northward and dip at low to moderate angles to the east. A unique sense of overturn was not established for these folds. The Goodsprings was subsequently refolded into concentric and flattened concentric-style folds, many of which are overturned to the east. These later folds have subhorizontal north-trending axes and axial surfaces which strike northward and dip eastward at low angles; fold amplitudes are 5 to 30 feet. Where the lower contact of this body of folded Goodsprings Dolomite has not been intruded by igneous rocks, a zone of intense shearing is present, suggesting that the Goodsprings is allochthonous or perhaps parallochthonous.

The Lower Volcanic Unit exposed over much of the southern Cowhole Mountains may also be folded about roughly north-trending axes. Although no fold closures were observed in the field, both east and west dips of flow layering were measured in this unit which may indicate the presence of broad, open folds. Alternately, these opposed dips may reflect primary irregularities in flow layering or perhaps tilting of blocks on unobserved faults.

A major thrust fault which passes through Cowhole Mountain is referred to informally as the Cowhole thrust fault. The
thrust surface strikes approximately north-south and dips 30° to 35° to the east. A 6 inch to 3 foot thick layer of mylonitic carbonate rock occurs immediately above this surface. The thrust plate consists primarily of Bird Spring strata which dip to the east at angles of 40° to 50°. The discrepancy in the angles between the thrust surface and the strata within the plate clearly indicate that the geometry of this thrust is not that of a décollement. Scattered small blocks of Monte Cristo (?) Limestone are faulted into the Bird Spring. These are not shown on Plate 1. The Cowhole thrust plate directly overlies folded Goodsprings Dolomite, and has been intruded by Tertiary (?) - Mesozoic (?) hypabyssal rocks which have destroyed the thrust surface on the south face of Cowhole Mountain.

Several anomalous structural/stratigraphic features are present in the Cowhole Mountains which are interpreted to be related to "hidden faults". A hidden fault is herein defined as a fault of considerable (one-half mile or more) displacement which is not presently exposed or which has been altered by later geologic processes to the extent that its identity as a major fault is obscured. Hidden faults might be detected by the near-juxtaposition of rocks of markedly different age, degree of metamorphism, structural style, facies, etc. In the central Cowhole Mountains near M-34, outcrops of the Lower Volcanic Unit are separated from exposures of Goodsprings Dolomite by narrow stretches of Quaternary sand. Approximately 6000 feet of strata normally lie between these units in undisturbed sections. Thus they have been juxtaposed by a hidden fault having a considerable amount of slip.

Another hidden fault occurs near P-35. There, Goodsprings Dolomite, limestone of the Bird Spring Formation, and the Aztec Sandstone are juxtaposed in a zone marked by hypabyssal
intrusives separated by small faults. Approximately 2000 feet of strata normally separate the Good springs and Bird Spring units while about 6000 feet of rock are thought to lie between the Bird Spring and the Aztec in this area. The Good springs Dolomite at this locality is thought to be part of a hidden thrust plate (see below). The juxtaposition of Bird Spring and Aztec strata appears to have occurred on another hidden fault. After the major movement on this fault, shallow intrusions were emplaced along this zone of weakness, followed by additional minor faulting.

The contact between the Good springs Dolomite and the granitic rocks of the Cowhole Mountain pluton around Q-36 appears to have originated by the intrusion of the pluton against an overlying thrust plate of Good springs. The contact between these two units resembles other thrust surfaces in the area in two ways. First, the contact is a fairly flat surface dipping at a moderate angle to the east, thus mimicking both the Playground and Cowhole thrusts. In addition, the base of the Good springs is in many places a smooth, slightly undulatory surface. This feature is best seen in three-dimensional exposures of the contact created by the preferential weathering of granitic rock.

In summary, the hidden faults present near P-35 and Q-36 are postulated to have evolved in the following sequence:

1) the Bird Spring and Aztec units are juxtaposed on a steeply dipping fault;
2) Good springs Dolomite is thrust over the Bird Spring and Aztec units;
3) the Cowhole Mountain pluton is emplaced, its upward movement being largely controlled by the thrust surface;
4) hypabyssal rocks are intruded along the Bird Spring-
Aztec fault zone, and small fault movements in the
zone juxtapose slices of the Goodsprings, Bird Spring
Aztec, and hypabyssal units.

The age or ages of the structures of the Cowhole Mountains
described above can be limited no more closely than post-Early
Triassic and pre-Quaternary based on geologic evidence present-
ly available in the study area. These structures are tenta-
ively correlated with the two Mesozoic orogenies that af-
ected the eastern Mojave Desert.

Speculations Concerning Mesozoic Deformation

Several aspects of the Mesozoic structural evolution of
the Devil's Playground area are deserving of further atten-
tion. Comments concerning the age and sequence of deforma-
tion and the extent of allochthonous terrain in the study
area are presented on the following pages. It is worthwhile
to reiterate at the beginning of this section that the various
structures and deformational events discussed below are re-
ferred to the Mesozoic Era rather than the Cenozoic on the
grounds that thrust faults found in other areas of the east-
ern Mojave Desert are known or inferred to be of Mesozoic age.

Either one or two periods of deformation may be inferred
to have given rise to Mesozoic structures in the Playground.
A sequential development of structures is evident at two lo-
calities. In Powerline Canyon, the Powerline Canyon shear
zone is overlain by the Playground thrust fault, while on
Cowhole Mountain, the relatively undeformed Cowhole thrust
plate overlies refolded Goodsprings Dolomite. Conclusive
evidence is not presently available to determine whether these
sequential structures resulted from one rather complex pro-
gressive deformation or two separate deformational events.
The author prefers the two-event hypothesis on the admittedly
tenuous grounds that thrust and fold structures of significantly different Mesozoic ages are present at Clark Mountain (Burchfiel and Davis, 1971), just 30 miles northeast of the Devil's Playground area. Burchfiel and Davis (1972) correlate these structures with the early Mesozoic Mesocordilleran orogeny and the late Mesozoic Sevier orogeny, both of which they suggest affected much of the eastern Mojave Desert.

Two extreme or end-member interpretations may be made concerning the relative amounts of allochthonous and autochthonous terrain in the Playground. The most conservative interpretation is that only terrain directly underlain by presently-exposed thrust faults may be considered allochthonous. This appears to have been the viewpoint of Barca and Yelverton in their descriptions of the structure of portions of the study area. At the opposite extreme is what may be called the super-allochthonous interpretation in which virtually all of the post-Early Cambrian Paleozoic and much of the Mesozoic strata in the Old Dad Mountain block and the Cowhole Mountains are considered to be allochthonous, having moved in a generally eastward direction on both exposed and hidden thrusts. The recognition of several thrusts—both hidden and exposed—in the Cowhole Mountains, as well as the possibility that Old Dad Mountain may be underlain by two thrust faults suggest that the amount of allochthonous terrain in these areas is greater than had previously been recognized. Thus the super-allochthonous interpretation may describe the geology of the Playground more correctly than the more conservative interpretation. A speculative super-allochthonous interpretation of the Mesozoic structural evolution of the Playground is presented in the following paragraphs.

According to the super-allochthonous hypothesis, almost all of the post-Middle Cambrian Paleozoic rocks of the Cow-
hole Mountains were emplaced during two periods of thrusting, one possibly related to the Mesocordilleran orogeny and the other to the Sevier orogeny. During the older event, Goodsprings Dolomite exposed in the Cowhole Mountains was moved eastward(?) onto Mesozoic (eg. 1-33.5) and Paleozoic (P-35) strata which had been juxtaposed by still earlier faults (eg. Bird Spring Formation against Aztec Sandstone north of O-34.5). As noted on page 64, the Goodsprings Dolomite on Cowhole Mountain may be parautochthonous rather than allochthonous, perhaps representing a minor thrust slice beneath the main thrust surface. The development of foliation and similar folding in this slice of Goodsprings probably occurred during this older thrusting event.

During a second deformation event in the Cowhole Mountains, a thrust plate of middle and upper Paleozoic strata was emplaced above the previously deformed Goodsprings Dolomite. This younger thrust surface is exposed on Cowhole Mountain as the Cowhole thrust fault, but near M-33.5, it is hidden by sand. J.M. Novitsky (pers. comm., 1972) reports that blocks of Bird Spring strata rest with thrust fault contacts upon Goodsprings Dolomite on a hill approximately 1 mile north of Cowhole Mountain. Thus, this younger thrust plate appears to have had a lateral (north-south) extent of at least 6 miles. The second folding event which affected the Goodsprings Dolomite on Cowhole Mountain probably occurred during the emplacement of this younger thrust plate. A sketch showing the inferred distribution of remnants of the two thrust plates and the hidden and exposed segments of the thrust surfaces is presented in Figure 15.

In the super-allochthonous interpretation of the Old Dad Mountain block, the two-thrust hypothesis for the Playground thrust fault (see p. 60) is accepted. Thus, all of the Pale-
Figure 15. Super-allochthonous interpretation of Paleozoic rocks of the Cowhole Mountains.
ozoic and Mesozoic strata of this block are allochthonous (see Plate 3b).

In the super-allochthonous interpretation of the Devil's Playground area presented above, a considerable volume and area of material has been postulated to be allochthonous, having moved to its present position from a source area to the west and/or northwest. There appears to be no shortage of potential source terrain from which these thrust plates may have been derived. The large area covered by Quaternary sand lying between the Old Dad Mountain block and the Cowhole Mountains could have been the original site of one or both of the thrust plates in the Old Dad Mountain block. Alternately, these thrust plates as well as those in the Cowhole Mountains may have been derived from the Soda Lake basin lying to the west and northwest of the Cowhole Mountains (Fig. 1). Both of these potential source areas are acceptable not only because they are large enough and in the correct position, but also because they are not far removed from the present location of the thrust plates. The stratigraphy of the allochthonous Paleozoic rocks of the Devil's Playground area appears to be similar enough to that of their counterparts in the autochthonous Paleozoic section in the Providence Mountains that long-range transport of these thrust plates seems unlikely.

In order to complete this chapter, it is necessary to comment upon the relationship between the Mesozoic structural evolution of the Devil's Playground area and that of the Clark Mountain area lying 30 miles to the northeast. Investigations in the Clark Mountain area by Burchfiel and Davis (1971; 1972) indicate that this area holds the key to understanding several aspects of the Mesozoic structural history of a large region to the west of the mountain, including the Playground. They report that the Clark Mountain complex contains a minimum
structural overlap of 40 miles created by stacking of Precambrian and Paleozoic strata in three major thrust plates. This thrusting occurred during two periods of deformation, one related to the early Mesozoic Mesocordilleran orogeny and the other tentatively correlated with late Mesozoic Sevier orogeny. A schematic east-west cross section through the thrust complex is presented in Figure 16.

Burchfiel and Davis believe that successively higher thrust plates in the complex were derived from source terrains farther to the west than the underlying plate. The significance of this interpretation is that after the Keystone and Mesquite Pass thrust plates are restored to their probable source terrains west of Clark Mountain, it becomes necessary to search at least as far west as the Halloran Hills-Playground area for adequate source terrain for the Precambrian rocks and (inferred) Eocambrian and Paleozoic strata of the Winters Pass thrust plate. Although it is possible that the Winters Pass thrust may have originated west of the Halloran Hills-Playground area and passed eastward over this area, Burchfiel and Davis tentatively prefer the interpretation (1971, p. 27) that the Winters Pass thrust fault passes beneath the Halloran Hills-Playground area. If they are correct, all of the Precambrian metamorphic and overlying Eocambrian through Middle(?) Jurassic strata (assuming the Winters Pass thrust is late Mesozoic in age) in the Playground have been transported northeastward for a distance of perhaps 16 miles and possibly farther. Furthermore, those Paleozoic and Mesozoic strata which are proven or inferred to be immediately underlain by thrust faults above the Winters Pass thrust are doubly allochthonous.

The geology of the Devil's Playground area is in permissive accord with the hypothesis that the Winters Pass thrust fault passes beneath the area. The inferred direction of trans-
Figure 16. Schematic reconstruction of Clark Mountain thrust complex (after Burchfiel and Davis, 1971). Note the similarity of Kokoweef fault - Keystone thrust relation here to Powerline Canyon shearzone - Playground thrust in study area.
port is approximately parallel to Eocambrian and Paleozoic facies and isopach trends in the Playground area; thus, movement on the Winters Pass thrust would be nearly impossible to detect by comparison of thicknesses and/or lithologies of Eocambrian and Paleozoic strata from areas suspected to be within the thrust plate with outcrops of these units outside the plate (e.g., Devil's Playground area and Providence Mountains). Although the thrust plate moved at nearly right angles to the trend of Mesozoic facies and isopachs associated with the volcano-plutonic arc, outcrops of these strata are so few and far between and their stratigraphy in many areas so poorly understood that analysis of possible relative lateral displacements of these Mesozoic strata is presently impossible. Finally, all of the Precambrian metamorphic rocks in the Playground appear to have undergone a similar history of metamorphism and deformation. Thus the various outcrops of these rocks probably have not been transported significant distances relative to one another. They may lie above the Winters Pass thrust fault or below it.
Geologic History

Precambrian metamorphic rocks which form the basement of the Devil's Playground area record a history of regional metamorphism, granitic intrusion, and deformation tentatively assigned to the interval 1650 - 1730 m.y.b.p. This was followed by a period of retrograde thermal metamorphism. Mafic dikes were emplaced in one area sometime during the interval 1100 - 1200 m.y.b.p.

Following a period of erosion, a shallow sea transgressed southeastward over the area during later Precambrian time; this marked the beginning of deposition in this part of the southern Cordilleran miogeosyncline. Fourteen hundred feet of predominantly detrital sediments deposited during the Eocambrian and Early Cambrian were followed by approximately 8000 to 10,000 feet of predominantly carbonate Paleozoic strata; several periods of nondeposition and/or erosion during the Paleozoic are marked by disconformities. Fine-grained, siliceous clastic material present in Pennsylvanian and Permian strata may reflect the onset of tectonic activity in regions to the west. A widespread erosional unconformity not presently exposed in the Playground marked the end of Paleozoic deposition in the eastern Mojave Desert.

Rocks in the study area reflect a complex Mesozoic history of the Devil's Playground marked by the onset of igneous and tectonic activity. Marine waters returned to the area during the Early Triassic and deposited interbedded fine-grained detrital and limestone strata thought to correlative with the Moenkopi Formation. Following this came several hundred feet of conglomeratic quartzite also thought to be of shallow marine origin. Seas withdrew from the area in early Middle Triassic (?) time and several thousand feet of calc-alkaline volcanic rocks with interbedded quartzite and volcanioclastic
material were deposited. During a period of volcanic quiescence in the Early Jurassic, quartzites of the Aztec Sandstone spread westward; these sands were deposited in or reworked by waters of a shallow marine embayment which developed in the eastern Mojave Desert. Another period of volcanic activity covered the Playground and surrounding regions with a few thousand to perhaps several thousand feet of suberial, calc-alkaline volcanic strata during the Middle(?) Jurassic. Late Jurassic and Cretaceous strata are not present in the study area. During and following the deposition of these volcanic and clastic rocks, a wide variety of hypabyssal and granitic rocks were intruded into the Devil's Playground area. Also during the Mesozoic, most of the Paleozoic and some of the Mesozoic strata in the area were transported eastward and southeastward during two periods of thrust faulting tentatively correlated with the early Mesozoic Mesocordilleran orogeny and the late Mesozoic Sevier orogeny.

A period of relative tectonic quiescence and intense erosion ensued during the first half of the Tertiary. In Oligocene/Miocene times, normal-slip movement on the Old Dad and similar faults now buried gave rise to the northwest-trending Basin and Range structure and topography in the Playground. Many of the blocks created during this time were tilted to the east and southeast and broken by internal faults. Late Tertiary fanglomerate deposited on the flanks of these blocks was subsequently cut by Pliocene or younger dip-slip(?) faults. Erosion and alluvial deposition continue today.
CONCLUSIONS

The present study of the geology of the Devil's Playground area has provided new data concerning the depositional and deformational history of this region which will be useful in future syntheses of the geologic history of the eastern Mojave Desert. The most important geologic features of the Devil's Playground determined during this study are summarized below.

1) Outcrops of Precambrian metamorphic rocks in the study area display similar metamorphic and deformational histories. There is no evidence to suggest that important thrust faults occur within these rocks, though such faults may exist below the present surface.

2) Eocambrian and Early Cambrian strata of the study area are transitional between similar coeval strata in adjacent areas. These strata in the study area appear to be authochthonous with respect to their counterparts in adjacent areas, though the possibility remains that Eocambrian and Early Cambrian strata in the study area (and the metamorphic basement upon which they rest) may have been thrust northeastward in a direction parallel to isopach and facies trends on thrust faults which do not crop out in the study area.

3) Post-Early CambrianPaleozoic strata in the study area are similar to coeval strata deposited along the southeastern margin of the Cordilleran geosyncline in nearby areas.

4) Mesozoic strata of the study area are transitional between predominately volcanic Mesozoic strata deposited to the west of the Devil's Playground and pre-
dominantly non-volcanic Mesozoic strata deposited to the east. Two distinct pulses of volcanic activity during the Triassic and Jurassic were separated by a period of relative volcanic quiescence during the Early Jurassic.

5) Sequential development of thrust fault, strike-slip fault, and fold structures during the Mesozoic are interpreted to indicate two periods of tectonic activity within the area, possibly correlative with the early-middle Mesozoic Mesocordilleran orogeny and the late Mesozoic Sevier orogeny. The possibility remains, however, that these sequential structures may have developed during one complex, progressive deformation.

6) During Mesozoic deformation(s), all post-Early Cambrian Paleozoic strata in the study area are inferred to have been thrust to the southeast. Some of the thrust faults upon which this movement occurred are presently exposed whereas others are hidden by Cenozoic strata. These Paleozoic strata are interpreted to have moved relatively short distances from their sites of deposition because their stratigraphy is nearly identical to that of authochthonous Paleozoic strata in the nearby Providence Mountains (see #5 preceding).

7) One northwest-trending, late Tertiary normal fault crops out in the study area and several similar faults are inferred to be present in the area (beneath Quaternary alluvium) on the basis of regional topography. The Devil's Playground probably underwent considerable extension in a direction normal to these faults (ie., in a northeast-southwest direction) during the late Tertiary.
References Cited


Barca, R.A., 1965, Geology of the northern part of the Old Dad Mountain quadrangle, San Bernardino County, California; California Div. of Mines and Geology Map Sheet 7, 9p.


Lanphere, M.A., 1964, Geochronological studies in the eastern Mojave Desert, California: Jour. Geol., v. 72, p. 381-399.


Southern Pacific Company Land Department, 1959, unpublished geologic map of the southwest part of the Old Dad Mountain quadrangle, by W.L. Coonrad.


EXPLANATION

Contact, showing dip
dashed where approximately located

Fault
dashed where approximately located; dotted where concealed; queried where inferred; ball on downthrown side

Thrust fault
barbs on upper plate

Gravity slide block

Sheared rock in fault zone

Brecciated rock

Mixed rock zone
includes variable amounts of intrusive and metamorphic or sedimentary rock

Axis of anticline, showing direction of plunge

Axis of overturned syncline, showing direction of plunge

Axis of syncline

Strike and dip of beds

Generalized strike and dip of beds disrupted by brecciation

Strike and dip of overturned beds

Strike of vertical beds

Strike and dip of flow layering in volcanic rock

Strike and dip of metamorphic foliation

Strike of vertical foliation
LOWER VOLCANIC UNIT
pattern denotes quartz-rich detrital material

TA

MOENKOPI FORMATION

P-CPb

BIRD SPRING FORMATION

MONTE CRISTO LIMESTONE

SULTAN LIMESTONE

GOODSPRINGS DOLOMITE

CARRARA FORMATION

ZABRISKIE QUARTZITE

WOOD CANYON FORMATION

UPPER STIRLING QUARTZITE

LOWER STIRLING QUARTZITE - JOHNNIE FORMATION, UNDIVIDED

PALEOZOIC CARBONATE, UNDIVIDED

MIDDLE CAMBRIAN - PRECAMBRIAN, UNDIVIDED

GNEISS
EXPLANATION

STRATIFIED UNITS

Qs  Qa1
Qs-sand
Qa1-alluvium

Pi-Mf  Pi-Mib  Pi-Mlv
Pi-Mf-fanglomerate
Pi-Mlv-volcanic rock
Pi-Mib-megaschist

DELFONTE VOLCANICS
Jo
AZTEC SANDSTONE

Lower Volcanic Unit

Moenkopi Formation

Bird Spring Formation

Monte Cristo Limestone

Sultan Limestone

Goodsprings Dolomite

Carrara Formation

Zabriskie Quartzite

Wood Canyon Formation

Upper Stirling Quartzite

Lower Stirling Quartzite-Johnnie Formation, undivided

INTRUSIVE UNITS

Felsite hypabyssal rock
Leucocratic hypabyssal rock
Melanocratic hypabyssal rock
Pi-Mib diabase
Sands Granite
Cowhole Mountain Pluton
Kelsa Peak Pluton

All granitic rocks are assumed to be Mesozoic, hypabyssal rocks may be Mesozoic or Tertiary. Age relationships shown are approximate.
EXPLANATION

STRATIFIED UNITS

Quaternary
- Qs, Qo1, Qa1
  - Qs-sand
  - Qoi-alluvium

Tertiary
- Pi-NeP, Pi-Mib, Pi-Mib
  - Pi-Mib-fanglomerate
  - Pi-Mib-volcanic rock
  - Pi-Mib-megabrecia

Jurassic
- Delfonte Volcanics

Triassic
- Aztec Sandstone

Lower Volcanic Unit
- Rmb
  - Moenkopi Formation

Pleistocene
- Bird Spring Formation

Monte Cristo Limestone

Sultan Limestone

Good Springs Dolomite

Carrara Formation

Zabriskie Quartzite

Wood Canyon Formation

Upper Stirling Quartzite

Lower Stirling Quartzite- Johnnie Formation, Undivided

Intrusive Units

- metamorphic rock
  - felsite hypabyssal rock
  - leucocratic hypabyssal rock
  - melanocratic hypabyssal rock
  - diabase
  - Sand Granite

Cowhole Mountain Pluton

Kelso Peak Pluton

All granite rocks are assumed to be Mesozoic; hypabyssal rocks may be Mesozoic or Tertiary. Ages relationships shown are approximate.
A. ONE-THRUST HYPOTHESIS
ALTERNATE INTERPRETATIONS OF PLAYGROUND THRUST FAULTS

ESIS
B. TWO-THRUST HYPOTHESIS
NO-THRUST HYPOTHESIS
Cz - Cenozoic rocks
Mz - Mesozoic rocks
Pz - Paleozoic rocks
Pc - Precambrian rocks

Faulted where
1 in block

Section

Fault zone
Beneath allochthon
AUTOCHTHON

LOWER PLAYGROUND ALLOCHTHON

UPPER PLAYGROUND ALLOCHTHON

UPPER PLAYGROUND THRUST

dashed where inferred

OTHER SYMBOLS AS IN A.
AUTOCHTHON

LOWER PLAYGROUND ALLOCHTHON

UPPER PLAYGROUND ALLOCHTHON

LOWER PLAYGROUND THRUST FAULT

UPPER PLAYGROUND THRUST FAULT
dashed where inferred

OTHER SYMBOLS AS IN A.