Reconnaissance Geology Between Lake Mead and Davis Dam Arizona-Nevada

GEOLOGICAL SURVEY PROFESSIONAL PAPER 374-E

Reconnaissance Geology Between Lake Mead and Davis Dam Arizona-Nevada

By CHESTER R. LONGWELL

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 374-E

Bedrock and structural features in a belt along the Colorado River

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1963

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

[Plate 1 in Pocket]

TABLES

RECONNAISSANCE GEOLOGY BETWEEN LAKE MEAD AND DAVIS DAM, ARIZONA-NEVADA

By Chester R. Longwell

ABSTRACT

Between Hoover and Davis dams the Colorado River valley, trending south-southeast, separates the Black Mountains on the east from the Eldorado and Newberry Mountains on the west. For more than 20 miles directly south of Lake Mead the river is deeply incised in Black Canyon; farther south the stream course is in large part between wide alluviated slopes. Maximum relief within the area is about 4,500 feet.

Thick Paleozoic and Mesozoic formations found in ranges north and west of Lake Mead are not present south of the lake except as fragmentary xenoliths within igneous bodies. The principal bedrock units in a wide area bordering the Colorado River consist of Precambrian gneiss, schist, and granitic rocks; volcanic rocks in four distinctive series, with intercalated clastic sediments; and numerous plutonic bodies, ranging in size from stocks to small dikes, diverse in composition and in texture. Some plutons, through which the oldest lavas in the area were erupted, may be contemporaneous with tuff beds in Cretaceous formations north of the lake. The Patsy Mine volcanics, oldest of the eruptive series, consist mainly of brown andesitic lavas and agglomerates with maximum thicknesses of several thousand feet. The second episode produced the more siliceous Golden Door volcanics, equally thick and widespread, containing abundant glass and light-colored tuff. A third series, the Mount Davis volcanics, consists largely of basalt and dark andesite but at several horizons includes conspicuous units of high-silica glass and pumiceous tuff. Thick beds of extremely coarse sedimentary debris, much of it derived from Precambrian bedrock, are interspersed through the upper part of this volcanic formation.

The three older volcanic assemblages have been strongly tilted, and commonly they are discordant one on another. All have been cut by intrusive bodies. In the northern part of the area the Muddy Creek formation, made up of clastic sediments, saline beds, and thick basaltic lavas, is unconformable on all older rock units. Still later igneous activity is recorded in local basaltic flows and dikes associated with weakly cemented slope gravels.

The area holds a network of faults, some of large displacement and at least two with important reverse movement. The Black Mountains block is a compound horst, west of which repetitive faulting has tilted some blocks eastward, others westward. Considerable movement was in progress during the Mount Davis volcanism, as indicated by abundant coarse debris mingled with lavas near large faults. In Muddy Creek time great landslide masses moved from the rising west margin of the Black Mountains. Colorado River gravel beds of Pleistocene age were strongly deformed near some faults.

Evidence now in hand establishes an order of events within the area but not an exact chronology. All the volcanic assemblages appear to be younger than the Horse Spring formation, which is tentatively dated as early Tertiary. A lead-alpha analysis on a sample of quartz monzonite from a pluton intrusive into Golden Door volcanics gave an age of about 50 million years, suggesting that these volcanics and the older Patsy Mine volcanics are at least as old as Eocene. Mount Davis volcanics grade upward into sediments mapped as part of the Muddy Creek formation, now dated tentatively as Pliocene. The Colorado River, as a through-flowing stream in its present course west of the Plateau, originated later than the interior-basin conditions of Muddy Creek time. The river was temporarily impounded late in the Pleistocene epoch, as indicated by numerous remnants of lake deposits that lie on and are capped by river gravels.

INTRODUCTION

PURPOSE AND METHOD OF PRESENT STUDY

The main body of Lake Mead, from Boulder Basin eastward, marks a general boundary between wide areas characterized by very different bedrock. Ranges directly north of this latitude reveal sedimentary formations that total many thousand feet in thickness; south of the lake, volcanic, plutonic, and metamorphic rocks are predominant at the surface, as has been known since Ives (1861) made his exploratory trip up the Colorado River in 1857–58. Published maps and reports dealing with the geology near the river south of the lake are based on rapid reconnaissance, and therefore this wide region offers prospects of new information that may be critical for deciphering the history of an important fraction of the Basin and Range province. The present study was undertaken to extend and supplement a mapping program covering several ranges north and northwest of Lake Mead (fig. 1).

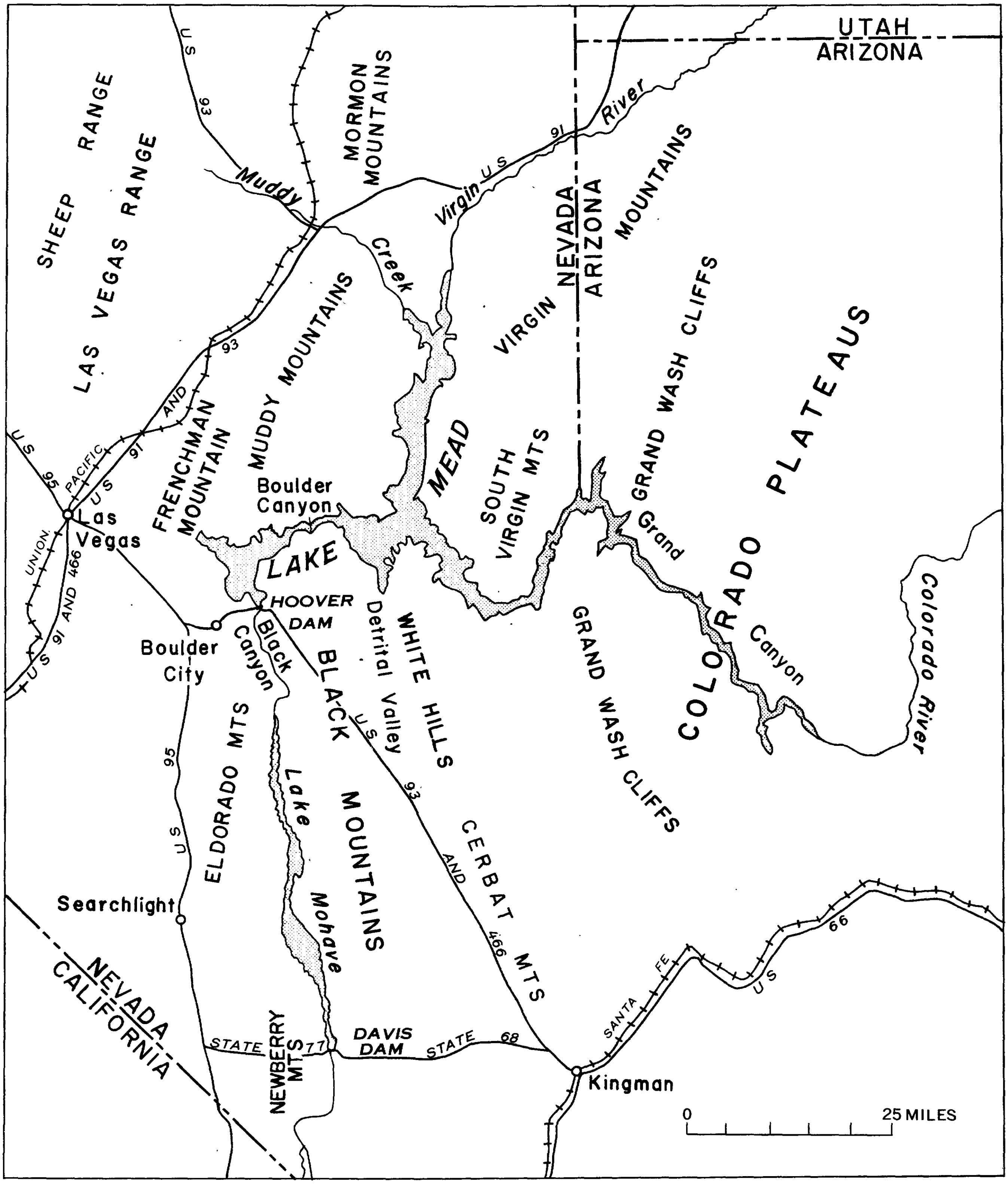


FIGURE 1.—Index map showing location and relations of principal geographic features mentioned in text.

Fieldwork in the spring of 1949 was timed to anticipate completion of Davis Dam, then under construction by the United States Bureau of Reclamation. Although this dam has only moderate height, and the lake it impounds (Lake Mohave) is both narrow and shallow in comparison with Lake Mead, some features of local importance that were visible in 1949 are now under water. The area studied is more than 60 miles long and averages about 18 miles wide. So large an area, much of it with rugged surface, could not be covered in detail within the 4 months available for fieldwork, and the resulting map is necessarily of reconnaissance nature. Considerably more time and effort could not have produced a strictly accurate result on the base maps then available, especially on the Arizona side. The Boulder Canyon, Nelson, and Camp Mohave preliminary sheets of the U.S. Geological Survey, on the scale 1:96,000 and with contour interval 100 feet, cover the Nevada side and a limited area in Arizona northeast of Hoover Dam. These maps, based on surveys by engineers of the Los Angeles Metropolitan Water District, are fairly accurate. For the belt in Arizona between Hoover and Davis Dams, the topographic base of plate 1 was improvised from the old Camp Mohave sheet (scale 1:250,000) of the U.S. Geological Survey and from special maps issued by the National Park Service. In that part of plate 1, representation even of major topographic features is inaccurate, and a contour interval less than 200 feet would not be justified.

In preparation for the Lake Mohave project, the U.S. Bureau of Reclamation completed in 1939 an accurate map, on a scale of 1 inch to 1,000 feet and with a 10-foot contour interval, of a narrow belt along the Colorado River between Hoover Dam and a point several miles south of the Davis Dam site. The only aerial photographs available in 1948 for the area of the present report were made by the U.S. Forest Service and covered a strip along the river somewhat wider than the Reclamation map. After the field study was completed, the U.S. Geological Survey issued three 15-minute topographic maps: the Henderson and Hoover Dam quadrangles bordering the lower part of Lake Mead and the Davis Dam quadrangle. Parts of these three maps and the corresponding aerial photographs have been useful in correcting the northern and southern parts of plate 1 in the present report.[1]

Until recent years access to much of the area was difficult, but with developments along the Colorado River, new roads have been constructed and old roads improved. Boats on the artificial lakes Mead and Mohave now facilitate work in the main valley, particularly in Black Canyon where the river had several stretches of swift rapids. The jeep is indispensable for covering much of the rough country still remote from good roads.

[1] Fifteen-minute quadrangles now available include the entire area of this report.

ACKNOWLEDGMENTS

Several organizations cooperated with the U.S. Geological Survey in support of this study. The Geological Society of America aided with a generous grant from the Penrose Bequest. Yale University gave the writer extended leave of absence in the season most favorable for fieldwork along the Colorado River. Later stages of the study were helped by results of a lengthy field season northwest of Lake Mead, made possible by a grant in 1954 from the National Science Foundation. Officers of the Bureau of Reclamation and of the National Park Service supplied maps and photographs, and extended other courtesies.

Thin sections for petrographic study, made by the U.S. Geological Survey, were studied by Gerald V. Carroll and Matt Walton. A grant from the Higgins Fund of Yale University paid for 13 chemical analyses of volcanic glasses. Philip Orville made the study of these glasses summarized in figure 11. Howard R. Gould, at that time a member of the U.S. Geological Survey, made measurements of fine clastic grains in the beds of the Chemehuevi formation (p. E14).

Grateful acknowledgment is hereby extended to the above organizations and individuals for their aid. Special thanks go to Henry C. Rainey, who as field assistant gave invaluable help and pleasant companionship.

CLIMATE AND VEGETATION

Because the climate of the region is arid, soil cover is poorly developed, and on the steeper slopes excellent examples of bedrock are exposed. The desert vegetation is sparse, and most of the individual plants are small, though locally along the river, mesquite, willow, cottonwood, and a few other large shrubs and trees once grew in clumps and thickets on some of the low ground now covered by the lake. Yuccas of several kinds are the largest plants on upland surfaces. "Joshuas" (tree yuccas), found as scattered individuals on alluvial ground at altitudes near 3,000 feet, grow in small groves on many higher slopes. Spanish bayonet and smaller kinds of yucca are common through a considerable range of altitudes. Creosote brush and the thorny ocotillo thrive on many of the gravelly slopes, and many kinds of cactus are widely dispersed. Sage thrives locally at altitudes above 3,000 feet.

Annual precipitation averages little more than 5 inches. During the summer months, temperatures generally are too high for effective fieldwork in any part of the area. From October to the end of May, conditions for field study are as a rule comfortable, though in exceptional years midwinter brings short periods with moderately low temperatures and occasional snow, even at low altitudes.

SURFACE FEATURES

Between Lake Mead and Davis Dam, the Colorado River valley, with average trend somewhat east of south, is flanked on the east by the Black Mountains and on the west by the Eldorado and Newberry Mountains (fig. 1; pl. 1). Each of these ranges has moderately high and rugged stretches separated by much lower divides. The highest points in each range have altitudes of about 5,000 feet, and maximum relief of the valley sides is about 4,500 feet in a horizontal distance of 6 to 9 miles from the river.

Topography of the valley slopes varies widely. From the wide Boulder Basin at the lower end of Lake Mead, the old course of the river enters the narrow confines of Black Canyon, the walls of which, either as sheer cliffs or in successive steps, reach several hundred feet above the former river bed (pl. 1). Along the 25-mile length of the canyon most of the tributary washes enter with grades that are steep, many of them precipitous. Below the mouth of Black Canyon, the valley widens and its slopes for the most part are covered with gravels derived from adjacent highlands. Considerable thicknesses of the gravel are unconsolidated, but at the lower exposed levels much of it is cemented and has been incised by the river and tributary washes to depths of some tens of feet (fig. 4). Locally hills of bedrock, some of them steep and of large size, protrude through the widespread gravel cover. The most thorough grading of slopes, on both sides of the river, has been accomplished in a stretch east of Searchlight, where the gentle, alluvium-covered valley sides are about 20 miles wide. Farther south the steep eastern front of the Newberry Mountains extends to the river, and near Davis Dam the valley is again incised to form a gorge with rather low discontinuous walls.

The several kinds of bedrock represent a wide range in resistance and in structure, reflected in the highly varied topography. Gneiss, schist, and granite, together with younger plutonic rocks, underlie high parts of the Black, Eldorado, and Newberry Mountains. Although these crystalline rocks are extremely heterogeneous in composition and in detailed structure, in many large masses they have responded to erosion generally as homogeneous bodies. Exceptionally large granitic plutons are more resistant than the bordering metamorphic complex, as is conspicuous in the highest part of the Newberry Mountains (pl. 1). In parts of the Black Mountains, however, the gneiss and schist underlie the highest topographic features. The steepest walls of Black Canyon are supported by thick volcanic flows and breccias. Tuffs, on the other hand, have yielded to vigorous attack and are commonly found in lowlands or valleys. Weak sedimentary deposits, some of considerable thickness, form badlands. Even the weakest rocks are protected locally in buttes and mesas capped by gently dipping flows of basalt, as in Fortification Hill and Malpais Mesa (fig. 3).

Surface forms of large extent within the area have important bearing on the history of drainage in a wide region. The western rim of the Colorado River valley borders active basins of interior drainage, only a few miles from the river and at much higher altitude. The eastern rim of one of these basins, containing the large playa southwest of Boulder City, is only 3 miles from Black Canyon and 1,600 feet or more above the river. Short tributaries to the river are cutting headward into some of the basin deposits. About 1,800 feet above the river, on the west rim of Black Canyon, remnants of caliche form east-facing cliffs as high as 30 feet. These remnants wedge out westward and apparently represent the capping of a deposit that occupied the adjacent part of the Colorado River valley. Remnants of a once extensive fill, ranging in coarseness and composition from large angular rock fragments to gypsiferous clay, appear beneath high basalt caps, as in Fortification Hill, and at much lower altitude in the area of badlands east of Willow Beach. These deposits are like those found in basins with interior drainage; therefore, they raise a question of the date at which the Colorado River had its beginning as a through-flowing stream.

Terraces and other surface features that record definite events in the history of the river are discussed on subsequent pages.

EARLIER WORK IN THE AREA

The earliest published map representing the general geology in the area here considered was offered by Jules Marcou (1858), who in 1853–54 was geologist in the expeditionary force charged with finding a route suitable for a railroad to the Pacific coast. Marcou's crude map had scant basis in field observation. A more informative report was given by J. S. Newberry (1861), who as geologist with the Ives expedition of 1857–58 ascended the Colorado River from the Gulf of California to the mouth of the Virgin River and made numerous traverses into the adjacent country. G. K. Gilbert (1875), geologist with the Wheeler Survey in 1871–73, followed the river from the southern tip of Nevada into the Grand Canyon; he made notes on the principal kinds of rocks along the route and on locations of major faults.

A more detailed geologic reconnaissance in the area, by Willis T. Lee (1908), of the U.S. Geological Survey, resulted in a small-scale (about 1:580,000) geologic map showing the distribution of principal rock types on the Arizona side of the river, accompanied by explanatory text and a series of structure sections. A supplemental study by F. C. Schrader (1909) emphasized mineral deposits of a large area in western Arizona and produced a geologic map of larger scale (1:250,000) covering a belt along the Colorado River extending south of lat 36° and westward into Nevada to long 114° 45′. At about the same time, F. L. Ransome (1907) studied several mining properties in the Searchlight and Eldorado districts of southern Nevada and published brief notes and a reconnaissance map. N. H. Darton's geologic map of Arizona (1924, scale 1:500,000) covers the part of the area of this report that lies east of the river.

Carl Lausen (1931) contributed some details for the Katherine mining district, near the present site of Davis Dam.

During early stages of construction work on Hoover Dam, Ransome made a careful geologic study of an area along Black Canyon for the Bureau of Reclamation. His map, with parts of his descriptive text, was published nearly 20 years later (U.S. Bur. Reclamation, 1950). In 1941 a group of U.S. Geological Survey geologists examined the region from Lake Mead southward for promising ore deposits, especially those containing managanese. Two of the resulting publications (Hunt, McKelvey, and Wiese, 1942; McKelvey, Wiese, and Johnson, 1949) have information useful for the present report. Written communications from several workers in the area were also made available to the present writer.

GEOLOGY OF THE AREA

GENERAL STATEMENT

Precambrian metamorphic and igneous rocks, and much younger igneous rocks, both extrusive and intrusive, are overwhelmingly dominant in the exposed bedrock. Sedimentary deposits that merit formation status occupy only very limited areas within a radius of 15 miles from Hoover Dam. Large quantities of sedimentary debris, chiefly coarse and locally derived, are interlayered with and therefore mapped with sequences of volcanic rocks. Alluvium that covers wide surfaces embraces deposits of several kinds: unconsolidated slope gravels, playa silt, stream alluvium of varied coarseness, remnants of lake beds, and still older gravel and silt that are well cemented.

PRECAMBRIAN ROCKS

Metamorphic and coarse-grained igneous rocks make up a large part of the bedrock exposed in the Black, Eldorado, and Newberry Mountains, and underlie other areas near the Colorado River. Several kinds of gneiss, schist, and granitic rocks are included. Although this assemblage cannot be dated directly in relation to known Cambrian strata within the area of this report, comparison with rocks not far distant to the north and northeast makes the correlation reasonably certain. At the west base of Frenchman Mountain, about 20 miles northwest of Hoover Dam, beds containing Lower Cambrian fossils lie unconformably above a crystalline complex strikingly similar to that in the Black, Eldorado, and Newberry Mountains. The Precambrian rocks of the southern Virgin Mountains and at the base of the Grand Wash Cliffs also closely resemble those so classified south of Lake Mead. Suggestions that some of the metamorphic rocks in the river belt may belong in Paleozoic or even later systems do not pass the test of regional comparative study.

The complex here classed as Precambrian is highly varied lithologically. Most conspicuous are strongly banded gneisses, many with granitic composition, others consisting largely of quartz, hornblende, and biotite. Schists, both micaceous and chloritic, are an important ingredient, and local masses of considerable size consist of hornblende schist. Garnets, some of large size, are conspicuous at many localities in gneiss, schist, and granite. Some prominent quartzose bands may be strongly metamorphosed beds of a sedimentary sequence. Coarse granitic rock, both pink and gray, is intrusive into the gneisses and schists as layers, irregular dikelets, and scattered bodies of larger size. Some irregular masses of pink granite have pegmatitic texture, but well-defined veins of pegmatite are uncommon. One of the most conspicuous rock types is a crudely banded gneiss rich in biotite and thickly studded with large porphyroblasts of feldspar. This rock forms large masses in Newberry Mountains and on both sides of the river near Davis Dam.

Banding of the Precambrian rocks generally has steep dips and northerly strikes prevail (pl. 1); but adjacent to large faults and younger intrusive igneous bodies, the attitude has been considerably modified. In the Black Mountains east of Willow Beach, a

661-325 O - 63 - 2

general westward dip at about 50° steepens to nearly vertical near the reverse fault along the west base of the range. On Saddle Island, at the west end of Lake Mead, the dips are westward at angles as low as 15° to 20°. The dominant rock in this isolated outcrop is a distinctive greenish schist (Longwell, 1936, p. 1406).

Many bodies of younger granitic rocks cut the Precambrian rocks on both sides of the Colorado River valley. Only a few of these are indicated on the map, and these with approximate boundaries; many others are not differentiated in areas mapped generally as Precambrian. Moreover, the map does not show numerous dikes and irregular intrusive bodies, ranging in lithology from basalt to rhyolite, which cut the Precambrian rocks in many areas. Some of these younger bodies are isolated; but many are grouped and at several localities form swarms. All these intrusive bodies, large and small, have escaped the intensive shearing and granulation that are characteristic of granitic rocks in the Precambrian complex. On evidence explained in a subsequent section, the igneous bodies younger than Precambrian are supposed to be no older than Mesozoic, and probably they are in large part Cenozoic. Many of these intrusive masses are directly related to the volcanic rocks described elsewhere.

SEDIMENTARY ROCKS

FORMATIONS NORTHWEST OF LAKE MEAD

One of the most notable facts about the geology south of Lake Mead is the absence of the thick sedimentary section that characterizes all the high ranges directly north and northwest of the lake. Only a few miles northwest of Las Vegas Wash, in Frenchman Mountain and in the hilly country east of it, a thick section of Paleozoic and Mesozoic strata is tilted steeply eastward. The formations are mostly those recognized in the belt of country north of Lake Mead from the Grand Wash Cliffs westward through the Virgin and Muddy Mountains. As shown in the columnar section (fig. 2), all Paleozoic systems except the Silurian (and questionably the Ordovician) are represented, a total thickness of about 8,000 feet. In normal development and with combined thickness of about 3,000 feet, the Triassic Moenkopi and Chinle formations are overlain by typical Aztec (Jurassic?) sandstone, which is here much reduced beneath an angular unconformity from its normal thickness of more than 2,000 feet.

Above the unconformable contact lies 2,000–3,000 feet of red beds, largely siltstone and sandstone, interbedded with fresh-water limestone, considerable gypsum, and great lenses of coarse conglomerate and sedimentary breccia. This thick section constitutes the Thumb formation—the new formation whose name is suggested by Thumb Valley, a small valley tributary to Las Vegas Wash about 4 miles southeast of Frenchman Mountain. A large part of the section is well exposed in this valley, though the base, resting on Triassic and Jurassic formations, is a short distance to the west. At this type section the beds are in homoclinal attitude, with eastward dips ranging from 45° to more than 60°. Several members are distinguished as follows:

	Feet
Horse Spring formation.	
Erosional unconformity.	
Thumb formation:	
Breccia, coarse; probably of landslide origin: made up of Precambrian metamorphic and granitic rock fragments	50–300
Sandstone, brown and flaggy; grades laterally into gypsiferous siltstone and claystone; locally includes thick section of basaltic lavas	900±
Sandstone and siltstone, reddish-brown, and thick lenses of coarse conglomerate. Locally include large bodies of breccia made of Precambrian rock fragments	750±
Coarse conglomerate, thinning and growing less coarse northward	150±
Sandstone, yellow and fine-grained; above and below thick-bedded gypsum and gypsiferous clay	200–250
Fresh-water limestone, gray and yellowish, thin-bedded; lower and upper parts interlayered with siltstone	200–300
Sandstone and siltstone, reddish-brown; lenses of conglomerate and fresh-water limestone	300–400
Basal conglomerate, well-indurated; cobbles and boulders derived from all older formations exposed in surrounding area	30–150
Angular unconformity.	
Jurassic and Triassic formations.	

No fossil evidence has been found to date the Thumb formation. From its stratigraphic relations and some general similarities to the Willow Tank formation and the Baseline sandstone exposed 35 miles to the northeast near Muddy Valley, the Thumb formation is tentatively classified as Cretaceous(?). Above it lies the Horse Spring formation, more than 2,000 feet thick, consisting largely of fresh-water limestone but including basaltic lavas, some siltstone, and lenses of coarse fan deposit. This formation also has yielded no diagnostic fossils, but from its stratigraphic position in the Muddy Mountains, it may be either Late Cretaceous or Tertiary in age. It is tentatively assigned to the Eocene(?).[2] Strong angular unconformity separates the formation from

[2] Two recent analyses of biotite in volcanic ash near the base of the formation indicate a date of 22–23 million years. This suggests Miocene age.

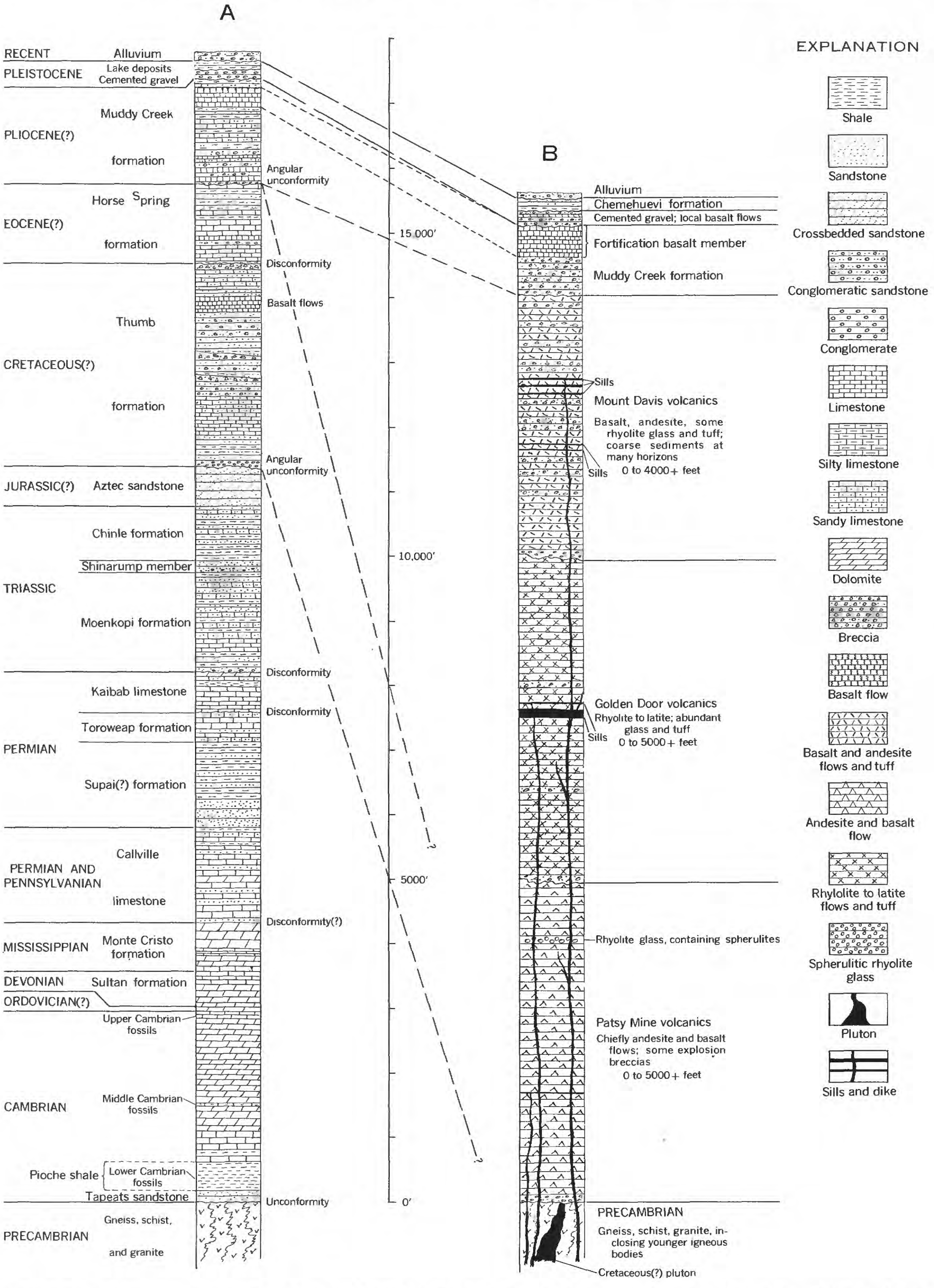


FIGURE 2.—Columnar sections north and south of Lake Mead: *A*, Section in Frenchman Mountain block, 13–20 miles northwest of Hoover Dam; *B*, Composite section between Lake Mead and Davis Dam.

the overlying sands, silts, and clays of the Pliocene(?) Muddy Creek formation, which extend beneath the western basin of Lake Mead.

Parts of the Thumb and Horse Spring formations reach a short distance south of Las Vegas Wash, in the northwestern part of the map area, where they end against younger volcanic and intrusive rocks. In general, however, the entire Frenchman Mountain section which, from Cambrian to Tertiary(?) units inclusive, has a total thickness of about 17,000 feet, is absent from most of the area of this report and from a much larger contiguous area on the east, south, and west. There is some evidence that at least part of the Paleozoic section once extended farther south. In the Black Mountains directly south of Boulder Canyon, a large fault block made up of Cambrian shale and limestone is intruded and virtually engulfed by igneous rock (Longwell, 1936, pl. 2). Numerous blocks of limestone and dolomite, lithologically like that in several Paleozoic formations, occur as xenoliths in plutonic bodies in the southeastern part of the River Mountains, near the head of Hemenway Wash. Barite in and around some of these xenoliths has been prospected extensively.

A distinctive section of sedimentary rocks exposed north of Boulder Canyon, between the Ransome fault and Boulder Wash, consists of yellowish dolomite, extremely coarse breccia, and thin beds of sandstone, shale, and limestone. The higher part of the section encloses sheets of andesitic lava, which become dominant upward (Longwell, 1936, p. 1407–1409). This isolated unit of unknown age is included on plate 1 with the group of igneous rocks labelled Tiv.

Indirect but strongly suggestive evidence bearing on the former extent of some formations is supplied by the Cretaceous(?) redbeds section east of Frenchman Mountain, in which northward-tapering wedges of coarse debris indicate a highland source directly to the south. The basal conglomerate, which bevels across the Triassic and Jurassic(?) formations from south to north, is made up largely of limestone fragments, many of boulder and cobble size; lithologic peculiarities and included fossils indicate their derivation from several Paleozoic and Mesozoic formations. Scattered pebbles from Precambrian bedrock also are included. Higher in the section great lenses of breccia, probably of landslide origin, contain fragments of Precambrian rocks only (Longwell, 1951, p. 352). It is inferred, therefore, that a broad area south of Las Vegas Wash and Lake Mead was strongly uplifted in late Mesozoic time and denuded of its Mesozoic and Paleozoic sedimentary formations. The area of uplift was later a theater of prolonged igneous activity, and resulting lava accumulations conceal the older bedrock which supplied the debris of the breccia lenses. The ridge that forms Saddle Island, which possibly marks a high part of the old land surface, has been exhumed by erosion following localized deformation (Longwell, 1936, pl. 2).

Because the Horse Spring formation and older sedimentary units occupy only a small fraction of the map area considered here, they are represented in somewhat generalized fashion on plate 1.

PLIOCENE(?) BASIN DEPOSITS

MUDDY CREEK FORMATION

Along the river south of Lake Mead, the oldest sedimentary beds, other than local accumulations of coarse detritus interbedded with volcanic rocks, were deposited in small enclosed basins. These deposits are strikingly like those of the Muddy Creek formation, which are widely exposed east of the Frenchman Mountain block and were well displayed in the wide basin directly north of Black Canyon before the formation of Lake Mead (Longwell, 1936). A thick section of these characteristic beds underlying the basal cap of Fortification Hill (fig. 3) doubtless was once continuous with similar beds that emerge locally from the alluvial cover southeast of Hoover Dam. East of Willow Beach the alluvium has been effectively eroded, exposing the Muddy Creek formation continuously over an area of several square miles. There the section near a fault contact with Precambrian rocks of the Black Mountains is made up of

FIGURE 3.—View westward on north side of Fortification Hill. Visible capping of superposed basaltic lavas is more than 400 feet thick. Deposits of the Muddy Creek formation, bouldery and poorly bedded in foreground (near Fortification fault) are finer grained and better stratified near middle of view.

coarse gravels containing angular fragments of gneiss, schist, and granite. Within a few hundreds of feet to the west, these gravels intertongue with and grade into layers of sand, silt, and clay that locally contain considerable gypsum. On the west side of the outcrop area, the section again coarsens and includes angular pieces of gneissic and volcanic rocks. Small remnants of basalt on layers of fine-grained sediments near the Willow Beach road apparently correlate with the basalt cap of Malpais Mesa, about 4 miles to the southwest.

All known evidence suggests deposition within a basin that contained a lake during at least a part of the sedimentary history; standing water seems a requirement to rationalize the rapid lateral gradation from coarse marginal to fine-grained interior deposits, the regular thin bedding of the fine sediments, and the recurrence of bedded gypsum, gypsiferous clay, and sporadic limestone. These characteristics are shared with the Muddy Creek formation farther north (Longwell, 1928, p. 90; 1936, p. 1419). Three of the limestone beds, 8 inches to 2 feet thick, carry a low percentage of manganese in exposures half a mile in extent (McKelvey and others, 1949, p. 99).

On the east side of Malpais Mesa, the cover of basalt lies on very coarse debris, which in part grades or intertongues westward into regular layers of gray siltstone and yellowish clay like that in the section east of Willow Beach. These fine-grained layers are well displayed in walls of a small valley that heads near the northwest corner of Malpais Mesa. The arrangement of coarse and fine sediments in this section suggests that a basin of deposition extended westward from the position of the mesa, and presumably the greater part of the deposit was eroded after strong uplift near and west of the position now occupied by the river. The basal part of the section around Malpais Mesa has particular interest. It lies on a rugged surface fashioned on Precambrian rocks east of the mesa, on volcanic rocks to the west. This basal deposit is a very coarse conglomerate and breccia in which the laregst blocks range in length from 1 to 4 feet. East of the mesa, fragments that make up the conglomerate in its lower part are almost exclusively of Precambrian rock types; west of the mesa, fragments of volcanic rock predominate in the deposit, but Precambrian types are important. The coarse well-cemented debris, of a pronounced brownish color, fills an old steep-walled valley hundreds of feet deep, reaching below the present level of the river and heading south-southwest. Overlapping of angular cobbles and small slabs indicates that a swift stream flowed southward in this valley. The Muddy Creek deposition clearly began on very rugged topography, which became much modified as sediments accumulated.

A third area underlain by typical deposits of the Muddy Creek formation lies from 2 to 3 miles east of Boulder City. The best exposures are in the upper part of Rifle Range Wash where, as noted by C. B. Hunt (written communication), the formation "is represented by about 75 feet of gypsiferous and manganiferous tuff, clay, silt, and sand." These beds, dissected into subdued badland topography, cover a considerable area and disappear toward the south and west beneath unconsolidated gravel. A shaft and two drill holes put down by the U.S. Bureau of Mines revealed that a silty gypsum bed, 60 to 65 feet thick, contains 3 to 5 percent manganese (McKelvey and others, 1949, p. 99). The manganiferous beds are dark gray to nearly black; other beds have the tan color that is dominant in fine-grained deposits of the Muddy Creek formation. North of Rifle Range Wash, the sediments coarsen, by gradation and intertonguing, and are in sedimentary contact with older bedrock. Along the east side of the outcrop area, the section includes at least one flow of basalt and is faulted down against older rocks.

Directly south of Boulder City, beds of sedimentary breccia that include tuff are faulted down against Precambrian rocks and quartz monzonite in Boulder Hill. These beds are probably in the Muddy Creek sequence, but alluvial cover conceals their relation to outcrops farther east.

The Muddy Creek formation in the vicinity of Las Vegas Wash has been described and mapped by Hunt and others (1942) and McKelvey and others (1949), who report that the section contains three distinct members, separated at least locally by angular unconformities. The lowest member, conglomeratic and of irregular thickness, locally contains some flows of basalt and andesite. A thick section of similar volcanic rocks underlies the lowest of the sedimentary units, generally with strong angular unconformity. These older volcanic rocks, which Hunt and McKelvey included with the basal member of the Muddy Creek formation, are now recognized as part of the Mount Davis volcanics and are so represented on plate 1. Apparently the deposition of some sediments in the lower part of the Muddy Creek formation began during late stages of the Mount Davis volcanism. Movements on faults, which initiated basins of deposition, are reflected widely in angular unconformity. As the movements and the volcanic activity doubtless were irregular in space and time, the base of the Muddy Creek formation is not everywhere sharply defined.

Widespread eruption of basaltic lavas was renewed later in Muddy Creek time. The Fortification basalt member, locally found in the upper part of the formation, is mapped as a distinct unit because of its wide distribution in contact with rocks older than the Muddy Creek formation.

The following stratigraphic table, modified from Hunt and others (1942, p. 301) and McKelvey and others (1949, p. 87), represents the formation at the Three Kids mine and near Boulder Basin of Lake Mead.

TABLE 1.—*Sequence of Tertiary rocks near Lake Mead*

Age	Formation and Member		Description	Thickness (feet)
Pliocene(?)	Muddy Creek formation	Member 3	Marginal conglomerate and sandstone, grading basinward into siltstone, clay, tuff, and gypsum. Includes thick sheets of basalt; these form cap of Fortification Hill, and their probable equivalents to east and south are mapped separately as the Fortification basalt member of the Muddy Creek.	0–2,000
		Unconformity		
		Member 2	Conglomerate, sandstone, shale, and gypsum	0–300
		Unconformity		
		Member 1	(c) Gypsum (locally manganiferous), limestone, clay, siltstone, and sandstone.	0–1,500
			(b) Tuffaceous sandstone and siltstone, generally manganiferous, some beds with high content of manganese.	0–150
			(a) Bedded conglomerate, with some locally interlayered basalt flows.	0–500
		Unconformity		
Miocene(?)	Mount Davis volcanics		Basalt and andesite flows and agglomerate. Coarse sedimentary debris included locally.	0–2,000+
		Unconformity		
Oligocene or Eocene(?)	Golden Door volcanics		Complex of volcanic rocks, latites to rhyolites, with much glass and tuff. Cut by dikes, stocks, and irregular intrusive bodies.	Thousands of feet

Cumulative evidence in a wide region indicates that sediments of the Muddy Creek formation were deposited in several adjacent basins under conditions of interior drainage (Longwell, 1928, p. 95; 1936, p. 1422). Coarse sediments near upland sources graded into and intertongued with fine-grained clastics and chemical precipitates in basin interiors. Evidently the Muddy Creek sedimentation began on a surface made rugged by faulting, and there were recurrent movements and volcanic activity while the deposition was in progress. Although the several areas of outcrop south of the lake may represent separate basins, possibly all these coalesced as the sections built upward and spread laterally. As the formation east of the Black Mountains includes evaporites, chiefly halite and gypsum, hundreds of feet thick (Longwell, 1936, p. 1423), and at a maximum the total section measures thousands of feet, perhaps the Muddy Creek interval was of long duration. During that time the Colorado River, as a through-flowing stream, could not have existed in its present location (Longwell, 1946, p. 831).

High in the formation, Stock (1921, p. 260) found some fragmentary vertebrate fossils which he considered suggestive of Miocene age. Later study indicates that these remains have no diagnostic value (M. C. McKenna, written communication, 1956). No additional fossils have been reported, and no evidence for definite correlation is available for sections south of Hoover Dam, which are referred to the Muddy Creek formation tentatively on the basis of physical characteristics and relations. The formation as it is widely exposed in areas bordering the Muddy Mountains is strikingly like the Panaca formation, about 100 miles farther north, which is well dated as Pliocene (Stock, 1921, p. 257).

LANDSLIDE BRECCIA

Coarse breccia that consists typically of broken fresh rock, with little or no matrix of weathered material, covers an area of several square miles southeast of Hoover Dam. This material, discussed in detail elsewhere (Longwell, 1951), had its source in the Precambrian bedrock of the Black Mountains and is most logically explained as a landslide mass that moved westward over basin deposits. The mass is an erosion remnant with a maximum thickness of several hundred feet. Much of it rests on the Muddy Creek formation; and since locally, near its southern limit, some of the breccia also lies below beds of this formation, the mass seems to be an exceptional unit of the Muddy Creek formation.

The base of the breccia is well exposed in deep washes. In its lower part the breccia is finely comminuted; and the basal surface of the mass, polished by abrasion in movement, has a low westward dip. Striae marking this surface, in the direction of inclination, increase its similarity to a fault surface. Upward in the section the rock fragments increase in size to maximum lengths of several hundred feet. The larger fragments retain the banding characteristic of Precambrian bedrock, though in detail most of the rock is minutely shattered. Blocks of basalt, locally mixed with the broken gneiss and granite, probably came from a flow like the one still partly preserved on the flank of the range 3 miles east of Willow Beach (pl. 1), or from local dikes.

Near the southern limit of outcrop, the breccia consists of two distinct units; a lower part, brown and softened by chemical weathering, is separated by stream-laid gravels from fresh breccia above. The gravels, 25 to 40 feet thick, have in the lower beds some reworked material from the weathered breccia beneath. Since the two units of breccia are similar fractions of the same formation, the contrast in degree of weathering suggests a radical change in local environment. Presumably the older mass, after its emplacement, was exposed for a considerable time to attack by the weather under a climate more humid than that of the present. Some change brought on rapid aggradation, and the younger landslide mass, deeply buried under basin deposits, was sealed from weathering until it was exposed by erosion in the Colorado River drainage area. Chemical decay under the present aridity is extremely slow.

Similar breccia, locally 200 to 300 feet thick, occurs at several places between flows in a volcanic assemblage older than the Muddy Creek formation. The most striking of these breccias were seen northwest of Malpais Mesa, and in sections of volcanic rocks exposed on the slope east of the Eldorado Mountains and northwest of Mount Davis. Probably landslide masses of this kind came from steep fronts of upthrown blocks along active faults (Longwell, 1951, p. 349).

The oldest breccia of this type recognized within the report area is within the Thumb formation, discussed above (p. E8) as probably of Cretaceous age.

OLDER ALLUVIUM

The older part of the deposits mapped as alluvium is complex in origin, and probably various parts of it differ widely in age. At several localities beds of well-indurated gravel are tilted as much as 20° to 25°, and possibly some of these beds are older than Quaternary. A cover of later alluvium conceals older deposits over wide areas, and there is no practical way of correlating isolated outcrops of similar clastic beds that yield no fossils.

In the wide valley of the Colorado River southward from Black Canyon, widely distributed well-cemented gravels are exposed in steep cliffs facing the river and along many large washes (fig. 4). These gravels closely resemble the unconsolidated gravels now on the floors of active washes and on slopes between the intermittent stream channels. The rock fragments, most of which were derived from lavas or from Precambrian bedrock, range from sand size to large boulders and are either angular or subangular.

Sections of the cemented gravels exhibit differences in arrangement, coarseness, and lithology of the rock fragments. In the lower part of Eldorado Wash (fig. 4), the basal part of each cliff contains many angular boulders as much as 2 feet long, derived from lavas of several lithologic types. Beds extend below the river level. An erosional unconformity separates this unit from overlying beds that are more regular, less coarse in average texture, and made up chiefly of fragments derived from Precambrian rocks. At the top of the section is a massive layer, about 20 feet thick, in which fragments are of moderate size, with isolated blocks as much as a foot long. In large part the arrangement is disordered; suggestion of layering and size sorting is faint and localized. Crude bedding indicates that the two lower units were deposited by swiftly running water, whereas disorder in the upper layer suggests that it accumulated on a slope removed from active stream channels, under influence of slope wash at times of exceptional runoff, supplemented by slow creep and perhaps by mudflow.

FIGURE 4.—Cliff of cemented gravels on south side of Eldorado Wash. Channel of Colorado River is short distance to the left of view. Gravels in three distinct units: *a*, fragments derived from volcanic rocks; *b*, fragments chiefly of Precambrian rocks; *c*, unstratified unit. Cliff is about 40 feet high.

Events in the history of the Colorado River are recorded in these deposits, and possibly a thorough study would reveal important details of the story. Does the unconformity above the lower unit in Eldorado Wash record lowering of the river bed, with consequent erosion of widespread alluvium? Abrupt passage from the middle to the upper member in the section also suggests an important change in regimen, for which more than one hypothesis may be offered. Assuredly large shifts in the river level occurred, as evidenced by the highest remnants of cemented river gravel. In the wide basin east of the river and northeast of the Newberry Mountains, and particularly on slopes a few miles southwest of the Portland Mine, such remnants outline a surface which, 3 miles from the river, has an altitude near 1,300 feet and a westward slope of approximately 100 feet per mile (fig. 5). Since the surface presumably leveled off in the middle of the basin, alluvium must have filled the valley to a height more than 500 feet above the modern riverbed. Perhaps fluctuations, both upward and downward through hundreds of feet, occurred during development of the river valley. Evidence of cutting to a level more than a hundred feet below the modern bed was found at the Hoover Dam site (Longwell, 1936, pl. 17) and during earlier investigations by test boring (La Rue, 1925, pl. X).

Cemented Colorado River gravels are exposed at several localities, most of them along washes where concealing slope gravels have been removed. One of the best exposures is beside the road about midway between the Portland and Katherine mines, on the east side of the valley opposite the Newberry Mountains, where the sediments consist of crossbedded sand and gravel, the latter containing well-rounded pebbles of lava, gneiss, granite, quartz, chert, and limestone. Only the river could have brought together such an assemblage and developed the forms of resistant pebbles that are evidence of long transport. This outcrop, which is nearly 3 miles from the modern channel and more than 600 feet above it, records one location of the stream during its long and varied history of lateral migration and vertical fluctuation. The cemented slope gravels, which support remnants of a widespread high-level surface (fig. 5), were deposited across the beds of river gravel after these beds were tilted locally, probably by faulting, to dips as high as 30°.

It is to the credit of Newberry that he saw these cemented gravels about 100 years ago, and differentiated those laid down by the river from the local slope deposits.

Relations among the several kinds of alluvium along the Colorado in the wide valley above Davis Dam are shown in figure 5. The river trenched coarse deposits of local origin and laid down thick beds made of far-traveled gravel and sand. After the channel shifted, the abandoned stream deposits were cemented, locally deformed, and in many places buried under local gravels which in turn became consolidated. Development of the wide and thick cap of caliche indicates an episode of stability. We have no evidence to suggest the exact geologic date represented by the widespread caliche; but it was clearly formed while the Colorado River was in operation, and therefore long after the Muddy Creek sediments were laid down in interior basins. The caliche cap is older than the lake beds of the Chemehuevi formation of Pleistocene age.

CHEMEHUEVI FORMATION

Evidence for a deep lake that occupied a vast area in the lower part of the Colorado River valley has been discussed elsewhere (Longwell, 1946, p. 827). Remnants of sediments that now are recognized as lacustrine were reported by Lee (1908, p. 41), who called the assemblage the Chemehuevis gravel and interpreted the entire sedimentary unit as a deposit made by the Colorado River. Lee, in his reconnaissance over a wide region, was impressed by the abundant loose river gravel that covers many remnants of the fine-grained sediment to a depth of several feet. Actually the gravel was deposited at various levels as the river cut down toward its old course at

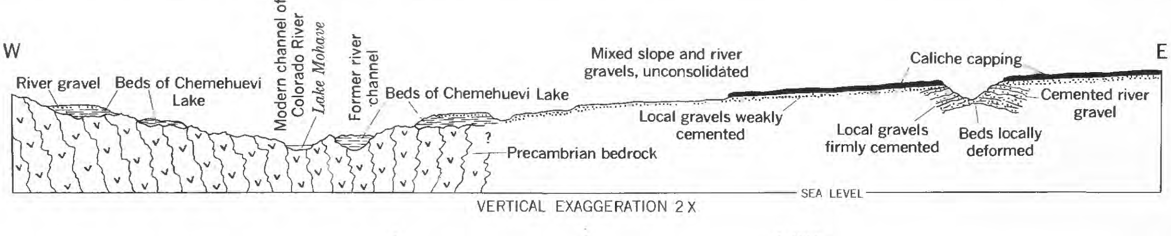


FIGURE 5.—General relations among sedimentary units designated alluvium on the geologic map, as seen on long slope east of Newberry Mountains.

the end of the lake episode. Gravels in basal beds of the few Chemehuevi remnants preserved near the present river level were no doubt deposited in the incipient stage of filling, while the lake was growing headward from the obstruction that blocked the earlier river.

Many dozens of the remnants of lake deposits, some of large size, are distributed in a belt on either side of the river; they are best preserved in areas free from large washes, particularly where hills of bedrock shield the weak material from erosion. Few remnants remain in the wide section of the valley between Black Canyon and the Newberry Mountains. Large quantities of the lake sediment have survived in pockets among the hills northeast of Davis Dam (fig. 6), and clay from that vicinity was used to make the impervious core of this earthfill dam. Characteristic lake deposits, consisting chiefly of clay in thin laminae, lie at various altitudes because the lake was deep and its floor was on rugged topography.

FIGURE 6.—View generally eastward, north of Davis Dam site, to Black Mountains. Precambrian rocks exposed in lower and middle parts of view, volcanic rocks in distant range. Light-colored clay and silt of the Chemehuevi formation fill former channel of river and lie in remnants at higher levels. Tailings from old Katherine mill in wash, upper left. Skyline at right is about 10 miles from foreground. (U.S. Bureau of Reclamation photograph.)

Near Davis Dam the laminated clays extend to a height about 300 feet above the river, where there is an abrupt change to crossbedded fine sand, remarkably uniform in grain size except in local wedges containing coarser, angular fragments that were brought in by tributary washes. Howard R. Gould, of the U.S. Geological Survey, kindly analyzed samples of the Chemehuevi sediments from the Davis Dam vicinity, and others from a large remnant of the sediments west of Boulder Canyon. At each locality the median particle diameter of the clay is less than 3 microns. Gould found the samples markedly similar to each other and also to clay in the bottomset beds of the present delta of Lake Mead, where the average median is about 2 microns. Sand in the upper member of the Chemehuevi has a median diameter of about 300 microns, and Gould found that the sand has about the same texture as the sand of the topset and foreset beds in the present delta (written communication, 1949).

The sum of evidence from the area of the present study supports the conclusion regarding the former lake on the basis of the sediments upstream from Hoover Dam (Longwell, 1946, p. 827). The fine-grained sedimentary unit represents conditions on the bottom of a deep lake far from the mouth of any large permanent stream. Local wedges of angular fragments are interpreted as delta fans contributed by intermittent streams from bordering highlands (Longwell, 1936, pl. 15). The abrupt change to the overlying sand marks arrival of the foreset beds as filling proceeded and the delta front advanced southward. No doubt the extreme reach of these foreset sands was many miles in advance of topset beds, as is true of the Lake Mead delta; therefore, the basal foreset sands of the Chemehuevi lake may well have been deposited in deep water, in accord with evidence that the upper deltaic member, predominantly of sand, was hundreds of feet thick in the deeper parts of the lake. As the area of total fill advanced down the lake, the river played laterally over the area, cutting and redepositing; as a result, over much of the delta the topmost member was a coarse stream deposit. In contrast with the Lake Mead delta, to which the Colorado River in flood contributes nothing coarser than sand, the stream in Chemehuevi time spread vast quantities of coarse gravel. Most of it was far-traveled, as is indicated by the advanced rounding of pebbles, cobbles, and boulders of peculiar lithologic composition, many of which were moved tens or even hundreds of miles from parent bedrock.

The contrast in stream loads noted above suggests that the river of Chemeheuvi time was more powerful than the present Colorado. As the terraces floored with the coarse gravel have downstream slopes closely comparable to the modern stream gradient, presumably a decline in the volume of flow since the terraces were formed is responsible for the decrease in carrying power. Probably, then, the regional climate during Chemehuevi time was more humid than now, at least in the headwaters areas of the river.

Many surface features are related to the lake history. Remnants of terraces capped by characteristic river gravels are at many altitudes, and wherever the gravels lie directly on the lake deposits, they record some stage in downcutting from the highest lake level. The lake sediments, especially the topset sands, are inherently weak, and it is not likely any of these have survived at the highest level. Coarse river gravels, on the other hand, are highly persistent if they are on a firm base. The shifting stream on the advancing topset beds must have impinged against bedrock at many points on the valley sides and at the margins of high island masses. At several places large remnants of gravel are on bedrock at altitudes somewhat above 1,500 feet; one of these is on Delmar Butte, on the south slope of the South Virgin Mountains (Longwell, 1936, p. 1454). Another is at Sugarloaf Mountain, a rounded peak of volcanic rock and a conspicuous landmark on the Arizona side south of Hoover Dam. A broad shoulder along the east and south base of the steep knob carries an extensive deposit of typical Colorado River gravels. This conspicuous bench, fashioned on bedrock and veneered with gravel, may actually be a fragment of shoreline of the former lake. Its inner margin is at about 1,530 feet altitude, or nearly 900 feet above the stream bed in Black Canyon before the dam was built.

About a mile northeast of and a little lower than the Sugarloaf bench is a group of large potholes containing river gravel (Ransome, 1923*b*). Presumably these features mark a temporary channel of the river at some stage of adjustment on the Chemehuevi sediments.

If the bench at Sugarloaf represents the highest level the river reached on the Chemehuevi fill, the lake at maximum extent was nearly 1,000 feet deep in the vicinity of Davis Dam, and 9 to 10 miles wide in the broad part of the valley south of Mount Davis. Farther south, in the basin north of the Mohave Mountains, the extreme width of the lake must have exceeded 15 miles. The basin still farther south, between the Mohave and Whipple Mountains, is known as Chemehuevi Valley and properly gives its name to the deposits, which are exceptionally displayed there. South of this basin, part of which is now occupied by Havasu Lake behind Parker Dam, many remnants of Chemehuevi sediments lie in protected recesses along the canyon cut through the Whipple Mountains. The lowland south of these mountains is extensive both east and west of the river, and although slopes are well graded and generally veneered with recent alluvium, scattered exposures indicate that the lake covered an immense area within which some mountain masses stood as islands.

J. S. Newberry (1861, p. 38), apparently the first to study these sediments, found near the river, in gravels that lie beneath clay of the Chemehuevi formation "a very large and perfect tooth of *Elephas primigenius*." The gravel bed accords with the beds above (fig. 7) and probably is a stream deposit near the temporary head of the growing lake. Newberry's account mentioned the clay overlying the gravel, but he supposed all the sediments were laid down by the river.

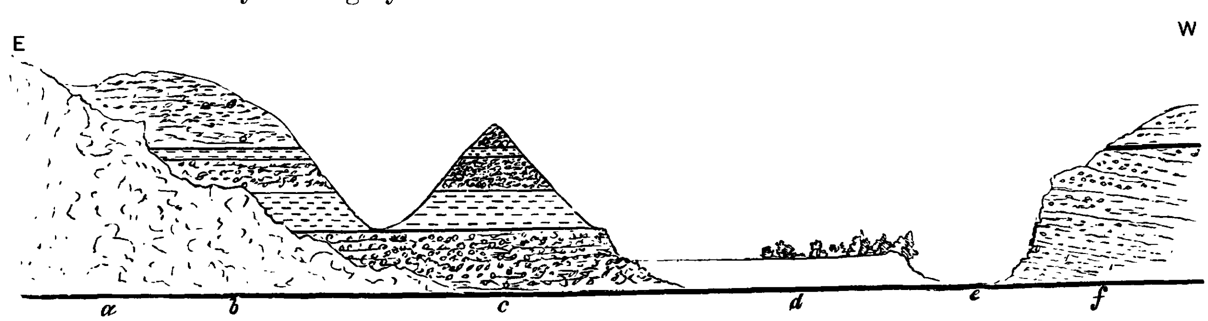
Mammal bones and numerous mollusk shells have been found more recently, not directly in the Colorado River valley but in tributary valleys and in deposits that seem to be closely related to the Chemehuevi formation (Longwell, 1946, p. 828). A Pleistocene age was assigned to the bones by Simpson (1933), and to the shells by F. C. Baker (written communication, 1932).

A map of the Chemehuevi formation would have value if it represented nearly all the remnants on a highly accurate topographic base, and preferably with differentiation of the significant kinds of sediment. Since most of the remnants are small and scattered over an enormous area, such a map would be very expensive in time and labor. In the present report the deposits are included among those mapped together as alluvium. They are highly distinctive deposits, and fortunately many remnants lie well above the level of Lake Mohave, though only a few escaped submergence or wave erosion by Lake Mead.

YOUNGER ALLUVIUM

Although the larger washes are only intermittent, many are fairly well graded, particularly in the wide segment of the valley between the Newberry Mountains and Black Canyon. The washes are floored with rock debris that ranges in size from silt to boulders. Coarse fragments are predominantly angular or subrounded, but some well-rounded pebbles are interspersed, probably contributed by old river bars left at high levels. As suggested by the topographic map, large interwash areas in the wide part of the valley have fairly uniform and gentle slopes. East of Searchlight, the slopes on either side of the valley range between 200 and 250 feet per mile through distances of 8 to 10 miles. These slopes are floored with gravelly debris, made up chiefly of coarse fragments but containing also much silt and sand that probably was contributed, at least in part, by the Chemehuevi fill. Locally, recent gullying has exposed remnants of the old lake clay veneered with slope gravel. The proportion of coarse gravel increases generally upslope and toward hills of bedrock.

Before the closing of Davis Dam, much of the river south of Black Canyon was margined by alluvial flats that varied in width and in height above low-water stage. The most impressive of these flats, now covered by the widest part of Lake Mohave, lay on both sides of the stream, from the latitude of Searchlight southward beyond Cottonwood Island (pl. 1). In this area the nearly level surfaces, underlain chiefly by stream-laid silt and sand, extended a maximum of more than a mile back from the river. The surface



a Trap hills rising eastward to the Black mountains
b Bluffs of stratified Quaternary gravel and sand
c Elephant Hill
d Alluvial bottom land
e Bed of river
f Tertiary conglomerates, inclined and covered with horizontal beds of gravel

FIGURE 7.—Newberry's section through Elephant Hill, near mouth of Eldorado Wash (copied from report of 1861). Elephant tooth came from basal unit of Chemehuevi formation, above *c*. His Tertiary conglomerates are the cemented gravels shown in figure 4 of present report.

of this old flood plain was on the average about 20 feet above low-water mark, and in many places steep banks adjacent to the stream indicated active lateral cutting. The larger tributary washes kept their channels incised below the level of the plain and formed small delta fans that forced the river toward the opposite bank. These terminal deposits of tributaries contained debris much coarser than that beneath the alluvial flat.

Large remnants of terraces on old river gravels were numerous on both sides of the stream course, at altitudes of 60 to 100 feet above low water stage. One of the most extensive of these lay northeast of the Old Ferry at the outer edge of the wide flood plain east of the river. The terrace front sloped up from the flat at the angle of repose of the coarse gravel, made up largely of cobbles with diameters as much as 8 inches, nearly all well rounded and many smoothly polished. The top of the terrace, 60 to 70 feet above low river stage, sloped gradually upward through a width of several hundreds of feet to its outer margin. A similar terrace west of the river and south of Aztec Wash was nearly 100 feet above stream grade. The coarseness of these gravels and the large original volume indicated by the remnants are evidence of great power of the river down to a late stage of its return to the pre-Chemehuevi grade. Pebbles and cobbles in the gravel represent many lithic origins, some of which are common in the Precambrian bedrock and in younger igneous rocks of the immediate region, whereas others, particularly quartzites, fossiliferous limestones, and cherts, are not known in any outcrops nearer than the Virgin Mountains.

In the broad part of the valley, remnants of river terraces at high levels are exceptional and small. On the resistant bedrock along Black Canyon numerous gravel bars, some of large size, record changing levels of the stream. Above the cliffs a mile upstream from Willow Beach, on each side of the present lake, extensive terrace remnants lie as much as 140 feet above the river bed of 1949. A mile directly west of Willow Beach, a wide saddle in the high ridge north of the river is floored with the river gravels at altitude 1,225 feet; and directly east of the saddle, pockets of the gravel extend to 1,320 feet, or about 700 feet above the channel of 1949. More than a mile farther downstream and on the south wall of the valley, remnants of terrace gravels lie near 1,300 feet altitude. Of many other occurrences in or near Black Canyon, the exceptional remnant at Sugarloaf is the only one thus far recorded as high as the 1,500-foot contour.

West of the river valley the alluvial cover is in two basins of interior drainage, separated by a low divide just north of Searchlight. Each basin is margined with an irregular assemblage of fans, which pass outward into a well-graded bajada slope furrowed by shallow washes. On many areas between washes, the slope gravels have settled into the smooth mosaic pattern of desert pavements. A long arm of the northern basin drains northward to the flat floor, where gravelly slope debris merges with clay and silt in the floor of an extensive playa.

East of the Black Mountains the long flat-floored Detrital Valley, draining northward to Lake Mead, is veneered with alluvial deposits that in kind and general arrangement resemble those of interior basins, although no playa is present in Detrital Valley. Detrital Wash has a clearly defined channel, with a low gradient to the north, although a stream carries through only in times of exceptional runoff, and during dry periods windblown deposits locally obstruct the streambed. Fine sediments in considerable quantity lie on the valley floor, not in continuous accumulation but undergoing slow, halting transportation down the valley. The advent of Lake Mead has of course created a new control, and doubtless there will be a growing deposit of sediment, dominantly fine grained, near the mouth of the wash, and steady decrease in a carrying power that was feeble before the lake was formed.

CRETACEOUS(?) AND CENOZOIC IGNEOUS ROCKS

Igneous rocks, both extrusive and intrusive, are of major importance in the bedrock of the area. The larger intrusive bodies are holocrystalline, and at least some of them are appreciably older than any of the volcanic rocks. On the other hand, many of the smaller injected bodies cut thick sections of lavas and tuffs, and some of these bodies occupy positions of vents through which volcanic products issued. Of these products lavas are predominant, but tuffs and explosion breccias are widespread, and some extensive sheets of perlitic glass may represent fusion of ash distributed in nuées ardentes.

The diverse igneous units are considered in a group separate from the sedimentary formations, because the position of these igneous rocks in the geologic column is uncertain. But all are geologically young in comparison with the Precambrian bedrock, and probably most of them originated in association with uplift and orogeny that affected the region in a relatively late stage of its history.

INTRUSIVE BODIES

LARGE PLUTONS

The geologic map (pl. 1) shows only part of the intrusive masses that have been recognized in the field; doubtless many others cut the Precambrian rocks in parts of the area not examined closely. For example, a large body of coarse-grained granite and another of quartz diorite are mapped as a single pluton near the head of Boulder Canyon, and a definite southern boundary of these plutonic rocks is not indicated because it is not known. Most of the boundaries shown on the map are inexact. The outline of a large mass of granite forming the highest part of the Newberry Mountains is estimated from hasty examination. Representation of a large granitic pluton in the upper part of Aztec Wash is much generalized. A special pattern is used where plutonic rocks make irregular contacts with gneiss in the northern part of the Black Mountains. Many bodies have highly complex borders that ramify the Precambrian basement. The present discussion, based on a preliminary sampling only, may have some value as a guide for later workers.

The larger bodies range in composition from diorite through quartz monzonite to granite. Outcrop areas of these bodies range from about a mile to more than 4 miles in largest dimension. Contacts with older adjacent rocks are for the most part steeply transgressive; but the mass exposed at Boulder City and extending more than 4 miles eastward is an unroofed sill or laccolith, whose base is generally conformable on lavas. Rocks that formed the roof have been wholly eroded from the pluton as exposed. About a mile east of Boulder City erosion has cut through the pluton along an anticlinal axis, from which the underlying lavas dip to the northeast and southwest. Farther east these lavas are essentially horizontal, and the contact with the pluton recedes and advances along walls of crosscutting canyons. Through 20 to 40 feet near the contact the lavas are conspicuously stained with iron oxide; this staining extends irregularly into the pluton also. Locally, the volcanic rocks have been recrystallized and have some resemblance to the adjoining plutonic rock, which near the contact is fine grained because of chilling.

In much of its exposed area, the Boulder City pluton stands above its surroundings, and in its eastern part the border of the mass forms steep slopes and precipitous cliffs. The ragged outline of its border along transgressive valleys suggests that the original lateral extent of the mass has been considerably reduced by erosion. In and south of Boulder City, alluvium conceals the mass except for scattered exposures, and the southern limit of outcrop is uncertain. At its western limit the outcrop is narrow, and apparently the body is covered by volcanic rocks of the River Mountains, though exposures in the critical area do not reveal an actual contact.

In specimens collected from the eastern part of the Boulder City pluton, the rock is granodiorite, with quartz highly poikilitic. Samples from the vicinity of Boulder City are quartz monzonite of medium to coarse grain size, with plagioclase zoned from An_{50} to An_{20}. Some of this rock, collected in 1956 by Earl Pampeyan and analyzed in the U.S. Geological Survey Laboratory by the zircon (lead-alpha) method (Larsen and others, 1952), gave an age of about 50 million years. This suggests that the pluton was emplaced in Eocene time.[3] Implications regarding date of the associated lavas are discussed on later pages.

The isolated Boulder Hill south of the city contains quartz monzonite similar to that exposed in Boulder City but coarser grained. In the southern part of the hill, the plutonic rock encloses masses of gneiss, presumably Precambrian, some of which merge imperceptibly with the quartz monzonite. In this area the igneous rock is less uniform in appearance and in size of grain than the rock in the northern part of the hill. Possibly the quartz monzonite in Boulder Hill represents part of a boss that served as feeder for the sheetlike body exposed in and east of Boulder City.

Granodiorite similar to that east of Boulder City underlies a large area east and northeast of Fortification Hill. Alteration along joints, perhaps in connection with later igneous activity, has developed bluish amphiboles, probably crossite and crocidolite (R. G. Coleman, written communication), that make conspicuous patches and streaks in the gray rock. South and west of Fortification Hill the lower slopes are on altered rock, much of it soft and claylike, characterized by bright colors which have earned for this area the name "Paint Pots." Local masses that show little or no alteration consist chiefly of gray and brownish monzonite porphyry. Ransome (U.S. Bur. Reclamation, 1950, p. 88) concluded that the widespread alteration was caused by introduction of finely disseminated pyrite, and subsequent oxidation with formation of sulfuric acid. The original minerals in the rock were changed to clay minerals, iron oxide, and other secondary products.

An assemblage of diverse intrusive bodies occupies much of the area extending southeast from Fortification Hill to the junction of the Horsethief and Indian Canyon faults. In the upper part of Kingman Wash, the bedrock is a complex of Precambrian gneiss and younger intrusive rocks of several kinds. South of Kingman Wash the intrusive rock, much of it rich in biotite, is dispersed irregularly through Precambrian gneiss east of the Fortification fault; in the block between this fault and the Horsethief fault, the intrusive rock surrounds large masses of siliceous lava.

[3] A potassium-argon analysis made in 1962 gave an age of about 23 million years. This indicates a Miocene age.

A similar network of intrusive bodies that engulf masses of volcanic rock lies west of the river and is transected by Rifle Range Wash. Some of the intrusive rock in the latter area is dark diorite.

Along the upper part of Eldorado Wash intrusive masses, shown on plate 1 as a continuous body, form discontinuous outcrops that make highly irregular contacts with Precambrian and volcanic rocks. East and west of Nelson the northern boundary of this intrusive complex transects a thick, tilted section of lavas, with contacts partly intrusive, partly faulted. Apparently this boundary is a complicated example of what Ransome (1904, p. 11) called an "intrusion fault," whereby the intruding body displaced upward great masses of the older volcanic rock. Ore deposits once extensively mined along and near Eldorado Canyon occurred in veins along crush zones in the intrusive rocks (Ransome, 1907, p. 76). Directly south and southwest of Nelson, large masses of volcanic rock are surrounded by and partly engulfed in monzonite porphyry that has conspicuous phenocrysts of feldspar in a dark-gray aphanitic groundmass.

North of the old Techatticup mine, the thick section of lavas dips steeply eastward and strikes almost at right angles to the nearly straight contact with a pluton of quartz monzonite. Dioritic rock along the north border may be part of a separate intrusive body. South of the mine, near an irregular boundary with Precambrian rocks, masses of gneiss and schist are engulfed in the pluton.

South and southwest of Nelson the contacts between intrusive and Precambrian rocks are highly irregular. Farther south, in the upper part of Aztec Wash, a large intrusive body has a composition at the borderline between quartz monzonite and granodiorite. Orthoclase in what appear to be phenocrysts actually is late porphyroblastic, replacing plagioclase. Biotite and hornblende make up to 15 percent of the groundmass. Analysis, in the U.S. Geological Survey Laboratory, of samples from this body by the zircon (lead-alpha) method gave an age of 35 million years.[4] Many prospects of metallic minerals have been explored in a wide area around this pluton.

The rock of lightest color seen in any of the large intrusive bodies is a granite that forms a prominent outcrop in the highest part of the Newberry Mountains. This rock has coarse texture, is rich in quartz, contains some oligoclase with the predominant orthoclase, small amounts of muscovite and biotite, and scattered grains of magnetite and zircon.

Study of all large intrusive bodies in the area would show a wide range in composition. Of the rocks that have medium to coarse grain the dominant kinds are quartz monzonite and granodiorite.

[4] A potassium-argon analysis made in 1962 reduces this age to 27 million years.

DIKES, SILLS, AND PLUGS

Small intrusive bodies are numerous and widely distributed; no attempt was made to map them. Dikes and sills range in thickness from a few inches to 100 feet or more and range in composition from basalt to rhyolite. In large part they are associated with volcanic rocks, and they occur in largest number near recognized centers of eruption. Many sills were injected between lava flows in thick volcanic sequences; some of the injected sheets are distinguished from flows only by generally coarser grain, by chilled upper margins, and by local crosscutting relations. Swarms of dikes that cut Precambrian rocks in wide exposures are assigned to a late geologic age because the dike rocks generally have not been sheared or crushed, and are similar, both in composition and in texture, to rocks in the volcanic sequences.

Several agglomerate plugs mark vents, and other irregular bodies perhaps had this origin. Two of the best examples are in the midst of a glass-and-pumice complex directly south of Square Butte, a prominent landmark 6 miles northeast of Nelson. Each plug has a nearly circular plan and nearly vertical walls; one is 300 feet in diameter, the other 150 feet. These and other similar bodies are more fully described in connection with the associated volcanic rocks.

VOLCANIC ROCKS

Five distinct episodes of volcanism are recognized along the river south of Lake Mead. Four of the resulting assemblages of rocks are widely distributed, and three of these, Eocene(?) to Miocene(?) in age, are here designated by formation names, from oldest upward, as follows: Patsy Mine volcanics, Golden Door volcanics, and Mount Davis volcanics. Volcanic rocks of the Muddy Creek formation make up the fourth assemblage. The fifth and latest episode is represented by local flows of basalt included in slope gravels that probably are of Pleistocene age.

Confident correlation of volcanic sequences over distances exceeding 60 miles may be greeted with some skepticism; but each of the named assemblages has distinctive lithologic characteristics, and the stratigraphic order of occurrence, wherever two or more of the units are recognized, is wholly consistent. Good evidence indicates more than one eruptive center for each assemblage, and there is of course no assurance that eruptions from several centers supplying similar products were exactly synchronous. Nevertheless, the striking consistency in order according to average lithologic composition, together with evidence for considerable crustal movement and erosion between successive units, clearly marks five chapters in the history of eruption. As noted in the several descriptions below, each of the three older assemblages has varied lithology, but the overall composition of each major unit is characteristic. A common kind of lava that recurs in two or more of the units presents problems of correlation wherever it forms isolated outcrops.

Locally, in several parts of the map area, complications caused by intrusive bodies and by widespread chemical alteration make identification of the volcanic rocks difficult or impossible.

PATSY MINE VOLCANICS

The oldest of the volcanic assemblages is widely exposed in a belt north of Nelson, in two areas along Black Canyon, and on both sides of Pope Wash. Smaller exposures lie along the road between Eppersons corral and the Portland mine, and remnants too small to map lie on the Precambrian rocks west of Union Pass. A thick and representative section that extends west to east through the vicinity of the Patsy mine, about 3 miles northwest of Nelson, is chosen as the type section, although the base is not there exposed.

The section consists dominantly of lavas, with some thick units of explosion breccia. Tuffaceous layers are local and of minor importance. The characteristic brown to gray brown of the rock, in varied shades but dominantly dark, is an important aid in recognizing the unit. Flows vary in thickness from a few feet to more than a hundred feet, but are common 20 to 40 feet thick. Many are vesicular or amygdaloidal in their upper parts, and some that contain large angular fragments in an aphanitic matrix probably were brecciated during flow. A few thick layers made up largely of angular fragments, both small and moderate in size, seem to be products of explosive eruption. The rock is predominantly aphanitic or has only scattered and rather obscure phenocrysts, chiefly of plagioclase; however, some of the layers are conspicuously porphyritic. Some flows of basalt in the upper part of the section are studded with reddish grains of iddingsite.

Under the microscope many specimens show both augite and pigeonite, with plagioclase zoned from An_{60} to An_{30}. Some are olivine-labradorite basalts, but more are pyroxene andesites. The latter predominate in the lower part of the section, basalts in the upper.

In the area north of Nelson, the thick succession of dark-colored lavas is sharply interrupted by a light-colored glassy unit, as much as 100 feet thick, in which yellowish welded tuff at the base is succeeded by gray to pinkish-brown aphanitic rhyolite containing lenses and small spheroidal aggregates of brown and greenish glass. At several horizons are numerous whitish spherulites, 2 to 18 inches in diameter, which weather free; many, especially the largest, are covered with smooth, warty excrescences. Some spherulites have concentric zoning and also conspicuous meridional markings. Chemical analysis of brown glass from this unit gave the result shown in table 2, p. E28 (sample 307). The glassy unit forms a ridge that parallels the road north of Nelson.

Offsetting and duplication of this highly distinctive horizon marker indicate the locations of several faults with large displacement. Above the glassy unit the flows are largely dark-brown basalt having a total thickness of perhaps as much as 1,000 feet, though some duplication by faulting may be present. Below the glass many strike faults break the section; nevertheless, the estimated thickness of this lower part exceeds 2,000 feet and may be more than 3,000 feet; thus, the total thickness of the Patsy Mine section appears to be at least 3,000 or 4,000 feet east of the large fault on which the basal part is dropped against Precambrian rocks and concealed. On the south, both west and east of Nelson, the continuous outcrop of lavas ends rather abruptly against bodies of intrusive rock that have surrounded and apparently engulfed large masses of the lavas.

Two major eruptive centers for the Patsy Mine volcanics are recognized. One of these, about 5 miles northeast of Nelson, is marked by a maze of intrusive bodies over an area covering more than a square mile. Near the center of the area great numbers of dikes radiate from large irregular plugs; many of these dikes cut across sections of lava and merge into either flows or sills. All the rock in this complex has the lithologic character and the brown color predominant in the Patsy Mine volcanics. To the south and northeast the complex passes into thick sections of the lavas resting on Precambrian basement. The second conspicuous eruptive center is along Pope Wash, about 3 miles east of the river, where lavas of the Patsy Mine volcanics dip outward from a large plug of gray-brown andesite porphyry. A complex of dikes, small plugs, and irregular bodies that cut the lavas forms a network outside the central body of porphyry. The total thickness of lavas in the section along Pope Wash appears to be well over 5,000 feet.

Another possible locus of eruption for the Patsy Mine volcanics is near Hoover Dam. About half a mile downstream from the dam, the characteristic brown lavas, inclined steeply eastward, emerge at stream level from a cover of younger rocks (fig. 8). The base of the volcanic mass is concealed west of the river, where blocks of the next younger series are lowered by faulting. The Patsy Mine lavas at the river, however, are crowded with fragments, large and small, of coarse-grained quartz monzonite; therefore, a plutonic mass was part of the bedrock through which the old volcanic material issued. Farther downstream the section is much confused by intrusive bodies of brown porphyry. The exact boundaries of these bodies were not mapped, and they are included as part of the Patsy Mine volcanics, with which they seem closely related lithologically. About 4 miles downstream from the dam, the lavas dip southward; and the strike swings in a wide arc northeastward, marginal to a massive body of the brown porphyry. Large dikes extend from this body into the lavas. Younger rocks at the eastern edge of Glass Plateau are faulted down against a mass of the brown porphyry, which there contains numerous large xenoliths of Precambrian gneiss, schist, and pegmatite. Thin sections of the porphyry reveal zoned andesine and oligoclase, with biotite, pyroxene, and much sanidine.

The base of the Patsy Mine volcanics, resting on Precambrian rocks, is well exposed at several localities in and near Black Canyon; also at many points farther southwest, and east of the river near the head of Gold Bug Wash. Although at some places the volcanic rocks are in direct contact with the old basement rocks, commonly a layer of coarse conglomerate or sedimentary breccia, a few feet to 40 or 50 feet thick, separates the two units. Cobbles and boulders in this deposit are made of the several types of Precambrian bedrock, of volcanic rocks presumably older than the Patsy Mine volcanics, or exceptionally of quartz monzonite probably derived from bodies intrusive into the Precambrian. At many places, particularly along Black Canyon, the basal unit of the volcanic series is a layer, 100 or more feet thick, of resistant explosion breccia. Many sheer cliffs adjacent to the river are on this resistant unit.

Relations at the exposed upper limit of the Patsy Mine assemblage are highly varied. In the wide belt of exposure northeast of Nelson, including the type section, there is an abrupt change in lithology to the next higher volcanic unit, with no apparent unconformity. In much of the map area, however, considerable disturbance and erosion occurred between eruption of the Patsy Mine and later volcanic rocks. Downstream from Hoover Dam a thick sedimentary breccia is essentially concordant on the Patsy Mine volcanics, which dip to the east much more steeply

FIGURE 8.—Unconformity between Patsy Mine and Golden Door volcanics. Older lavas dip 40° E., younger series nearly horizontal (note remnant at upper right). View southward, about 1 mile south of Hoover Dam.

than the overlying Golden Door volcanics (fig. 8). The breccia is conspicuously exposed at the base of the canyon walls at and below the dam, and Ransome (U.S. Bur. Reclamation, 1950, p. 91), in his study of the damsite, reported the thickness of the coarse detrital deposit as 350 to 400 feet. Logically, and in keeping with his sardonic humor, Ransome called this unit the Dam breccia. Since it thins and disappears within half a mile downstream, evidently the breccia represents a local accumulation on a surface with considerable relief. The fragments, as long as 1 foot, consist of porphyry and brown volcanic rock.

West of Union Pass the brown Patsy Mine volcanics are exposed only in small isolated remnants, and the younger Golden Door volcanics in general rest directly on the Precambrian basement. The Patsy Mine volcanics may be present northwest of Eppersons Corral, but if so they have been dropped below the present erosion surface by the Epperson fault. South of Square Butte and also in the upper part of Pope Wash, the Mount Davis volcanics rest directly on the Patsy Mine volcanics, with angular unconformity in varying degree.

GOLDEN DOOR VOLCANICS

The second major unit in the succession of volcanic rocks in the map area consists of lavas, breccias, tuffs, and glasses that average considerably higher in silica content than the next older and younger units. This distinctive lithology is expressed in color terms: the Golden Door volcanics are generally light colored, in contrast to the somber brown tones of the Patsy Mine volcanics and the dark gray, brown, and black of the Mount Davis volcanics. A thick section of the second volcanic assemblage is particularly well displayed in a large area on the flank of the Black Mountains west and southwest of Mount Perkins. In a limited part of this area near the road to Old Searchlight Ferry, the contact between the Golden Door and the younger Mount Davis volcanics is clearly exposed. The volcanic rocks are in fault contact with Precambrian rocks for several miles north of the road, and this relation continues southward to a point about a mile southwest of Eppersons Corral, where typical lavas of the Patsy Mine volcanics in the footwall block dip southward in normal contact with Golden Door volcanics.

The type section near the Golden Door mine, about 3 miles southwest of Mount Perkins, is essentially complete for the general locality, though the top and base are not exposed.

Thickness of the Golden Door volcanics at the type locality appears to be at least 5,000 feet, though there may be some duplication by obscure faults. Absence of these rocks from a large area near the head of Pope Wash may be the result of uplift and erosion before the next younger assemblage was erupted. Near Hoover Dam the thickness of Golden Door volcanics is somewhat more than 1,500 feet; but outcrops are absent in a large area south of the dam, where strong uplift attended by extensive erosion is indicated by prominent exposures of the Precambrian basement in the river belt. Locally in this area the Mount Davis volcanics lie directly either on the Patsy Mine volcanics or on Precambrian rocks; probably considerable movement occurred after the Golden Door volcanism and before or during eruption of the next younger assemblage. This history is indicated particularly by relations north and northeast of Eldorado Wash. In a belt northeast of Nelson the Golden Door volcanics, stepped down by a succession of faults west of the Eldorado fault, have a thickness as great as 1,200 feet, thinning eastward in each footwall block. East of the Eldorado fault these rocks are absent, and a thick section of Mount Davis volcanics lies with strong unconformity on Patsy Mine volcanics (pl. 1, sec. *D–D′*).

Rhyolites form an important part of the Golden Door volcanics; but there is a wide range in composition between rhyolite and andesite, and the average composition of the sequence varies from one locality to another. Generally the abundance of lavas high in silica appears to increase southward in the belt along the river. Rhyolite and its close relatives make up half or more of the section east of Davis Dam, and at least a third of the type section near the Golden Door mine. By contrast, no rhyolite has been recognized near Hoover Dam, where latites predominate; but rhyolite is an important constituent higher in the section, near Boulder City. Andesites and latites are the abundant types in the lower part of the type section, whereas rhyolite becomes more abundant upward. In view of the evidence for extensive erosion of these rocks in the northern part of the area, the Hoover Dam and Nelson sections may represent only a lower fraction that escaped destruction before the Mount Davis eruptions began. This would not imply, of course, that the basal parts of sections at any two localities are essentially identical. Aside from the probability that products erupted at several centers differed among themselves, crustal movements attended by vigorous local erosion may have been active during the volcanism, and the part of the assemblage preserved at one locality may be the time equivalent of any fraction, high or low, in the thick type section.

Detailed measurement and analysis of the thick type section have not been attempted. The lower half consists of flows and breccias, light brown to gray, aphanitic with subordinate porphyritic texture. Megascopically the predominant lithologic type is andesite, but a considerable part of the rock may be latite. Dikes and sills, some of rhyolitic composition, intrude the volcanic rocks locally, and sills may form an appreciable part of the total thickness. Above the middle of the section, dacite and rhyolite are increasingly abundant, and the upper 1,000 feet consists chiefly of rhyolite, rhyolite tuff, and rhyolite glass. Some units that appear to be flows are on microscopic examination revealed as welded tuffs. Much of the glass is perlitic, and discontinuous layers of light-gray flow-banded aphanitic rock included in thick yellowish tuff is found by thin-section study to be perlitic rhyolite.

Thin-section study of two flows in the lower part of the type section shows one to be pyroxene andesite, the other quartz latite. A third specimen, probably from a sill, is rhyolite porphyry. Flows in the upper part of the section are identified as perlitic rhyolite, dacite porphyry, rhyolite porphyry, and welded tuff; the latter is full of glassy and spherulitic rock fragments and contorted shards. Layers of dark-gray perlitic glass, also near the top of the type section, have the compositions shown in table 2, specimens 111 and 185. Glass (specimen 148) from a similar section in Gold Bug Wash is remarkably like specimen 185 in chemical composition but has no phenocrysts.

An exceptional section of the Golden Door volcanics, in the area east of Davis Dam, has considerable rhyolite in the lower part. One flow of spherulitic rhyolite vitrophyre contains sanidine, embayed quartz, and frondlike groups of crystallites, with some sphene and biotite. Several mines and prospects are in rhyolite at horizons not far above the Precambrian basement

661-325 O - 63 - 4

rocks, which in the large outcrop area west of Union Pass are cut by numerous rhyolite dikes. One of these, a striking rhyolite porphyry, includes phenocrysts of oligoclase jacketed by albite, sanidine, and quartz. Near the summit of Union Pass, a thick whitish tuff contains masses of yellow translucent opal.

A block of volcanic rocks faulted down against Precambrian gneiss several miles west of Davis Dam is indicated on the map as part of the Golden Door sequence, though some Mount Davis volcanics may be included. The lower part of the exposed section contains rhyolite breccia and tuff, which are cut by doleritic sills and irregular bodies that at a higher level seem to merge with basaltic lavas. Similar intrusive bodies of dolerite are common also in a wide belt east of Davis Dam. Directly west of Union Pass along the highway, an extensive mass of this dark rock appears to be intrusive into Precambrian rocks below the Golden Door volcanics. Between this location and the river, numerous smaller masses of dolerite cut both the Precambrian and the volcanic rocks. Probably some of these intrusive bodies represent channelways through which the Mount Davis volcanics were erupted.

The rocks exposed in the vicinity of Hoover Dam (fig. 9) were studied by F. L. Ransome for the Bureau of Reclamation, before the dam was built; and his report (U.S. Bur. Reclamation, 1950), of which only a part was printed in modified form has been available to the present writer. Ransome recognized an "older volcanic series"—the gray-brown assemblage downstream from the damsite, here called the Patsy Mine volcanics—and a "younger volcanic series," including all higher units in the sequence of volcanic rocks in the vicinity of the damsite. As Ransome noted, the coarse-grained and locally thick sedimentary unit that he called the Dam breccia shows an eastward tilt comparable to that of the underlying brown lavas, whereas the younger units have been less disturbed. Ransome's "younger series" is here correlated in part with the Golden Door volcanics, in part with the younger Mount Davis volcanics. This separation is based chiefly on lithology; the lower units of the series are definitely more siliceous than higher units, which consist largely of basalt or trachydolerite. Structural definition between the two sequences is not as distinct as in other parts of the area; evidence of some gradational overlap is discussed in later paragraphs.

The lowest and the thickest lithologic unit in the Golden Door section near the damsite is a latite flow breccia, light brown to light red brown on fresh surfaces, littered with fragments, both angular and somewhat rounded, of rock identical with that forming the matrix. This mass, making a large part of the steep canyon walls at and near the dam, ranges in thickness from 300 to more than 600 feet. Apparently its top was much eroded, and depressions so formed were filled with coarse sedimentary rubble, containing fragments as much as 6 feet long. This rubble, firmly cemented to form what Ransome called the Spillway breccia (U.S. Bur. of Reclamation, 1950, fig. 34), was in part contemporaneous with a thick flow which contributed many of the fragments. This flow, resting on the basal volcanic unit or locally on the Spillway breccia, consists of brownish aphanitic rock, with small phenocrysts sparsely distributed. Ransome commented that this rock has the appearance of andesite, but he called it "basic latite" because it has a high content of potassium. Near the head of Black Canyon, this rock interfingers with the Spillway breccia in a way that suggests a local intrusive relation.

Although the latite, with thickness locally exceeding 300 feet, is extensively distributed on both sides of Black Canyon, it is conspicuously absent over considerable areas. These discontinuities may have resulted from extrusion on a highly irregular hill-and-valley topography, with continued vigorous erosion during and after emplacement of the latite sheet. The Spillway breccia of Ransome supports this suggested history by its highly irregular thickness and also by local variations in its content from fragments representing wholly bedrock units older than the latite to a dominance of latite fragments.

A discontinuous deposit of tuff, locally as much as 200 feet thick, rests on the basic latite along the north flank of Sugarloaf Mountain. On the southwest slope, where the tuff is best displayed, the latite flow is absent, and the tuff lies on the older flow breccia. East of the dam the tuff is broken by faults, and a segment exposed beside the highway includes a layer of dark-gray perlitic glass (table 2, specimen 414).

The next unit in the section is a widespread lava sheet, 200 to 400 feet thick, diagnosed by Ransome (U.S. Bur. Reclamation, 1950, fig. 34) as "biotite latite." The fresh rock is light red to gray brown and contains conspicuous phenocrysts of biotite set in a groundmass in part aphanitic, in part glassy. The feldspar is andesine. Some oxyhornblende accompanies the more abundant biotite, and calcite pseudomorphs after the ferromagnesian minerals are present locally. At a few localities two or more flows can be distinguished, but elsewhere the sheet appears to be undivided.

Partial chemical analyses of five specimens show a range in silica content of 66 to 70 percent; yet these specimens have no visible free quartz. The analyses resemble strongly that of the underlying glass, and probably this glass and accompanying tuff repre sent the initial eruption leading to formation of the lava sheet.

The entire Golden Door section in the vicinity of Hoover Dam is complicated by irregular intrusive bodies, large and small, of a dark rock with the megascopic appearance of basalt but with chemical composition like that of trachydolerite. Some of the intrusive bodies, well exposed in the canyon walls, are ordinary dikes; others have nondescript form, with overall dimensions as much as half a mile long and several hundred feet wide. This rock contains scattered reddish specks described by Ransome as "ferruginous pseudomorphs after olivine." The trachydolerite in this vicinity resembles, in general appearance and in mode of occurrence, irregular bodies intrusive into Golden Door volcanics near Davis Dam (p. E27) and in many other parts of the map area.

The boundary between the Golden Door and Mount Davis assemblages east of Hoover Dam is not sharply defined. A coarse sedimentary deposit, named by

FIGURE 9.—Airview southeastward across Hoover Dam and eastward-dipping volcanic rocks. The Dry Camp breccia of Ransome (U.S. Bureau of Reclamation, 1950) is locally the basal member of Mount Davis volcanics. Dissected gravel deposits (top of view) accumulated in great thickness on subsiding block southwest of Horsethief fault. Golden Door volcanics exposed in canyon wall. Bench at left of Sugarloaf Mountain is mantled with Colorado River gravels, at altitude above 1,500 feet. (U.S. Bureau of Reclamation photograph.)

Ransome (U.S. Bur. Reclamation, 1950, fig. 34) the Dry Camp breccia (fig. 9), lies on the biotite latite and on local lenses of waterlaid tuff. The breccia, with thickness of as much as 200 feet, contains fragments chiefly of monzonite porphyry locally admixed with numerous fragments of basaltic rock. Thus, although some of the intrusive bodies of trachydolerite cut the Dry Camp breccia, and the section directly above is made up dominantly of basaltic flows, clearly a considerable quantity of these dark rocks was exposed at the surface while deposition of the Dry Camp breccia was in progress. In fact, a flow of the basalt lies on the biotite latite and beneath the sedimentary breccia less than a mile southeast from the east portal to the Hoover Dam area. Confused contacts among several lithologic units in a belt east of the dam probably reflect simultaneous volcanism and crustal disturbance, attended by locally rapid erosion and sedimentation. Later faulting and erosion further complicated the pattern. It seems best to include in the Mount Davis sequence Ransome's Dry Camp breccia, and also basaltic flows that locally underlie this breccia.

West and southwest of Hoover Dam, beyond the limited area studied by Ransome, the highest lavas exposed in the Golden Door section include several thick flows of rhyolite. Apparently the thickness of the section increases westward into the River Mountains, where a complex of volcanic rocks and intrusive bodies presumably represents an important eruptive center. The Boulder City pluton (p. E17), which is similar in chemical composition to the underlying lavas, probably had its origin at this general center during an advanced stage of the Golden Door igneous activity. Most of the rocks in the River Mountains block are similar to the Golden Door volcanics. Two miles north of Boulder City, a small stock of quartz monzonite has a nearly circular outcrop within a wide frame made of steeply upturned lavas that are cut by a network of dikes and irregular intrusive bodies.

North and east of Nelson the Golden Door volcanics consist chiefly of explosion breccias and tuffs in thick layers. No petrographic or chemical analyses of these pyroclastic units have been made. In that part of the area, the appearance of the light-colored pyroclastics marks an abrupt lithologic change from the underlying dark lavas in the Patsy Mine volcanics, but no structural discordance is apparent.

MOUNT DAVIS VOLCANICS

A third thick assemblage of volcanic rocks, which in many places lies with angular unconformity on the Golden Door volcanics or on older rocks, is well exposed at its type locality on and near Mount Davis, in western Mohave County, Arizona, and is here called the Mount Davis volcanics. This assemblage consists largely of lavas, commonly intercalated with coarse gravels. Although basalt and dark andesite are the most abundant kinds of volcanic rock in the formation, at some horizons sheets of glass and pumiceous tuff with compositions corresponding to latite and rhyolite are widespread. White tuffs in particular make a striking contrast with the large thicknesses of basaltic flows below and above (fig. 10). These interruptions in the section are similar to the occurrence of rhyolitic glass in the Patsy Mine sequence north of Nelson.

The following features and relations of the Mount Davis volcanics suggest crustal unrest before, during and after the period of eruptions: (1) In some places the sequence rests on Golden Door volcanics conformably, elsewhere with strong unconformity. (2) Over large areas the Mount Davis rocks lie on Patsy Mine volcanics, usually with strong unconformity. Commonly, a fault or fault zone with large throw separates blocks, in one of which the Mount Davis sequence rests on Golden Door volcanics, in the other on Patsy Mine volcanics. (3) At several localities the Mount Davis volcanics lie on Precambrian rocks, only a short distance from normal contacts of these lavas on Patsy Mine or on Golden Door volcanics. (4) In many places great quantities of extremely coarse rubble, derived largely from Precambrian bedrock, are interspersed with the Mount Davis volcanics. Several of the larger sedimentary units, exposed along important faults, have a chaotic arrangement suggesting landslides from steep scarps. (5) The exposed sections of Mount Davis rocks are tilted, commonly to dips of 30° or more; and many faults with large displacement transect these sections together with older rocks.

Where the Mount Davis rests on Golden Door volcanics, the change in lithology above the contact is abrupt, and the dark lavas in the younger unit generally continue without interruption through a large thickness. In this respect the outcrops directly north of Searchlight Ferry road and about 7 miles east of the old ferry location are somewhat exceptional. There a thick flow of rhyolite with abundant quartz phenocrysts is enclosed in dark basaltic lavas about 300 feet above the top of the Golden Door section. Above the solitary flow of rhyolite the exposed section consists wholly of dark basalt.

Marked differences among sections, both in thickness and in general composition, doubtless reflect differences in topography at times of eruption and also varying distance from eruptive centers. Thus at

Mount Davis the lower part of the section, overlying Golden Door volcanics with slight angular discordance, consists of dark basalt flows hundreds of feet thick. Both units dip steeply westward (pl. 1). This general relation continues along the strike through several miles northward, though in Gold Bug Wash the angular discordance is more pronounced and a layer of coarse conglomerate 10 to 12 feet thick underlies the basal flow of the Mount Davis. Five miles farther northeast, along Pope Wash, the Golden Door section is absent; and the Mount Davis volcanics lie directly above Patsy Mine volcanics, both major units dipping steeply eastward though with noticeable angular discordance. The following section is exposed:

Mount Davis volcanics and Brown Patsy Mine volcanics in upthrown block east of large north-south fault

Mount Davis volcanics (partial thickness) in downthrown block; lavas and beds dip 30° E. Nine units recognized as follows:

	Feet
Basalt flows, brownish	100
Gravel, bedded, very coarse, weakly cemented. Pebbles of Precambrian and volcanic rocks	60
Andesite and basalt, dark-gray, in flows 15 to 40 ft thick	250
Gravel, bedded, coarse, with pebbles and angular blocks of Precambrian and volcanic rocks	75
Basalt flow, brownish	25
Coarse sedimentary debris in crude beds, weakly cemented. Blocks, as much as 5 ft long, of Precambrian and volcanic rocks	300
Andesite flows, gray-brown, alternating with beds of coarse gravel	100
Andesite and basalt flows, gray-brown, many weathering to rubble of blocks and sand-size particles	650
Basalt and andesite flows, 15 to 40 ft thick, alternating with beds of gravel and gray silt	250

Unconformable contact.

Brown Patsy Mine volcanics, dipping 25° to 40° E. Large thickness.

The total of the above measurements, 1,810 feet, probably is much too small for the tilted section, which is 1½ miles in width of outcrop. Correction was made for duplication by strike faults; but there are no confident key horizons for use in tracing faults and matching accurately between blocks. At any rate, this section is incomplete; its base probably is above the base of the sequence at Mount Davis as explained below; and the upper part, with unknown thickness, has been eroded from the hanging wall of the large fault on the east. Other belts of outcrop in the general area present similar difficulties; nearly all are broken by faults, and the top of the Mount Davis assemblage in its typical development was nowhere certainly identified. But several partial sections appear to be fully 3,000 feet thick, and maximum thicknesses may well exceed 4,000 feet.

FIGURE 10.—Three units of volcanic rocks north of Nelson. View looking northeast. Light-colored breccia and tuff, left foreground, is in upper member of Golden Door volcanics. Thick section of overlying Mount Davis volcanics is largely basaltic but includes layers of whitish tuff. Horizontal Fortification basalt member of Muddy Creek formation forms mesa cap in middle background about 2 miles from camera.

Some of the best exposures of the Mount Davis volcanics are in the rugged hill country about 5 miles north of Nelson, where valleys with steep walls run nearly at right angles to the strike (fig. 10). There the basal flows of dark basalt are nearly conformable to the yellow-white tuff and breccia of the Golden Door volcanics. As at Mount Davis the lower part of the younger unit consists chiefly of basalt and dark andesite flows. Dikes that cut the section of flows represent feeding channels that supplied magma for numerous sills of dark porphyry, and probably also for flows at higher levels. Above the middle of the section, layers of white pumiceous tuff contrast sharply with the dark lavas. One of these old ash beds is the basal member of a tripartite unit, highly distinctive, which recurs in widely separated localities; the most extensive outcrop is under Glass Plateau, a few miles south of Hoover Dam.

The section north of Nelson (fig. 10) is very thick, though large strike faults and the lack of key horizons make an exact measurement impossible. An estimate of the thickness, from the base to the large fault cutting off the outcrop on the east, is 3,200 feet, of which the lower 2,200 feet consists almost wholly of volcanic rocks and related sills, whereas in the upper 1,000 feet large quantities of coarse sedimentary debris are interspersed with lavas. This higher part of the section is generally like the complete sequence measured near Pope Wash; the lower part, made almost strictly of volcanic rocks, is like the sequence from Mount Davis northward. But the higher part of the section west of Mount Davis also includes many thick beds of coarse-grained sediment. The isolated ridges west of the river at that latitude are tilted fault blocks in which the bedrock consists of typical basalt and andesite flows of the Mount Davis volcanics, interspersed with beds of coarse conglomerate and breccia. Some of the sedimentary debris exhibits the disordered arrangement characteristic of landslide masses, and the fragments were derived almost entirely from Precambrian bedrock. Presumably the source was the Eldorado Mountain block, against which the Mount Davis volcanics are downfaulted. The abundant rubble intercalated with the lavas suggests that the fault was active in Mount Davis time.

Along Pope Wash and at several other localities, the coarse-grained sediments in the Mount Davis sequence extend from the base upward; such sections perhaps correspond mainly to the higher member in the general assemblage. In Pope Wash the layers of sedimentary breccia thicken and coarsen northward toward an area of Precambrian bedrock north of the Pope fault. Rock types represented in the conglomerate are largely Precambrian, in part volcanic rocks including basaltic lavas like those in the Mount Davis sequence. This evidence regarding provenance, found in several similar sections, suggests that the Mount Davis volcanism occurred while faulting was active. The thickest sections of lavas accumulated on blocks that were relatively sinking. Rising blocks were subject to rapid erosion, and the resulting debris, derived partly from lavas, partly from older bedrock, was deposited in maximum thicknesses near the borders of the positive blocks. During recurrent volcanism some of the lavas buried slope gravels, and in favored locations the alternating sedimentary and volcanic record has been preserved. Abrupt appearance of coarse sediments in a distinct upper member, as in the section north of Nelson, may signify the resumption of active faulting near the border of a subsiding block on which a large thickness of volcanic rocks previously had accumulated.

The widest belt covered with Mount Davis volcanics is west of the river and extends several miles southward from Glass Plateau. Within this belt the prevailing dips are eastward, in many places at a steep angle, through a distance of 5 or 6 miles. The impression of great thickness is strong, though strike faults with large throw have caused much duplication. Lavas make up the greater part of the section, and lack of key horizons defeats efforts to map most of the faults continuously or to reckon accurate thicknesses and displacements. Another outcrop area, as much as 4 miles across the average strike, lies west of the river and north of Eldorado Wash. There the dip is generally eastward, above a base that along its outcrop bevels strongly across the Patsy Mine volcanics onto the Precambrian basement. This relation suggests accumulation on or bordering a rising upland; and this suggestion is reinforced by the quantities of coarse sedimentary breccia interspersed through the section of lavas. Probably this area is crossed by strike faults not shown on the map, and no estimate of the thickness is now possible. Directly northeast of the area, several faults of larger throw are conspicuous because of the contrast between the dark Mount Davis volcanics and underlying whitish tuffs and breccias in the Golden Door section.

A short distance farther north, directly west of Malpais Mesa, the Mount Davis volcanics again rest directly on the brown Patsy Mine volcanics, both units dipping steeply to the east. In that vicinity the Mount Davis section has particular interest for two reasons: from a composition dominantly of basaltic lavas near the southwest corner of the mesa there is gradation northward into a section with quantities of very coarse sedimentary debris; and the section grades upward, without detectable break, into tan siltstones that appear to be part of the Muddy Creek formation. A steep-walled valley leading to the river from the western slope of the mesa shows the following succession:

	Thickness (feet)
Siltstone, cream-yellow, with some thin-bedded clay, apparently part of Muddy Creek formation; grades downward into layers that have many pebbles and scattered angular cobbles; dip 12° to 15° E	100+
Conglomerate beds, coarse; many of the pebbles angular; Precambrian and volcanic rock types represented; dip increases downward in section to about 30° E	110
Limestone, gray, single layer, aphanitic	1
Conglomerate beds, coarse; dip increases downward to about 45° E	75
Breccia, extremely coarse sedimentary; bedding crude or in part lacking; contains many blocks of gneiss 100 to 200 ft long, shattered but intact; probably of landslide origin	480
Basalt flows with iddingsite, dark; abrupt contact with sedimentary layers above and below; dip 50° E	300
Breccia, very coarse sedimentary, in part crudely bedded. Much of it, with no perceptible bedding, contains blocks of gneiss 10, 20, and 30 ft long	800±
Breccia, volcanic, lavender-gray	45
Breccia, sedimentary; fragments largely of volcanic rocks but some of gneiss	300
Breccia, massive, sedimentary; blocks chiefly of Precambrian gneiss	100
Breccia, bedded, sedimentary; fragments largely of volcanic rocks	225
Breccia, massive, sedimentary; blocks chiefly of Precambrian gneiss	150

Breccia, bedded, sedimentary; fragments of volcanic rock with several thin layers of tuff interspersed	100
Basalt flows with iddingsite, brown; interlayered with coarse sedimentary breccia containing fragments of gneiss and of volcanic rocks; dip 55° E	200
Slight unconformity.	
Patsy Mine volcanics, dipping steeply eastward.	

The northward increase in coarse sediment, much of it unassorted breccia containing blocks of Precambrian rock tens of feet long, suggests that the faults bounding the Precambrian block west and south of Willow Beach were active while Mount Davis volcanism was in progress. Flows that accumulated in large thickness in the area southwest of Malpais Mesa thinned and wedged out northward against an aggrading slope adjacent to the rising block of basement rocks. The abundant coarse rubble that recurs through a thick section testifies to a south-facing scarp that was renewed time after time by faulting.

Southeast of Hoover Dam a peculiar glassy member that elsewhere is recognized high in the Mount Davis volcanics lies only a few hundred feet above the base; therefore, the total thickness is comparatively small in that vicinity. In the southern part of the map area, the section of dark lavas is very thick, though it was not studied in detail. A few miles north of Union Pass these lavas, resting on Golden Door volcanics, dip steeply northeastward, and the belt of outcrop extends east of the area mapped. Northeast of the Portland Mine and west of a large fault, glassy rocks that belong high in the Mount Davis assemblage lie on brown Patsy Mine volcanics. In view of the thick Golden Door section a short distance northeast of and dipping toward this fault, presumably there was important displacement during as well as after the Mount Davis volcanism.

Two miles northwest of Davis Dam, a block of dark lavas interlayered with coarse conglomerate, apparently part of the Mount Davis, is faulted against Precambrian and Golden Door bedrock. Dikes, sills, and irregular intrusive bodies of basalt and andesite in that vicinity probably are related to the Mount Davis volcanics.

Although the lavas of the Mount Davis volcanics are predominantly dark and are properly described as basaltic, flows of dark-gray andesite make up considerable thicknesses, and an exhaustive study would be required to determine the relative proportions of basalt and andesite. A random specimen from the lower part of the type section near Mount Davis shows in thin section the following features:

No. 146. Glassy basalt. Dark groundmass, in large part glassy. Many minute grains of pyroxene. Abundant olivine, altered marginally to iddingsite.

Similar rock, dark brown in many flows, is abundant in the wide area of outcrop 8 to 9 miles south-southeast from Boulder City. A sample thin section is the following:

No. 168. Brown amygdaloidal basalt. Dark, glassy groundmass. Labradorite has outer zones crowded with glass inclusions. Much olivine, in part altered to iddingsite and serpentine. Some grains of pigeonite. Amygdales consist largely of zeolites.

Many of the dark flows are glassy in such degree that little or no feldspar can be identified in thin section. Two specimens from the vicinity of Square Butte, one of them a flow directly overlying a layer of pumiceous tuff, can be diagnosed simply as glassy olivine basalts, with iddingsite and minor pigeonite and biotite. These aphanitic dark-gray to nearly black specimens are common in large thicknesses of the Mount Davis assemblage.

On the other hand, some gray flows are identified as andesites, even on megascopic examination. A specimen collected northwest of Davis Dam has the following thin-section description:

No. 374. Groundmass of fine grain, rich in andesine. Some grains of pigeonite, augite, and magnetite masking biotite.

Gray rock similar to this makes up many of the flows that are interlayered with conglomerate, along Pope Wash and also in the area of outcrop 2 to 3 miles south of Square Butte. Flows with this lithology are not resistant to arid-climate weathering; many outcrops are partly masked by heaps of disintegrated rock, much of it in sand-size particles.

Glassy rocks with high content of silica make a subordinate but conspicuous part of the Mount Davis sequence. Two eruptive centers for this glassy material are conspicuous: one nearly 5 miles north of Nelson and the other directly south of Square Butte. At each of these localities, plugs made of glassy agglomerate cut across the underlying lavas, which are steeply upturned and disrupted through a radius of a quarter of a mile or more. Layers of pumiceous tuff and dark glass are particularly thick around the centers of eruption. At both localities much of the glassy section was strongly upturned and broken before it was covered discordantly by flows of dark basalt. These relations may suggest successive eruptions from a source of highly siliceous magma, followed by resumption of effusions low in silica. But more probably the glassy materials were erupted incidentally at a few isolated centers, while the more mafic lavas continued to be poured out in the general area.

The plugs of glassy agglomerate were moved appreciably as solid units. Their outer surfaces are strongly slickensided and show vertical striae and flutings, and the agglomerate is much fractured. No doubt the siliceous magma stiffened rapidly on nearing the surface, at least when activity was waning, and each congealing plug was driven upward by pressure from the magma chamber. The two plugs at the Square Butte center were punched up through whitish porcelaneous glass. Three or four hundred feet south of these plugs, a mass of brecciated glass 250 feet long and more than 100 feet wide was driven up through thick layers of glass which locally are vertical or dip steeply westward, in overturned attitude.

At a distance from eruption centers, where a glassy section may be seen in normal order, generally the basal part consists of nearly white pumiceous breccia and tuff, including some fragments of basalt, the layer totaling 10 to 100 feet in thickness. Above this is compact glass, in part brecciated, much of it dark gray or nearly black in bulk, though transparent and almost white on thin edges. Some sections have successive irregular layers with colors ranging through brown, red, orange, yellow, and other colors. Many of the glasses have phenocrysts, but some are glassy throughout.

A high content of silica appears to be characteristic of the glasses in the Mount Davis volcanics. Of seven specimens analyzed (table 2) the lowest in silica came from the section 5 miles north of Nelson, high in the thick member of lavas but below the member containing coarse sediments.

One glassy unit high in the sequence of Mount Davis volcanics is remarkably widespread and is characterized by a persistent combination of features. The upper member of the unit forms the cap of Glass Plateau, and cliffs at the south rim of that plateau show the full makeup of the unit, as follows:

	Feet
Felsite or "stony glass," chocolate-brown	60–100
Perlitic glass, black	20–40
Coarse breccia, fragments of black glass and gray pumice	10–15
Tuff and breccia, white, pumiceous	20–60
Flows of basalt and andesite, thick section.	

Exposures along a wash 3 miles southeast of Hoover Dam and east of the highway show:

Cemented gravels of Muddy Creek(?) formation.
Unconformity.

	Feet
Basalt with iddingsite, vesicular	25
Felsite, chocolate-brown	50
Perlitic glass, dark-gray to black, locally replete with brownish spherical bodies 2 to 3 in. in diameter	10–40
Tuff and breccia, gray, containing large angular blocks of pumice	50–200

Irregular contact.
Basalt flows, brown to blackish.

TABLE 2.—*Chemical analyses of 13 volcanic glasses*

[Rock Analysis Laboratory, University of Minnesota. Eileen Oslund, Analyst]

Lab. specimen	R1542	R1543	R1536	R1537	R1538	R1546	R1539	R1540	R1541	R1544	R1545	R1547	R1548
Original No.	307	311	111	148	185	414	207	297	298	345	350	421	424
SiO_2	76.19	72.21	69.40	73.93	73.93	65.86	66.85	71.55	70.94	72.91	73.65	72.40	79.46
Al_2O_3	12.62	12.34	13.62	12.09	12.46	15.18	15.25	13.50	13.41	12.53	12.78	12.94	10.57
Fe_2O_3	.68	.59	.99	.52	.55	1.99	1.26	.80	1.12	.43	.78	.73	.64
FeO	.14	.18	.63	.26	.30	.80	.57	.28	.03	.30	.09	.16	.09
MgO	.13	.12	.46	.18	.16	1.12	.46	.24	.34	.13	.19	.34	.17
CaO	.79	.97	1.31	.81	.75	2.86	1.38	1.02	1.42	.69	.79	.79	.68
Na_2O	4.23	3.33	2.94	3.23	3.21	3.52	3.90	3.58	3.44	3.67	3.49	3.27	2.92
K_2O	3.32	4.16	5.33	4.46	4.74	3.83	5.74	5.02	5.00	4.52	4.58	4.99	4.16
H_2O+	1.04	4.75	4.50	3.77	3.34	3.19	3.53	3.06	3.08	3.99	2.96	3.35	.45
H_2O-	.54	1.00	.21	.32	.16	.49	.18	.26	.31	.24	.20	.40	.20
TiO_2	.11	.12	.30	.12	.15	.42	.41	.18	.18	.13	.11	.13	.12
P_2O_5	.01	.01	.07	.01	.01	.18	.07	.03	.03	.01	.01	.01	.02
MnO	.03	.05	.04	.04	.04	.06	.06	.06	.06	.04	.05	.05	.04
Total	99.83	99.83	99.80	99.74	99.80	99.50	99.66	99.58	99.36	99.59	99.68	99.56	99.52

Specimen	*Description and locality*
307.	Uniform glass with no phenocrysts, from glassy member in Patsy Mine volcanics, in ridge east of Welcome fault and 1 mile northwest of Techatticup mine, Eldorado district, Nevada. Specimen is one of many brownish spheroids, with diameters 1–3 in., more resistant than enclosing glassy matrix.
311.	Uniform glass, no phenocrysts, from glassy matrix enclosing specimen 307.
111.	Glass, dark-green to black, forming layer 25 ft thick in Golden Door volcanics, about 500 ft below base of Mount Davis volcanics, directly north of Searchlight Ferry road, Arizona, about 7 miles east of Colorado River. Small phenocrysts in sample.
148.	Nonporphyritic glass, light-gray, from thick glassy unit in Golden Door volcanics at Gold Bug Wash, about 2 miles east of Colorado River.
185.	Glass, dark-gray, with whitish phenocrysts, from Golden Door volcanics in wash 1½ miles west of Golden Door mine, Arizona.
414.	Perlitic glass in Golden Door volcanics, half a mile northeast of Sugarloaf Mountain, at east side of large loop to south in road leading east from Hoover Dam.
207.	Glass, dark-gray to black, from layer high in Mount Davis volcanics, on west side of Welcome fault near north end of the fault as exposed.
297.	Porphyritic glass, dark-gray, in upper part of Mount Davis volcanics, east of highway and 2 miles (straight map distance) southeast of Hoover Dam. Glass layer is below thick section of brownish felsite and above thick pumiceous tuff-breccia.
298.	Glass, reddish-brown, from block in tuff breccia below glass layer of specimen 297.
345.	Glass, dark-gray, from eruptive center in Mount Davis volcanics south of Square Butte, from layer steeply tilted away from plug of agglomerate, has no phenocrysts.
350.	Glass, light-brown, from layer directly below basaltic lavas of the Mount Davis volcanics, at east side of eruptive center south of Square Butte.
421.	Glass, dark-gray, from layer directly below brown felsite, half a mile southeast of Three Kids mine. Glass overlies pumiceous tuff.
424.	Brown felsite above glass layer, locality of specimen 421. The assemblage resembles that in upper part of Mount Davis volcanics.

South of Las Vegas Wash, near the Three Kids manganese mine, the following sequence is at the top of a thick section of volcanic rocks:

Muddy Creek formation.
Angular unconformity.

Felsite, chocolate-brown, porphyritic; in thick flows	200±
Perlitic glass, black; in part thin banded	50
Tuff and breccia, with large blocks of pumice	100+
Thick lavas and volcanic breccias.	

Many other exposures of these distinctive glassy rocks range at least as far south as the latitude of the Portland Mine. Hunt (written communication, 1941) reported a similar glassy unit east of the Black Mountains and north of the Colorado River, at a location more than 60 miles from the Portland Mine. Presumably, therefore, this unit of the Mount Davis volcanic records a volcanic episode that affected a very large area. Although the unit is in general conformable within the Mount Davis, there are several local departures from this relation. Three miles southeast of Hoover Dam, the irregular contact between the glassy unit and underlying basalt appears to be an erosional unconformity. Along the north edge of Glass Plateau, the glassy unit lies on intrusive rocks apparently older than any part of the Mount Davis assemblage. Near the Three Kids Mine, the lavas directly beneath the glassy unit consist of latite and more siliceous rock types and apparently belong to the Golden Door sequence. This varied relation merely strengthens the conclusion, based on other evidence cited above, that crustal movements and local erosion were pronounced while the Mount Davis volcanism was in progress.

Comparison of three specimens (297, 298, 421) by chemical analyses given in table 2, shows the high content of silica in these similar units of glass. Specimen 424, the felsite directly above specimen 421, is abnormally high in silica, some of which may be secondary.

A study of nine glass specimens containing phenocrysts for thin-section examination gave the results summarized in figure 11. Six of the glasses (207, 297, 298, 350, 421, 424) are from the Mount Davis volcanics and are closely comparable to the Golden Door glass (185) that is highest in silica. A perlitic glass (414) from latite in the Golden Door volcanics near Hoover Dam has a rather distinctive composition.

VOLCANIC ROCKS OF MUDDY CREEK FORMATION

Although the volcanic rocks in this assemblage are part of the Muddy Creek formation, they merit separate treatment as a fourth major division in the record of volcanism within the map area. Basalt flows locally interlayered with clastic sediments in the basal member of the formation, as at the Three Kids mine (p. E10), probably represent closing stages of the volcanism that produced the Mount Davis volcanics. Widespread sheets of basaltic lavas in the upper part of the Muddy Creek formation indicate renewal of volcanic activity after a considerable interval of time. A remnant of these lavas forms the cap of Fortification Hill, which has an area of nearly 2 square miles. In the thickest part of this prominent residual, about 50 superposed flows of olivine basalt have a combined thickness of 500 feet.

Other large remnants of similar basalt in the map area appear to represent a widespread cover that once was continuous over hundreds of square miles. Some remnants are conformable on sedimentary beds that probably belong in the Muddy Creek formation; other remnants lie unconformably on older rocks. The largest known remnant, covering more than 10 square miles, lies east of the Black mountain divide.

Because of its prominence and distinctive lithology, this upper unit in the Muddy Creek formation is mapped separately as the Fortification basalt member (table 1).

Vigorous local erosion in early Muddy Creek time, as indicated by coarse sediments of highly varied thickness, suggests active faulting in the closing phases of Mount Davis volcanism. Basalt flows in these basal deposits of the formation are succeeded by layers of andesite tuff and tuffaceous sand, which indicate that the Mount Davis volcanism closed with explosive eruptions from reservoirs in which the magmas had become less mafic. There followed a lull in volcanic activity, as indicated by nearly 2,000 feet of sandstone, siltstone, clay, and saline materials in which no volcanic rocks have been observed.

The thick and uninterrupted succession of basalt flows resting on an equally thick sedimentary sequence, both in Fortification Hill and in Malpais Mesa, suggests that the flood of lavas in late Muddy Creek time began abruptly and continued rapidly. Although no Muddy Creek deposits now cover the cap of Fortification Hill, the base of the lava sequence is conformable on the beds below. Northwest of the hill the lavas have been downfaulted and tilted northward; and north of Boulder Basin a closely similar but thinner section of basaltic flows, tilted gently southward, is included in the Muddy Creek sedimentary sequence. Study of this basin before Lake Mead was formed led to correlation of the basalts of the Fortification Hill area with the uppermost of those exposed north of the lake (Longwwell, 1936, p. 1421).

In the vicinity of Lake Mead, therefore, the Fortification basalt member, as here defined, is part of the

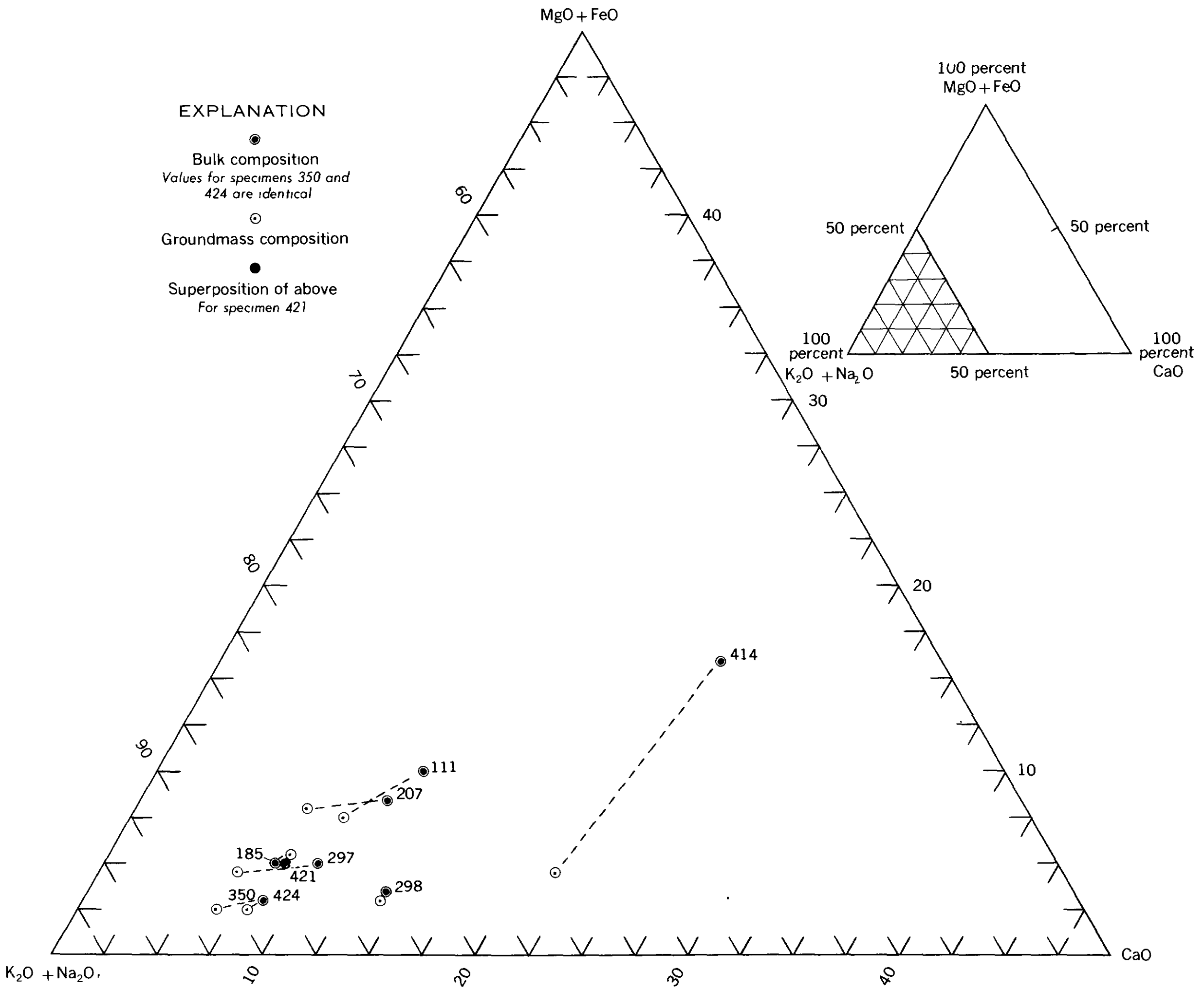


FIGURE 11.—(K_2O+Na_2O), $(FeO+MgO)$, CaO ratios in nine porphyritic volcanic glasses, plotted from data in table 3.

Muddy Creek formation. At Malpais Mesa the thick cap of basaltic flows is conformable on beds that resemble Muddy Creek deposits; but no sedimentary layers now cover any part of the cap. Remnants of basalt forming tops of small buttes in the area mapped as Muddy Creek formation east of Willow Beach are logically correlated with the lavas on Malpais Mesa and Fortification Hill. Other residuals south of Lake Mead rest on varied types of older rock and in themselves give no hint of any relationship to the Muddy Creek. Several of the larger remnants, lying with strong angular unconformity on tilted Mount Davis

TABLE 3.—*Bulk composition versus groundmass composition* [1] *in nine volcanic glasses, in percent.*

[Philip Orville, analyst]

Specimen	SiO_2		Al_2O_3		FeO	MgO	CaO		Na_2O		K_2O		Volcanic unit [2]
	Bulk	Ground-mass	Bulk	Ground-mass	Bulk	Ground-mass	Bulk	Ground-mass	Bulk	Ground-mass	Bulk	Ground-mass	
111	69.40	70.57	13.62	12.61	1.09	0.75	1.31	0.96	2.94	2.40	5.33	5.69	G.D.
185	73.93	74.63	12.46	11.85	.46	.47	.75	.75	3.21	3.14	4.74	4.26	G.D.
414	65.86	69.19	15.18	12.99	1.92	.46	2.86	2.13	3.52	2.85	3.83	4.50	G.D.
207	66.85	67.70	15.25	13.87	1.03	.92	1.38	.92	3.90	3.51	5.74	5.97	M.D.
297	71.55	72.85	13.50	12.40	.52	.44	1.02	.63	3.58	2.98	5.02	5.58	M.D.
298	70.94	71.69	13.41	12.69	.37	.27	1.42	1.37	3.44	3.14	5.00	4.96	M.D.
350	73.65	74.46	12.78	12.05	.28	.24	.79	.55	3.49	3.28	4.58	4.87	M.D.
421	72.40	73.12	12.94	12.32	.50	.49	.79	.75	3.27	3.12	4.99	4.67	M.D.
424	79.46	80.07	11.57	11.29	.26	.21	.68	.62	2.92	2.82	4.16	4.14	M.D.

[1] Groundmass composition is the difference between the bulk chemical composition and the chemical composition calculated for the phenocrysts.

[2] G. D., Golden Door volcanics, M. D., Mount Davis volcanics.

volcanics, form prominent mesas in a wide area between Nelson and Glass Plateau (fig. 10). A smaller but equally conspicuous residual makes the cap of Square Butte. East of Willow Beach an elongate remnant of basaltic lava rests on Precambrian rocks and extends from the summit of the Black Mountain block to U.S. Highway 93 (pl. 1). The largest residual, several miles south of Boulder Canyon, is closely associated with large basaltic dikes.

There is no positive proof that all these remnants represent one and the same sequence of lavas, but inference of this relation is very strong. All consist of vesicular or amygdaloidal olivine basalt, in individual flows that are thin or of moderate thickness. In all remnants the flows are nearly horizontal or dip gently; the steepest dip, about 10°, is in the large residual mass east of Willow Beach and is readily explained by some tilting of the Black Mountains block in post-Pliocene faulting. Altitudes at the bases of some remnants differ as much as a few hundreds of feet; but topographic relief in Muddy Creek time must have been considerable, and there has been later deformation by faulting and warping (p. E10). In a logical reconstruction the flows of the Fortification basalt member, as they appeared west of the Black Mountains before their dissection by the Colorado River drainage, would form a thick and continuous sheet extending at least 30 miles from north to south, 10 to 15 miles from east to west, overlapping both rims of the present river valley and with the top of the sheet at an average height at least 2,500 feet above the present river channel. Wide extension of the flows across older rocks bordering the basins of sedimentary deposition indicates that upland sources of sediments had been reduced to moderate relief.

The lavas of the Fortification member range in color from nearly black through gray brown to dark brown. Some flows have numerous small vesicles, irregular in form; others have rounded vesicles with diameters as much as three-quarters of an inch, many filled with white amygdales made of zeolites. Most of the rock is glassy olivine basalt, in which the olivine is considerably altered to serpentine and iddingsite. Some hand specimens show conspicuous aggregates, as much as half an inch long, made up wholly of olivine; others have large grains of plagioclase crowded with glass inclusions. In Fortification Hill a few layers of dark-brown slaggy tuff are included between flows. The only layers of sedimentary material seen in any section of the lavas are local lenses of conglomerate near the base of the section at the southeast corner of Fortification Hill.

Probably the lavas of the Fortification member were erupted in large part from fissures. Many dikes of dark basalt transect the Mount Davis and older rocks, and such dikes are conspicuous in a considerable area adjacent to Kingman Wash. But one central vent is marked by a plug, about 300 feet in diameter, etched into relief by erosion near the highest part of Fortification Hill. Near this plug are numerous brown slaggy bombs, which, with enclosing scoriaceous tuff, indicate some localized explosive activity in addition to widespread eruption of lavas.

COMPARISON WITH ADJACENT AREAS

Ransome (1907), Lee (1908), and Schrader (1909) gave brief and generalized descriptions of volcanic rocks in parts of the area here considered. All were limited to hasty and scattered field observations in rapid reconnaissance. In an area covering more than 6,000 square miles, Schrader recognized three general assembages which he designated from oldest to youngest: (1) chloritic andesite; (2) undifferentiated andesites trachytes, rhyolites, and latites; (3) basalt. Ransome (1923a) later studied in some detail the geology of the Oatman mining district, Arizona, in the Black Mountains about 10 miles south of Union Pass. His classification of volcanic rocks exposed within an area of about 75 square miles is shown in table 4. Lausen (1931), in a later study of the district, adopted Ransome's volcanic sequence with little change.

The geologic map of the limited area centering at Oatman is more detailed than any part of the map in the present report. Ransome (1923a) and Lausen (1931) recognized more lithologic units than does the present report, and they applied to each unit a precise petrologic designation. But Ransome noted that attempts to distinguish among andesite, trachyte, and latite present difficulties because these kinds of rock grade almost insensibly one into another. Moreover, widespread alteration, perhaps caused by ore-bearing solutions, has obscured the original nature of many flows in the Oatman section, making exact classification impossible. Finally, Ransome's succession at Oatman is incomplete; the upper part of the eastward-dipping section lies beyond the eastern boundary of his map. For several reasons, then, correlation of the volcanic rocks near Oatman with the sequences only a moderate distance to the north is more difficult than might be expected.

Probably the Oatman andesite and the two underlying units of trachyte correspond in a general way to the Patsy Mine volcanics. Largely on the basis of megascopic examination, brown andesite seems predominant in the latter unit, but detailed petrographic study may show that much of the rock is trachyte. Ransome's descriptions (1923a) indicate a wider variety of colors in his three lower units than

TABLE 4.—*Volcanic rocks of Oatman district, Ariz.*

[Summarized from F. L. Ransome (1923a)]

Unit	General character	Thickness (feet)	Probable equivalence
Basalt	Basaltic lavas, rich in olivine	0–1, 000	Fortification basalt member of the Muddy Creek formation.
	—Angular discordance—		
Cotton rhyolite	Glassy lavas, in part spherulitic	500–600	Golden Door volcanics.
Sitgreaves tuff	Pumiceous tuff, cream	200–300	
Meadow Creek and Flag Creek trachyte.	Lavas, reddish-brown with local development	250±	
Gold Road latite	Complex assemblage of lavas and tuffs. Lavas have abundant grains of biotite and feldspar. Considerable rhyolite included.	3, 000–4, 000	
	—Conformable contact—		
Oatman andesite	Lavas, greenish-gray, in part porphyritic; considerably altered	800–2, 700	Patsy Mine volcanics.
Esperanza trachyte	Lavas, reddish-brown, with local distribution	0–1, 000	
Alcyone trachyte	Flows of gray lava, in part porphyritic. Locally altered, greenish; some gray shale in upper part.	1, 000–2, 800	
Bedded breccia	Fragments derived from Precambrian and volcanic rocks. Has of shale and sandstone.	100–200	
	—Unconformity—		
Precambrian complex	Gneiss, schist, and granite.		

is evident in the Patsy Mine volcanics, but this difference may reflect more extensive chemical alteration in the Oatman district than farther north. In favor of the suggested correlation are (1) similar average composition of the two assemblages, near or identical with that of andesite; (2) location in the lower part of each section; (3) similar maximum thickness—5,000 to 6,500 feet.

Neither Ransome nor Lausen mentioned, as occurring below the top of the Oatman andesite, any lavas with high content of silica such as the spherulite-bearing rhyolite within the Patsy Mine section near Nelson (p. 19). A distinctive unit of this kind, if it were widely distributed, would be useful in attempts at correlation.

Ransome's (1923a) Gold Road latite, marking an abrupt and enduring change in composition of lavas, is similar in many ways to the latite section in the Golden Door sequence at Hoover Dam. At the latter locality the latite is strongly unconformable on the older andesite; but this is not the invariable relation between the Golden Door and Patsy Mine units (p. E20). Lausen (1931) described the colors of the latite near Oatman as dark to light gray, lavender, and light brown; he stated that the typical rock has well-developed phenocrysts of feldspar, sparkling flakes of biotite, and some pyroxene, and that in thin section the predominant feldspar is recognized as andesine, and orthoclase is conspicuous. These descriptions apply well to the Black Canyon latites. Although no complete chemical analyses of the typical latite near Hoover Dam are available, perlitic glass in the section east of the dam is strikingly like some of the latite near Oatman, as shown in the following table:

TABLE 5.—*Comparison of chemical compositions of two volcanic rocks*

	(1)	(2)
SiO_2	65. 86	62. 96
Al_2O_3	15. 18	15. 36
Fe_2O_3	1. 99	2. 57
FeO	. 80	2. 09
MgO	1. 12	2. 50
CaO	2. 86	4. 26
Na_2O	3. 52	3. 84
K_2O	3. 83	3. 96
H_2O+	3. 19	1. 37
H_2O-	. 49	. 23
TiO_2	. 42	. 72
P_2O_5	. 18	. 28
MnO	. 06	. 04
Total	99. 50	100. 18

1. Perlitic glass beside highway, a quarter of a mile (in straight line) southeast of Hoover Dam. Analysis by Univ. of Minnesota Rock Analysis L boratory.
2. Latite 1 mile southwest of Sunnyside mine, Oatman District, Arizona. Analysis by R. C. Wells, U.S. Geol. Survey.

Because of these similarities, Ransome's Gold Road latite may be correlated with the lower part of the Golden Door volcanics, which in the type section has a considerable thickness of flows resembling the latite of Black Canyon. The trachyte, tuff, and rhyolite above the Gold Road unit also are correlated with the Golden Door volcanics, and perhaps considerably more rhyolite higher in the section lies east of Ransome's (1923a) map area. Therefore the Oatman section as described by Ransome (1923a) and Lausen (1931) may omit much of a sequence equivalent to the Golden Door volcanics, and all the Mount Davis volcanics.

The highest volcanic unit recognized by Schrader, Ransome, and Lausen consists of olivine basalt in flows that are nearly horizontal and unconformable to older volcanic rocks. Schrader (1909), in his generalized map covering much more than a square degree, included in one category flows probably equivalent to the Fortification basalt member of the Muddy Creek formation and others, much younger, enclosed by Quaternary(?) gravels. The basalt mapped near Oatman occurs in remnants at a high altitude, and both in composition and in mode of occurrence it is strongly suggestive of the Fortification basalt member.

PLEISTOCENE(?) IGNEOUS ROCKS

Flows of basalt and several mafic dikes are associated with weakly cemented gravels in a limited area 6 to 8 miles southeast of Hoover Dam. The outcrops of basalt are erosion remnants of sheets, originally of small or moderate extent, that were erupted on the alluvial slope west of the Black Mountains and at least in part buried as the coarse fan debris continued to build up. In more recent dissection by washes tributary to the Colorado River, the sheets have been more or less laid bare and cut away. Steep cliffs at the edges of some remnants show well-developed columnar structure. The sheets, about 20 feet in greatest thickness, consist of slaggy rock at the top, vesicular rock extending downward through 3 or 4 feet, and a varied thickness of compact basalt grading into vesicular rock at the base. On fresh surfaces the rock is nearly black. Thin sections show a groundmass aphanitic to glassy, small laths of labradorite, and scattered grains of olivine, pyroxene, and magnetite. Composition is virtually uniform in all the flows.

Near the flows of basalt several camptonite dikes cut the deposits of weakly cemented slope gravels. Campbell and Schenk (1950, p. 672) mapped three general lines of the dike outcrops, all discontinuous and with some abrupt offsets in strike. The area including these outcrops extends about 2 miles from north to south and has maximum width of about 1,500 feet. The dikes have a northward trend, with a range in strike from N. 20° W. to N. 25° E.; the easternmost of the three lines has an average direction slightly east of north. Thickness of the dikes ranges from 2 to 6 feet; in dip the average is near vertical, with extreme variations from 65° E. to 75° W. Probably the best single exposure is in the east wall of a deep artificial cut along U.S. Highway 93, 8 miles southeast of the dam in a straight line or nearly 9 miles as measured along the road. The dike is essentially vertical, has a nearly uniform thickness of about 4 feet, and cuts rather evenly across the coarse fan deposit in which there is little suggestion of bedding. Numerous phenocrysts of black amphibole in the middle of the dike are 2 to 4 inches long, but the size decreases outward to small fractions of an inch, and no phenocrysts are present in the chilled margins. Many vesicles in the marginal parts of the dike, elongate parallel to the walls, suggest light overburden at the time of emplacement.

The groundmass of the dike is largely microaphanitic and encloses crystals of somewhat altered olivine, as much as half an inch in diameter, together with scattered small grains of calcic andesine, magnetite, and apatite. Sporadic grains of quartz are probably xenocrysts derived from the fan deposits or other rocks cut by the dike. According to Campbell and Schenk (1950, p. 683), the crystals of amphibole, which on fractured surfaces resemble obsidian, appear to be kaersutite or a near relative. One chemical analysis of the dike rock shows 42.26 percent SiO_2, slightly higher than the average of 40.70 percent for camptonites listed by Hatch, Wells, and Wells (1949, p. 353).

Near the southern limit of these dike exposures an old vent, irregularly circular in plan and about 400 feet in diameter, is filled with brown tuff-breccia and some extrusive camptonite. The breccia encloses breadcrust bombs 1 to 2 feet long and angular fragments of basalt as large as 2 feet in diameter. This material, indicating eruptive activity, is closely adjacent to and probably connected with one of the camptonite dikes and supplies additional strong evidence that the dikes as now exposed were emplaced at very shallow depth.

Campbell and Schenk (1950, p. 688) were impressed by the decrease in size of phenocrysts from the middle of the dike outward, and they concluded that the crystals formed between emplacement and solidification of the magma. They recognized the evidence for very shallow emplacement and estimated that the crystals of amphibole must have formed in a period no longer than 25 days. S. Warren Carey (oral communication, 1959), in an alternative hypothesis, supposed that a magma chamber at considerable depth was stationary long enough for growth of the large phenocrysts. Crystals that started forming in the upper part of the chamber slowly sank, and eventually there was gradation in size from incipient crystals near the upper boundary to large crystals at some depth. When magma was forced upward to form the dikes, the upper part of the fluid, wedging the walls aside, became the marginal parts of a dike; fluid containing crystals of small and medium size followed; and material from a deeper part of the chamber carried the large crystals to the middle of the growing dike. Under this concept the large phenocrysts present no special problem.

The location and orientation of the dikes suggest strongly that intrusion occurred along fractures related to the north-south fault at the west base of the Black Mountains. All exposures of the main fracture in the vicinity of the dikes indicate that it is a reverse fault dipping steeply eastward. The three nearly parallel lines of dikes in a belt more than a quarter of a mile wide suggest a fault zone of considerable width, in large part hidden under fan debris. Perhaps repeated movements along several major fractures in this belt, in part after the slope gravels were weakly cemented, extended the fractures upward across the fan debris and so prepared the way for emplacement of the dikes.

STRUCTURE

A principal objective of the present study is the deciphering and mapping of major structural features south of Lake Mead, for comparison with those directly north and west of the lake. Ranges within the latter belt are characterized by thick sections of sedimentary formations that have large areal extent; such bedrock is ideal for effective display and accurate mapping of faults and folds. South of the lake much of the bedrock is far less favorable for structural studies. The complex of Precambrian metamorphic rocks and later plutons has no effective horizon markers that outline structural forms or give any satisfactory measure of displacements. Fortunately those needs are in some degree served by the volcanic rocks that cover large areas on both sides of the Colorado River.

Recognition of four distinctive assemblages within the thick volcanic accumulation provides, over considerable parts of the river belt, a crude substitute for extensive sedimentary formations. Displacement of major volcanic units makes many faults clearly evident; and at exceptional localities it is possible to measure displacements precisely through use of distinctive markers such as layers of peculiar glass or tuff. Generally, however, quantitative measurements are impossible, because the volcanic formations are lithologically monotonous over wide areas and along the strike are subject to abrupt changes in character and in thickness. Such variations, inherent in deposits built up around scattered eruptive centers, are intensified in the present case because faulting movements during the volcanism provided local basins for thick accumulations, with bordering ridges from which all volcanic products were quickly eroded.

Great thrust faults, conspicuous in many ranges of southern Nevada, are not known in the area of the present report. Failure to find such faults in the belt south of Lake Mead is not surprising, because within that area we must rely chiefly on volcanic rocks for evidence of deformation, and probably all such rocks that have been preserved were formed after the regional thrusting ended. Moreover the large thrusts of southern Nevada, so far as they have been reported, are confined to the section of Paleozoic and Mesozoic sedimentary formations. Perhaps some of these faults "root" in the Precambrian complex, and this possibility was kept in mind while the field study was in progress. But any thrusts cutting the metamorphic and plutonic rocks south of Lake Mead probably would be obscure at best and might be wholly concealed by the widespread cover of volcanic rocks and later alluvium. One fault zone revealed by excavations during construction of Davis Dam has low dip and possibly represents local thrusting; this exceptional fault (fig. 15) is described elsewhere in the report.

The principal structural features between Lake Mead and Davis Dam are steep faults, many with large displacement. Most of these faults are normal, but at least two of the largest have reverse displacement along much of their exposed lengths. Blocks between faults generally are tilted, and in the tilting movements several large normal faults were rotated to low angles of dip. Strikes of faults range widely; but northerly components prevail, and in general the displacements seem to be related to relative uplift of the Black Mountains block east of the river, and of the Eldorado-Newberry Mountains block west of the river. Through most of its length in this map area, the river valley follows a structural depression between the two major units of uplift. Although much of the depressed area is masked by alluvium, excavation by the river has exposed large masses of bedrock and many structural features. Therefore the exhibit of basin-range structure offered by this area is in some respects more satisfactory than any to be found in the Great Basin, where interior drainage is covering most of the downthrown blocks with increasing thicknesses of debris.

In an overall view the structural pattern southward from the Boulder Basin of Lake Mead falls into three well-defined units. (1) In a northern division, extending south to the latitude of Eldorado Wash, blocks are tilted consistently eastward toward a major fault zone along the west base of the Black Mountains.

(2) In a middle division, between Eldorado Wash and the Dead Mountains, the tilt of fault blocks is conspicuously westward, away from the Black Mountains block. (3) In the southern part of the area, tilting generally to the east is pronounced on the Arizona side, and apparently this general attitude continues to the south through the Oatman mining district (Ransome, 1923a; Lausen, 1931).

Faulting has been intensive in nearly all parts of the area, and numerous faults visible in the field are not shown on the map. The aim has been to represent faults and fault zones that seem most significant in the structural picture and to omit many related fractures that are grouped too closely to be shown clearly on a map of small scale. Of the faults represented on plate 1, some are very clear field exhibits that can be traced mile after mile without question; others are well exposed in some stretches but elsewhere are obscure because of monotonous bedrock, igneous intrusions, or alluvial cover. Some fault zones that are complicated by multiple fractures or en echelon displacements are represented as single faults, usually with broken-line symbol. No doubt many faults that merit places on the map were not seen in the time available for study of so large an area.

The following detailed discussion considers first the dominant Black Mountains block, and proceeds to the several structural divisions west of this range, taking them in order from north to south.

STRUCTURE OF BLACK MOUNTAINS

SECTION ALONG BOULDER CANYON

Faults mark the western edge of the Black Mountains structural unit through much of its extent within the area of this report. Near Boulder Canyon, where stream erosion has provided exceptional exposures, the mountain mass is revealed as a horst, bounded by large faults along both eastern and western margins. Other important faults, with northerly trends and varied displacements, subdivide the mass into several distinct blocks. The overall width of the compound horst is about 8 miles.

The Boulder Wash and Ransome faults are paired in bounding a high horst, which is transected by the narrowest and deepest part of Boulder Canyon. Directly south of the canyon and west of the horst, beds of Cambrian limestone and shale dip toward the Ransome fault. Before Lake Mead was filled, the lower part of the Cambrian exposure was at river level, at an altitude near 700 feet. In the ridge east of the fault, Precambrian rocks are at an altitude of over 3,700 feet. Hence, the minimum throw on the fault is about 3,000 feet, and perhaps the full measure is much more, as prolonged erosion may have reduced the top of the ridge far below the basal Cambrian horizon. Probably the total throw on the Boulder Wash fault is still greater, as the footwall block contains the thick Muddy Creek section, whereas all rocks in the downthrown block of the Ransome fault are older than Muddy Creek.

The block west of the Ransome fault is a graben about 3 miles wide, bounded on the west by the Emery fault. This downthrown block and the bounding faults have clear topographic expression because of differential erosion (pl. 1).

Complex faulting marks the west border of the Black Mountains. Directly north of the lake the Precambrian rocks are in fault contact with cemented Colorado River gravels and older deposits. Probably the fault dips steeply eastward,[5] and compression attending the reverse displacement deformed the gravel beds in a wide belt (Longwell, 1946, p. 827; pl. 5). South of the lake two east-dipping faults that strike nearly north cut the complex of Precambrian gneiss and younger plutonic rocks. Along one of these breaks, here called the Indian Canyon fault, deformed bands of gneiss indicate reverse movement but tell nothing about the measure of displacement. This fault shows clearly on aerial photographs and can be traced southward nearly 10 miles to its intersection with the Kingman Road fault. The fault a short distance west of Indian Canyon joins the larger fault north of present exposures (Longwell, 1936, pl. 2).

The reverse fault north of the lake that displaces Colorado River gravels appears to be continued southward as the Fortification[6] fault, on which, however, there is large normal displacement. Directly south of the river the fault surface was well exposed before Lake Mead was formed; the dip is 65° to 75°W., and dragged up on the side of downthrow are fan deposits of the Muddy Creek formation and also old Colorado River gravels (Longwell, 1936, fig. 10). As these gravels are either Pleistocene or late Pliocene (Longwell, 1946, p. 828), movement on this part of the Fortification fault continued until late geologic time. The scarp is bold (fig. 12), but probably it was in large part buried and later exposed by erosion of weak deposits in the hanging wall. In Fortification Hill, 4 miles south of the lake, coarse Muddy Creek deposits near the fault suggest derivation from the steep front of the footwall block (fig. 3). As the

[5] This fault has been represented as normal (Longwell, 1936, pl. 2, section *E–E'*), but reconsideration of the field evidence has changed this earlier verdict (Longwell, 1946, fig. 2).

[6] Earlier named the Callville fault (Longwell, 1936, fig. 10), but it seems best to use the name of the adjacent ridge as printed on the Hoover Dam topographic map.

FIGURE 12.—Scarp of Fortification fault, in view southeastward across Colorado River and ruins of old Fort Callville before Lake Mead was formed. Mountain mass is composed of granitic rocks intrusive into Precambrian gneiss. Muddy Creek formation and overlying cemented river gravels, here shown along the former stream, are in fault contact with rocks in the scarp.

cap of the Fortification basalt member continues across the fault trace without perceptible dislocation, probably most of the displacement on this fault occurred before the end of Muddy Creek time; and the later movement involving Colorado River gravels was confined to the part of the fault north of Fortification Hill.

A considerable part of the Mead Slope fault is concealed by Lake Mead; along this part, once well exposed (Longwell, 1936, pl. 2), beds of coarse breccia in the Muddy Creek formation were brought up by reverse movement against old Colorado River gravels. At present the best exposures of this fault are about a mile northwest of Fortification Hill, where Muddy Creek deposits and included basalt are downthrown against altered igneous rocks. Farther northeast, much of the trace is obscured by gravel cover on the dissected slope.

STRUCTURE NEAR FORTIFICATION HILL

A group of faults with diverse trends outlines several blocks in a roughly triangular area around Fortification Hill. In this group the Indian Canyon and Fortification faults strike nearly north, the Mead Slope fault strikes northeast, and the Horsethief fault strikes northwest. At the north end of the triangular area, the Fortification fault is the logical boundary of the Black Mountains. In the southern part of the triangle, relations are less definite. The Fortification fault ends abruptly against the Horsethief fault, and neither of these has the strong topographic expression that marks the Fortification fault near Lake Mead (fig. 12). Directly south and west of Fortification Hill, all bedrock older than the Muddy Creek formation has been chemically altered, locally with such intensity that the rock has become a weak, claylike mass retaining little evidence of its origin (p. E17). Because of this change the rock varies in resistance to erosion, and positions of faults are in part obscured.

South of the basalt-capped mesa, the Fortification fault divides to form a complicated zone of fractures in varied bedrock. A complex of plutonic bodies intruded into Precambrian gneiss forms the footwall, and porphyritic intrusive rocks enclosing large xenoliths of Golden Door volcanics make up the hanging wall, in which several prospects of metallic minerals have been opened.

The Horsethief fault is best exposed along White Rock Wash, where a clearly defined fracture dipping 70° NE. separates plutonic rocks and gneiss in the hanging wall from brown andesitic lavas in the footwall. The lavas, dragged up to dip steeply southwest, are mapped on the basis of color and lithologic character as part of the Patsy Mine volcanics. Beds of the Muddy Creek formation that lie on the lavas with strong angular unconformity also are dragged up to moderate southwest dips. Presumably much of the displacement occurred before these beds were laid down, though possibly in the earlier part of Muddy Creek time. No evidence has been found for dating the latest movements on this fault.

In large part the footwall block of the Horsethief fault is hidden by alluvium, but the nearly straight edge of the hanging-wall block clearly suggests a continuous fault trace (pl. 1), along a line that leads to confirmatory outcrops near the lake. These outcrops show the altered igneous rocks south of Fortification Hill faulted upward against Golden Door and Mount Davis volcanics, and beds of the Muddy Creek formation. Although nothing in the visible evidence gives a trustworthy measure of throw on the fault, comparison of bedrock on opposite sides indicates large vertical displacement. Volcanic rocks identified locally in the belt of altered bedrock south of Fortification Hill are very like the Golden Door volcanics. If this correlation is correct, a short distance south of the lake the fault displacement at a minimum must approximate the combined thicknesses of the Golden Door and Mount Davis sequences, which near Hoover Dam is 2,000 feet or more. A much smaller throw is suggested by beds of the Muddy Creek; but these beds were deposited on an uneven surface, probably through various stages of the faulting. Beds on one side of the fault may differ considerably in date of deposition from those on the opposite side. Moreover, as noted above, the beds of the Muddy Creek exposed in White Rock Wash must have been laid down after a large part of the displacement on the fault had occurred.

Convergence of the traces of the Horesthief and Mead Slope faults, and reverse movement on both, may suggest that a wedge-shaped block including Fortification Hill was forced to move westward and upward under compressive stress, but it is not known that these faults were in operation at the same time. The Horsethief fault was active after some part of Muddy Creek deposition but is not known to have involved Colorado River gravel. So far as the evidence is known, the Mead Slope fault may have originated after the older river gravels were laid down.

FAULTED WESTERN BORDER

South of the Horsethief fault the border of the range has four nearly straight segments that alternate in direction between southeast and south through a distance of 14 miles. Faulting along this part of the range border is strongly implied, though actual exposures of the fault are few. Conceivably this fault, here called the Kingman Road fault, is continuous with either the Horsethief or the Indian Canyon fault. But the three features are distinctive in themselves, and discussion is simplified if each has a distinguishing name.

In its northern segment the Kingman Road fault is closely parallel to conspicuous layering in the adjoining Precambrian rocks, but the succeeding north-south segment cuts across the layering at a small angle. Through the two segments, evidence for faulting is of two kinds: (1) general straightness of the contact between bedrock and alluvium and (2) numerous fractures in the bedrock that are nearly parallel to the border. These fractures are seen to best advantage in and near workings of a mineral prospect at the north side of West Petroglyph Wash. Presumably these fractures are genetically related to the border fault. Most of the observed fractures dip steeply eastward and suggest reverse displacement on the border fault. This suggestion is supported by observations south of U.S. Highway 93, where the Muddy Creek formation is in contact with the fault. Although few actual exposures of a fault surface were seen, the beds of the Muddy Creek are turned up to or past the vertical near the fault and are much deformed in a belt more than 1,000 feet wide. In the adjacent Precambrian rocks the gneissic layers, which near the range crest dip westward at a moderate angle, steepen progressively down the slope and near the fault are vertical or even overturned to a steep dip eastward. The sum of evidence strongly indicates reverse movement on the fault.

South of the Willow Beach road, the Muddy Creek overlaps fault blocks that consist largely of dark basaltic lavas, apparently part of the Mount Davis sequence. In some of the tilted blocks, the basalt lies directly on Precambrian gneiss. Presumably the whole assemblage of blocks is faulted against the high block forming the range, though the actual trace of the principal fault is concealed by waste. In this segment of the Kingman Road fault, therefore, the dip of the fault surface is not known.

Near the Pope Mine the western border of the Black Mountains Precambrian block is offset by an important northwesterly fault. If the Kingman Road fault extends to this locality, its position is effectively hidden, but a fault with about the same strike is conspicuous from the Pope fault southward. A fault extending eastward along the upper course of Pope Wash is logically the extension of the Pope fault offset by the north-trending fault. Possibly the latter fault continues northward, and this possibility is suggested on plate 1; but as no evidence of the continuation was found, the border fault from Pope Wash southward is considered as a separate structural unit. It is represented on the map as running continuously southward about 22 miles to the vicinity of Eppersons Corral, but it has not been fully walked out; the map representation is the result of extrapolating fault segments studied in a number of separate localities, and the line as mapped may represent a zone of related fractures. The name Epperson fault is chosen because evidence of large displacement is well displayed near Eppersons Corral.

In the 3-mile stretch between Pope and Gold Bug Washes, the fault is clearly marked and has large throw. Resistant andesite flows of the Patsy Mine volcanics maintain a prominent scarp on the side of upthrow; weaker basalts and gravel beds in the Mount Davis sequence underlie a lower surface on the downthrown block. The fault surface was not seen, but it is assumed to dip steeply westward, as do three parallel faults that cut the downthrown block. These faults cause repetition in the Mount Davis section, and much coarse alluvium further hides relations; but thickness of the younger volcanic sequence exposed here is computed as more than 1,800 feet (p. E25); in estimating throw on the Epperson fault, to this figure must be added an unknown but probably large thickness of Patsy Mine volcanics eroded from the footwall.

Near and for some distance south of Gold Bug Wash the structure is obscure, especially at the supposed location of the northwestward trending Gold Bug fault. Because of poor exposures this location is uncertain; but no indication was seen that this fault continues east of the Epperson fault. Farther south the Golden Door volcanics, dipping consistently westward, are normally downfaulted against Precambrian gneiss in the range. The fault is revealed in particularly clear exposures directly east of the Golden Door mine and on both sides of the Searchlight Ferry road. The westerly dip of the fault, at angles ranging from 45° to 65°, is seen in outcrops and is expressed in retreat of the Precambrian–Golden Door contact in the valley followed by the road. Near the road there is a marked change in topographic expression of the main bedrock units. Northward for about 17 miles the volcanic rocks in the hanging-wall block form a hilly belt, locally rugged but distinctly lower than the mountain ridge on Precambrian gneiss. South of the road the fault crosses diagonally to the east side of the ridge, which through several miles is on Golden Door volcanics, whereas the Precambrian footwall block is low on the eastern slope.

South of Eppersons Corral the structure is complex and at some points not entirely clear. Along the road the Precambrian rocks disappear southward under brown andesite identified as part of the Patsy Mine volcanics. These andesites in turn dip southward beneath Golden Door volcanics and are cut off to the west by the Epperson fault, which apparently dies out southward in a zone marked by sharp change of strike from southeast to east. A normal fault east of the road drops Golden Door volcanics with steep westward dip against the footwall block of Patsy Mine volcanics and Precambrian gneiss; this fault has a sinuous trace because it dips to the east no more than 20°. A later fault, inclined more steeply eastward and with large throw, transects the highly deformed Golden Door rocks and drops against them, on the east, Mount Davis volcanics that dip westward. Probably these faults are related to sharp downwarping along an axis trending north of west, which is responsible for the broad outcrop of Mount Davis rocks athwart the range between Eppersons Corral and Union Pass. This downwarp is in line with the low, alluviated pass west of the river, between the Eldorado and Newberry Mountains. Probably the structural depression is reflected near Searchlight in wide outcrops of volcanic rocks (not mapped), which locally extend eastward into the broad pass.

Several miles southwest of Eppersons Corral, the Mount Davis volcanics, dipping southwestward, are faulted down against brown andesites of the Patsy Mine sequence. In the upthrown block, glass and tuff that normally are found high in the Mount Davis section rest directly on the andesite of the Patsy Mine volcanics. Absence here of the Golden Door rocks, which form a thick section less than 2 miles to the northeast, and representation of Mount Davis time by only the upper part of the normal section suggest local uplift and much erosion in the vicinity of the present wash, during and perhaps before the Mount Davis episode of volcanism. Many faults and small intrusive bodies, not shown on plate 1, cut the Mount Davis rocks, especially near the old Portland Mine.

The downwarp south of Eppersons Corral breaks the continuity of the Black Mountains topographically, lithologically, and structurally. Precambrian basement rocks are again dominant farther south, near

Union Pass; but the structure of that area, closely related to the section near Davis Dam, is discussed with that section on later pages.

STRUCTURE NORTH AND WEST OF BOULDER BASIN

Directly north of Boulder Basin, where the bedrock consists chiefly of weak deposits in the Muddy Creek formation with included and older basaltic lavas, the structure is not of critical value in the present discussion. The extreme northwestern part of the map area presents a sample of the Frenchman Mountain block, where the geology contrasts sharply with that southward from Lake Mead; the structure section (fig. 13) illustrates some of the differences. On the other hand, the Frenchman block lacks the large-scale thrust faults common in neighboring ranges directly to the north and west; its structure of fault blocks tilted steeply eastward is generally similar to the structure near Hoover Dam.

South of Las Vegas Wash, limestone of the Horse Spring formation lies unconformably below volcanic rocks that probably are part of the Golden Door sequence; but the relation of these limestone beds to older volcanic rocks is not visible. In and around the Three Kids mining district, the Muddy Creek formation is strongly faulted and tilted. Nothing in the pattern of this deformation suggests a close relation to the structural pattern south of the lake. Deformation in the Three Kids neighborhood is marginal to the River Mountains mass, which has a complex pattern of faults and tilted blocks that can be deciphered only after a systematic study of the volcanic and plutonic bedrock.

The isolated outcrop of Precambrian schist in Saddle Island may seem anomalous, but sediments in the Thumb formation serve as evidence that in late Mesozoic time the old basement rocks formed an upland extending westward beyond the present River Mountains (p. E8). No doubt the old rocks now exposed in Saddle Island and in areas south of the lake were mantled with volcanic and sedimentary deposits until they were laid bare by erosion in late Cenozoic time.

STRUCTURE WEST OF THE BLACK MOUNTAINS

BOULDER BASIN TO ELDORADO WASH

In a large area south of Boulder Basin, many rock units are distributed in irregular fashion and broken by faults that have diverse trends. There is, however, considerable order in the apparent chaos. The large outcrops of Precambrian rocks along Black Canyon, with overlying Patsy Mine volcanics, represent a northeastward trend of the Eldorado Mountain block; near Willow Beach the interval between that block and the Black Mountains is reduced to a minimum. Exposures of Precambrian rocks father west, including Saddle Island, part of the hill south of Boulder City, and the large area 5 miles west of Nelson, seem to mark high parts of a complex structural block west of and tilted toward the main Eldorado block. This western structural unit, here called the Nelson block, is bounded on the east and subdivided by a set of large normal faults, nearly all with the downthrow on the west, which strike more northerly than the Eldorado axis, toward which they die out southward to form a crude en echelon pattern.

The two divisions of the area north of Eldorado Wash, as defined above, are now described and discussed as distinct structural units.

NORTHERN ELDORADO MOUNTAINS BLOCK

This unit, from Eldorado Wash northward, is tilted generally to the east and faulted down against the Black Mountains. The abrupt eastern boundary of this block consists of the Kingman Road and Horsethief faults which, in contrast to all the large faults

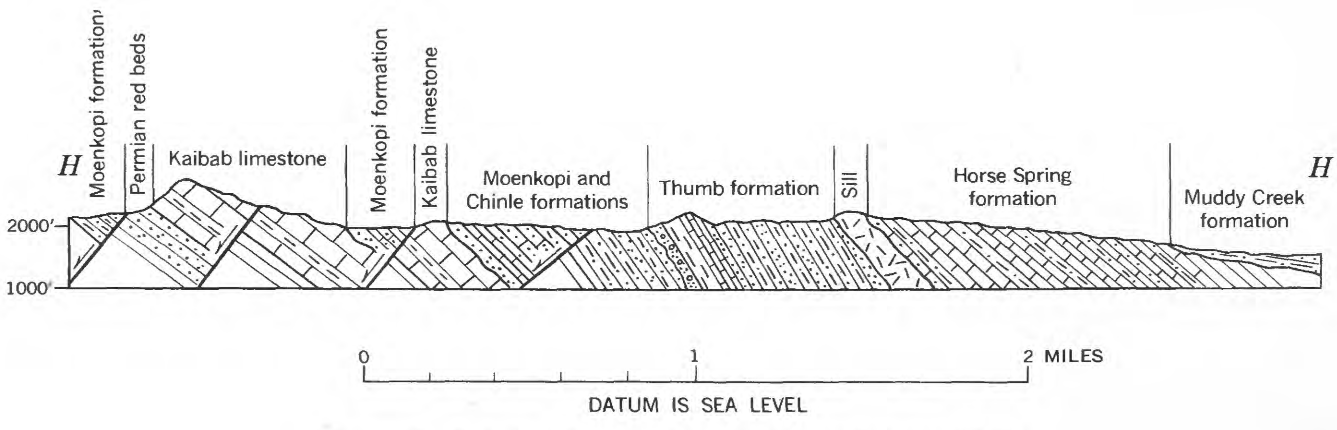


FIGURE 13.—Geologic section along the line H–H' on geologic map (pl. 1).

west of them, have reverse displacement. Measure of the throw along this fault boundary can only be conjectured, as no stratigraphic markers are available for comparison on hanging-wall and footwall sides; but the total vertical displacement must be thousands of feet. East of Hoover Dam a minimum figure is given by the combined thicknesses of the volcanic sequences, Patsy Mine through Mount Davis, which in the downthrown block dip toward the fault boundary.

A point of interest is the appearance in White Rock Wash of brown andesite of the Patsy Mine volcanics, turned up steeply against the Horsethief fault. Absence of younger volcanic rocks in the outcrop there may be attributed to concealment beneath the Muddy Creek formation. Deformation in the footwall perhaps affects a zone of considerable width; and volcanic rocks younger than the brown andesites may lie under cover at some distance from the fault. This possibility is in accord with the strong disturbance of the Muddy Creek formation along the Kingman Road fault east of Willow Beach (pl. 1, section *C–C′*). Presumably the displacement on the two large reverse faults was cumulative through a long time interval. The Muddy Creek, unconformable on lavas that dip more steeply, contains coarse rubble probably shed from a growing scarp to the east; and these beds in their turn have been deformed in later stages of the movement.

Deformation within the major structural blocks is expressed in groups of faults with varied patterns, and in warping effects. Near Hoover Dam, where exposures in the walls of Black Canyon are almost continuous, a set of faults nearly parallel to the edge of the main block occupies a belt about 2 miles wide. Nearly all these faults are normal, with downthrow on the west; some surfaces with horizontal striae suggest important strike-slip movements, and a few reverse faults have local development. With mapping in detail, no doubt the larger faults in this group can be traced farther southeast than they are shown on plate 1. General parallelism of the set to the Horsethief fault suggests a genetic relation. Another set, cutting the volcanic rocks south of the Willow Beach road junction, closely parallels the Kingman Road fault. Two faults in this set are exceptional, so far as movements have been deciphered, in having downthrow toward the Black Mountains block. This type of displacement may reflect adjustment to the weight of the overriding hanging-wall block of the main fault.

Warping is especially pronounced around the two large outcrops of Precambrian rocks west and southwest of Willow Beach. Structure in these areas suggests effects of strong local doming complicated by faulting. Around the Precambrian outcrop north of Square Butte the lavas dip strongly outward in nearly all directions. The set of faults striking northwesterly into this dome, all with downthrow on the southwest, may reflect torsional strain; a strong vertical couple is suggested by the east-west portion of the Jeep Pass fault, with upthrow on the south, and the large east-west fault with opposite throw directly north of Malpais Mesa (fig. 14). Complex local strains are indicated also by the faults northeast and east of the mesa, which in combination have large displacement. Two of these, largely in Precambrian rocks, are clearly recognized only where remnants of volcanic rocks are preserved on the downthrown side.

FIGURE 14.—View northeastward across the east-west fault north of Malpais Mesa. Dark lavas (*a*) of the Patsy Mine volcanics, dipping away from Precambrian rocks in foreground, are faulted down against Precambrian rocks (*b*) forming high ridge. Mount Davis volcanics (*c*), beneath low ground in right middle distance, overlie Patsy Mine volcanics in tilted section.

NELSON BLOCK

The Nelson structural unit is broken by many faults, some with large displacement. In the northern part of the block, the eastern margin is marked by the Jeep Pass fault, in whose hanging wall a thick section of Mount Davis volcanics dips steeply toward the footwall of Precambrian gneiss and Patsy Mine volcanics. Northward the fault divides both directly and en echelon, and displacement appears to die out south of Hoover Dam. The Rifle Range fault borders the west side of a horst which, with the fault at its eastern border, disappears southward under glassy volcanic rocks that floor Glass Plateau. South of this plateau the section of Mount Davis volcanics is duplicated by many local faults and by at least four normal faults of considerable magnitude, the easternmost of which extends northward from the east-west extension of the Jeep Pass fault. More than a mile farther west in the Hidden Valley fault, also with northerly strike, clearly visible where Precambrian gneiss is in the footwall but obscure farther north in the section of basaltic lavas. At the south this fault is cut off by another, striking northwest, which hinges out to the southeast in Patsy Mine volcanics. The Fuller Road fault has caused large displacement of the Mount Davis volcanics, but the trace has not been followed to an assured limit, either north or south. West of it is the Eldorado fault, which has exceptionally clear expression through several miles because of contrasting rocks on opposite sides. This fault, on which the throw is among the largest in the map area, may extend considerably father than shown on the map; it is obscured at the south in plutonic rocks and Precambrian gneiss, at the north in basaltic lavas. Through 5 miles or more from Eldorado Wash northward, the vertical displacement presumably is measured in thousands of feet, even if allowance is made for possible eastward thinning of the 3 volcanic assemblages west of the fault. Farther north the throw may decrease, though the Mount Davis section is very thick and the measure of duplication by faulting seems indeterminate.

Faults in a set west of the Eldorado fault are clearly expressed because of the distinctive pattern made by offsetting of the three volcanic units, Patsy Mine through Mount Davis. The tuffs and breccias of the Golden Door volcanics, lighter colored and more resistant to weathering than the lavas above and below, mark locations of faults unmistakably. All faults in the set dip to the west and have normal displacement. The easternmost member of this set makes oblique junction northward with the Eldorado fault; at the south this member, and the one next west of it, end abruptly near the old Techatticup mine. Although waste hides the critical relations, clearly the thick volcanic sequences also end along a nearly straight line, trending somewhat north of west, at the boundary of a coarse-grained intrusive body. This boundary is interpreted as an intrusion fault (Ransome, 1904, p. 11), south of which the volcanic rocks were lifted by the rising pluton and eroded. The Welcome fault offsets the pluton; possibly part of the displacement on this fault also occurred while the intrusion was in progress.

West of the Welcome fault, relations between volcanic and intrusive rocks are obscure. South and west of Nelson, masses of the old lavas are surrounded by plutonic rock and boundaries are indistinct. The thick section of Patsy Mine volcanics on the north, repeated by faults and tilted to the east, strikes southward directly into a wide zone occupied in large part by irregular intrusive bodies. The northern boundary of this zone is vaguely marked. Possibly many intrusion faults, trending generally east, traverse the belt of intrusive bodies, and masses of the volcanic rocks that were lifted by intrusive action have been eroded, though many engulfed blocks remain. North of the old Wall Street mine a large mass of clay developed by hydrothermal action has been used in brickmaking.

Several miles northwest of Nelson, a large fault with downthrow on the east separates the Patsy Mine volcanics from Precambrian gneiss. The north and south limits of this fault are not determined. Broad anticlinal structure involves the Patsy Mine section at the north end of the Precambrian outcrop. Along the structure section *D–D′*, plate 1, the outcrop of Patsy Mine volcanics is nearly 4 miles across the strike, and prevailing dips to the east are particularly steep in the eastern half of this distance. A number of large strike faults repeat the section; but it seems impossible to follow some of the traces through the brown lavas, and even where a distinctive horizon of glass provides a guide, only generalized traces have been mapped, as shown on plate 1. Dips of the faults thus represented are low, locally no more than 20°. Vagueness of the structural details defeats attempts to make a reliable estimate of thickness in this section.

West of the Colorado River the structure characterized by east-dipping fault blocks ends abruptly on the south near the latitude of Eldorado Wash. East of the river the structural boundary is more irregular. In the hanging-wall block of the Ives fault, westward dips prevail as far north as the lower end of Black Canyon; but east of this fault the belt of eastward dips extends to and irregularly south of Pope Wash. In the wide outcrop area of Patsy Mine volcanics traversed by this wash, dips are roughly quaquaversal around an igneous plug. The large northwesterly faults bordering this large block are of considerable interest. Three of these—the Pope fault, the fault paired with it to bound a northwest-trending graben, and the Gold Bug fault—are closely parallel, and they are similar in strike to the set of northwesterly faults between Square Butte and the river. The Ives fault, on the west border of the Pope Wash block, becomes an important member of that set in its extension west of the river.

ELDORADO WASH TO NEWBERRY MOUNTAINS

South of the Gold Bug fault, dips to the west are general; abruptness of the change in structure along this fault is shown in the structure section *E–E′*, plate 1. Southward from the lower end of Black

Canyon, widening sheets of alluvium hide much of the bedrock; but through a distance of 15 miles, outcrops in scattered ridges reveal that between the Black and Eldorado Mountains the Golden Door and Mount Davis volcanics make up several fault blocks that are tilted consistently to the west. Section *F–F′*, plate 1, illustrates this structure, some elements of which must be inferred. The Epperson fault dips west; the Big Blackstop fault dips east; and close similarity of exposed structure from Mount Davis westward suggests that the other faults also dip to the east. Outcrops of Golden Door volcanics along the river indicate an important fault east of them. Evidence supporting the two faults next in order to the west is obscured by alluvium; but they are suggested by changes in dip, probably caused by drag. The fault nearest the west end of the section is established by the dip of volcanic rocks toward the nearly straight border of the range.

The plug of andesite porphyry at the main border fault along the east side of the Eldorado Mountains, and several bodies of similar rocks alined to the south, indicate that intrusion was controlled in some degree by the fault zone. Northward branching of the fault and irregularity of the range front farther north imply that faulting at this border is complex, perhaps on a set of en echelon fractures. Large thicknesses of the exposed volcanics indicate very large displacement in the vicinity of the section *F–F′*.

In the large alluviated area south of Mount Davis, there are no outcrops of the older bedrock; but in the Black Mountains belt the westward dips persist, except in the zone of sharp flexure south of Eppersons Corral. The axis of downwarp south of the Portland mine, in line with the north end of the Newberry Mountains, is the logical southern limit of the structural unit with prevailing dips westward. Though outcrops are limited in this unit as a whole, apparently the structure is much simpler than in the wide belt north of Eldorado Wash.

STRUCTURE EAST OF NEWBERRY MOUNTAINS

The Newberry Mountains afford the widest continuous outcrop of Precambrian rocks within the map area. Generally the banding in these rocks trends west of north, and west of the river the average dip of the banding is steep toward the east. Persistence of Precambrian outcrops across the broad valley and eastward to Union Pass marks a broad belt of uplift along an axis trending somewhat north of west, parallel to the Portland mine downwarp.

Most of the faults in this part of the area are revealed by their effects on volcanic rocks, but excavations during the building of Davis Dam gave information on an exceptional fault zone that involves Precambrian bedrock exclusively (Lundgren, written communication, 1949). The only surface indication of this feature was a saddle floored with crushed rock and clay. Exploration by trenching and core drilling showed a continuous though irregular zone with average strike N. 60° to 65° E., dipping 15° to 25° SE.; it is continuous at least 1,000 feet along the strike, and extends underground at least 800 feet southeast of the power plant, which is east of the river channel (fig. 15). The full zone includes in its upper part an irregular layer of crushed gneiss, as thick as 30 feet, crossed by seams of clay 1 inch to 2 feet thick. Ten to 100 feet vertically below this layer is another with similar content. In many parts of the fault zone, the power shovels could excavate without blasting.

Nothing in available descriptions of this zone suggests the nature and measure of displacement. The low average dip and the extent of thorough crushing suggest thrust faulting. Because of the limited ob-

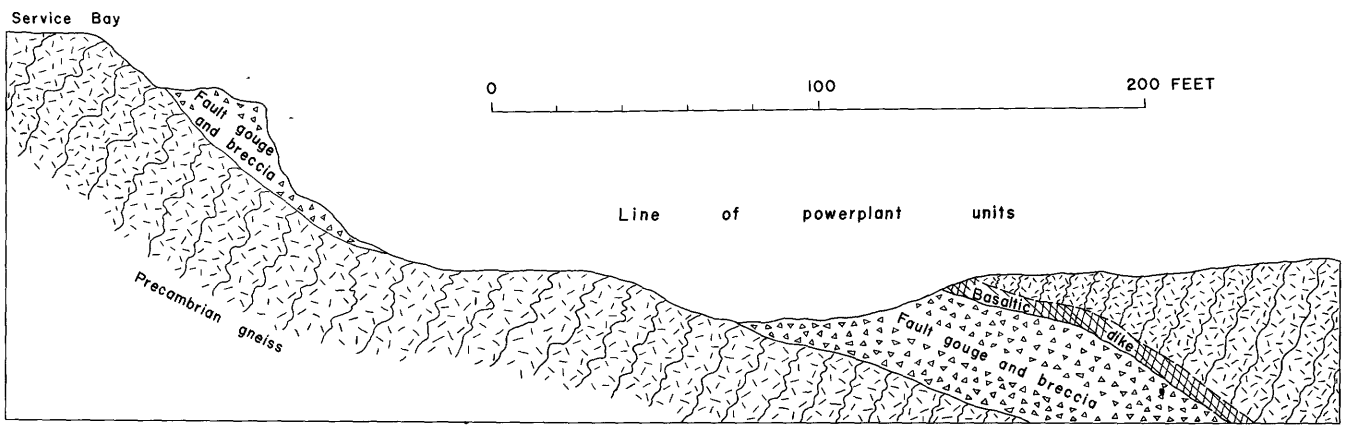


FIGURE 15.—Fault zone in Precambrian rocks at Davis Dam, exposed by excavation east of river. Zone strikes N. 60°–65° E., dips 15°–25° SE. (modified from W. K. Lundgren, U.S. Bureau of Reclamation written communication, 1949).

servations the fault is not shown on the map, plate 1, but its position is indicated in section *G–G'*.

About 2 miles west and northwest of Davis Dam, volcanic rocks are downthrown on faults that make an irregular pattern. In one block with steep eastward tilt, basaltic lavas interspersed with beds of gravel appear to be part of the Mount Davis volcanics. An adjoining block tilted to the west has typical Golden Door volcanics, including basaltic sills and dikes. Several miles east of the dam, a set of normal faults with northwest strike repeats a section of Golden Door volcanics. The large outcrop of Precambrian rocks west of Union Pass appears to represent a much-faulted arch whose axis trends northwest. Some of the faults are clearly marked by remnants of lava and tuff, as at the old Frisco mine. The large fault at the Arabian mine, exceptional in direction of strike, has exposed in the hanging wall south of the mine a very coarse breccia that includes quantities of gray limestone. Conceivably the source was in Paleozoic beds that have been eroded from the footwall block.

DATING OF FAULTS

In the area south of Boulder Basin, none of the many faults can be assigned definitely to geologic epochs, and few can be bracketed closely in relation to lithologic units. For example, two faults about a mile west of Willow Beach cut only Precambrian rocks and Patsy Mine volcanics, but as no younger bedrock has survived erosion there, an upper limit for the date of faulting is indeterminate. Northeast of Nelson, the Welcome fault cuts a thick Mount Davis section that is strongly tilted; but flows of the Fortification basalt member of the Muddy Creek formation, covering a nearly even surface of erosion, cross the fault unbroken. The Rifle Range fault, and another 2 miles west of it, have lowered beds of the Muddy Creek with strong drag effects. Movements on many faults may have continued to a date as late as on the Mead Slope fault, which is favorably located to show involvement of the early Colorado River gravels.

No faulting of recent alluvium was detected with certainty anywhere in the area, although topographic features southwest of Railroad Pass suggest possible breaks in the fan slope that are not yet obliterated by erosion and deposition.

MINERAL DEPOSITS

The region south of Lake Mead has long been a prospectors' paradise, as evidenced by claim notices bearing a wide range in dates and by widely distributed prospecting pits. Some old mines whose records show large production lie within the area represented on plate 1. The Eldorado Canyon district, with its center near Nelson, boasted the Techatticup and Wall Street mines, credited with total yield of gold and silver valued at several millions of dollars (Ransome, 1907). Production was begun at the Techatticup in 1863 and continued with interruptions until 1942. Development of some properties within or near this district has been started or renewed recently, as at Knob Hill. The Searchlight district, once very active, has been the scene of only small operations in recent years. On the Arizona side of the river, the Katherine mine ended a varied record about 1930. Among other properties that prospered for a time were the Gold Bug and Mocking Bird (Schrader, 1909), and the Arabian and Frisco (Lausen, 1931). Gold and silver were the chief objectives in the older operations, though more recently some other metals, including lead, zinc, and copper, have received attention.

In the present study no attempt was made to locate and catalog the active prospects and mines within the area; but a few mines, most of them now inactive, are shown on plate 1 to serve as reference points.

Nearly all mineral deposits exploited within the area have been in igneous rocks, either plutonic or volcanic, or in closely associated metamorphic rocks. Exceptions are the manganese ore mined in the Three Kids district from sedimentary beds of the Muddy Creek formation, and gypsum quarried from several bedded formations northwest of Lake Mead.

GEOLOGIC HISTORY OF THE AREA

Evidence now in hand from a large area south of Lake Mead outlines a sequence of events but gives little basis for fixing definite dates. A large part of the history must be deduced indirectly from evidence in the thick stratigraphic sequence directly north and northwest of Lake Mead. Unfortunately the formations of most critical interest, representing the Cretaceous period and much of Tertiary time, have thus far yielded few diagnostic fossils. But at least the physical evidence given by the sediments has large value, and eventually we may have a more satisfactory basis for dating features and events. Conceivably some local deposits, particularly waterlaid ash-beds, that are interlayered with volcanic rocks south of the lake may hold fossils of value.

PALEOZOIC ERA

The section of Paleozoic formations totals about 8,000 feet in Frenchman Mountain, and somewhat less in the Muddy Mountains, only a few miles from Lake Mead. Ranges farther north and northwest show a much larger total thickness, and regional stratigraphic evidence indicates clearly a thinning of the Paleozoic toward the southeast. This evidence has been summarized and shown graphically by McKee (1951). His isopach maps indicate for each Paleozoic system a marked decrease in thickness southward through the area of the present report, though according to his logical extrapolations the full Paleozoic section may have measured more than 4,000 feet in the vicinity of the Davis Dam site.

At Frenchman Mountain the continuous section from Middle Cambrian through Mississippian is made up almost wholly of marine carbonate rocks. Only the Pennsylvanian and lowermost Permian beds show a considerable increase in content of sand and silt as compared with the same part of the section in the Spring Mountains to the northwest. In general, therefore, the evidence suggests gradual overlap through a considerable distance toward the southeast, as represented by McKee (1951, pl. 1, 2).

MESOZOIC ERA

Marine limestone in the Lower Triassic Moenkopi formation is much thinner near Frenchman Mountain than in the Spring Mountains, whereas a much greater abundance of gypsum suggests lagunal conditions near shore. Probably the shoreline of that time was not far south of the present position of Lake Mead, and through all later Triassic and Jurassic time continental conditions extended much farther north. Fine-grained clastic deposits of the Moenkopi and Chinle formations, and the Jurassic crossbedded sandstones, probably covered the area of this report; McKee's (1951, pl. 2) estimate of about 1,500 feet for each system seems reasonable. We may suppose, then, that at the close of Jurassic sedimentation the thickness of sedimentary rocks in the area was several thousand feet.

Widespread deformation occurred before deposition of the Thumb formation, which lies with angular unconformity on the Triassic and Jurassic rocks. The old erosion surface cuts across successively older formations from north to south; this cross-cutting indicates that uplift increased toward the south. A widespread conglomerate at the base of the Thumb contains pebbles and cobbles that represent several Paleozoic formations and the Precambrian complex. Higher in the Thumb formation are numerous great lenses of shattered Precambrian bedrock; probably these breccias moved northward by landsliding from a fault scarp at the border of a rising land mass from which nearly all rocks younger than Precambrian had been eroded (Longwell, 1951, p. 352).

The Thumb formation is provisionally correlated with the Willow Tank and Baseline formations of the Muddy Mountain area, which are orogenic deposits of Cretaceous age (Longwell, 1949, p. 931). If this correlation is correct, the deformation in the area of the present report probably began as early as mid-Cretaceous time, in connection with the development of thrust sheets in southern Nevada and related to the orogeny farther north (Spieker, 1946, p. 150). Presumably the emplacement of plutons in the Black and Eldorado Mountains accompanied this orogeny, and some of the bodies invaded the cover of sedimentary formations before these were stripped away, as evidenced by xenoliths or roof pendants consisting of Cambrian beds. Extensive layers of tuff in the Willow Tank formation of the northern Muddy Mountains (Longwell, 1949, p. 931), and in the Thumb formation near Lake Mead, mark eruptive activity probably related to the rise of plutons now exposed in the Black and Eldorado Mountain blocks. Provisional dating of the older plutons there as Cretaceous is based on this supposed relationship. The generally acidic composition of the Cretaceous tuffs and of the older intrusive bodies is consistent with this correlation.

The Patsy Mine volcanics were erupted through plutonic bodies, and basal layers of the sequence contain fragments of older volcanic rocks. Moreover the base of the Patsy Mine volcanics, wherever exposed, rests on a surface that transects Precambrian rocks and younger intrusive bodies that presumably are Cretaceous in age. A considerable interval marked by wide uplift and erosion must have preceded the Patsy Mine episode, and the Thumb rocks bear witness to at least a part of this interval. The basaltic flows in the upper part of the Thumb formation (fig. 2) can hardly represent any part of the Patsy Mine volcanism, which from some of its nearby vents would have flooded with distinctive andesitic lavas the Thumb basin if in active subsidence. Probably the Patsy Mine volcanics were erupted after the Cretaceous beds were laid down and deformed. The land surface that received the lavas may have extended northward across Cretaceous and younger bedrock; any Patsy Mine volcanics deposited there must have been removed by later erosion. Presumably, therefore, the only volcanic rocks of Cretaceous age preserved within the area of this report are the basaltic lavas and tuffaceous beds included in the sedimentary section north of Las Vegas Wash.

CENOZOIC ERA

The Horse Spring formation is separated from the Thumb formation by an erosional surface only; there is no perceptible angular divergence between the two units, which were deformed together in equal degree. Possibly the Horse Spring was deposited in latest Cretaceous or in Paleocene time; the Eocene date now assigned is tentative and uncertain. Many features common to the two formations indicate deposition in subsiding basins, with frequent interruptions. Fresh-water limestone, which forms an important fraction of the Horse Spring section, occurs also, with similar lithology but smaller thickness, in a unit of the Thumb formation. Abrupt wedges of very coarse debris are present in the Horse Spring, though less conspicuous than in the Thumb. Similar basaltic and tuffaceous rocks occur in the two formations, in comparatively small amounts. No lavas resembling the brown andesites of the Patsy Mine volcanics are present in Horse Spring sections; surely these great effusions would have filled any subsiding basins near the present location of Lake Mead. Therefore the reasoning on which the Patsy Mine eruptive history is dated as post-Thumb is equally valid in assigning that history to a date later than the Horse Spring sedimentation.

Volcanic activity, intermittent and moderate in this immediate area until the end of Horse Spring sedimentation, later became more pronounced. Evidence that this activity was accompanied by large-scale movements on fault blocks has been cited on earlier pages, in descriptions of the volcanic formations. These formations establish an order of events, and the absolute-age value of 50 million years for the Boulder City pluton (p. E17) gives a clue in the search for geologic dates. This value indicates a middle Eocene date for the pluton, and the relation of this body to adjoining lavas suggests a closely similar date for the Golden Door volcanics. The Patsy Mine volcanics are older; but the early part of the Eocene epoch was long, and this volcanic episode may have occupied only a small fraction of that time. As all available evidence indicates that the Horse Spring formation was laid down before the Patsy Mine episode, that formation is dated logically as Eocene or older. Additional radiogenic age values are needed to check the few now available.[7]

The Mount Davis volcanics can now be dated only within wide limits. South of Rifle Range Wash lavas and tuffs in the upper part of the Mount Davis sequence overlie a surface of erosion that transects part of the Golden Door volcanics. At the northwest corner of Malpais Mesa, sedimentary deposits in the upper part of the Mount Davis sequence grade upward, without perceptible break, into a section mapped as part of the Muddy Creek formation. If this correlation and the tentative date for the Muddy Creek are accepted, the Mount Davis history is bracketed between middle Eocene and Pliocene dates.

Sediments of the Muddy Creek formation reflect relief maintained by continued movements on faults (figs. 3, 12). Coarse deposits at the margins of basins grade into or intertongue with fine sediments laid down on playas or in open lakes. Several large basins of this kind, with sediments reflecting centripetal drainage and containing great quantities of saline deposits, lie athwart the present course of the Colorado River. Therefore the river, as a through-flowing stream, was not in its present location in Muddy Creek time (Longwell, 1946, p. 821). Great thicknesses of gypsum and anhydrite in the lower part of the Muddy Creek formation east of Boulder Canyon pose a problem of origin. Estuarine beds in southwestern Arizona record a northward encroachment of the sea in Pliocene or Miocene time (Wilson, 1933, p. 31). Conceivably the arm of the sea extended 200 miles north of these known deposits to the present site of Lake Mead; but this speculation has no support in known evidence. Perhaps the saline deposits of the Muddy Creek were derived from older formations and concentrated in interior basins.

Widespread lavas in the lower and upper parts of the Muddy Creek are almost entirely basaltic. Progressive changes in average composition of volcanic rocks in the general region are of considerable interest. The Patsy Mine volcanics, which were erupted through more silicic plutons that probably gave off volcanic products, are predominantly andesitic; but the upper part of the Patsy Mine volcanics includes a unit of rhyolite glass, overlain by considerable basalt. The Golden Door sequence starts with latites and in general becomes more siliceous upward to a predominance of rhyolites. Mount Davis rocks are predominantly basalts and dark andesites, interrupted sharply at several horizons by tuffs and glasses that range in composition from latite to rhyolite. The rule of basalt begun in Muddy Creek time continued into the Pleistocene. Thus there has been more than one pronounced swing in predominance from high to low silica content in the volcanic products, and several brief but pronounced changes in composition during each major episode.

Any outline of structural development within the area can be in general terms only until more specific information may become available. Large-scale thrust faulting, widespread in the region on the north and west, did not directly involve the Frenchman Moun-

[7] See footnote, p. E17.

tain block which was tilted strongly and broken by normal faults (fig. 13). But probably this tilting occurred in connection with movement on large strike-slip faults that were active in late stages of the regional thrusting. Since the Horse Spring formation is tilted as steeply as older formations, deformation under regional compression may have continued from Cretaceous into Cenozoic time.

Vertical displacements on steep faults have been recurrent through several long epochs. Landslide breccias in the Thumb formation suggest that an east-west fault or fault zone, with upthrow on the south, was active near the latitude of Boulder Basin in late Cretaceous time. Presumably the large normal faults that break the Frenchman Mountain block were developed and rotated to their present attitudes during the tilting movement that began early in the Cenozoic era. Important faulting in the several episodes of volcanism is attested by abrupt terminations of thick volcanic sequences, and by localized occurrences within these sequences of very coarse sedimentary debris, presumably shed from growing scarps. As this kind of evidence is especially pronounced in the Mount Davis sections, perhaps the faulting activity was at a maximum during that volcanic episode, which on the basis of the present tentative chronology continued into the Pliocene epoch. Some faults, occurring singly or in sets, are localized near plutonic bodies and probably reflect stresses during intrusion. But the larger faults that were active at the time of Mount Davis volcanism and later have the northerly orientation that is characteristic in neighboring parts of the Basin and Range province. This regional pattern was well established through Muddy Creek time.

The earliest known Colorado River deposits in the area are unconformable on beds of the Muddy Creek, and are of Pliocene or Pleistocene age (Longwell, 1946, p. 828). Presumably the course of the stream in deep gorges such as Boulder Canyon and Black Canyon, a course that appears illogical in relation to present topography, has resulted from superposition as the river cut down from a higher horizon where it had its initial course on the weak Muddy Creek formation. Local remnants of these weak beds, capped by the Fortification basalt member (fig. 3), testify that the formation once obliterated much of the rugged relief now supported by resistant bedrock. Possibly the important movements on faults that have occurred at least locally since the stream course was established have increased relief in the vicinity of Boulder Canyon.

Apparently no major changes in the course of the river have occurred between Boulder Canyon and Davis Dam. One may suspect that a former course extended southward from the lower part of Kingman Wash; a depression filled with old slope debris from the Black Mountains has some resemblance to a large abandoned stream valley (fig. 9). But no Colorado River gravels are found there, and the depression probably owes its origin to progressive eastward tilting of the block southwest of the Horsethief fault. Minor changes in the course occurred as the river cut down through the lake deposits of the Chemehuevi formation. At Davis Dam the modern valley runs obliquely across the earlier trench which is filled with the lake sediments (fig. 6). Many temporary locations of the stream channel at various levels on the lake beds were abandoned in later adjustments; the high-level potholes and terrace remnants near Hoover Dam mark one such location.

Origin of the Pleistocene Lake Chemehuevi presents a problem of much interest. Through hundreds of miles downstream from the Grand Canyon, many remnants of the basal lake deposits lie close to the river channel (fig. 6); therefore, the stream returned almost exactly to its earlier profile, once the obstruction that caused ponding was removed. A natural dam in a narrow canyon, formed by lavas or a landslide, seems the most likely cause. South of Davis Dam the only restricted part of the valley with walls high enough to meet requirements is Aubrey Canyon in the Whipple Mountains, where Parker Dam is located. No evidence of a breached natural dam has been found there; moreover, many remnants of lake beds lie downstream from Aubrey Canyon. Solution of the problem will require careful study in a large part of the lower Colorado River valley.

REFERENCES CITED

Campbell, Ian, and Schenk, E. T., 1950, Camptonite dikes near Boulder Dam, Arizona: Am. Mineralogist, v. 35, nos. 9–10, p. 671–692.

Darton, N. H., and others, 1924, Geologic map of the State of Arizona: Arizona Bur. Mines, in cooperation with U.S. Geol. Survey.

Gilbert, G. K., 1875, Report on the geology of portions of Nevada, Utah, California, and Arizona: U.S. Geog. and Geol. Surveys W. 100th Meridian Rept. (Wheeler), v. 3, p. 17–187.

Hatch, F. H., Wells, A. K., and Wells, M. K., 1949, The petrology of the igneous rocks: 10th ed., London, Thomas Murby and Co.

Hunt, C. B., McKelvey, V. E., and Wiese, J. H., 1942, The Three Kids manganese district, Clark County, Nev.: U.S. Geol. Survey Bull. 936–L, p. 297–319.

Ives, J. C., 1861, Report upon the Colorado River of the West: Washington, U.S. Govt. Printing Office.

Larsen, E. S., Jr., and others, 1952, Method for determining the age of igneous rocks using the accessory minerals: Geol. Soc. America Bull., v. 63, no. 10, p. 1045–1052.

LaRue, E. C., 1925, Water power and flood control of Colorado River below Green River, Utah: U.S. Geol. Survey Water Supply Paper 556, 176 p.

Lausen, Carl, 1931, Geology and ore deposits of the Oatman and Katherine districts, Arizona: Arizona Bur. Mines Bull. 131, Geol. ser. 6, (Univ. Bull., v. 2, no. 2), 126 p., 30 figs.

Lee, W. T., 1908, Geologic reconnaissance of a part of western Arizona: U.S. Geol. Survey Bull. 352, 96 p.

Longwell, C. R., 1928, Geology of the Muddy Mountains, Nev.: U.S. Geol. Survey Bull. 798, 152 p.

———1936, Geology of the Boulder Reservoir floor, Arizona-Nevada: Geol. Soc. America Bull., v. 47, no. 9, p. 1393–1476.

———1946, How old is the Colorado River?: Am. Jour. Sci., v. 244, no. 12, p. 817–835.

———1949, Structure of the northern Muddy Mountain area, Nevada: Geol. Soc. America Bull., v. 60, no. 5, p. 923–968.

———1951, Megabreccia developed downslope from large faults: Am. Jour. Sci., v. 249, no. 5, p. 343–355.

McKee, E. D., 1951, Sedimentary basins of Arizona and adjoining states: Geol. Soc. America Bull., v. 62, no. 5, p. 481–506.

McKelvey, V. E., Wiese, J. H., and Johnson, V. H., 1949, Preliminary report on the bedded manganese of the Lake Mead region, Nevada and Arizona: U.S. Geol. Survey Bull. 948–D, p. 83–101 [1952].

Marcou, Jules, 1858, Geology of North America, etc., 144 p., map: Zurich, Switzerland. Review in Am. Jour. Sci., v. 26, p. 323–333.

Newberry, J. S., 1861, Geological report, *in* Ives, J. C., Report upon the Colorado River of the West: U.S. 36th Cong., 1st sess., House Executive Doc. 90, pt. 3, 154 p.

Ransome, F. L., 1904, Description of the Globe quadrangle [Ariz.]: U.S. Geol. Survey Geol. Atlas, Folio 111.

———1907, Preliminary account of Goldfield, Bullfrog, and other mining districts in southern Nevada: U.S. Geol. Survey Bull. 303, 98 p.

———1923a, Geology of the Oatman gold district, Ariz., a preliminary report: U.S. Geol. Survey Bull. 743, 58 p.

———1923b, Ancient high-level potholes near the Colorado River [abs.]: Science, New ser., v. 57, p. 593.

Schrader, F. C., 1909, Mineral deposits of the Cerbat Range, Black Mountains, and Grand Wash Cliffs, Mohave County, Ariz.: U.S. Geol. Survey Bull. 397, 226 p.

Simpson, G. G., 1933, A Nevada fauna of Pleistocene type and its probable association with man: Am. Mus. Novitates, v. 667, p. 1–10.

Spieker, E. M., 1946, Late Mesozoic and Early Cenozoic history of central Utah: U.S. Geol. Survey Prof. Paper 205–D, p. 117–161.

Stock, Chester, 1921, Later Cenozoic mammalian remains from the Meadow Valley region, southeastern Nevada: Am. Jour. Sci., 5th ser., v. 2, p. 250–264.

U.S. Bureau of Reclamation, 1950, Geological investigations *in* U.S. Bur. Reclamation, Boulder Canyon Project final reports: pt. 3, Bull. 1, 231 p.

Wilson, E. D., 1933, Geology and mineral deposits of southern Yuma County, Arizona: Arizona Bur. Mines Bull. 134, Geol. ser. 7, 236 p.

INDEX