Geology and Artesian Water Supply Grand Junction Area Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 451

Prepared in cooperation with the Colorado Water Conservation Board

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By S. W. LOHMAN

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[Plates are in pocket]

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GEOLOGY AND ARTESIAN WATER SUPPLY OF THE GRAND JUNCTION AREA, COLORADO

By S. W. Lohman

ABSTRACT

The Grand Junction area, as defined in this report, comprises about 332 square miles in the west-central part of Mesa County, Colo.; it includes the part of the northeastern flank of the Uncompahgre Plateau known as Piñon Mesa and the southwestern side of the Grand Valley including parts of Orchard Mesa and the Redlands. The area also includes the Colorado National Monument, noted for its colorful cliffs and deep canyons, and Grand Junction—the largest city in western Colorado.

The highest part of the area, on the flank of Piñon Mesa, has an altitude of about 8,200 feet. From the mesa the surface slopes gently northeastward to the Colorado River, which leaves the northwest corner of the area at an altitude of about 4,430 feet. The area as a whole has a relief of more than 3,700 feet. The northeastward-sloping surface is interrupted by a series of faults and monoclines and is cut by many deep canyons, some of which are 500 to 1,000 feet deep. Many of the canyon walls, particularly in the Colorado National Monument, are sheer cliffs of the Wingate Sandstone and, locally, even higher cliffs are formed by the Wingate and overlying formations.

The area is drained by the Colorado and Gunnison Rivers, at whose confluence Grand Junction is situated. Most of the tributaries are ephemeral because of the mild arid climate.

The varied flora and fauna include types adapted to climates ranging from arid to subhumid.

Soon after settlement of the area began in 1881 it was realized that crops could not be grown successfully without irrigation, and the first irrigation system was begun near Palisade in 1882. By 1960 nearly 100,000 acres of the Grand Valley was under ditches, mainly from the Colorado River but in part from the Gunnison River. Seventy to eighty percent of this area was irrigated most seasons. Much of the irrigated land is in fruit orchards, mainly peaches, but many other crops also are grown.

The geologic map accompanying this report (scale 1:31,680) is the first detailed geologic map of the Grand Junction area, and is the result of the first geologic mapping in the area since the reconnaissance by members of the Hayden survey in 1875 and 1876.

The pre-Quaternary geologic formations exposed in the Grand Junction area range in age from Precambrian to Upper Cretaceous and include Precambrian schist, gneiss, granite, and pegmatite; Chinle Formation and Wingate Sandstone, Upper Triassic; Kayenta Formation, Upper Triassic(?); Entrada Sandstone (Slick Rock and Moab Members), Summerville Formation, and Morrison Formation (Salt Wash and Brushy Basin Members), Upper Jurassic; Burro Canyon Formation, Lower Cretaceous; and Dakota Sandstone and Mancos Shale, Upper Cretaceous.

A profound unconformity separates an almost smooth erosion surface on the Precambrian complex from the Chinle Formation and marks the absence from this area of part of the Precambrian, all the Paleozoic, and much of the Triassic, including most of the Chinle. This old erosion surface was formed on the San Luis-Uncompahgre highland, which was a mountainous area undergoing erosion from Pennsylvanian to Late Triassic time.

The 80 to 120 feet of the Chinle Formation present in the area, which has been correlated with the Church Rock Member, consists largely of soft red siltstone, but it also contains thin hard ledge-forming beds or lenses of red siltstone, limestone, and conglomerate, and thin layers of greenish siltstone. The Chinle yields no water to wells in this area.

The Wingate Sandstone, which conformably overlies the Chinle Formation, comprises about 215 to 370 feet of mainly buff to reddish-buff or red, very fine-grained sandstone and some fine-grained sandstone, silt, and clay. The Wingate is well cemented and generally forms cliffs or steep slopes, particularly in the Colorado National Monument. It is partly crossbedded and partly level bedded, and is in part of eolian origin and in part fresh-water laid. The Wingate is the thickest and lowermost of four artesian acquifers in the area; it yields small supplies of generally soft water to a few wells whose main supply comes from the overlying Entrada Sandstone.

In the western part of the area the Wingate Sandstone is overlain conformably by 16 to 80 feet of the Kayenta Formation, but in the southeastern part, where the Kayenta is absent, the Wingate is separated from the overlying Entrada Sandstone by an erosional unconformity. The Kayenta consists mainly of fluvial lenticular to irregularly bedded layers of fine- to medium-grained sandstone, irregular lenses of red, purple, or green siltstone, and a few lenses of conglomerate or conglomeratic sandstone. The Kayenta is not an aquifer in this area.

An erosional unconformity at the base of the Entrada Sandstone marks the absence from this area of much of the Entrada, all the Carmel Formation and Navajo Sandstone, most of the Kayenta Formation west of North East Creek, and all the Kayenta and possibly part of the Wingate Sandstone in and east of North East Creek Canyon.

In this area the Entrada Sandstone comprises the Slick Rock and Moab Members, which together form a distinctive and colorful series of cliffs in much of the lower part of the area, but which weather to more subdued forms at higher altitude. The beds of the Slick Rock are partly crossbedded and partly level bedded and are probably wholly continental eolian and water-laid deposits. The overlying, generally white or light-buff Moab Member is made up of thin, evenly bedded sandstones that generally weather to a series of steps or benches. The Moab may represent a beach deposit laid down on the margin of the Curtis sea, and is probably of Curtis age. The Entrada ranges in thickness from 100 to 200 feet in the western part of the area to about 60 feet in the eastern part, and consists mainly of fine to very fine grained sand, some medium-grained sand, and some silt and clay, all cemented by calcium carbonate.

The Slick Rock Member generally contains, particularly near the base, scattered grains or laminae of coarse-grained sand known as "Entrada berries." The Entrada is the principal artesian aquifer in the area, and yields small amounts of generally soft water.

The Summerville Formation conformably overlies the Moab Member of the Entrada Sandstone. The Summerville, which is only 40 to 60 feet thick in this area, consists mainly of thin beds of gray, blue-gray, greenish-gray, chocolate-brown, reddish-brown and red siltstone; thin beds of gray, yellow, greenish-gray, and reddish-gray fine- to medium-grained, hard, laterally persistent sandstone; thin beds of shale and mudstone; and, near the top, at least one thin bed or lens of limestone. The Summerville probably was formed as a marginal marine deposit in shallow water, possibly in or near a shallow arm of the Summerville sea. The Summerville yields no water to wells in this area, but it and the overlying Morrison Formation serve as a confining bed to artesian water in the underlying Entrada and Wingate Sandstones.

The Summerville Formation is overlain, probably conformably, by the Morrison Formation, which, in this area, includes only the Salt Wash and Brushy Basin Members. The Morrison comprises a varied and colorful assemblage of beds of siltstone, mudstone, sandstone, some conglomerate and limestone, and a little fresh and altered volcanic ash. The sandstones are highly lenticular and generally restricted to the Salt Wash Member, but locally the Salt Wash is nearly devoid of sandstone, and in other places a few sandstone lenses occur in the Brushy Basin Member. The Morrison, the lower one-third to one-half of which is formed by the Salt Wash Member, is 500 to 600 feet thick in this area; it has yielded fresh-water invertebrate fossils and many dinosaur remains, including the type specimen of *Brachiosaurus altithorax* Riggs. Sandstone lenses in the Salt Wash Member yield small supplies of soft water to a few flowing artesian wells.

The Burro Canyon Formation is virtually conformable on the Brushy Basin Member of the Morrison Formation, and locally the two units intertongue. In the western part of the area the Burro Canyon is 50 to 60 feet thick and consists mainly of green shale, but it includes a basal sandstone or conglomerate and one or more additional beds of sandstone; in the eastern part the Burro Canyon is as much as 120 feet thick and dominantly sandstone in most places. The Burro Canyon and Dakota yield small supplies of water to a few nonflowing artesian wells, but in most places the water is salty or brackish.

An erosional unconformity separates the Burro Canyon Formation from the overlying Dakota Sandstone. The Dakota, which probably is more than 200 feet thick, comprises a basal white sandstone or conglomerate, dark lignitic shale, lignite coal, and beds of buff sandstone. Some of the sandstone beds are fluvial but others are beach deposits formed in the gradually transgressing Mancos sea, and the lignitic beds were formed in coastal swamps.

The contact between the marine Mancos Shale and the Dakota sandstone is conformable and gradational, and locally the two formations intertongue. The Mancos, which is 3,800 feet thick in the general area, underlies most of the Grand Valley and forms most of the Book Cliffs, which border the valley on the northeast, but only the lowermost few hundred feet of the Mancos is present in the area mapped. It is a drab sequence of mainly soft olive-gray to gray-black fissile shale that contains a few sandy zones, thin beds of sandstone, and some light-buff to cream-colored chalky shale. The Mancos contains no usable shallow ground water, but it serves to confine artesian water in the Burro Canyon and Dakota Formations.

Although the Mancos Shale is the youngest pre-Quaternary formation in the Grand Junction area, deposits of late Mesozoic and Tertiary age remain in the Piceance Creek basin just to the northeast of the area, some of which probably formerly covered the Grand Junction area. There the marine Mancos is succeeded by the partly marine and partly continental Mesaverde Group and the wholly continental Paleocene and Eocene Wasatch Formation, the Green River Formation, and post-Green River basalt flows.

The Uncompahgre arch probably began to rise at about the close of the Cretaceous; it received renewed uplift and folding in post-Green River time, when the Green River Formation and older rocks were folded to form the Unita and Piceance Creek structural basins. Although late Tertiary vulcanism occurred in some nearby areas, events of Oligocene and Miocene times were not recorded in the Grand Junction area except for the outpouring of lava sometime after the Green River deposition.

The course of the Colorado River may have been established by superposition before or soon after extrusion of the post-Green River lavas, and, during epeirogenic uplifts in late Miocene to middle Pliocene time, the streams deepened their channels without regard to hardness of rocks or underlying structure. It seems likely that Unaweep Canyon was cut down to and probably into the Precambrian core of the Uncompahgre Plateau during this interval.

There is evidence that renewed differential uplift of the Uncompahgre arch occurred in Pliocene time, before abandonment of Unaweep Canyon, and again in latest Pliocene and earliest Pleistocene time, after abandonment of the canyon. Evidence is presented that abandonment of Unaweep Canyon was caused by successive captures of the superposed ancestral Colorado and Gunnison Rivers by a subsequent tributary of the ancestral Colorado that cut in the soft Mancos Shale around the northwestward-plunging Uncompahgre arch while downcutting by the ancestral Colorado was retarded by the hard rocks in the canyon. Capture of a tributary (East Creek), probably in the Pleistocene, completed the principal drainage changes.

The drainage divide in Unaweep Canyon stands about 2,500 feet above Gateway and Grand Junction. Studies of dissected pediments and other erosional features in and above Grand Junction suggest that this difference in altitude may include 600 to 800 feet of erosion and 1,700 to 1,900 feet of differential uplift of the Uncompahgre arch that occurred subsequent to abandonment of Unaweep Canyon in the Pliocene. The deep cliff-walled canyons in and near the Colorado National Monument were cut during this erosion interval. The nearly vertical, generally sun-facing cliffs probably were formed in part by daily alternate freezing and thawing in the winter, while the gentler northward-facing canyon walls remained frozen for long periods; the ephemeral streams in these canyons serve mainly as sewers to carry away the products of several types of erosion. During the latest period of erosion, pediments were cut in places and minor amounts of terrace deposits, pediment deposits, landslide deposits and alluvium were laid down.

The structure of the area is shown on the geologic map by structure contours drawn on top of the Entrada Sandstone, by one short cross section, by several stereoscopic pairs of aerial photographs, and by oblique aerial photographs. The strata on the northeastern flank of the Uncompahgre arch dip gently toward the Piceance Creek basin to the northeast, except where interrupted by a series of named major monoclines and faults generally parallel or nearly parallel to the axis of the uplift and

by some minor structural features that trend in various directions There probably were several successive periods of deformation, but many of the details are obscure. The monoclines, whose upper bends generally are sharper than the lower bends, probably are the result of lateral compression from the southwest or northeast. The faults all seem to be dip slip and are mainly normal. One fault (Redlands fault) is normal throughout most of its 6-mile length, but in two places it is a reverse fault that dips about 45° to the southwest, presumably because of rotation of a vertical fault by later compressive forces. Because the principal structural features have an important bearing on the recharge areas of the Entrada and Wingate Sandstones, they were examined in detail.

The total structural displacement of the Uncompahgre arch within or near the area is about 5,000 feet, 1,600 to 1,900 feet of which is presumed to have occurred in late Pliocene or early Pleistocene time, and about 3,100 to 3,400 feet of which occurred earlier, probably mainly in post-Green River time.

Unconfined ground water is relatively unimportant in the Grand Junction area, and its occurrence is discussed only briefly. Most of the Grand Valley is almost devoid of shallow ground water, and such meager supplies as are obtainable locally from soil, weathered rock, arroyo fill, or terrace deposits generally are too highly mineralized for most uses. Where thick, the alluvium along the principal streams should yield considerable water, but the water probably would be too hard for domestic use. Small supplies of unconfined water of reported good quality are obtained from the Entrada or the Wingate Sandstone in parts of Glade Park.

Confined, or artesian, ground water is obtained from four artesian aquifers in the Grand Junction area, which are, in order of importance and productivity: (1) the Entrada Sandstone, (2) the Wingate Sandstone, (3) lenticular sandstones in the Salt Wash Member of the Morrison Formation, and (4) the Dakota Sandstone and sandstones in the Burro Canyon Formation. These aquifers contain water under artesian pressure only in areas northeast of the principal faults and monoclines, where they are overlain by younger, relatively impermeable strata that serve as confining beds. In these areas, determination of depth to the two principal aquifers, the Entrada and the Wingate, is facilitated by use of the structure contours. The top of the Entrada has been reached at depths ranging from 188 to 1,555 feet, but in most wells it is reached at 600 to 800 feet.

The finding of water in the Morrison Formation is generally not predictable owing to the lenticularity of the sandstone beds. Water in the Dakota and the Burro Canyon Formations generally is of poor quality for most uses.

The coefficients of transmissibility (T) and storage (S) were determined in the field for 11 of the 48 artesian wells for which records are given, by flow tests using equipment and methods designed for this investigation; the T values were checked by the Theis recovery method and in part by laboratory determinations of outcrop samples. The average values of T and S for the Entrada Sandstone are 150 gpd per ft (gallons per day per foot) and 5×10^{-5}, respectively, and scanty data for the combined Entrada and Wingate Sandstones suggest values of about 300 gpd per ft and 10^{-4}. Field tests of wells tapping a sandstone lens in the Morrison Formation indicate T values of only 35–50 gpd per ft. No tests were made of wells in the Dakota and Burro Canyon Formations. Field and laboratory tests of the two principal aquifers suggest coefficients of permeability of about 1 gpd per sq ft (gallons per day per square foot) and 0.5 gpd per sq ft, respectively. The laboratory tests indicate that the permeability of these sandstones parallel to the bedding planes is much greater than at right angles to this direction.

The artesian aquifers are recharged mainly where streams cross the outcrops, but a small amount of recharge may result from precipitation on the outcrops. Except for the Gunnison River and North East Creek, the streams that produce recharge are all ephemeral. Because of the low permeability of the aquifers, the rate of recharge probably is very small and not readily determinable.

From known and assumed nondischarging conditions, an average velocity is computed for down-dip movement of water in the Entrada Sandstone to be only about 0.013 foot per day, or about 5 feet per year.

Natural discharge from the aquifers probably occurs throughout the Piceance Creek basin by slow leakage upward through relatively impermeable confining beds and possibly along faults. It is postulated that the amount of such natural discharge at any one place is too small to measure by conventional methods and that such water as may reach the surface probably is in a gaseous state.

The first deep wells in the Grand Junction area seemingly were drilled in the hope of finding oil or gas, but artesian water was found instead. The first well may have been drilled in 1903 or 1904, and by 1946 only 14 wells were in use, 13 of which were flowing wells. Twenty-seven additional wells were drilled during the 10-year period, 1947–56, but before the end of this period interference between wells had caused considerable decline in artesian heads and flows, some well owners had installed pumps, and enthusiasm for drilling additional wells had diminished. Thus, from 1956 to 1960, only seven additional wells were drilled.

Forty-three of the 48 wells for which records were obtained were drilled by the cable-tool method, and five wells were drilled all or in part by the hydraulic-rotary method. Most of the wells contain at least two casings, but some contain one to four. Many different types of commercial or homemade well seals, generally augmented by gravity or pressure cementing, were used, but in some wells water is leaking to the surface. Most of the wells are cased only to the well seal above the aquifer and are open holes through or into the aquifer, but a few have perforated pipe, and two wells have well screens surrounded by gravel. By 1960 most of the wells had been equipped with jet, turbine, or submersible pumps.

Because of the low permeability of the artesian aquifers, the wells have small yields by either natural flow or pumping, and average specific capacities of less than 0.1 gpm per foot of drawdown for the Entrada Sandstone, slightly more than 0.1 gpm per ft for the Entrada and Wingate Sandstones, and as low as about 0.01 gpm per ft for some wells in the Morrison Formation. Most of the wells are operated at rates of 5 to about 40 gpm; larger rates generally are not practicable. Such wells would be considered dry holes in many parts of the country but are valued in the arid Grand Junction area where water of good quality is scarce.

Curves are given in the report to show the amount of drawdown that might be expected at different distances from wells discharging at given rates for different periods of time from the two principal artesian aquifers. These curves show that there is considerable drawdown interference between wells in the same aquifer or aquifers, particularly in the most intensely developed areas.

Initial artesian heads ranged from near land surface to more than 150 feet above land surface, but overdevelopment and interference between wells has caused known declines in head of more than 50 feet in some wells and probably more than 100 feet in a few others.

Analyses of 26 samples of water from 23 wells are given to indicate the quality of water from the principal artesian aquifers.

The samples from the Entrada Sandstone or the Entrada and Wingate Sandstones were soft sodium bicarbonate water, most of which had a hardness of less than 50 ppm (parts per million) and some of which had a hardness of 10 ppm or less; three samples had a hardness ranging from 100 to 124 ppm. Samples from the Morrison were soft sodium bicarbonate-sodium sulfate water. These waters are of good quality for domestic use, but contain high percentages of sodium and may be harmful to certain plants or crops. No samples were obtained from the Burro canyon Formation or Dakota Sandstone, but reports from well drillers and owners indicate that the water generally is brackish or salty.

In all the water analyzed, the relative softness is attributed to natural softening by base exchange, whereby calcium and magnesium ions in the water are exchanged for sodium ions in certain minerals in the aquifers and thus remove part or most of the hardness-producing calcium and magnesium from the water. Petrographic and X-ray examinations of samples of the Entrada and Wingate Sandstones indicate that clay minerals cause the softening. There is an almost linear decrease in hardness of water in the Entrada with increased distance from the recharge area.

Most of the artesian water in the Grand Junction area is used for domestic purposes, either by the owner alone, by the owner and nearby homes connected by pipeline, or by hauling to homes equipped with storage tanks or cisterns. From 1 to as many as 30 tank-loads (1,100-gallon tanks) per day are hauled from 13 of the wells. Some of the water is used for watering livestock, filling a swimming pool, supplying a meat-packing plant, or watering small plots of lawn or shrubs.

Declines in artesian heads and flows indicate that the principal aquifer—the Entrada Sandstone and to a lesser extent the Wingate Sandstone—have been overdeveloped in parts of the Grand Junction area, but two relatively large areas are undeveloped or only slightly developed and would yield additional water to wells, preferably spaced more than a mile apart. One area comprises the southwest side of the Grand Valley and the Redlands, in and northwest from the northwestern part of the area. The other area comprises the southwestern side of the Grand Valley, parts of Orchard Mesa, and the lower part of the Gunnison River Valley in and southeast from the eastern part of the area.

Grand Junction and Fruita have municipal water supplies piped from distant surface-water sources. The Colbran Project of the U.S. Bureau of Reclamation will supply water for irrigation and power in Plateau Creek valley north of Grand Mesa and to the Ute Conservancy District for piping to several cities and towns and most rural residents in the Grand Valley, including those of the Redlands and Orchard Mesa. Completion of this water system should greatly reduce the draft on the artesian wells in in the Grand Junction area. This reduction should arrest the decline of the artesian head or should allow the head to recover gradually. Because of the small rate of recharge, however, the recovery in head will take considerable time.

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

An investigation of the geography, geology, and artesian water supply of the Grand Junction area, Mesa County, Colo., was begun in 1946 as a part of the program of cooperative ground-water investigations being made by the Colorado Water conservation Board and the U.S. Geological Survey. The study was the outgrowth of a request from the late Mr. Frank C. Merriell, a widely known water engineer of Grand Junction to the late Judge Clifford H. Stone, former Director of the Colorado Water Conservation Board, concerning the degree of interference between flowing artesian wells in the Grand Junction area and the danger of even greater overdevelopment. The purpose of the study first was to determine the locations, depths, and yields of the wells, hydrologic properties of the aquifers, chemical quality of the water, and degree of interference between wells. Later, the investigation was broadened to include studies of the recharge conditions and areas of outcrop of the several aquifers, which required a detailed study of the geology of the area.

The Grand Valley, which includes the northeastern part of the area studied, is underlain largely by the thick Mancos Shale, which is nearly devoid of usable ground water. For this reason, rural domestic water has to be hauled either from the few towns having water-supply systems or from some of the artesian wells described in this report. The wells are along the southwestern side of the Grand Valley, mainly in tracts known as Orchard Mesa and the Redlands. As the population and water needs grew, more and more wells were drilled and the draft on each well increased, as did attendant interference between wells and lowering of the artesian head. The demand for artesian water was accelerated during and after World War II owing to the exploration for and development of uranium in areas southwest of Grand Junction, which served as headquarters for many of these operations and, hence, increased in population. Information gained during this investigation has been requested by many well owners, drillers, engineers, geologists, lawyers, and others ever since the work began and has been very helpful in solving some of the water problems. It is hoped this report will augment the assistance already given to some by making the information available to all who need it. The investigation was under the direct supervision of S. W. Lohman, T. G. McLaughlin, and E. A. Moulder, successive district supervisors in charge of cooperative ground-water investigations in Colorado,

LOCATION AND SIZE OF AREA

The Grand Junction area, as referred to in this report, comprises about 332 square miles in the west-central part of Mesa County, in central-western Colorado. It lies between lat 38°47½′ and 39°12½′ N., and long 108°25′ and 108°47½′ W. The location of the Grand Junction area and of other areas in Colorado in which cooperative ground-water studies have been made or are in progress is shown in figure 1.

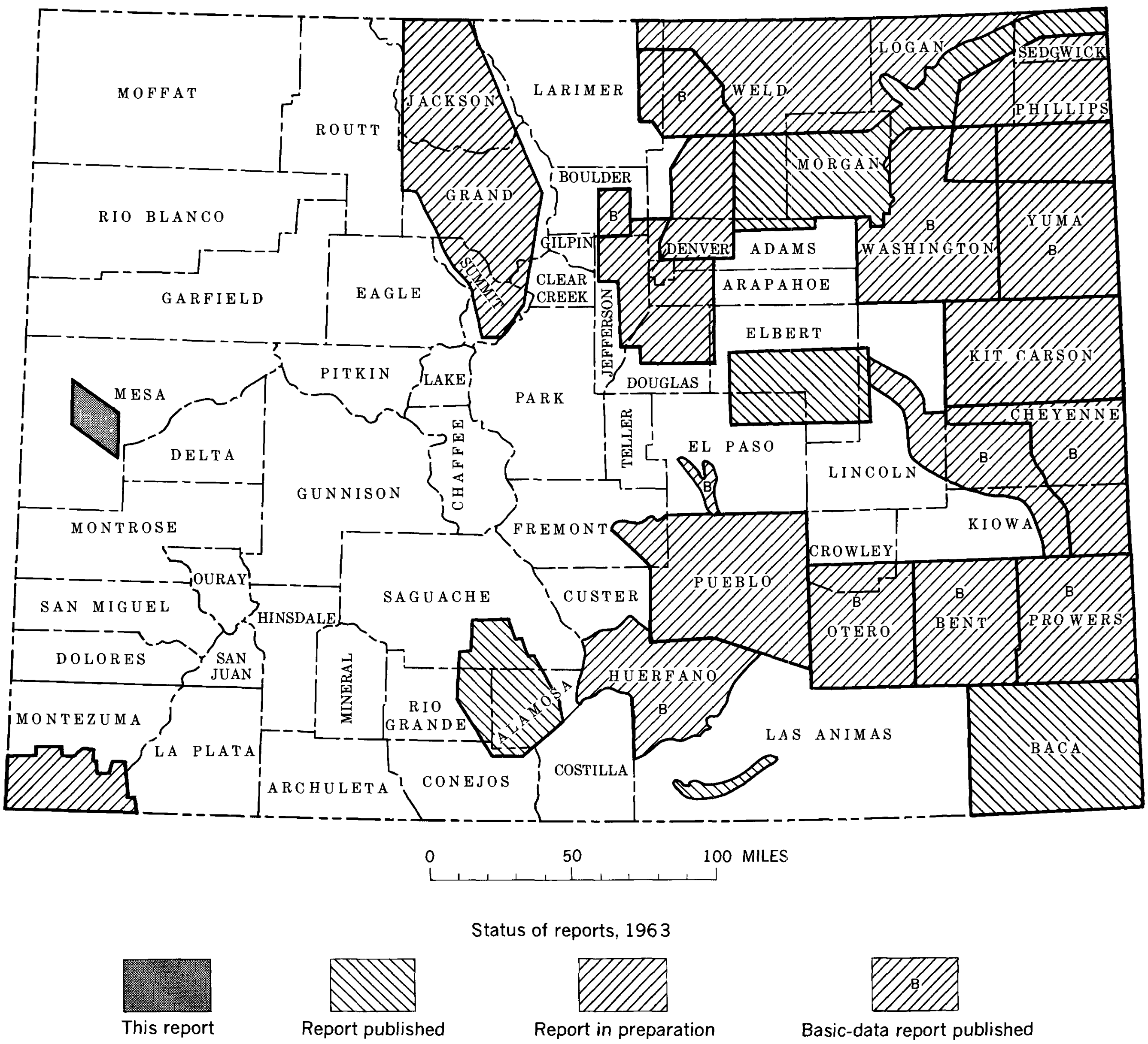

FIGURE 1.—Index map of Colorado showing area described in this report and other areas in which ground-water studies have been made or are in progress.

The Grand Junction area includes all the Colorado National Monument, the boundaries of which are shown in plate 1.

PREVIOUS INVESTIGATIONS

The first topographic and geologic maps of the Grand Junction area and of Colorado were the result of work by the U.S. Geological and Geographical Survey of the Territories (Hayden, 1877b). The topography and geology of the Grand Junction area were studied and mapped by those masters of reconnaissance, Henry Gannett and A. C. Peale, respectively, in 1875 and 1876—long before there were any white settlers or towns. In his report on the Grand River District, Peale (1877) made many observations on the geology. In a 28-page letter of transmittal of the progress report for 1875, Hayden (1877a, p. 26) said: "When [the survey is] finished, Colorado will have a better map than any other State in the Union, and the work will be of such a character that it will never need to be done again. Colorado will never support so dense a population that a more detailed survey will be required." Nevertheless, by 1913 the growth of the State and the completion of more detailed geologic studies of the major mining districts led to the publication of a new geologic map of Colorado (George and others, 1913).

For the 1913 geologic map of Colorado, that part of the Grand Junction area southwest of the Grand [Colorado] and Gunnison Rivers was taken from the geologic map of the Hayden survey, but the parts northeast of these rivers were taken from coal studies by Richardson (1909) and Lee (1912) of the U.S. Geological Survey.

In 1935 a more detailed geologic map of Colorado on a revised base was prepared by the U.S. Geological Survey in cooperation with the Colorado Metal Mining Fund. Changes shown in the geology of the Grand Junction area included more detailed geology of the Book Cliffs and a part of the Grand Valley by Erdmann (1934), of parts of the Gunnison and Grand Valleys by Campbell (1922), of parts of the Gunnison River valley by Weeks (1925), and changes in nomenclature and some revisions in geologic contacts of the area southwest and west of Grand Junction by C. H. Dane and C. B. Hunt, done in connection with an investigation in Grand County, Utah (Dane, 1935). The 1935 geologic map of Colorado includes considerable revisions in southwestern Colorado based upon the geologic mapping of Coffin (1921), but his geologic map does not extend far enough north to touch the Grand Junction area.

Several reports of the U.S. Geological Survey on areas in eastern Utah, published in the twenties and thirties, had an important bearing on the stratigraphic units now in use in the Grand Junction area, notably those of Gilluly and Reeside (1928) and Baker, Dane, and Reeside (1936). The sudden demand for uranium during World War II prompted detailed studies of known and potential uranium-producing areas and formations of southwestern Colorado, southeastern Utah, and adjacent parts of Arizona and New Mexico by the U.S. Atomic Energy Commission, the U.S. Geological Survey, and private parties. These studies provided a wealth of geologic information on the area to the southwest of the Grand Junction area, and some of the general studies included geologic sections measured within the latter area.

The only previous ground-water reports on the area are that of Weeks (1925), which discusses the occurrence of ground water in what are now called the Morrison and Burro Canyon Formations and Dakota Sandstone in the southeast corner of the area, and that of Jacob and Lohman (1952), which briefly describes the artesian aquifers and gives a new method for determining hydrologic properties of artesian aquifers from flow tests of wells.

Several road logs containing information on the geology and artesian water-supply of part of the area have been published (Lohman 1956; 1959; 1960a; Lohman and Donnell, 1959, 1960; Borden, 1960), and brief descriptions of the geology of parts of the area have been published (Lohman, 1960b, 1961a).

HISTORY AND METHODS OF INVESTIGATION

In the fall of 1945, Mr. Frank C. Merriell took me on a trip through the Grand Junction area, during which time all or most of the flowing artesian wells were visited and well owners and well drillers were interviewed. The geology of the recharge areas of the several artesian aquifers also was observed briefly.

The brief inspection of the area indicated that, as a first step toward a better understanding of some of the problems of declining artesian head and interference between wells, it would be necessary to measure the shut-in head of as many wells as possible and to perform pumping or flow tests on selected wells. During the winter of 1945–46, I designed and built an ink-well mercury gage [1] [2] for accurately measuring not only static shut-in head but also slowly recovering head after a period of flow; as a result the recovery method also could be used in determining the transmissibility of the aquifers. A method was developed (Jacob and Lohman, 1952) for determining the coefficients of both transmissibility and storage from a flow test on a single artesian well. The depths of the wells, which ranged from 500 to more than 1,600 feet, precluded the practicability of drilling observation wells, and existing wells were too far apart for use of multiplewell methods.

During the summer of 1946, head and flow tests were made on eight of the artesian wells, records were obtained for other wells, and a reconnaissance was made of the geology of the area. This reconnaissance indicated the need for a more detailed study of the geology to determine the location and nature of the recharge areas, the effect of folding and faulting on the recharge areas, and the lateral changes in character and thickness of the strata. Because most of my time was devoted to administrative matters and because virtually all the funds available for cooperative ground-water studies in Colorado were required for investigations of higher priority in eastern Colorado, fieldwork in the Grand Junction area was carried on intermittently from a week to several weeks each year through 1956. Samples of water were collected from representative wells for chemical analysis in the laboratories of the U.S. Geological Survey, at Albuquerque, N. Mex., and and at Salt Lake City, Utah. Samples of sandstone were collected from the two principal artesian aquifers for determination of physical and hydrological properties in the survey's hydrologic laboratory by W. H.

[1] Lohman, S. W., 1947a, Ink-well gage for measuring artesian head: U.S. Geological Survey, 6 p., mimeographed.

[2] ———1947b, Ink-well mercury gage for measuring artesian head, improved by the use of stainless steel valves: U.S. Geological Survey, 1 p., mimeographed.

Lohman and R. A. Speirer, for petrographic examination by H. A. Tourtelot, and for X-ray determination of the clays by V. J. Janzer, all of the Geological Survey, at Denver, Colo. Measurements of shut-in artesian head were made on certain wells almost annually through 1952 but, because of the increased use of the water, the number of wells for which permission could be obtained for shutting off the flow overnight decreased each year, and after 1952 it was considered impracticable to continue the measurements.

Field mapping of the geology was done on stereo pairs of aerial photographs obtained from the U.S. Soil Conservation Service. The photographs were made in 1937 at a scale of approximately 1:21,000. Parts of the area were accessible by automobile or jeep, but large areas were covered on foot, and much of the Gunnison River Canyon was accessible only by a rail motor car rented from the Denver and Rio Grande-Western Railroad Co.

The geologic and hydrologic data thus obtained sufficed to help many well owners and well drillers in solving water-supply problems and to assist the Mesa County District Court in handling litigation between well owners.

After field mapping of the geology was completed, high-altitude aerial photographs made in 1954 and 1955 became available from the U.S. Army Map Service; these photographs were used by other Survey geologists in preparing photogeologic maps of areas immediately to the south. In order to reconcile the photogeologic mapping and my field mapping, Donald G. Wyant, of the Survey had the geology of the Grand Junction area replotted by Kelsh plotter. The replotting was done by Charles H. Marshall with my part-time assistance. Small inaccessible or relatively inaccessible areas, mostly along the Gunnison River valley in the southeastern part of the area, were mapped photogeologically by Mr. Marshall and me, but most of the resulting map (pl. 1) closely follows my original field mapping. The stereoscopic model scale was about 1:12,000, reduced by pantograph to 1:24,000; this scale was in turn reduced to 1:31,680 during final compilation. Most of the township and section lines and the place and stream names on plate 1 were taken mainly from planimetric base maps prepared by the U.S. Soil Conservation Service, scale 1:31,680, but some were taken from township plats of the U.S. Bureau of Land Management and from maps of the U.S. National Park Service. The roads and drainage were plotted by Mr. Marshall at the time the geology was plotted.

Soon after the Grand Valley and Gunnison River valley were opened to settlement in 1881, a group of townships was surveyed by the General Land Office and referred to the locally established Ute principal meridian and base line. Later, when surveys referred to the sixth principal meridian and base line reached and surrounded the area, the two surveys did not fit properly. As shown on plate 1 the junction of the two surveys follows an irregular boundary and causes some confusion.

The wells on plate 1 and in table 7 are numbered consecutively from 1 to 48 in order by township and section from east to west and from north to south. Within each section the wells are numbered by quarter section in a counterclockwise direction; and a similar system is used within each quarter-quarter section. Locations based on the earlier survey are followed by "Ute P.M." throughout this report.

I was assisted at various times in running flow tests by Thad G. McLaughlin and William J. Powell, U.S. Geological Survey; Charles C. Williams and William R. Smith, formerly with the U.S. Geological Survey; Mahmood Hussain, of Madras Province, India; and by my son, William H. Lohman. I was assisted in the geologic mapping during the summer of 1947 by W. J. Powell, during the summers of 1948 through 1953 by W. H. Lohman, and during the summers of 1955 and 1956 by my sons, James T. and Robert M. Lohman. W. R. Smith also determined the altitudes of measuring points on some of the wells by plane table and alidade.

ACKNOWLEDGMENTS

I am indebted to the many well owners who supplied information on their wells and gave permission for head or flow tests or both, to the several well drillers for logs and other information on wells in the area, and to others in the area who supplied information concerning artesian wells. Special acknowledgment is given to the late Frank C. Merriell for his foresight in making known to the Colorado Water Conservation Board the need for a study of this critical water-supply problem and for his assistance and continued interest during the course of the investigation.

I am indebted to B. R. Finch, Russell Mahan, Homer Robinson, and F. G. Bussey, successive Superintendents, and Dwight L. Hamilton and Pat H. Miller, successive Chief Park Naturalists, of the Colorado National Monument, for assistance in supplying information and in providing access to parts of the Monument not open to the public. Several members of U.S. Geological Survey formerly stationed at Grand Junction provided information on the geology of the area, and I am particularly indebted to Richard P. Fischer, Lawrence C. Craig, J. C. Wright, F. W. Cater, F. G. Poole and Clifford N. Holmes for providing copies of data or geologic sections measured in the area and for many discussions of geologic problems. Mr. Craig also reviewed the section on geology and made many helpful comments. I am greatly indebted to H. A. Tourtelot of the Survey for microscopic and X-ray examination of sandstone and clay samples, and for reviewing parts of the manuscript. I am indebted to V. J. Janzer of the Survey for X-ray and microscopic examination of clay samples. E. B. Leopold, J. H. Irwin, G. E. Lewis, R. A. Scott, S. A. Schumm, D. R. Shawe, R. W. Stallman, F. W. Cater, Ogden Tweto, J. R. Donnell, D. G. Wyant, P. L. Williams, W. R. Hansen, and J. C. Wright, of the U.S. Geological Survey, and W. C. Bradley, of the University of Colorado, read parts of the report and made many helpful suggestions.

I am indebted to the commanding officer of Lowry Air Force Base, U.S. Air Force, Denver, Colo., for authorizing an aerial photographic mission over the Grand Junction area in response to my written request of March 30, 1960, and to Master Sergeants M. M. Friedman and C. M. Fetterman for taking a series of excellent low-angle oblique aerial photographs of the area, two of which are included in this report as figures 29 and 35.

I am greatly indebted to my sons and to my wife, Ruth H. Lohman, who accompanied me during most of the fieldwork, for their assistance and encouragement.

GEOGRAPHY

The Grand Junction area is in the northeastern part of the Canyon Lands section of the Colorado Plateaus province (Fenneman, 1928), the province being more generally referred to simply as the Colorado Plateau. The Canyon Lands section terminates against the Book Cliffs, which form the northeastern wall of the Grand Valley, northeast of which is the Uinta Basin section. The Canyon Lands section is an upwarped plateau containing several large folds, laccolithic mountains that rise above the plateau surface, generally deeply incised drainage, and an intricate set of deep canyons (Hunt, 1956a, p. 2). The Grand Junction area, as defined in this report, contains examples of all these features except laccolithic mountains; but the nearest of these, the La Sal Mountains, are in eastern Utah only about 35 miles to the southwest.

Most of the Grand Junction area is on the northeastern flank of the Uncompahgre Plateau or uplift, but it includes parts of the Grand Valley and the lower Gunnison River valley. The area includes the city of Grand Junction, the town of Fruita, and the villages of Appleton, Whitewater, and Glade Park. A tract of almost flat terrace land south of the Colorado River above the mouth of the Gunnison River is called Orchard Mesa. A rolling and somewhat hilly area south of the Colorado River and between the mouth of the Gunnison River and Fruita is called the Redlands.

When the Gunnison expedition traversed the area in 1853, the present Gunnison River was known by its Spanish name "Rio Javier" or by its Indian name "Tomichi" (Hafen, 1927, p. 269), but Beckwith (1854, p. 57), who wrote the report of the Gunnison expedition, incorrectly referred to what is now named the Gunnison as the Grand River and to what is now named the Colorado River above Grand Junction as the "Blue River" or, as the Indians called it, the "Nah-un-kah-rea." The present Colorado River above Grand Junction was known as the Grand River at least as early as 1842, however (Fremont, 1845, p. 284). The city of Grand Junction was so named because of its position at the junction of the Gunnison and Grand Rivers. The Green and Grand Rivers united in eastern Utah to become the Colorado River. Sometime after the death of Captain Gunnison in the fall of 1853, the Rio Javier was named the Gunnison River in his memory. The Grand River was renamed Colorado River by act of the Colorado State Legislature approved March 24, 1921, and by act of Congress approved July 25, 1921; but, in addition to Grand Junction, the name Grand still remains in the Grand Valley, between Palisade and Mack; in Grand Mesa, which stands more than a mile above the Grand and Gunnison Valleys; in the town of Grand Valley, 46 miles upstream from Grand Junction; and in Grand County, Colo., and Grand County, Utah.

TOPOGRAPHY

Before 1917 the only topographic map of the Grand Junction area was that made by Henry Gannett during the Hayden survey (Hayden, 1877b) at a scale of 1:253,400 and a contour interval of 200 feet. In 1917 a topographic map of the Grand [Colorado] River below Grand Junction, scale 1:31,680, contour interval 25 feet, was published by the U.S. Geological Survey (Herron, 1917, pls. 27–32). In 1942 a topographic map of the Colorado National Monument (pl. 1), scale 1:31,680, contour interval 20 feet, was published by the U.S. Geological Survey. This map was reprinted in 1948, and a shaded-relief edition was published in 1958. In 1948 a topographic map (2 sheets) of the Whitewater Reservoir site on the lower Gunnison River, scale 1:24,000, contour interval 5, 10, and 20 feet, was published by the U.S. Geological Survey. It includes a stretch of the Gunnison River valley from a few miles above Grand Junction to Escalante, in Delta County, and shows the topography from river level up to the proposed pool altitude of 4,800 feet. These were the only topographic maps available during the fieldwork and until 1959, when the U.S. Army Map Service published topographic maps of the Grand Junction and Moab, Colorado-Utah sheets, scale 1:250,000, contour interval 100 and 200 feet. The entire area of this report is included on these two maps, which were made from high altitude aerial photographs taken in 1954 and 1955. If 7½-minute topographic quadrangle maps had been available for the Grand Junction area to serve as a base for plate 1, greater accuracy of the structure contours would have been possible, and the maps would have been very useful, in conjunction with the structure contours, in estimating the depths to the several artesian aquifers.

That part of the Uncompahgre Plateau northwest of Unaweep Canyon is known as Piñon Mesa; its highest altitude is 9,545 feet, just a few miles southwest of the mapped area. Piñon Mesa includes the Fruita Division of Grand Mesa National Forest. The highest part of the area shown on plate 1 is about 2 miles northwest of North East Creek, where several mesas have altitudes of more than 8,200 feet. From Piñon Mesa the area slopes northeastward generally at about 2° to 3°, but in places the slope is 3° to 7° and along some of the folds the local dip of the rocks and slope of the land surface is as much as 80°. Much of this sloping surface, particularly in the southeastern part of the area, is on the Dakota Sandstone (pl. 1), but in other parts it is on older rocks. The Colorado River leaves the northwest corner of the area at an altitude of less than 4,430 feet, and the area as a whole has a relief of more than 3,700 feet.

The northeastward-sloping surface is cut by a series of deep canyons that trend generally northeastward. Many of these canyons are more than 500 feet deep, and No Thoroughfare and North East Creek Canyons are 1,000 feet deep in places. Many of the canyon walls, particularly in the Colorado National Monument (fig. 2), are sheer cliffs of the Wingate Sandstone, but in some places even higher vertical or nearly vertical

FIGURE 2.—Independence Monument, separating North and East Entrances of Monument Canyon, in Colorado National Monument. Looking north down North Entrance from Grand View Point; Colorado River, Grand Valley, and Book Cliffs in distance. Roan Cliffs are white cliffs at extreme distance on right skyline. pЄ, Precambrian schist, gneiss, and granite; Ћc, Chinle Formation; Ћw, Wingate Sandstone; Ћk, Kayenta Formation; Jm, Morrison Formation. Note how thin capping of resistant sandstone of Kayenta Formation protects underlying Wingate Sandstone from erosion. Where this protective capping has been eroded away, as from the left part of Independence Monument and from the Pipe Organ at left, Wingate erodes to rounded domes and spires. Note also smooth exhumed erosion surface on top of Precambrian rocks and monocline in middle background. Top of Independence Monument is nearly 450 feet above floor of canyon. Infrared photograph.

cliffs are formed by the Wingate and the overlying Kayenta Formation and Entrada Sandstone (fig. 10). Most of the canyons are box canyons accessible only by laboriously following the streams upward over rapids and waterfalls, but a few have trails that lead up to the adjacent mesas. The general configuration and trends of these canyons are well shown by the closely spaced geologic contacts on plate 1. Travel in directions at right angles to the trend generally is impossible, and some "peninsulas" between canyons can be reached only with great difficulty by long and circuitous routes.

Steep cliffs of Precambrian rocks occur in several places, notably along the Redlands fault and the Ladder Creek monocline.

The area is drained entirely by the Colorado River and its tributaries, including the Gunnison River. Most of the area is drained by tributaries that flow generally northeastward to these rivers, but the southwest corner of the area is drained by tributaries of the Little Dolores River, which flows westward to join the Colorado River in eastern Utah. Except for the Colorado and Gunnison Rivers, most of the streams in the area are ephemeral and carry water only during or after heavy rains or during the melting of unusually heavy snow. North East Creek, in the southeastern part of the area, is perennial to within a short distance of its confluence with East Creek, and intermittent below. Diversions for irrigation cause the lower reaches to go dry for various periods of time. Drainage changes involving Unaweep Canyon and East Creek are discussed on pages 69–75, and the importance of the streams in recharging the artesian aquifers is discussed on pages 100, 101.

CLIMATE

The climate of the Grand Junction area is characterized by a high percentage of sunshine the year round, warm summers, mild winters having relatively little snowfall, and a high evaporation rate. The Gunnison River and Grand Valley have an arid climate and receive less than 10 inches of precipitation annually. The mesas surrounding these valleys receive greater precipitation at increasing altitude. Thus Piñon Mesa, the crest of the Uncompahgre Plateau southwest of the area, receives about 25 inches of precipitation annually, and slopes and mesas at lower altitudes receive between 10 and 25 inches. Grand Mesa, east of the area, receives more than 30 inches of precipitation, including very heavy winter snows, annually.

All climatic data presented in this report were compiled from records of the U.S. Weather Bureau. Weather data have been recorded at Grand Junction since 1892, at Fruita since 1904, and at the Colorado National Monument since 1941.

The mean annual temperature is 52.1°F at Grand Junction and 51.3°F at Fruita. The highest temperatures occur in July, but the normal monthly temperature is more than 60°F from May through September. In the Grand Valley, temperatures of 32°F or below may be expected as late as May 8 and as early as October 3; thus, on the average, 147 frost-free days may be expected during each growing season. According to Look (1951, p. 34, 35), the Palisade area at the head of the Grand Valley is especially free of frosts in the critical early spring because of what he termed a "gigantic air conditioning system," wherein night air descending into DeBeque Canyon is compressed and, hence, warmed before if spreads out over the Grand Valley to warm the fruit orchards. Knobel, Dandsdill, and Richardson (1955, p. 7) have also commented on this phenomenon.

The normal annual precipitation is 9.06 inches at Grand Junction and 8.31 inches at Fruita. The annual precipitation at the three Weather Bureau stations for the periods of record is shown in figure 3. The minimum annual precipitation of record was 3.64 inches at Grand Junction in 1900 and 4.75 inches at Fruita in 1924. The maximum annual precipitation of record was 17.46 inches at Grand Junction in 1941, 18.08 inches at Fruita in 1957, and 24.59 inches at the Colorado National Monument, also in 1957. Grand Junction received 15.69 inches in 1957, the second wettest year at Grand Junction since records began in 1892. Precipitation for the 8 years 1911–18 was recorded at stations at an altitude of 6,500 feet near Glade Park, in the southwestern part of the area. The minimum, average and maximum annual precipitation recorded here were 11.52, 13.63, and 15.80 inches, respectively, as compared to 6.00, 8.47, and 9.79 inches, respectively, during the same 8-year period at Grand Junction; these figures show the increase in precipitation at higher altitude.

The precipitation is greatest during August and September. Much of the summer precipitation occurs in thunderstorms, which can start and end very rapidly and which may be either local or regional in extent. Because these storms generally are more severe in the higher parts of the area, the higher drainages, such as North East Creek and Bangs, Ladder, and No Thoroughfare Canyons, are apt to have large temporary flows while shorter streams may be dry. When one of the normally dry streams suddenly receives the runoff from a severe thunderstorm, the results are spectacular to see and hear. The red or brown water travels rapidly down the canyon in a wall several feet high and suddenly plunges over a high cliff into the head of a box canyon, landing with a roar on the rocks or in the plunge pool below.

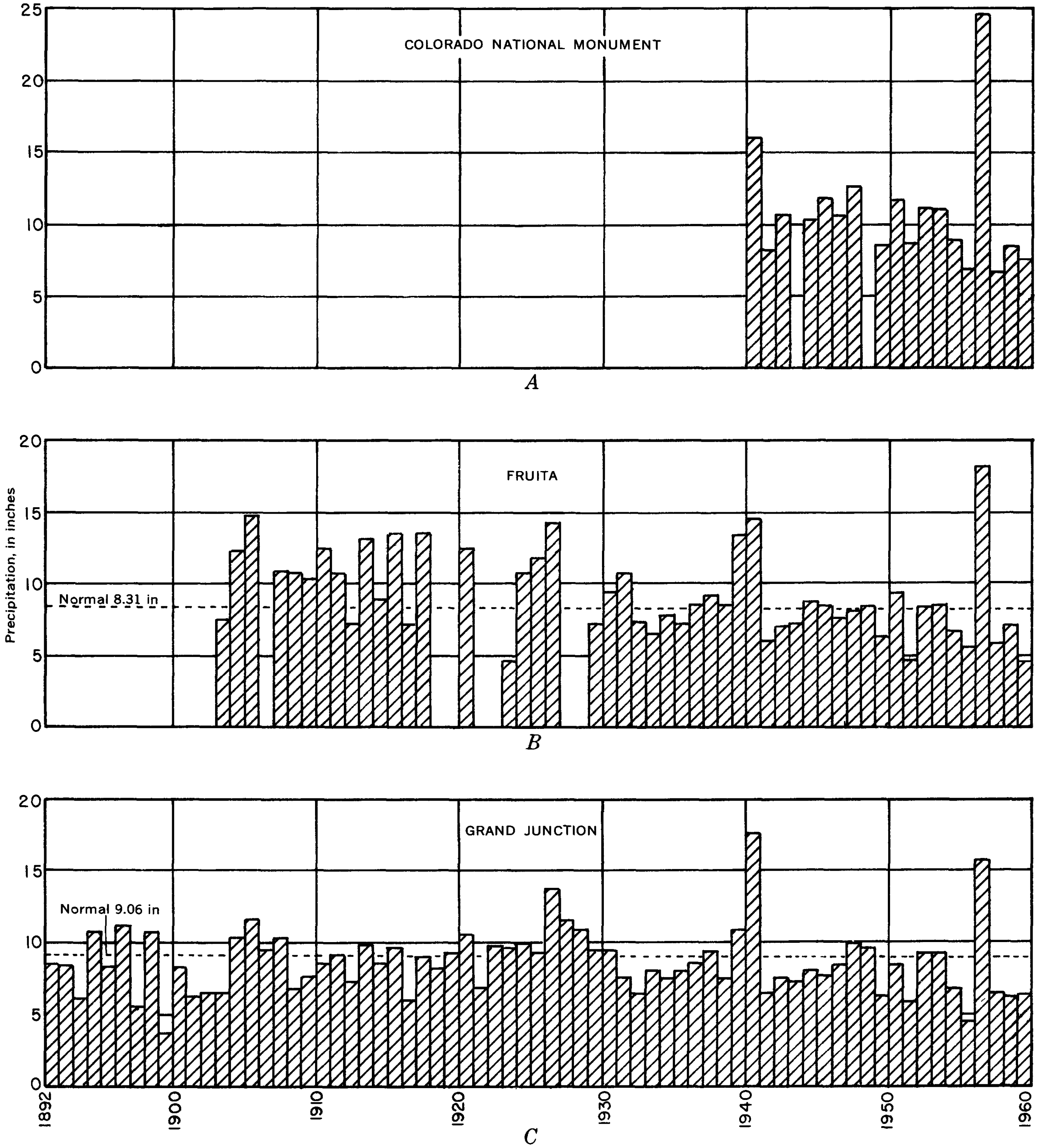

FIGURE 3.—Annual precipitation at three stations in the Grand Junction area. *A*, Colorado National monument; *B*, Fruita; *C*, Grand Junction. From records of the U.S. Weather Bureau.

FLORA AND FAUNA[3]

The flora and fauna of the Grand Junction area vary with the altitude as does the climate, which ranges from arid in the lower parts of the area to subhumid in the higher parts. For this reason the flora and fauna are discussed separately for three different zones of altitude and climate.

Gunnison River Valley and Grand Valley.—Trees are not common in the Gunnison River Valley and the Grand Valley; the native vegetation consists mainly of shrubs. Greasewood (*Sarcobatus vermiculatus*) is the commonest shrub in the valleys; it grows abundantly in alkali soil, especially where the water table is near the land surface. Big sagebrush (*Artemisia tridentata*) grows where there is less alkali (Harrington, 1954) and locally occurs in association with saltbush (*Atriplex* sp.). Rio Grande cottonwood (*Populus fremontii* var. *wislizenii*), tamarisk (*Tamarix pentandra*) and willow (*Salix* sp.) grow along water courses and contribute the major tall-growing flora in the valleys. In moist areas near the rivers and canals are found other hydrophytic plants such as cattail, sedge, and bulrush.

The longtailed meadow mouse (*Microtus longicaudus*), beaver (*Castor canadensis*), muskrat (*Ondatra zibethica*), and nutria (*Myocastor coypus*) also live in these valleys. Animal life in the valleys has been influenced considerably by agriculture since occupation of the area by white men. Mule deer (*Odocoileus hemionus*) are found over most of these valleys and often damage orchards in the Redlands. Large predators have retreated from the valleys, but small carnivores such as bobcat (*Lynx rufus*), gray fox (*Urocyron cinereoargenteus*), striped skunk (*Mephitis mephitis*), spotted skunk (*Spilogale gracilis*), and badger (*Taxidea taxus*) are still found.

The distribution of rodents and rabbits in these valleys probably is almost unchanged since settlement of the area. The shrub vegetation of the more arid sections of the valleys shelter the deer mouse (*Peromyscus manidulatus esgoodi*), kangaroo rat (*Dipodomys ordii*), and the Colorado cottontail (*Sylvilagus auduboni warreni*). The Old World mouse (*Mus musculus*) is found in the valleys, but the Norway rat (*Rattus norvegicus*) is absent.

Birds are varied, ecologically, in these valleys. The redwinged black bird (*Agelaius phoeniceus*), meadow lark (*Sturnella neglecta*), and ringnecked pheasant (*Phasianus colchicus*) prefer the irrigated parts, whereas the lark sparrow (*Chondestes grammacus*), Gambel's quail (*Lophortyx gambelii*), California quail (*Lophortyx californicus*), and chukar (*Alectoris graeca*) prefer the desert areas.

Cold-blooded vertebrates are represented in these valleys by several species of reptiles and amphibians. The Rocky Mountain toad (*Bufo woodhousei woodhousei*), wandering garter snake (*Thamnophis elegans, vagrans*), and the Utah milk snake (*Lampropeltis doliata taylori*) are found in moist areas. A different herpetological fauna occurs in the desert areas; it includes the northern plateau lizard (*Sceloporus undulatus elongatus*), the Great Basin sagebrush lizard (*Sceloporus graciosus graciosus*), and the desert striped whip snake (*Masticophis taeniatus taeniatus*).

Colorado National Monument, Glade Park, and areas of comparable altitude.—Harrington (1954) described the flora of the Uncompahgre Plateau as a typical piñon-juniper association. Colorado National Monument represents an undisturbed part of the plateau owing to National Park Service policies that preclude grazing, hunting, and mining. Warren (1941) placed the upper part of the Upper Sonoran Life Zone at an altitude a little less than 6,000 feet and extended the Transition Life Zone from that altitude to about 8,000 feet. The higher altitudes of Colorado National Monument and most of Glade Park are in the Transition Life Zone.

Species from the Grand Valley overlap into Glade Park, but there is also a gradual change within the 3,000-foot interval. The piñon-juniper forest is dominant at about 5,800 feet and continues on up through the Transition Life Zone onto Piñon Mesa. The principal components are the piñon pine (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*). Mountain brush makes up the understory of the piñon and juniper; it commonly includes mountain mahogany (*Cercocarpus* sp.), sagebrush (*Artemisia* sp.), serviceberry (*Amelanchier alnifolia*), and skunkbrush (*Rhus trilobata*). Gambel's oak (*Quercus gambelii*) appears at an altitude of about 6,400 feet and grows abundantly up to about 8,500 feet.

Wapiti (*Cervus canadensis*) (elk) were transplanted into Colorado National Monument during the 1920's and have since populated the monument and Piñon Mesa with enough animals to provide an open hunting season outside the monument boundaries. Mule deer are abundant throughout the plateau and are hunted regularly. During the winter, deer and wapiti migrate to the lower elevations and increase the animal population in the monument.

Predators include gray fox, ringtail (*Bassariscus astutus*), bobcat, striped and spotted skunks, badger, coyote (*Canis latrans*), and mountain lion (*Felis concolor*). The larger predators extend their range into the monument area only during the winter and especially when their prey has migrated to lower elevations.

The monument's mammal population includes several species of rabbits and rodents, many of which are found

[3] Adapted from Pat H. Miller, Chief Naturalist, Colorado National Monument (written communication, Oct. 18, 1961).

also in the valleys and in Glade Park. The rodents include the rock squirrel (*Citellus variegatus*), Colorado chipmunk (*Eutamias quadrivittatus*), kangaroo rat, pocket mouse (*Perognathus apache*), piñon mouse (*Peromyscus crinitus*), canyon mouse (*Peromyscus truei*), porcupine (*Erethizon dorsatum*), Mexican woodrat (*Neotoma mexicana*), and the bushy-tailed woodrat (*Neotuma cinerea*). The rabbits include Nuttall's cottontail (*Sylvilagus nuttallii*) and the black-tailed jack rabbit (*Lepus californicus*).

The scrub jay (*Aphelocoma coerulescens*), piñon jay (*Gymnorhinus cyanocephala*), Oregon junco (*Junco oreganus*), Say's phoebe (*Sayornis saya*), golden-crowned kinglet (*Regulus satrapa*), and the chipping sparrow (*Spizella passerina*) represent a cross-section of birds that nest in the area. Larger predaceous birds that reside on the plateau include the golden eagle (*Aquila chrysaetos*), red-tailed hawk (*Buteo jamaicenis*), and great horned owl (*Bubo virginianus*). Merriam's turkey (*Meleagris gallopava merriami*) is a transplanted bird that has become abundant enough to provide an open hunting season on some parts of the plateau.

A herpetological survey of Colorado National Monument found nine saurian species, six species of snakes, three species of toads, one tree frog, and one salamander. The most abundant lizards of the plateau are the *Sceloporus* previously described, two species of whiptail (*Cnemidophorus*), and two species of *Crotaphytus*). The most common snake is the Great Basin gopher snake (*Pituophis catenifer deserticola*). The faded midget rattlesnake (*Crotalus viridis*) is the only known species of poisonous reptile on the plateau. The red-spotted toad (*Bufo punctatus*), spadefoot toad (*Scaphiopus hammondi*), canyon treefrog (*Hyla arenicolor*), and the clouded tiger salamander (*Amystoma tigrinum*) are present in the monument.

Piñon Mesa.—Harrington (1954) stated that the ponderosa pine-Douglas-fir association starts at an altitude of 8,500 feet, where it meets the piñon-juniper forest, continues up to about 10,000 feet, and is eventually replaced by lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmanii*), and subalpine fir (*Abies lasiocarpa*). Marginally, ponderosa pine (*Pinus ponderosa*) is found on south-facing slopes and Douglas-fir (*Pseudotsuga taxifolia*) on north-facing slopes. The forest on Piñon Mesa alternates from Gambel's oak and other mountain brush shrubs at the lower altitudes to aspen (*Populus tremuloides*) at higher altitudes.

Anderson (1959) listed the following rodent and rabbit species for the upper altitudes of Grand Mesa: pika (*Ochotona princeps*), snowshoe rabbit (*Lepus americanus*), yellow-bellied marmot (*Marnota flaviventris*), golden-mantled ground squirrel (*Citellus lateralis*), least chipmunk (*Eutamias minimus*), pocket gopher (*Thomomys talpoides*), deer mouse (*Peromyscus maniculatus*), bushy-tailed woodrat (*Neotoma cinerea*), Gapper's red-backed mouse (*Clethrionomys gapperi*), meadow mouse (*Microtus montanus*), muskrat, and the western jumping mouse (*Zapus princeps*). No small-mammal survey has been made to confirm the occurrence of all these animals on Piñon Mesa, but it is very likely that most of them do occur there because of similarity of habitat and the lack of an effective barrier between the two high plateaus.

Predaceous mammals of Piñon Mesa include long-tailed weasel (*Mustela frenata*), badger, bobcat, coyote, and black bear (*Ursus americanus*). In addition to the predators, wapiti and mule deer are common. Other vertebrates that are characteristic of the mesa are: wandering garter snake, western leopard frog (*Rana pipiens*), tiger salamander, blue grouse (*Dendragapus obscurus*), dipper (*Cinclus mexicanus*), Steller's jay (*Cyanocitta stelleri*), gray jay (*Perisoreus canadensis*), and Clark's nutcracker (*Nucifraga columbiana*). Fishing is not a major activity on Piñon Mesa, although the Fruita reservoirs contain rainbow trout (*Salmo* sp.) and cutthroat trout (*Salmo* sp.).

SETTLEMENT[4] AND POPULATION

Prior to 1881 the Grand Junction area was inhabited only by Ute Indians, but it was visited from time to time by a few fur trappers and explorers. In 1776 an expedition led by Fathers Dominguez and Escalante passed northward across Grand Mesa just to the east of the Grand Junction area (Hafen, 1927, p. 269, 276, 277). A trading post was built by Joseph Roubdeau about 1838 just above the present site of Grand Junction. In 1853 Captain John W. Gunnison, seeking a feasible route for a transcontinental railroad (Beckwith, 1854), led an exploring party down the Gunnison River valley, past the confluence with what is now the Colorado River, and on down the Colorado River valley. Members of the Hayden survey found only Ute Indians in the area in 1875 and 1876; the field season of 1875 was abruptly cut short because of skirmishes with hostile Utes (Hayden, 1877a). After the Meeker (Colorado) Massacre of 1879, treaties were signed forcing the Utes out of western Colorado onto reservations in eastern Utah, and the last of the Utes were reported out of the Grand Valley by September 1881. The Grand Valley was immediately opened to settlement, and the first ranch was staked out near Roubdeau's trading post on September 7, 1881. On September 26 of the same year, George A. Crawford founded Grand Junction as a townsite and formed the Grand Junction

[4] Taken largely from Colorado State Planning Commission (1959) and from Hamilton (1956).

Town Co. the following October 10. The success of Grand Junction was assured on November 21, 1882, when the narrow-gage line of the Denver and Rio Grande Railroad reached it via the Gunnison River valley. The town of Fruita was founded by William E. Pabor in 1883 and incorporated the following year.

After much of the land in Grand Valley was taken up, settlers homesteaded smaller tracts of mesa land higher up on the slopes of Piñon Mesa in the areas known as Glade Park and East Park. East Park, reached by the old Jacob's Ladder Road, is now virtually uninhabited, and the sites of former homesteads are marked by decaying log cabins. There are still a few ranches and a general store and post office in Glade Park and several cattle and sheep ranches and camps at and near the summit of Piñon Mesa.

The population of Grand Junction, the county seat, and of smaller towns and villages from the earliest available figures through 1960 is given in table 1; the gradual reduction in population of the smaller places in contrast to the steady growth of Grand Junction is quite apparent. Grand Junction, the largest city in Colorado west of the Continental Divide, has long been the trade center for much of western Colorado and a part of eastern Utah, but its normal rate of growth was greatly accelerated during and after World War II by the development of the uranium industry.

TABLE 1.—*Population of Grand Junction and of smaller places in the Grand Junction area* [1]

[From U.S. Bureau of Census]

Place	Population in year shown							
	1890	1900	1910	1920	1930	1940	1950	1960
Appleton [1]							949	
Fruita						1,466	1,463	1,830
Glade Park [1]					381	321	163	824
Grand Junction	2,030	3,503	7,754	8,665	10,247	12,479	14,504	18,694
Whitewater [1]					216	263	215	511

[1] Includes population of county precinct bearing same name as village, therfore includes some or mostly rural residents.

AGRICULTURE AND IRRIGATION [5]

The agricultural possibilities of the Grand and lower Gunnison Valleys were considered nil by members of early exploration and survey parties. In 1853, Beckwith (1854, p. 57) described the Grand Valley thus: "The valley, twenty miles in diameter, enclosed by these mountains, is quite level and very barren, except scattered fields of the greasewood and sage varieties of artemisia—the margins of Grand [Gunnison] and Blue [Colorado] Rivers affording but a meagre supply of grass, cotton-wood and willow." In discussing the agricultural possibilities of a larger part of western Colorado in 1875, Peale (1877, p. 33) completely ignored the dry Grand and lower Gunnison Valleys: "A comparatively small proportion of the country is fitted for agricultural purposes, farming land being confined to portions of the valleys of the Uncompahgre and Gunnison Rivers [upstream from the Grand Junction area], and to some small valleys on the upper part of the Dolores, and a few of the streams draining the Sierra la Sal [La Sal Mountains]."

After the Grand Valley was opened to settlement in 1881, it was soon realized that the climate was too arid to grow crops successfully without irrigation. The Grand Valley Irrigation Co., started in 1882, diverted water from the Colorado River near the present site of Palisade to irrigate 22,500 acres. From 1889 to 1907, five other small irrigation districts were formed, each of which diverted water from the Colorado River to irrigate from a few hundred to a few thousand acres, part of which was on Orchard Mesa. In 1907 a diversion dam was built on the Gunnison River near its mouth to supply water to the Redlands Power Canal for development of electric power. In 1917 this canal began supplying water by pumping to the Redlands Irrigation Co. for the irrigation of 3,800 acres on the Redlands.

The big boost to the agricultural economy of the Grand Valley occurred on September 23, 1912, when President Taft signed the bill authorizing construction of the Grand Valley project by the U.S. Bureau of Reclamation. Construction began the same year and was 60 percent completed by 1915, when the first water became available for irrigation. As of March 1960, this project included a movable-crest diversion dam on the Colorado River 8 miles northeast of Palisade, a powerplant (built in 1933 on the Orchard Mesa irrigation district's canal), two pumping plants, two canals aggregating 99 miles in length, 166 miles of lateral ditches, and 165 miles of drainage ditches. Information on current irrigation systems in Grand Valley is given in table 2.

All the land irrigated by the Redlands Irrigation Co. and a small part of the other irrigated land are within the area described in this report. In addition, smaller areas near Whitewater are irrigated by diversions from tributaries of the Gunnison River, and a few small islands and patches of flood plain between Grand Junction and Bridgeport are irrigated by diversions directly from the Gunnison River. One such diversion just east of the area is made by a large undershot water wheel. Several ranches in Unaweep Canyon are irrigated by diversions from East Creek and its tributaries, and a small area along North East Creek is irrigated by diversions from North East Creek.

[5] Information on irrigation systems and irrigated acreages was obtained from the following sources: A. B. McLauthlin, Colorado Water Conservation Board; A. H. Yeates, U.S. Bureau of Reclamation; W. J. Chiesman, Grand Valley Water Users Association; and Follansbee (1929, p. 120-125).

TABLE 2.—*Irrigation systems in Grand Valley*

System	Method of irrigation	Area under ditches (acres)
Grand Valley project (Bureau of Reclamation)	Gravity and pumping	[1] 42,416
Supplied by Grand Valley project:		
Orchard Mesa irrigation district [2]	Pumping and gravity	[3] 10,027
Palisade irrigation district	Gravity	[3] 5,950
Mesa County irrigation district	Gravity and pumping	[3] 2,400
Grand Valley Irrigation Co	Gravity	[3 4] 35,000
Redlands Irrigation Co	Pumping	[5] 3,800
Total		[6] 99,593

[1] From U.S. Bureau of Reclamation. Of this theoretical maximum, from 33,000 to 38,000 acres is irrigated in any one season.
[2] Includes facilities, and acreage of old East Palisade irrigation district.
[3] From Grand Valley Water Users Association.
[4] Estimated.
[5] From Follansbee (1929, p. 121).
[6] Only 70-80 percent of this total acreage is irrigated in any one season.

The irrigated acreage is largely in peach orchards, for which the Grand Valley is widely known, but pears, plums, prunes, apricots, apples, and cherries also are grown, as are sugar beets, onions, and other vegetables, and livestock feed. Descriptions of the several types of soil and their suitability for growing crops are given by Knobel, Dansdill, and Richardson (1955). Cattle, sheep, and hogs are raised in the valley, and cattle and sheep are grazed on the slopes and crest of Piñon Mesa. Except for a small area in Glade Park, most of the area is too arid for dry farming.

NATURAL RESOURCES AND INDUSTRIES

The principal natural resources of the Grand Junction area are an abundant supply of irrigation water, large tracts of irrigable land, mild climate, beautiful scenery, and recreational facilities. Large and small game and game birds are plentiful on the slopes of Piñon Mesa and in the National Forests to the south and east. Little fishing is done within the area described, owing to the paucity of small perennial streams, but excellent fishing is available on Grand Mesa to the east and, to a lesser extent, on Piñon Mesa to the south.

Mineral deposits are unimportant in the Grand Junction area in comparison with many nearby areas. In contrast to a large producing area just southwest of the Uncompahgre Plateau, no commercial deposits of uranium (Finch, 1955) or vanadium (Fischer, 1942) have been found on the northeastern flank of the plateau in or near the area described.

Sand and gravel are obtained at several places, and small amounts of bentonite or bentonitic material have been obtained from the Brushy Basin Member of the Morrison Formation. Low-grade thin lignite coals has been prospected or mined from the Dakota Sandstone at several places along the Gunnison River valley (Woodruff, 1912), but it has not been mined for many years owing to the abundance of better bituminous coal nearby in the Grand Mesa coal field (Lee, 1909, 1912) to the east and in the Book Cliffs coal field (Erdmann, 1934) to the north. All tests for oil or gas in the area have been unsuccessful owing to the absence of Paleozoic rocks and the shallow depths of Mesozoic rocks beneath the Grand and Gunnison Valleys, but there is commercial production of oil and gas not far to the north. Small pockets of natural gas have been found in the Dakota Sandstone during the drilling of some of the deeper artesian wells in the area (see p. 66), but none has been in commercial amount. Attempts were made to mine copper ore in Unaweep Canyon just south of the area, but the workings were abandoned many years ago (Butler, 1914). The Entrada Sandstone has been quarried at several places in and near the Colorado National Monument to supply building stone for the older monument buildings and curbstone for Rim Rock Drive.

A mica deposit was discovered before 1900 in Ladder Canyon, in sec. 25, T. 12 S., R. 101 W., about 6½ miles southwest of Grand Junction, and by 1911 it had been explored by a short tunnel and open cut (Sterrett, 1913, p. 389). Production records are scanty, but some mica was reported to have been produced in 1946; the mine, known as the Williamson mine, was in operation when I visited it on July 2, 1948, but operations were discontinued a year or two later. The muscovite mica occurs generally in small crystals but rarely in large books near the middle of a nearly vertical pegmatite dike in the Precambrian schist. The mica is in pink feldspar surrounded by quartz containing large crystals of black tourmaline, particularly near the contact with the schist. In 1948 some mica and feldspar were being produced and trucked to Grand Junction, by the Mica Corporation of America; from Grand Junction it was shipped by rail to eastern markets. According to A. Polland, vice president of the Corporation, the mica was ground and used mainly in paints, insulation, and greases (oral communication, July 2, 1948).

Although agriculture is the principal occupation in the area, Grand Junction and suburbs have many small and several large industries, including a uranium mill; fruit and vegetable canneries; bakeries; meat packing plants; candy factories; dairies; flour mills; wood-products plants that make fruit boxes, crates, and building materials; chemical plants that manufacture insecticides, fertilizers, and mining chemicals; aircraft-parts plants; brick plants; and many others. Owing to its strategic location, Grand Junction served as headquarters for exploration and development of uranium ores by the U.S. Atomic Energy Commission, for geologic investigations of uranium- and vanadium-producing areas by the U.S. Geological Survey, and was selected as headquarters for more than 100 mining firms and at least 200 firms engaged in supporting the mining industry.

The refinery of the American Gilsonite Co. near Loma is just west of the area described in this report.

Grand Junction is an important division point on the main line of the Denver and Rio Grande Western Railroad; a large freight-classification yard and a large icing station for refrigerator cars are located there.

Grand Junction's airport is served by two airlines and a host of motels and several hotels are required to handle the needs of travelers on transcontinental U.S. Highways 6 and 24, U.S. Highway 50, and several State highways.

COLORADO NATIONAL MONUMENT [6]

No description of the Grand Junction area would be complete without special mention of the Colorado National Monument—a scenic attraction that drew 243,484 visitors in 1961.

The fantastically eroded and vividly colored canyon country had a magic attraction for John Otto who, in 1906, camped near the mouth of the East Entrance of Monument Canyon and began building trails into the canyons and onto the mesas. In 1907 he interested the Grand Junction Chamber of Commerce in submitting a petition to the Secretary of Interior, James A. Garfield, asking that the area be set aside as a national monument. Otto's dream came true on May 24, 1911, when President Taft signed the proclamation creating the Colorado National Monument. Shortly thereafter Otto climbed to the top of Independence Monument (fig. 2), where he placed the United States flag in observance of National Flag Day. The holes he drilled for iron pitons can still be seen and are still used by climbers of this 450-foot sandstone monolith.

Until 1922 the only means of access to the monument were the trails built by John Otto, but in that year the ranchers of Glade Park joined with Otto in constructing the Serpents Trail from No Thoughfare Canyon to the mesa above, to provide a more direct route to Grand Junction (fig. 35). The trail reportedly contained 54 switchbacks and ascended about 1,500 feet in 2½ miles; it was included in the monument in 1933 and used until 1950 when an easier route was completed up the west side of No Thoroughfare Canyon and through a tunnel to the top of the mesa.

Construction of the scenic Rim Rock Drive through the monument was begun by the National Park Service in 1931, in spite of strenuous opposition from John Otto, who later left the area never to return; the drive was eventually completed to join roads from Fruita and from Grand Junction. The northwest entrance to the monument is by a winding road up Fruita Canyon and through two tunnels (fig. 34). From 1931 to 1942 about $3,865,000 was spent on this and other work in the monument; the money was distributed among two CCC camps, ERA projects, and crews of the National Park Service.

The monument originally included 13,749 acres, but it was enlarged to 17,539 acres in 1933 by the addition of large tracts in Fruita and No Thoroughfare Canyons and smaller areas along its western and northeastern boundaries. Additional minor boundary changes in 1959 resulted in a total area of 17,606 acres and the boundaries shown on plate 1.

Three buffalo were introduced into the canyons of the monument in 1926 and have since multiplied to the extent that the herd has to be reduced to about 20 animals at periodic intervals to keep within the natural food supply. They may be seen generally in some part of Monument, Ute, or Red Canyons or along the northern part of the northeastern boundary, where they are kept within the monument by a 7-foot steel fence. Deer, elk, coyote, bobcat, mountain lion, and fox also are reported to inhabit the monument, but only the deer and fox are in sufficient numbers to be seen frequently.

Since 1933 the monument has had a permanent staff that has gradually increased to about eight. During the summer a staff of about 25 is needed to handle an ever-increasing number of visitors. The staff has included a seasonal ranger-naturalist since 1955 and a permanent naturalist since 1956.

The headquarters area near the Fruita entrance includes camp and picnic grounds with sanitary rest rooms. Several modern homes for monument personnel have been built as a part of the Mission 66 program of the National Park Service, which began in 1956, and additional new facilities including an entrance station, ranger station, and residences at the No Thoroughfare Canyon entrance were completed in 1960. A visitors' center and other facilities were completed in 1963.

In addition to Independence Monument, many other monoliths or other features have been given descriptive or imaginative names, such as Balanced Rock, Window Rock, Sentinel Spire, Pipe Organ, Kissing Couple, Coke Ovens, Squaws Fingers, Liberty Cap, and—perhaps most accurately descriptive of all—Cold Shivers Point. (See pl. 1.)

GEOLOGIC FORMATIONS AND EVENTS AND THE WATER-BEARING PROPERTIES OF THE ROCKS

SUMMARY OF GEOLOGIC FORMATIONS

Except for Quaternary deposits, the rocks exposed in the Grand Junction area range in age from Pre-

[6] Taken in part from Minor (1943), Look (1951), Hamilton (1956), U.S. National Park Service (1958), and Pat H. Miller, Chief Park Naturalist, Colorado National Monument (written communications, Apr. 1 and 28, 1960, and Jan. 4, 1962; oral communication, Apr. 17, 1960).

cambrian to Upper Cretaceous. The Precambrian basement complex is composed of metamorphic and intrusive rocks, and the overlying sedimentary rocks are all of Mesozoic age. The lithologic characteristics, succession, stratigraphic relationships, ranges in thickness, and water-bearing characteristics of the formations exposed are summarized on plate 2.

Inspection of plate 2 suggests that the Grand Junction area is perhaps more noteworthy geologically because of the absence of the thick sequences of strata that are present in nearby areas than it is for the strata that are present. Along the great unconformity between the Precambrian rocks and the Upper Triassic Chinle Formation are missing part of the Precambrian, all the Paleozoic, and much of the Triassic rocks. The erosional unconformity at the base of the Entrada Sandstone marks the absence of most to all the Kayenta Formation, all the Navajo Sandstone and Carmel Formation, and part of the Entrada Sandstone. The reasons for some of these and other breaks or hiatuses in the geologic column and the character and water-bearing properties of the rocks in the area are discussed in the pages that follow.

The Mesozoic formations in the Grand Junction area have been called various names by different geologists. Many residents in the area know some of the formations by their older names, particularly by those of Cross (1907, p. 636), which were also used later by Coffin (1921, p. 46-113). Table 3 shows the many different names and geologic ages that have been assigned to the Mesozoic formations, the standard divisions of the U.S. Geological Survey (left-hand column), and the formation names and ages used in this paper (right-hand column). The correlations are mine, and differ somewhat from some of those of Baker, Dane, and Reeside (1936, tables 2 and 5).

PRECAMBRIAN COMPLEX

Throughout the area the Triassic Chinle Formation rests unconformably on a very smooth erosion surface of Precambrian granitic and metamorphic rocks which are exposed at 20 places in the area (pl. 1). Most of the larger exposures are southwest of the Redlands fault and the associated monoclines in the floors of the deep canyons of the Colorado National Monument; the rest are in canyons southwest of the Ladder Creek monocline and Bangs Canyon fault, in Unaweep Canyon, and in the canyon of Dominguez Creek, in the southeast corner of the area.

The Precambrian rocks in the Grand Junction area are divisible into two general types—schist and gneiss, and younger granitic intrusive rocks and dikes, but there are many local variations in composition and texture. This twofold subdivision was noted in the nearest exposures east of the area in the Black Canyon of the Gunnision by Hunter (1925, p. 8) and west of the area in Grand County, Utah, by Dane (1935, p. 21–23).

Most of the exposed Precambrian rocks are the older schist or gneiss. A typical exposure of schist in Ladder Canyon (SW¼ sec. 30, T. 12 S., R. 101 W.) reveals a dark-reddish-purple, thinly laminated, highly metamorphosed biotite schist, whose planes of schistosity are mainly vertical but in places are highly folded. In Lizard Canyon (NE¼ sec. 32, T. 1 N., R. 2 W. Ute P.M.) is a banded pinkish-purple to very dark granitic gneiss containing much biotite and pink feldspar and some porphyritic gneissic granite. In most places the schist and gneiss are cut by seams or dikes of pegmatite, quartz, or aplite. The largest pegmatite dike observed in the area is in schist at the abandoned mica mine in Ladder Canyon (SE¼ sec. 25, T. 12 S., R. 101 W.; see p. 15). This dike is about 300 feet wide and is mostly pink potassic feldspar and quartz. Throughout the dike, but particularly near the contact with the schist, are many large crystals of black tourmaline, and near the middle are several veins of potash feldspar and muscovite. One such vein 30 feet wide was mined for mica and feldspar and was reported by the mine operators to contain 60 to 75 percent mica. (See p. 15.) Most of the mica occurs in small crystals or small books, but one book was removed that measured 3 by 6 by 9 feet.

In Ute Canyon, just southwest of the Redlands fault (SE¼ sec. 34, T. 11 S., R. 101 W.), the Precambrian complex consists largely of hard gray granite and porphyritic granite, and contains seams and dikes of aplite and pegmatite. This granite is harder and more resistant to weathering and erosion than the more abundant schist or gneiss.

In Unaweep Canyon, just southwest of the southeast corner of the area, Butler (1914, p. 19) reported inclusions of mica and hornblende schist within the granite, dikes of both pegmatite and diabase which cut the granite and schist, and veins containing chalcopyrite, pyrite, calcite, quartz, and hematite. He reported that the granite is composed largely of feldspar (mainly microcline but some plagioclase), quartz, muscovite, and biotite, but also contains apatite, rutile, zircon, and magnetite—and, where the granite is coarser grained, abundant titanite. He found that, although the diabase varies somewhat in composition in different dikes, it is composed mainly of plagioclase (probably andesine), augite, and magnetite.

In a study of Precambrian rocks of the north-central Colorado Plateau, Shoemaker (1956, p. 54) noted that "Dark-colored mica schist and mica-hornblende gneisses

TABLE 3.—*Correlation of Mesozoic forma*

U.S. Geological Survey standard divisions, Utah, Colorado, 1961				1877 (Peale; Grand River district)		1901a (Riggs; Grand River valley)		1907 (Cross; San Juan Mountain region)			1912 (Lee; Gunnison River valley)			1918 (Lee; Grand Junction)			1921 (Coffin; Southwestern Colorado)	
Cretaceous	Upper Cretaceous		Mancos Shale	Middle and Upper Cretaceous	No. 2 and No. 3 shales		Not considered	Cretaceous		Mancos Shale	Cretaceous		Mancos Shale			Not considered	Cretaceous	Mancos Shale
			Dakota Sandstone	Lower Cretaceous	Dakota Group	Cretaceous	Dakota Sandstone			Dakota Sandstone			Dakota Sandstone	Upper Cretaceous		Dakota Sandstone		Dakota Sandstone
	Lower Cretaceous		Cedar Mountain Formation (Utah); Burro Canyon Formation (Colorado and Utah)															Post-McElmo
Jurassic	Upper Jurassic		Morrison Formation	Jurassic	Shale and marl	Jurassic	Variegated clay	Jurassic	Gunnison Group	McElmo Formation	Jurassic(?)	Gunnison Formation	Shale member	Lower Cretaceous	Gunnison Formation	McElmo Formation (Morrison)	Jurassic or Cretaceous	McElmo Formation
		San Rafael Group	Summerville Formation	Triassic	Cross-bedded light-colored sandstone		Cross-bedded sandstone						Sandstone member	Jurassic		La Plata Sandstone		
							Greenish clay											
			Curtis Formation				Lower or Marine Jura											
			Entrada Sandstone			Triassic	Red shale and sandstone			La Plata Formation	Pennsylvanian(?)		Maroon conglomerate and red beds of unknown age	Carboniferous		Red beds	Jurassic	Upper La Plata Sandstone
	Middle Jurassic		Carmel Formation															
	Lower Jurassic	Glen Canyon Group	Navajo Sandstone															Lower La Plata Sandstone
Triassic(?)	Upper Triassic(?)		Kayenta Formation		Blood-red massive sandstone and shale			Triassic		Dolores Formation							Permo-Triassic	Dolores and Cutler Formations
Triassic	Upper Triassic		Wingate Sandstone															
			Chinle Formation															

tions in and near the Grand Junction area

1922 (Campbell; Grand Junction area)			1923 (Prommel; Grand and San Juan Counties, Utah)			1925 (Weeks; Gunnison River valley)			1927 (Baker and others; Moab region, Utah)			1934 (Erdmann; Grand valley)		1936 (Baker, Dane, and Reeside; Serpents Trail, Colo.)			1964 (Lohman; Grand Junction area)			
Upper Cretaceous		Mancos Shale	Cretaceous		Mancos Shale	Cretaceous		Mancos Shale Formation	Upper Cretaceous		Mancos Shale	Upper Cretaceous	Mancos Shale			Not considered	Upper Cretaceous		Mancos Shale	
		Dakota Sandstone			"Dakota sandstone and conglomerate"			"Dakota" Formation			Dakota(?) Sandstone	Lower Cretaceous(?)	Dakota(?) Sandstone						Dakota Sandstone	
			Jurassic		McElmo Formation	Jurassic	Gunnison Group	McElmo Member									Lower Cretaceous		Burro Canyon Formation	
Jurassic and Cretaceous(?)	Gunnison Formation	McElmo Formation and La Plata Sandstone							Cretaceous (?)		Morrison Formation	Cretaceous (?)	Morrison Formation	Upper Jurassic		Morrison Formation	Upper Jurassic		Morrison Formation	Brushy Basin Member
								La Plata Member												Salt Wash Member
									Upper Jurassic	San Rafael Group	Summerville Formation	Upper Jurassic	Summerville Formation		San Rafael Group	Considered absent		San Rafael Group	Summerville Formation	
Triassic		White sandstone at top and brick-red massive sandstone below		La Plata Group	Upper Navajo	Triassic		Upper part of Dolores Formation			East West Moab Tongue		Considered absent						Entrada Sandstone	Moab Member
											Entrada Sandstone		Entrada Sandstone			Entrada Sandstone				Slick Rock Member
					Middle Navajo						Carmel Formation		Considered absent			Considered absent	Middle Jurassic		Absent	
					Lower Navajo				Jurassic (?)	Glen Canyon Group	Navajo Sandstone			Jurassic(?)	Glen Canyon Group		Lower Jurassic	Glen Canyon Group	Absent	
					Todilto Formation						Todilto(?) Formation	Jurassic (?)	Kayenta Formation and Wingate Sandstone			Kayenta Formation	Upper Triassic(?)		Kayenta Formation west	Absent east
					Wingate Sandstone						Wingate Sandstone					Wingate Sandstone	Upper Triassic		Wingate Sandstone	
			Triassic		Chinle Formation				Upper Triassic		Chinle Formation	Upper Triassic	Chinle Formation	Upper Triassic		Chinle Formation			Chinle Formation	

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predominate in exposures north of Unaweep Canyon [including most of the Grand Junction area] and lighter colored gneisses and massive granite predominate in Unaweep Canyon and to the south along the southwest flank of the [Uncompahgre] plateau." Shoemaker (1956, p. 56) considered the "* * * pale pinkish-gray medium-grained two-mica granite * * *" near the Taylor Ranch in eastern Unaweep Canyon probably one of the youngest intrusive masses in the Precambrian complex, for it seems to be free of any effects of regional metamorphism and is not cut by pegmatite dikes. He indicated that this granite is composed of "* * * about 40 percent quartz, 35 percent slightly perthitic microcline, 15 percent albite-oligoclase, 7 percent muscovite, 2 percent biotite, 1 percent garnet, and minute traces of apatite, zircon, magnetite, and hematite."

Peale (1877, p. 66) classed the metamorphic and granitic rocks of this area as Archean, but similar nearby rocks in and above the Black Canyon of the Gunnison were later subdivided by Hunter (1925, p. 8, 9) into Archean schist and gneiss and upper Algonkian or lower Paleozoic granitic intrusive rocks. Hunter also stated that the Archean Black Canyon Schist corresponds closely with the Archean Vishnu Schist of the Grand Canyon section. In Grand County, Utah, Dane (1935, p. 23) closely followed Hunter's age assignments, except that he restricted the age of the unmetamorphosed granite to late Precambrian. Shoemaker (1956, p. 54–56) considered the metamorphic rocks of this area to be the approximate equivalent of the Black Canyon Schist and tentatively correlated the porphyritic biotite granite and the two-mica granite of Unaweep Canyon with Hunter's Vernal Mesa and Curecanti Granites of the Gunnison River region, respectively.

Ages of apatite and biotite from the two-mica granite 2 or 3 miles west of the Taylor Ranch in eastern Unaweep Canyon, calculated by uranium-lead, lead, and rubidium-strontium isotope ratios, ranged from 1,050 to $1{,}810 \pm 160$ million years (Davis, 1954, p. 105; Shoemaker, 1965, p. 56, 57). More recently, Griffin and Kulp (1960, p. 220) reported the potassium-argon ages of two specimens of biotite gneiss from the Black Canyon of the Gunnison (presumably same age as the Black Canyon Schist of Hunter) to be 930 ± 40 and $1{,}130 \pm 40$ million years. These discrepancies result in part from the fundamental differences in the methods and the assumptions involved. The apparent discrepancy of a slightly younger age assignment for the metamorphic rock, which is believed by all geologists who have worked in the area to be older than the intruding granite, may be explained in part by the fact that the age by the potassium-argon method merely indicates the date of the last heating or metamorphism, which probably was caused in part by intrusion of the younger granite. In discussing the possibility of constructing a time scale based upon the few widely scattered age determinations available, Faul (1960, p. 642) pointed out that "* * * it becomes obvious that the available data are still too few, too poor, and internally inconsistent." According to the usage of the U.S. Geological Survey, rocks of these indicated ages are classed as Precambrian. Although the schist and gneiss are extremely old, even the younger intrusive rocks seemingly are fairly old, for in this area is lacking the great thickness of upper Precambrian slightly metamorphosed sedimentary rocks that rest with pronounced unconformity on the highly metamorphosed schist in the San Juan Mountain region of southwestern Colorado (Lovering, 1933, p. 272), and which possibly may be correlative with the thick Grand Canyon Series of Arizona. James (1960), however, has pointed out the riskiness of long-range correlation of Precambrian rocks without very detailed studies.

The Precambrian complex is unimportant as a source of ground water in the Grand Junction area. A few small springs that issue at the contact between the Precambrian rocks and the Chinle Formation in canyons of the Colorado National Monument supply water to the buffalo (Pat H. Miller, Chief Park Naturalist, oral communication, Apr. 12, 1960). Presumably the water comes from the weathered zone near the top of the Precambrian rocks.

UNCONFORMITY BETWEEN PRECAMBRIAN AND TRIASSIC ROCKS

LATE PRECAMBRIAN AND EARLY PALEOZOIC EVENTS

Although the details of the great hiatus at the unconformity between the Precambrian complex and the Upper Triassic Chinle Formation in and near the Grand Junction area are still imperfectly known, the broad features were surmised as early as 1875 by Peale (1877, p. 68, 69) and much additional data has been gathered by later workers.

The late Precambrian history of the area is obscure, but the great thickness of slightly metamorphosed upper Precambrian sedimentary rocks found in the San Juan Mountain region to the south (Lovering, 1933, p. 272) are missing in and near this area; if similar sediments were deposited here, they were subsequently removed by erosion.

Most geologists agree that the Early Cambrian sea was restricted to the Paleozoic Cordilleran trough west of Colorado. Middle Cambrian sedimentary rocks were found in the General Petroleum Corp. 1 Schulte-Government oil test in sec. 15, T. 6 S., R. 103 W. (Hallgarth, 1959), about 29 miles northwest of Fruita; these rocks indicate that by Middle Cambrian time the sea had advanced at least a few miles into western Colorado. If any deposits of this age were laid down as far east as the Grand Junction area, however, they were removed by subsequent erosion.

The Upper Cambrian Cordilleran trough seems to have extended eastward entirely across Colorado, except for a large positive area in the north-central and northeastern parts of the state, called by some the Siouxia positive (McCoy, 1953, p. 1877) or Transcontinental arch (Holmes, 1956, p. 30, 32), and another positive area in south-central Colorado called the Sierra Grande positive (McCoy, 1953, p. 1877). Upper Cambrian quartzite and carbonate rocks are found in parts of Colorado, but any deposits of this age that were laid down in the Grand Junction area have since been removed by erosion.

According to Burbank (1933, p. 279), the Ordovician sea invaded Colorado three times and left deposits in much of central and eastern Colorado, but much of southwestern Colorado remained a landmass during these invasions. Middle and Upper Ordovician strata were penetrated in the General Petroleum Corp. oil test referred to above but, if any rocks of these ages were deposited in the Grand Junction area, they were removed by subsequent erosion. Ordovician and Silurian strata are generally absent throughout the Colorado Plateau (Eardley, 1951, p. 393), and Silurian rocks have not been found in Colorado.

All of Colorado seems to have been subjected to erosion from the retreat of the Ordovician sea until Late Devonian time (Burbank, 1933, p. 279), and this long period of erosion may have removed all or a large part of any pre-Devonian sediments that were deposited in and near the Grand Junction area.

After this long period of erosion, most of Colorado and adjacent areas sank beneath the sea and received deposits of Late Devonian and Early and Late Mississippian age, including the widespread Lower and Upper Mississippian Leadville Limestone (Burbank, 1933, p. 279). Beds of Devonian(?) and Mississippian age were penetrated in the nearby General Petroleum Corp. oil test referred to above, and it seems likely that similar deposits covered the Grand Junction area. According to Burbank (1933, p. 279), warping of the crust which began in Late Mississippian time, allowed the widespread formation of a karst topography on the Leadville Limestone by a prolonged period of weathering and the formation of the Colorado geanticline including the ancestral Front Range and Wet Mountains.

LATE PALEOZOIC AND EARLY MESOZOIC EVENTS

In Early Pennsylvanian time a deep geosynclinal trough extended southeastward from northwestern Colorado to the eastern part of the San Luis Valley, and the upland to the west of this trough gradually rose to form the Uncompahgre-San Luis geanticline or highland and probably attained its maximum height in Later Pennsylvanian or Permian time (Burbank, 1933, p. 280, fig. 13). As this geanticline rose it was gradually stripped of all remaining sedimentary rocks, the removed material being deposited in the deep troughs to the northeast and southwest. Dane (1931, p. 28) estimated, from the volume of clastic sediments derived from the erosion of this landmass and deposited in part in a large trough just southwest of the Grand Junction area, that the crest of the Uncompahgre highland may have stood at least a mile above its margins, although the landmass was less than 100 miles wide.

In the Grand Junction area, erosion of the Uncompahgre highland continued until Late Triassic time, when the peneplained Precambrian complex was covered by a part of the Upper Triassic Chinle Formation. Precambrian rocks were found beneath the Chinle at a depth of about 4,098 feet in the Amerada Petroleum Corp. Ashbury Creek Unit 1 oil test in the SE¼NE¼ sec. 14, T. 9 S., R. 101 W., only 10 miles northeast of Fruita, and at a depth of about 4,155 feet in the Kerr-McGee Oil Industries' Unit 1 oil test in sec. 8, T. 8 S., R. 102 W., about 15 miles northwest of Fruita (Walter E. Hallgarth, oral communication, June 30, 1960). Thus, the relatively thick section of Paleozoic rocks penetrated in the Schulte-Government oil test diminishes to a featheredge somewhere within the 14-mile interval separating this test and the Kerr-McGee oil test and not far to the north of the Amerada Petroleum Corp. oil test. That the featheredge of the Paleozoic rocks may be present downdip not far to the north or northeast of the Grand Junction area, however, is suggested by the above-average content of chloride in a sample of water from well 1, in the SW¼NE¼ sec. 29, T. 1 N., R. 1. W. Ute P.M. (table 8, fig. 46). This sample could be diluted connate water that migrated both updip and vertically to the Entrada Sandstone from the featheredge of marine Paleozoic rocks.

East of the Grand Junction area higher parts of the Uncompahgre highland remained until at least mid-Morrison time (Late Jurassic), for the Triassic and most of the Jurassic strata thin to extinction eastward toward the old landmass and are absent over parts of it. The details of later Mesozoic events are discussed at appropriate places in the pages of that follow.

TRIASSIC SYSTEM

UPPER TRIASSIC SERIES

CHINLE FORMATION

Definition.—The Chinle Formation was named from Chinle Valley in northeastern Arizona by Gregory (1916, p. 79; 1917, p. 42).

Character, distribution, and thickness.—The Chinle Formation consists largely of soft red siltstone, but it also contains thin hard ledge-forming beds or lenses of red siltstone, limestone, and conglomerate, and thin layers of greenish siltstone. The bedding is irregular to wavy, and many beds contain concretions of siltstone. The limestone beds observed range in thickness from less than a foot to 4.5 feet, and are reddish purple, red, green, or pale green. The conglomerate, which is lenticular and occurs only locally, attains a thickness of more than 4 feet in the No Thoroughfare Canyon section, where it occurs near the middle of the formation. The upper 0.8 foot of this conglomerate is very hard and is ledge-forming; it consists of unsorted pebbles of limestone and red sandstone in a matrix of limestone. The lower 3.5 feet consists largely of pebbles of greenish, reddish, and purple limestone from ¼ to 1½ inches in diameter in a matrix of red siltstone, but grades upward into siltstone containing thin layers and concretions of limestone. Locally, thin lenses of conglomerate near the base of the Chinle contain pebbles of feldspar, quartz, or granitic rocks derived from the underlying Precambrian complex.

The Chinle forms a gentle to steep slope between the nearly vertical cliffs of Wingate Sandstone above and the generally smooth exhumed erosion surface on the underlying Precambrian complex in all canyons of the area that have been eroded deeply enough to intersect it. It is especially well exposed in the canyons of the Colorado National Monument (fig. 2), along the Redlands fault (figs. 34 and 35), and along the Ladder Creek monocline and Bangs Canyon fault (fig. 36).

The Chinle Formation was penetrated in the deeper water wells of the area and in the J. E. Dinger-Claybaugh 1 oil test in the SW¼SW¼ sec. 35, T. 2 S., R. 2 E., Ute P.M., about 4 miles east of the area.

In the Grand Junction area the Chinle Formation ranges in thickness from 80 to about 120 feet, but generally is about 100 feet thick.

The measured sections that follow are typical of the Chinle in this area. (See also the East Unaweep Canyon and Ladder Canyon sections at the end of this report.)

Section of Chinle Formation along east side of Fruita Canyon in SW¼ sec. 32, T. 1 N., R. 2 W., Ute P.M.

[Measured by S.W. Lohman and W.H. Lohman, Aug. 17, 1949]

	Thickness (feet)
Triassic:	
Wingate Sandstone (incomplete):	
Sandstone, fine-grained, buff; cemented with calcium carbonate. In bedded layers 1–4 in. thick separated by thin crossbedded layers. Lower 3–4 ft contains pellets of red siltstone and a few pellets of greenish limestone. Contact looks regular and conformable when	

Section of Chinle Formation along east side of Fruita Canyon in SW¼ sec. 32, T. 1 N., R. 2 W., Ute P.M.—Continued

	Thickness (feet)
Triassic—Continued	
Wingate Sandstone—Continued	
Sandstone—Continued	
viewed from distance, but locally is very irregular for distances of 20–30 ft. Locally, thin beds of Wingate-like sandstone are interbedded with red siltstone near top of Chinle Formation.	
Chinle Formation:	
Siltstone, red; cemented with calcium carbonate, fractures irregularly, weathers into rounded forms. Upper part contains irregular channel fillings containing round pebbles of green limestone 1–2 in. in diameter and pebbles and cobbles of pale-green shale as large as 4 in. in diameter. Contains harder beds of siltstone 3–4 ft thick. Lower part partly concealed	22. 2
Siltstone, red, hard; fractures irregularly; joints filled with calcite. Forms ledge	1. 9
Siltstone, red, mostly covered	4. 9
Siltstone, red, hard; fractures irregularly; joints filled with calcite. Near top contains concretions of green limestone. Forms ledge	4. 5
Siltstone, red, mostly covered	18. 3
Limestone, silty, hard, massive; fractures irregularly; reddish to purplish near base, green and red near top. Forms ledge	4. 5
Siltstone, red; in irregular hard and soft layers a few inches to 1 ft thick	7. 1
Siltstone, very hard, massive; fractures irregularly; dull brick red. Cemented mainly with hematite or silica but near base with calcium carbonate. Upper foot contains rounded pebbles of limestone ¼–½ in. in diameter	4. 0
Siltstone, red, partly concealed. Mostly soft but contains a few hard layers	20. 2
Limestone, hard, thinly laminated, pale green but stained red on exposure. Joints filled with calcite. Forms ledge	1. 9
Siltstone, red; cemented with calcium carbonate	7. 5
Covered interval, probably red siltstone	5. 6
Total Chinle (rounded)	103
Precambrian:	
Granite, biotitic, dark, thoroughly fractured and deeply weathered.	

Section of Chinle Formation along west side of No Thoroughfare Canyon in NE¼ sec. 31, T. 1 S., R. 1 W., Ute P.M.

[Measured by S.W. Lohman and W. H. Lohman, Aug. 22, 1949]

	Thickness (feet)
Triassic:	
Wingate Sandstone (incomplete):	
Sandstone, fine-grained, buff; cemented with calcium carbonate. First bed 9 ft thick, crossbedded in parallel layers 1–2 ft thick.	
Chinle Formation:	
Siltstone and shale, red; hard when fresh but weathers to form recess beneath cliff above	0. 6
Sandstone, fine-grained, reddish-buff, hard; contains some concretions of shale in lower	

Section of Chinle Formation along west side of No Thoroughfare Canyon in NE¼ sec. 31, T. 1 S., R. 1 W., Ute P.M.—Con.

	Thickness (feet)
Triassic—Continued	
Chinle Formation—Continued	
Sandstone—Continued	
part. Resembles Wingate but is evenly bedded. Forms protruding layer under base of Wingate	1.5
Siltstone; mostly red but includes several thin greenish layers, mostly hard and ledge forming; in layers 1–3 ft thick. Concretions scattered throughout and in several layers	34
Siltstone, red, hard; upper half ledge forming. Contains several concretionary layers, and upper part contains several thin lenses of conglomerate similar to bed below	9
Conglomerate, very hard, ledge-forming; contains unsorted pebbles of limestone and red sandstone as large as 2 in. in diameter in limestone matrix	.8
Conglomerate containing pebbles of greenish, reddish, and purple limestone ¼–1½ in. in diameter in matrix of red siltstone. Grades upward into siltstone containing limestone concretions and some thin layers of limestone	3.5
Siltstone, red, hard; contains hard limestone concretions in middle and upper parts and thin beds of purple concretionary limestone	12
Siltstone, red, soft	2
Limestone, silty, red, hard, ledge-forming	1.9
Siltstone, red, soft	1.6
Limestone, silty, concretionary, reddish-purple, hard. Conchoidal fracture. Forms small ledge	.6
Siltstone, red, soft, poorly exposed	2.0
Siltstone, red, calcareous, hard, ledge-forming; contains in upper part concretions of greenish sandy limestone	3.5
Conglomerate, greenish; contains small pebbles of granite	.5
Siltstone, red; base poorly exposed	7.7
Total Chinle (rounded)	81
Precambrian:	
Granite, dark-reddish; contains thin quartz veins and pegmatite dikes. Deeply weathered.	

Conditions of deposition.—The vertebrate fossils (Camp, 1930) and abundant silicified wood (Gregory, 1917, p. 49, 50) found in the Chinle Formation in the Navajo Country of northeastern Arizona and the freshwater invertebrates in the Chinle near Moab, Utah (Baker, 1933, p. 40, 41), and elsewhere (Dane, 1935, p. 63; Stewart, 1956, p. 91) all indicate the continental origin of the Chinle. From studies of Triassic rocks in a large part of the Colorado Plateau, Stewart (1956, p. 91; Stewart and others, 1959, p. 522) concluded that the Chinle probably formed on a widespread low-lying alluvial plain containing many lakes and that the source of the material, at least in part, was the Uncompahgre highland, as indicated by the dip of cross-strata in sandstone to the south and by the onlap of the formation onto the ancient landmass. The character of the Chinle Formation in the Grand Junction area is in accord with this suggested mode of origin. In some parts of the Colorado Plateau the deposition of the Chinle was accompanied by showers of volcanic ash (Stokes, 1958, p. 28), but no evidence of this was noted in the Grand Junction area.

Age and correlation.—In the Grand Junction area the Chinle Formation seems to be unfossiliferous, but on the basis of both vertebrate and invertebrate fossils found elsewhere (see Gregory, 1917, p. 46–48; Baker, 1933, p. 41) the Chinle is dated as Late Triassic. The Chinle is equivalent to a part of the Dolores Formation of Cross in the San Juan mountain region (Gilluly and Reeside, 1928, p. 67) and of Coffin (1921, p. 46–52) in the uranium-vanadium mining region south of the Grand Junction area. Only the upper part of the Chinle seems to be present in and near the area, for the lower members thin northward to extinction just south of Moab, Utah (Stewart, 1956, p. 89). In a report in preparation on the Triassic rocks of the Colorado Plateau by F. G. Poole (U.S. Geological Survey, oral communication, July 27, 1960), that part of the Chinle present in the Grand Junction area is included in the Church Rock Member of the Chinle, the type locality of which is in Monument Valley, Ariz. (See also Stewart and others, 1959, p. 517.) The Chinle thins to extinction east of the area against the higher parts of the ancient Uncompahgre highland, and is absent in the Black Canyon of the Gunnison (Siebenthal, 1905, p. 401–403).

Water supply.—The Chinle Formation is not water bearing in this area and, because it is dominantly siltstone, it doubtless has a very low permeability. Small springs at the basal contact of the Chinle in the canyons of the Colorado National Monument probably issue from the underlying weathered Precambrian rocks (p. 20).

TRIASSIC AND JURASSIC SYSTEMS

GLEN CANYON GROUP

The name "Glen Canyon group" was applied by Gregory and Moore (1931, p. 61), with the concurrence of James Gilluly and J. B. Reeside, Jr., to include, from oldest to youngest, the Wingate Sandstone, Kayenta Formation [their "Todilto?"], and Navajo Sandstone in Glen Canyon, Utah and Arizona, but the name first appeared in print in 1927 (Baker, Dobbin, McKnight, and Reeside, p. 787). The Glen Canyon Group comprises these three formations throughout most of the Colorado Plateau, but in the western part of the Navajo country a fourth formation, the Moenave Formation, was added to the group by Harshbarger, Repenning, and Irwin (1957, p. 12). There the

Moenave occurs between the Wingate and the Kayenta, but the Moenave and Kayenta were later considered partial stratigraphical equivalents (Lewis, Irwin, and Wilson, 1961, p. 1439).

In the Grand Junction area the Glen Canyon Group is represented by the Wingate Sandstone and locally also by the Kayenta Formation.

TRIASSIC SYSTEM

UPPER TRIASSIC SERIES

CONTACT BETWEEN CHINLE FORMATION AND WINGATE SANDSTONE

The contact between the Chinle Formation and the overlying Wingate Sandstone generally is fairly sharp, especially when viewed from a distance (fig. 2), but locally is irregular; in places, thin beds of Wingate-like sandstone occur near the top of the Chinle. In general, however, the contact appears conformable and locally gradational; no significant hiatus is apparent between the two formations. A similar relationship was found in the Moab region by Baker (1933, p. 1, 42) and in Grand County, Utah, by Dane (1935, p. 72–74). Farther to the west and south, this contact has been described by many as unconformable (for references, see Gilluly, 1929, p. 94 and footnote 13), and this was a factor in the erroneous earlier assignment of the generally unfossiliferous Wingate Sandstone to the Jurassic(?) System. Reexamination of the supposed unconformity between the Chinle Formation and the Wingate Sandstone in the Navajo Country of northeastern Arizona and adjacent States (Gregory, 1917, p. 48) by Harshbarger, Repenning, and Irwin (1957, p. 5) indicated that the deposition of the Chinle and Wingate was seemingly continuous and that the contact generally is conformable. Stewart and others (1959, p. 523), however, indicated a slight erosional unconformity at the top of the Chinle in much of southeastern Utah.

WINGATE SANDSTONE

Definition.—The Wingate Sandstone was named by Dutton (1885, p. 136–137) from cliff exposures north of Fort Wingate, N. Mex.

Baker, Dane, and Reeside (1936, p. 4–5) extended the use of the name Wingate to the spectacular cliff-forming sandstone throughout the Colorado Plateau. On the basis of later fieldwork, however, they (1947, p. 1666–1668) stated that the sandstone cliffs at Dutton's type locality of the Wingate Sandstone north of Fort Wingate, N. Mex., were formed by the Entrada Sandstone, and they proposed that the name Wingate be retained for the sandstone of the lower formation of the Glen Canyon Group and that the original type locality of the Wingate be abandoned. This somewhat paradoxical situation led many geologists to refer orally to the Wingate Sandstone in the western and northern parts of the Colorado Plateau as "Utah Wingate." This situation was later rectified by Harshbarger, Repenning, and Irwin (1957, p. 8), who found that the lower half of Dutton's type section is indeed the Wingate Sandstone (their Lukachukai Member of the Wingate) and that only the upper half is the Entrada Sandstone. Thus, the original type locality needed only a modified description—not abandonment.

Character, distribution, and thickness.—The Wingate Sandstone typically crops out in a sheer cliff and is the most strikingly exposed formation in the Grand Junction area (figs. 2, 5–10, 30–37). The particles composing the Wingate are, dominantly, very fine grained sand, lesser amounts of fine-grained sand and silt, and small amounts of clay, but one sample contained a small amount of medium-grained sand, and one was dominantly silt (fig. 4 and table 4). The median grain diameters for three samples ranged from 0.062 to 0.097 mm (very fine grained sand), and the values of the Trask sorting coefficient[7] for the three samples ranged from 1.3 to 1.6 and indicate well-sorted material.

Table 4 indicates also that 50 to 60 percent of the three samples of Wingate Sandstone consisted of quartz grains and that 15 to 20 percent of the sandstone consisted of feldspar grains (mostly orthoclase, and minor amounts of microcline and plagioclase). This characteristic also applies to the six samples of the Entrada Sandstone. The greatest variation in mineralogical composition among the three samples examined is the wide range in the content of calcite cement—also typical of the four samples of the Slick Rock Member of the Entrada Sandstone. From microscopic studies of thin sections, H. A. Tourtelot (written communication, July 14, 1960) described the three samples of the Wingate as follows:

Sample 7.—The grains of this rock are mostly subanglar in cross section. The matrix is very patchy in its distribution and consists of a mixture of kaolinite and a micaceous clay mineral. Where sand grains are in contact, there has been moderate solution along their boundaries so that the grains have intersutured contacts along which parts of one grain project into the other. Many of the grains have a highly birefringent rim and some of the feldspar grains are moderately altered. Red iron oxide is present only in minor amounts and is concentrated in the matrix.

Sample 8.—The cross section of most grains is subangular, but the shape of many grains has been considerably modified by replacement with calcite. The rock is vaguely layered; the coarse-grained parts, in which typical grains are 0.15–0.2 mm in diameter, contain somewhat less matrix clay than the finer grained parts, in which typical grains are about 0.05 mm in

[7] Trask's sorting coefficient (So), or the geometrical quartile deviation, is based on the square root of the ratio between the quartiles:

$$So=\sqrt{\frac{Q_3}{Q_1}}$$

in which the quartiles are the diameters that correspond to frequencies of 25(Q_1) and 75(Q_3) percent smaller than the sizes shown for these percentages in figure 4 (Trask, 1932, p. 70–72).

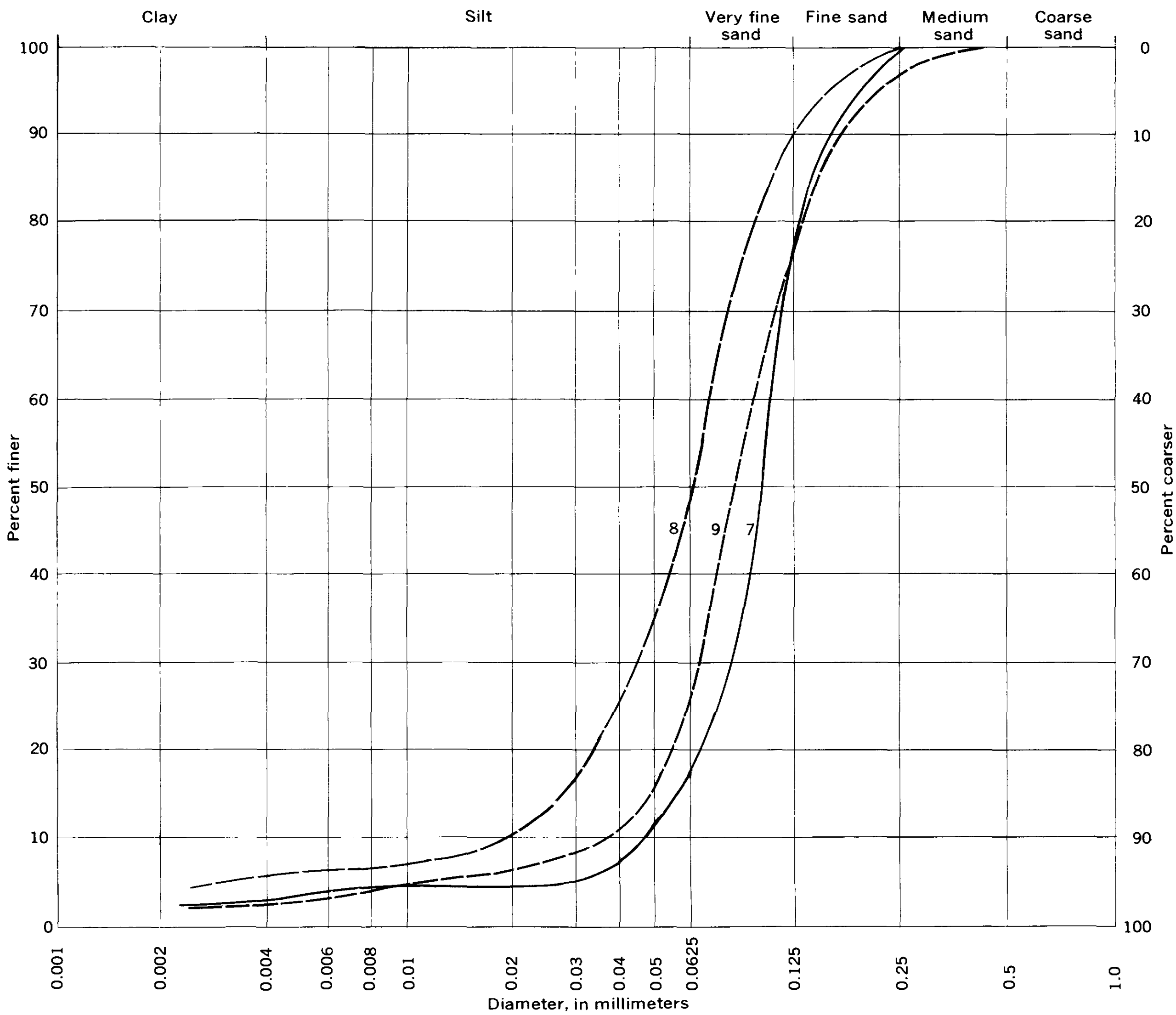

FIGURE 4.—Cumulative curves showing particle sizes of three samples of Wingate Sandstone. For locations of sampling points, see table 4.

diameter. The matrix clay also is more evenly distributed in the finer grained parts. A few flakes of biotite were noted. Few grains of feldspar are altered. Red iron oxide is mostly in the matrix clay, but also makes a thin coating on some grains.

Sample 9.—The cross section of most grains is subangular to subrounded. Although the amount of matrix is somewhat lower than in most other slides, grain suturing is only moderate. Red iron oxide is present in minor amounts and occurs mostly in discrete grains comparable in size to the other particles in the rock. The original nature of these grains cannot be made out. Some iron oxide is in the matrix also, and appears to be concentrated around grains less than 1 micron in diameter of a mineral with very high birefringence and very high relief. These grains are interperted to be siderite.

The 2.5 to 6.0 percent clay in the three samples of Wingate Sandstone consisted of 25 to 35 percent kaolinite and 65 to 75 percent mixed-layer clay, the latter comprising more than 50 percent illite and less then 50 percent montmorillonite. Although the kaolinite has some base-exchange capacity, most of the softening of the ground waters in the Wingate seems to have been caused by the small content of montmorillonite and illite in the mixed-layer clay, in this order (p. 117).

Certain elements of the mineralogical composition are in generally good agreement with some of the physical and hydrological properties (table 4). The percentages of matrix clay and natural voids compare favorably with the porosities, particularly when the percentages of calcite cement are taken into consideration. The apparent inverse relation of the percentage of calcite cement to the porosity and permeability is to be expected.

The Wingate Sandstone is horizontally bedded, generally in layers from 10 to 80 feet thick, but a few layers are only 1 to 2 feet thick. Most of the layers are crossbedded, generally at rather high angles (fig. 5), but some layers are horizontally bedded. In the western and central parts of the area most of the beds are buff to reddish buff, but some are salmon red; in and east of Unaweep Canyon the entire formation is red and

TABLE 4.—*Mineralogical composition and physical and hydrological properties of principal artesian aquifers*

Sample	Formation	Position within formation	Location	Mineralogical composition, in percent by grains or voids [1]				X-ray determinations of approximate composition of clay fraction, in percent [2]			Particle size (size in millimeters; percent by weight) [3]						Porosity (percent by volume) [3]	Laboratory coefficient of permeability (gpd per sq ft)[4]	
								Kaolinite	Mixed layer		Sand sizes				Silt size	Clay size			
				Quartz grains	Feldspar grains	Matrix clay and natural voids	Calcite cement		Montmorillonite	Illite	Coarse (0.5-1.0)	Medium (0.25-0.5)	Fine (0.125-0.25)	Very fine (0.0625-0.125)	(0.004-0.0625)	(>0.004)		Parallel to normal bedding	Perpendicular to normal bedding
1	Entrada Sandstone Moab Member.	About 4 ft below top.	About 0.2 mi northwest of Coke Oven Overlook.[5]	60	10	30	(6)	30	15	55	------	1.8	60.4	29.2	5.6	3.0	29.8	22	13
2	-----do-------------	About 5 ft above base.	-----do------------------	55	20	23	2	60	15	25	------	3.2	50.2	33.8	9.3	3.5	23.8	5	1
3	Entrada Sandstone Slick Rock Member.	About 55 ft above base.	About 0.4 mi south of Grand View Overlook.[5]	50	20	30	(6)	20	40	40	------	12.4	59.6	15.0	8.5	4.5	26.4	5	4
4	-----do-------------	About 40 ft above base.	About 0.3 mi south of Grand View Overlook.[5]	[7] 54	16	24	6	35	30	35	------	5.4	53.4	26.8	8.4	6.0	21.5	.3	.04
5	-----do-------------	About 15 ft above base.	About 0.2 mi south of Grand View Overlook.[5]	45	17	26	12	15	35	50	------	3.8	33.4	42.2	15.6	5.0	23.4	.6	.4
6	-----do-------------	Near base-------	About 0.1 mi south of Grand View Overlook.[5]	[8] 50	15	8	27	25	30	45	10.4	1.8	9.2	41.6	30.0	7.0	8.6	(9)	.0007
7	Wingate Sandstone--	Near top--------	SE¼ SE¼ sec. 2, T. 12 S., R. 101 W.	60	20	20	(6)	35	25	40	------	------	20.0	61.4	15.4	3.2	23.6	4	1
8	-----do-------------	Near middle----	SE¼ SE¼ sec. 2, T. 12 S., R. 101 W.	50	15	20	15	35	25	40	------	------	8.8	39.8	45.4	6.0	21.3	.02	.008
9	-----do-------------	Just above base-	NE¼ NE¼ sec. 11, T. 12 S., R. 101 W.	60	20	18	2	25	35	40	------	2.0	21.0	51.2	23.3	2.5	20.8	.7	.02

[1] From microscopic studies of thin sections by H. A. Tourtelot.
[2] By V. J. Janzer.
[3] By W. H. Lohman.
[4] By R. A. Speirer and M. L. Millgate.
[5] Colorado National Monument.
[6] Generally less than 1 percent.
[7] Includes 1 percent chert.
[8] Includes 2 percent chert.
[9] Indeterminate, but believed to be very small.

appears to contain more silt. Some of the buff beds are stained reddish by wash from the overlying Kayenta Formation. Many of the older sheer cliff faces are streaked or coated with blue-black desert varnish—a feature that assists in distinguishing the Wingate from the Entrada Sandstone in and east of North East Creek valley, where the intervening Kayenta Formation is absent, and particularly along the gorge of the Gunnison River, in the southeast corner of the area, where the two sandstones form a single sheer cliff (fig. 6).

The character and appearance of the outcrops of the Wingate Sandstone vary with a variety of climatic and geologic factors, most of which are taken up in a later section (p. 76, 77). At lower altitudes where it is capped by the very resistant lower sandstone lenses of the overlying Kayenta Formation, as in and near the Colorado National Monument, the Wingate forms spectacular, generally sheer cliffs and monoliths (figs. 2, 10, 30, 34). Where this protective capping has been removed, however, the Wingate is eroded rapidly and locally assumes rounded forms much like those of the Navajo Sandstone in areas to the southwest, as illustrated by the Coke Ovens shown in figure 7 and by several of the erosion forms shown in figures 2 and 9. Figure 6 also shows that the cliffs of Wingate Sandstone locally are jointed (p. 90), whereas those of the Entrada Sandstone generally are not. At higher altitude and along northward facing outcrops at low altitude, the outcrops are less abrupt and in places form a series of gentle steps and benches, some of which are accessible by foot. Many arches or alcoves (fig. 7) and a few caves have formed in the basal part of the Wingate in places where the incompetent underlying Chinle Formation has been undercut by erosion. Several of these caves were occupied by prehistoric peoples (p. 79) and one was used for human occupancy until 1958 (fig. 8 and p. 79). Although natural bridges are relatively rare in the Wingate, a small one (fig. 9) was observed just a few miles west of the cave shown in figure 8.

The Wingate Sandstone is well exposed in all the deep canyons in and near the Colorado National Monument, in Glade Park at the southwest corner of the area, in canyons south of the Ladder Creek monocline and Bangs Canyon fault, in North East and East Creek (Unaweep) canyons, and along the canyons of the Gunnison River and its larger tributaries in the southeast corner of the area.

The Wingate Sandstone generally ranges from about 315 to nearly 370 feet thick in the western and central parts of the area, but thins southeastward to 270 feet in Unaweep Canyon and to about 215 feet along the Gunnison River in sec. 2, T. 14 S., R. 99 W. Some of the thicknesses within this range were measured by

FIGURE 5.—Crossbedding in the Wingate Sandstone. True dip shown by beds in left background. Looking north along old Serpents Trail, Colorado National Monument, in NE¼ sec. 31, T. 1 S., R. 1 W., Ute P.M.

telescopic alidade, others were measured on aerial photos using the Kelsh plotter.

The section that follows is typical of the Wingate Sandstone as to lithology but not as to total thickness (400 feet), which may be too large by 20 to 30 feet—doubtless because of the difficulty in climbing and measuring the cliff section bed by bed. Additional sections of the Wingate are given at the end of this report.

Section of Wingate Sandstone along east side of No Thoroughfare Canyon in NE¼ sec. 32, T. 1 S., R. 1 W., Ute P.M.

[Measured by S. W. Lohman and W. H. Lohman, Aug. 22, 1956]

	Thickness (feet)
Triassic(?):	
Kayenta Formation:	
Triassic:	
Wingate Sandstone:	
Sandstone, fine-grained, buff, hard, crossbedded. Last 15 ft estimated (could not climb to top of cliff)	161
Sandstone, fine-grained, salmon-red, crossbedded	11
Sandstone, fine-grained, buff but containing a few reddish streaks; crossbedded	34
Sandstone, fine-grained, salmon-red, hard, crossbedded	19

Section of Wingate Sandstone along east side of No Thoroughfare Canyon in NE¼ sec. 32, T. 1 S., R. 1 W., Ute P.M.—Con.

	Thickness (feet)
Triassic—Continued	
Wingate Sandstone—Continued	
Sandstone, fine-grained, buff, hard, crossbedded	30.5
Sandstone, fine-grained, salmon-red, hard. Thin shale parting at top forms crevice, remainder forms ledge on cliff face. Upper part changes to buff laterally	39.5
Sandstone, fine-grained, red, soft. Thin shale or silt partings at intervals of few inches. Forms crevice between two ledges	1
Sandstone, fine-grained, salmon-red, crossbedded	25
Sandstone, mainly fine-grained but including some medium grains and, at the base, a few coarse grains. Mainly buff but contains salmon-red streaks	79
Wingate(?) Sandstone:	
Sandstone, fine-grained; contains thin red shale parting at top and lenses of red siltstone in lower part	1.5
Total Wingate (rounded)	400
Chinle Formation (incomplete):	
Siltstone, red.	

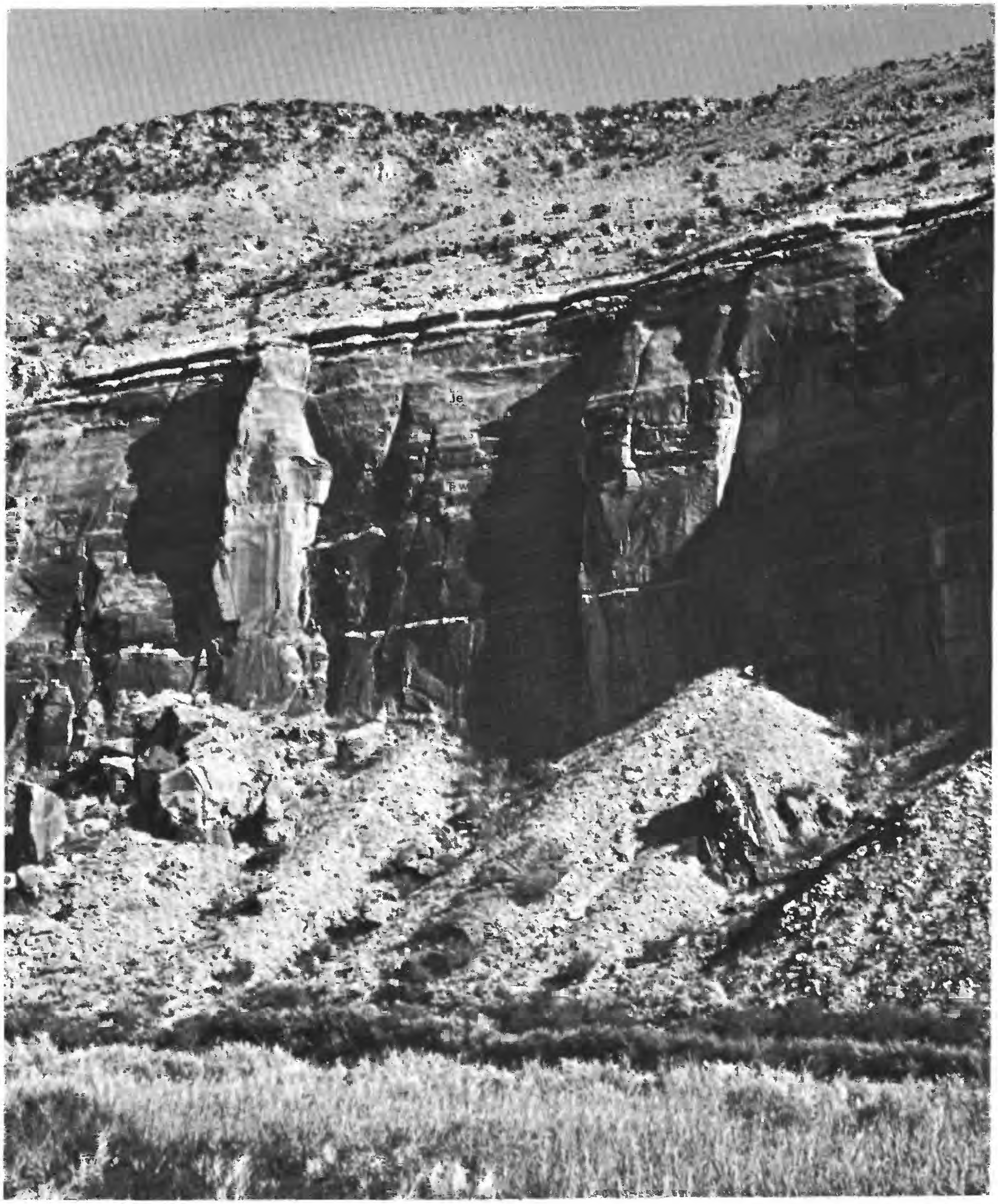

FIGURE 6.—Contact between the Entrada Sandstone (Je) and the Wingate Sandstone (ꞦW) near top of cliff in the Gunnison River valley, in the NW¼ sec. 1, T. 14 S., R. 99 W. Desert varnish on Wingate and absence of varnish on Entrada allows accurate placement of contact. Kayenta Formation is absent here.

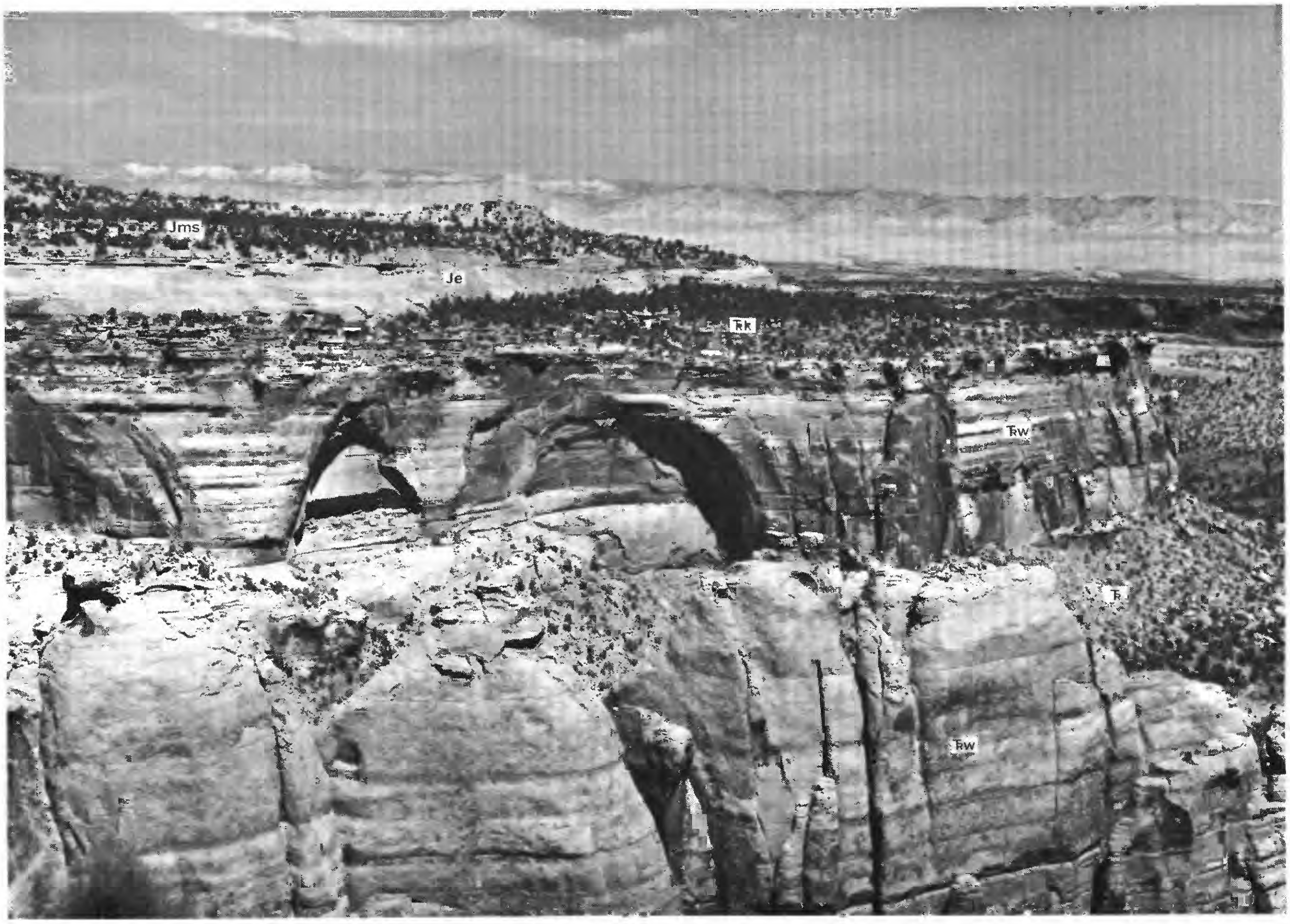

FIGURE 7.—The Coke Ovens, in Colorado National Monument. Looking north from Rim Rock Drive near Artists Point across arm of Monument Canyon. Ꞧc, Chinle Formation; Ꞧw, Wingate Sandstone; Ꞧk, Kayenta Formation; Je, Entrada Sandstone; Jms, Morrison and Summerville Formations. Note how general absence of protective cap of Kayenta Formation from monoliths of Wingate Sandstone in foreground has allowed erosion into rounded forms resembling beehive coke ovens. Note also formation of alcoves and arches in cliff beyond aided by removal of underlying Chinle Formation. Joints between Coke Ovens and in cliff beyond are in contrast to general absence of joints in Entrada Sandstone.

Conditions of deposition.—The high-angle cross-stratification of some beds and the level-bedding in other units suggest that the Wingate Sandstone is in part of eolian origin and in part water-laid. The fact that the level-bedded units seems to be as well sorted as the eolian cross-stratified beds, suggests that they may have been deposited in playa lakes (Stokes, 1958, p. 28), and the thin beds of limestone found in some other areas to the west also suggest this origin (Gilluly and Reeside, 1928, p. 70).

Studies of the cross-stratification in the Wingate over large areas of the Colorado Plateau by Stewart (1956, p. 92) indicate that, in general, the dune sand was blown in toward the southeast. This suggestion is in agreement with detailed studies of cross-stratification of the Wingate Sandstone in and near the Grand Junction area by F. G. Poole (oral communication, July 20, 1960), who determined wind directions ranging from S. 47° E. to S. 86° E. and dips of cross-strata from 20° to 22°. Petrographic studies of thin sections of three samples of Wingate Sandstone from the Grand Junction area by H. A. Tourtelot (written communication, July 14, 1960) indicate that 15 to 20 percent of the grains are feldspars (table 4) and that, in common with the samples of Entrada Sandstone, the general sequence of main events that have affected these samples were:

(1) Deposition of particles derived from a crystalline terrane and from sedimentary terranes in one or more cycles; (2) solution along grain boundaries, probably partly in response to increasing pressure from depth of burial; (3) recrystallization of kaolinitic clay matrix and perhaps some reorganization of the micaceous clay minerals (perhaps the grains interpreted as siderite were also deposited at this time); (4) alteration in place of feldspar to clay minerals similar to the clay in the matrix (events 2, 3, and 4 may have been almost simultaneous); and (5 deposition of calcite replacing clay mostly but also partly replacing grains of quartz and feldspar (may have immediately followed steps 2, 3, and 4 or taken place considerably later).

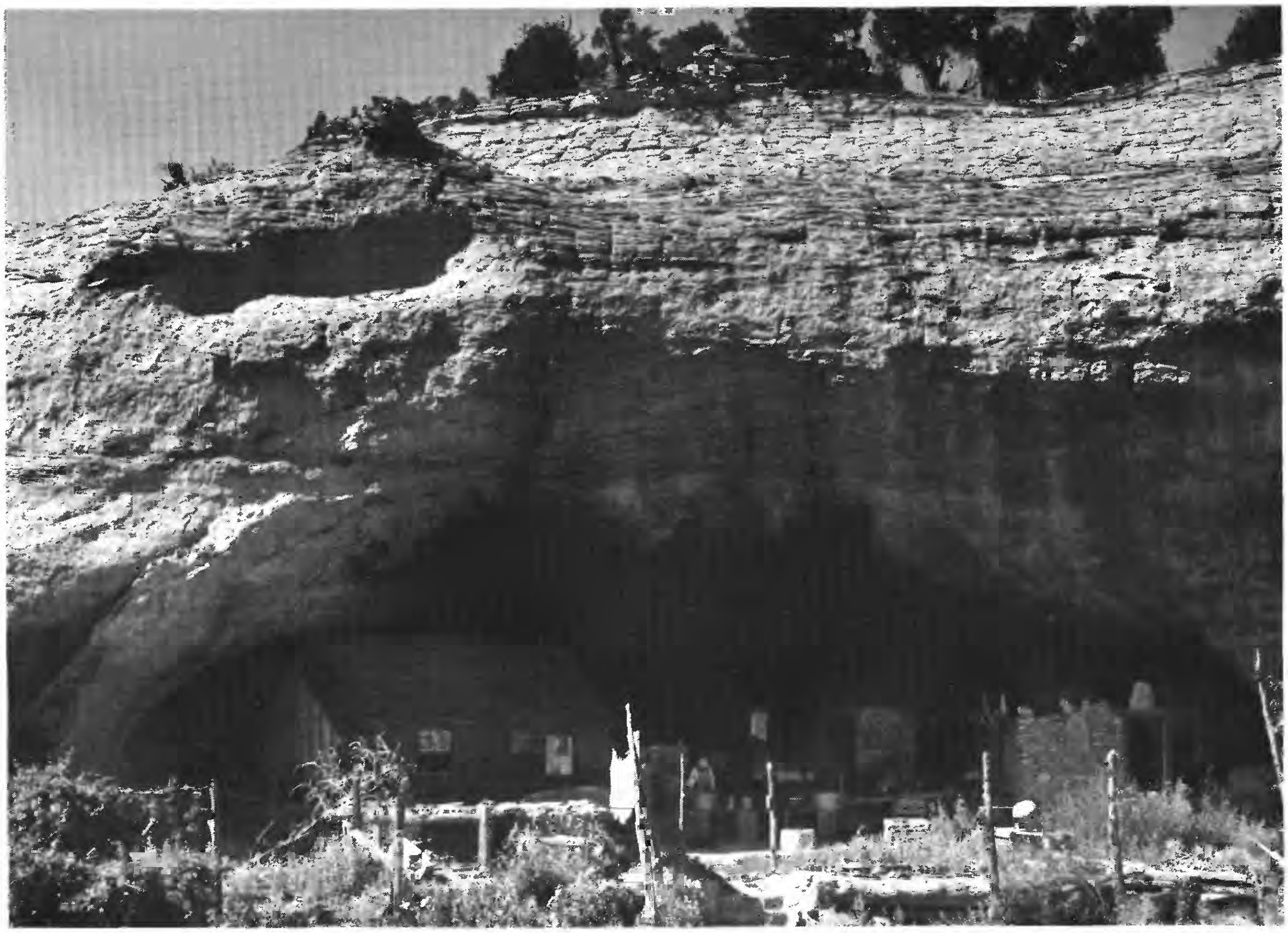

FIGURE 8.—Cave in Wingate Sandstone inhabited until 1958. On main road 3 miles west of Glade Park Post Office in N½ sec. 27, T. 12 S., R. 102 W. Lone inhabitant, Mrs. Laura Hazel Miller, visible between gateposts. One-room house is entirely within cave, and smaller storehouses extend back beyond limit of visibility.

The arkosic character of the sands, the sequence of events interpreted from petrographic studies, and the gradual thickening of the formation westward suggest that, at least in this area, the Wingate Sandstone probably was derived in one or more stages largely from the old Uncompahgre highland to the east. The water-laid parts could have reworked by winds from the northwest to form the eolian beds and, conversely, the eolian parts could have been reworked by water to form the evenly bedded strata. A possible common origin for both parts is thus suggested.

The continental origin of the Wingate Sandstone is indicated also by its transitional relations with both overlying and underlying formations of continental origin, by dinosaur tracks found in the Wingate Sandstone along the San Juan River (Longwell and others, 1925, p. 13) and in the San Rafael Swell (Gilluly and Reeside, 1928, p. 70), and by the remains of reptiles and fresh-water fish and invertebrates in the overlying Moenave and Kayenta Formations in the Navajo Country (Harshbarger, Repenning, and Irwin, 1957, p. 29, 30; Lewis, Irwin, and Wilson, 1961, p. 1437, 1438).

Age and correlation.—Much has been written about the age and correlation of the Wingate Sandstone and of the overlying formations of the Glen Canyon Group, and opinions as to the age of the Wingate and correltive units (table 3) have fluctuated from assignments: (1) to the Triassic by Peale (1877, p. 80–87), by Dutton (1885, p. 137), and by Cross (1907, p. 636, 652) who correlated the sandstone (now called Wingate) along the Colorado River about 12 miles north of Moab, Utah with the sandstone of his Dolores Formation and of the Vermilion Cliff Group of Powell; (2) to the Pennsylvanian(?) and later the Carboniferous by Lee (1912, p. 20–23, 50; 1918, p. 16–21); (3) to the Jurassic by Gregory (1917, p. 55), in part because of his miscorrelation of the Wingate with the lower member of the La Plata Sandstone of Cross

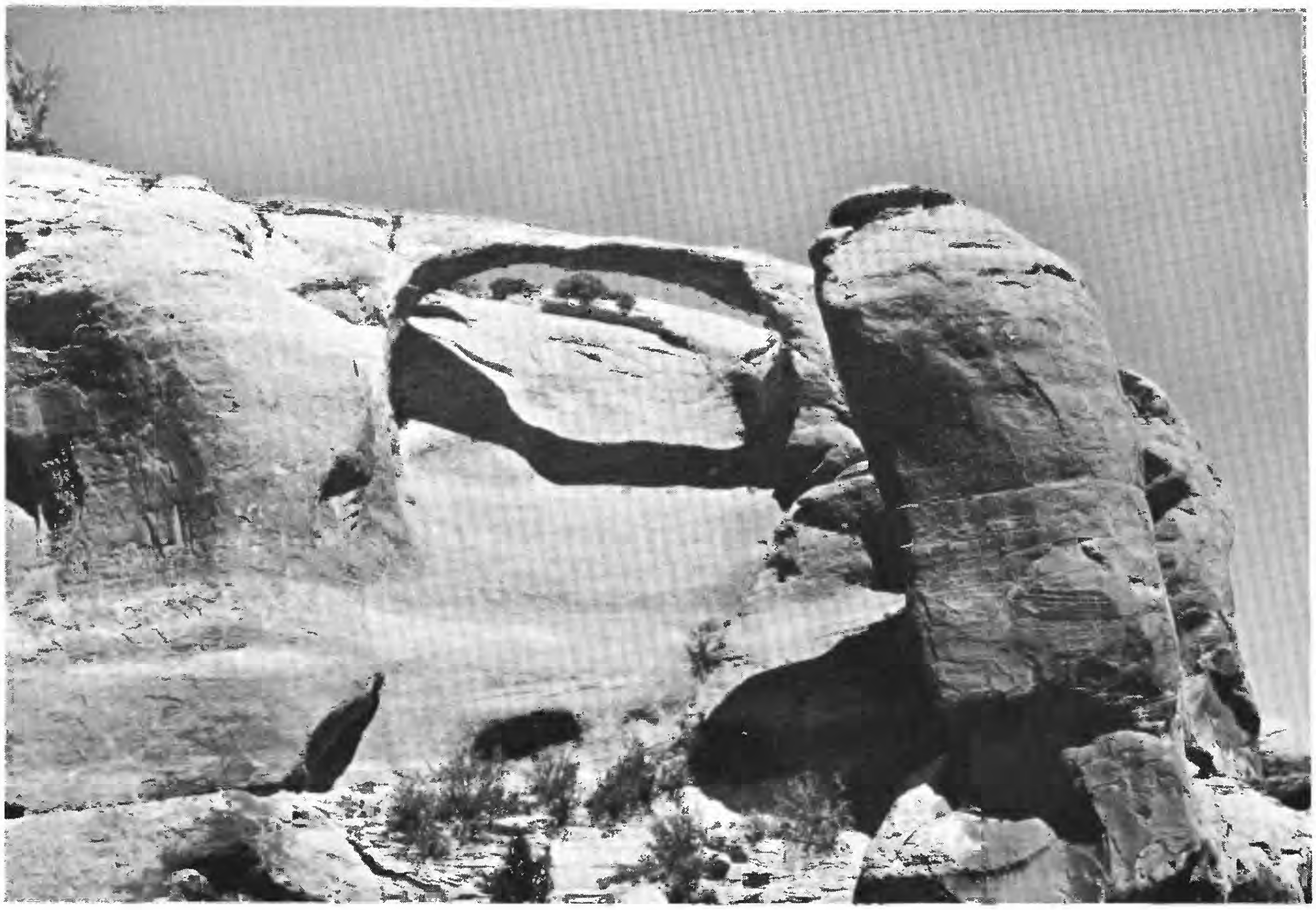

FIGURE 9.—Natural bridge in Wingate Sandstone. Along north side of road west of Glade Park Post Office a few miles west of southwest corner of map (pl. 1). Note rounded forms produced after removal of protective cap of Kayenta Formation.

and perhaps in part because of the supposed unconformity at the base of the Wingate (p. 24); (4) to the Jurassic(?) by Gilluly and Reeside (1928, p. 73), who stated, however, that the Glen Canyon Group might be Jurassic or Triassic; and (5) back to the Upper Triassic by Harshbarger, Repenning, and Irwin (1957, p. 25–32), on the basic of fossils in the Wingate and overlying formations. No fossils were found in the Wingate Sandstone in the Grand Junction area but, because of the seemingly continuous deposition of the Chinle Formation and the Wingate and the fossils found elsewhere in and above the Wingate, the Late Triassic age assignment seems to be fully warranted.

In the Navajo Country, Harshbarger, Repenning, and Irwin (1957, p. 8) divided the Wingate Sandstone into two units, the Rock Point Member and the overlying Lukachukai Member. In and near the Grand Junction area the Wingate Sandstone resembles the Lukachukai Member, and strata resembling the Rock Point Member are considered to be the Church Rock Member of the Chinle.

Water supply.—The Wingate Sandstone is the thickest and lowermost of four artesian aquifers in the Grand Junction area, although it is second in importance to the thinner but generally more permeable Entrada Sandstone. Data are lacking as to the quantity and quality of water obtainable from the Wingate, for of the 48 artesian wells for which records were obtained (table 7), only two (34, 48) seem to obtain water from the Wingate alone and both of these are nonflowing wells near the outcrop and on which pumping or flow tests could not be made.

Laboratory tests of the coefficient of permeability of samples of Wingate Sandstone (table 4) indicate that the Wingate has a low permeability comparable to that of much of the Slick Rock Member of the Entrada Sandstone but less than that of the Moab Member of the Entrada.

The recharge areas of the Wingate and Entrada Sandstones are nearly the same and are discussed on pages 100, 101. South of the recharge areas the Wingate is drained by canyon cutting, but locally, as in Glade

Park, it contains small amounts of unconfined ground water (p. 93).

Twelve of the 48 wells were drilled deep enough to tap both the Entrada and Wingate Sandstones (table 7), but a few of these are old wells for which casing records are scanty or lacking, so the contribution of the Wingate to the total production of each of these wells is not known. Inasmuch as the recharge areas of the Wingate are higher than those of the Entrada, however, the water in the Wingate normally is under the greater artesian head and hence may contribute appreciably to the discharge of wells that tap both aquifers. Locally, this natural difference in head has been increased by a gradual decline in head in the greater number of heavily pumped wells that tap the Entrada alone.

Some information on the yield of the Wingate Sandstone is given in the log of well 19. It was reported that this well flowed 2 gpm (gallons per minute) from the Entrada Sandstone at a depth of 769 feet, that the flow increased to 8½ gpm when an opening was penetrated at or near the base of the Kayenta Formation between the depths of 940 and 943 feet, and that the flow increased to 13 gpm when the well was completed in the Wingate at a depth of 996 feet. The opening may have resulted from solution in a limestone conglomerate in the Kayenta; the water it contained probably was collected and transmitted from the underlying Wingate.

For the reasons given above, no samples of water were collected from the Wingate Sandstone alone, but the analyses of five samples of water obtained from four wells that tap both the Wingate and Entrada Sandstones and two samples from a well that taps the Entrada, Wingate, and Kayenta Formations (table 8) indicate generally soft sodium bicarbonate waters of good quality for domestic use and most other uses. The water is similar chemically to that from the Entrada Sandstone alone. In common with all the samples analyzed, those from the Wingate and Entrada exhibit softening by natural base exchange (p. 117, 118) and become increasingly soft at increased distances from the recharge areas (fig. 46).

Some of the water has a sufficiently high sodium (alkali) hazard to be possibly injurious to lawns or other crops (fig. 47), but most is used entirely for domestic purposes.

CONTACT BETWEEN WINGATE SANDSTONE AND KAYENTA FORMATION

In the Grand Junction area the change from the dominantly eolian but partly water-laid beds of the Wingate Sandstone to the entirely fluvial beds of the Kayenta Formation is so gradational as to suggest continous deposition. The contact, which seems to be conformable and generally is difficult to pinpoint, was placed between the lowest lenticular to irregularly bedded, generally harder and coarser grained sandstone of the Kayenta and the highest finer grained, softer massive sandstone of the Wingate. This gradational relationship, shown in figures 7 and 10, seems to prevail throughout the Colorado Plateau (Baker, Dane, and Reeside, 1936, p. 5) except locally, as in the Navajo Country, where the Moenave Formation occurs between the Wingate and the Kayenta (Harshbarger, Repenning, and Irwin, 1957, p. 12).

UPPER TRIASSIC(?) SERIES

KAYENTA FORMATION

Definition.—The Kayenta Formation was named by Baker, Dane, and McKnight (1931) from exposures on Comb Ridge, 1 mile northeast of Kayenta, Ariz., but it was more completely described by Baker, Dane, and Reeside (1936, p. 5). The beds so named had formerly been designated as the Todilto Formation (Gregory, 1917, p. 55) or Todilto(?) Formation (Gilluly and Reeside, 1928, p. 70), but later work by Baker, Dane, and Reeside (1936, p. 5, 17) showed that the true Todilto at the type locality in Todilto Park, N. Mex., is much younger than the Kayenta.

Character, distribution, and thickness.—The Kayenta Formation consists mainly of lenticular to irregularly bedded layers of fine- to medium-grained sandstone, irregular lenses of siltstone and shale, and a few lenses of conglomerate or conglomeratic sandstone. The sandstones generally are harder and coarser grained than the underlying Wingate Sandstone—particularly the lower beds of the Kayenta, which serve as a protective capping to the Wingate. Along the cattle drive in the SE¼SE¼ sec. 30, T. 1 N., R. 2 W., Ute P.M., was observed a bed of hard conglomerate 4 to 5 feet thick containing well-rounded to subangular pebbles of red sandstone and reddish to bluish limestone from ¼ to 1½ inches in diameter. Some conglomeratic sandstones, as in the measured section given below, contain pebbles of green and red shale and some pebbles of siltstone. No beds of limestone were observed in the Kayenta, such as those reported in the San Rafael Swell, Utah, by Gilluly and Reeside (1928, p. 71), but limestone conglomerate may have been penetrated in the Kayenta in the drilling of well 19. Most of the sandstone beds are buff, white, or gray, but a few are lavender gray or red. The siltstone and shale generally are as red as the Chinle Formation, but locally are lavender, purple, or green. Locally, wash from the lenses of red siltstone imparts a reddish color to the underlying Wingate Sandstone. No exposure of the Kayenta may be considered typical, but figure 11 gives some idea of the lenticularity and irregular bedding.

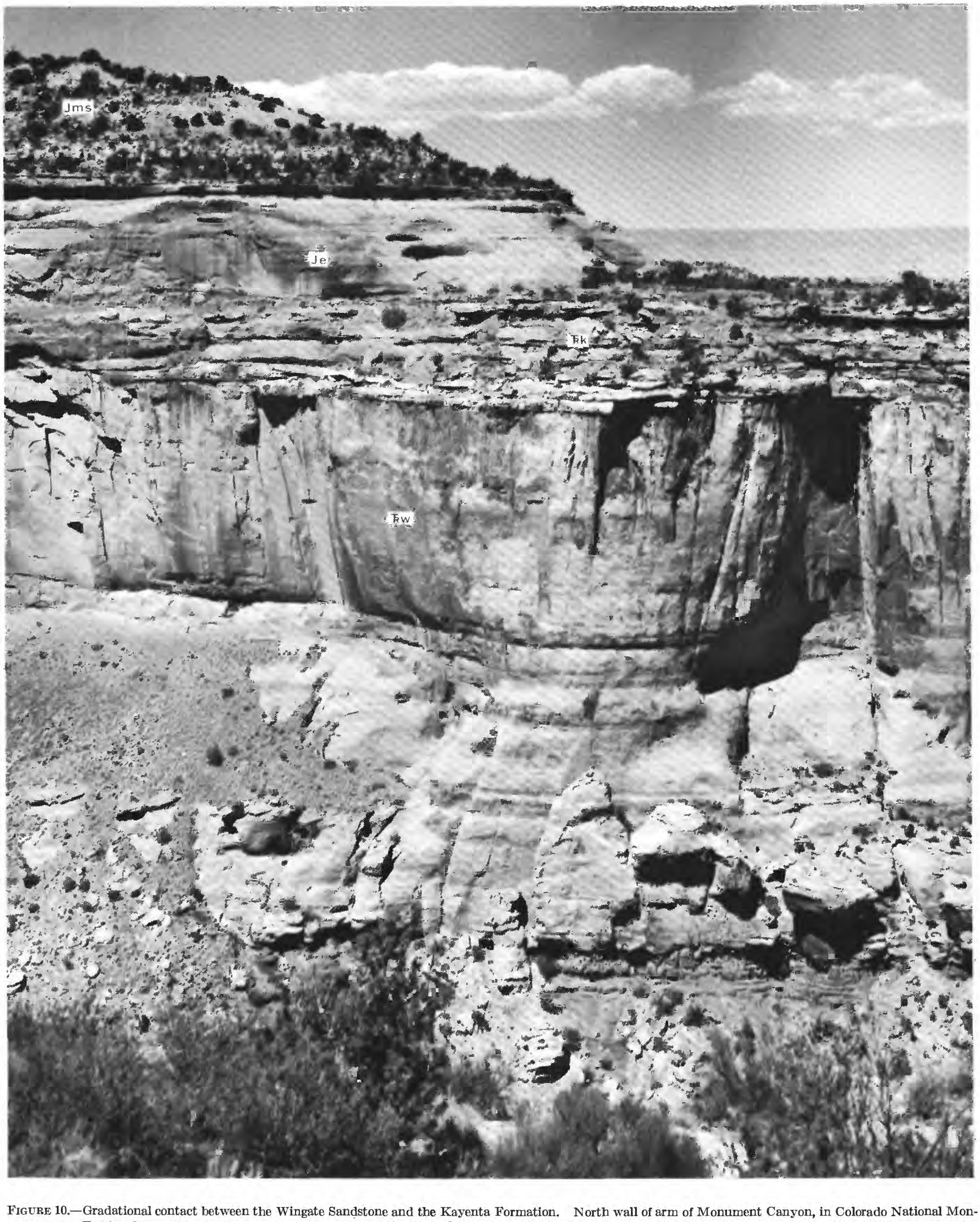

FIGURE 10.—Gradational contact between the Wingate Sandstone and the Kayenta Formation. North wall of arm of Monument Canyon, in Colorado National Monument. Erosional unconformity between Kayenta and overlying Entrada Sandstone is also shown. Normally a bench-former as on the right, the Kayenta on the left forms part of a single cliff. Ꞧw, Wingate Sandstone; Ꞧk, Kayenta Formation; Je, Entrada Sandstone; Jms, Morrison and Summerville Formations.

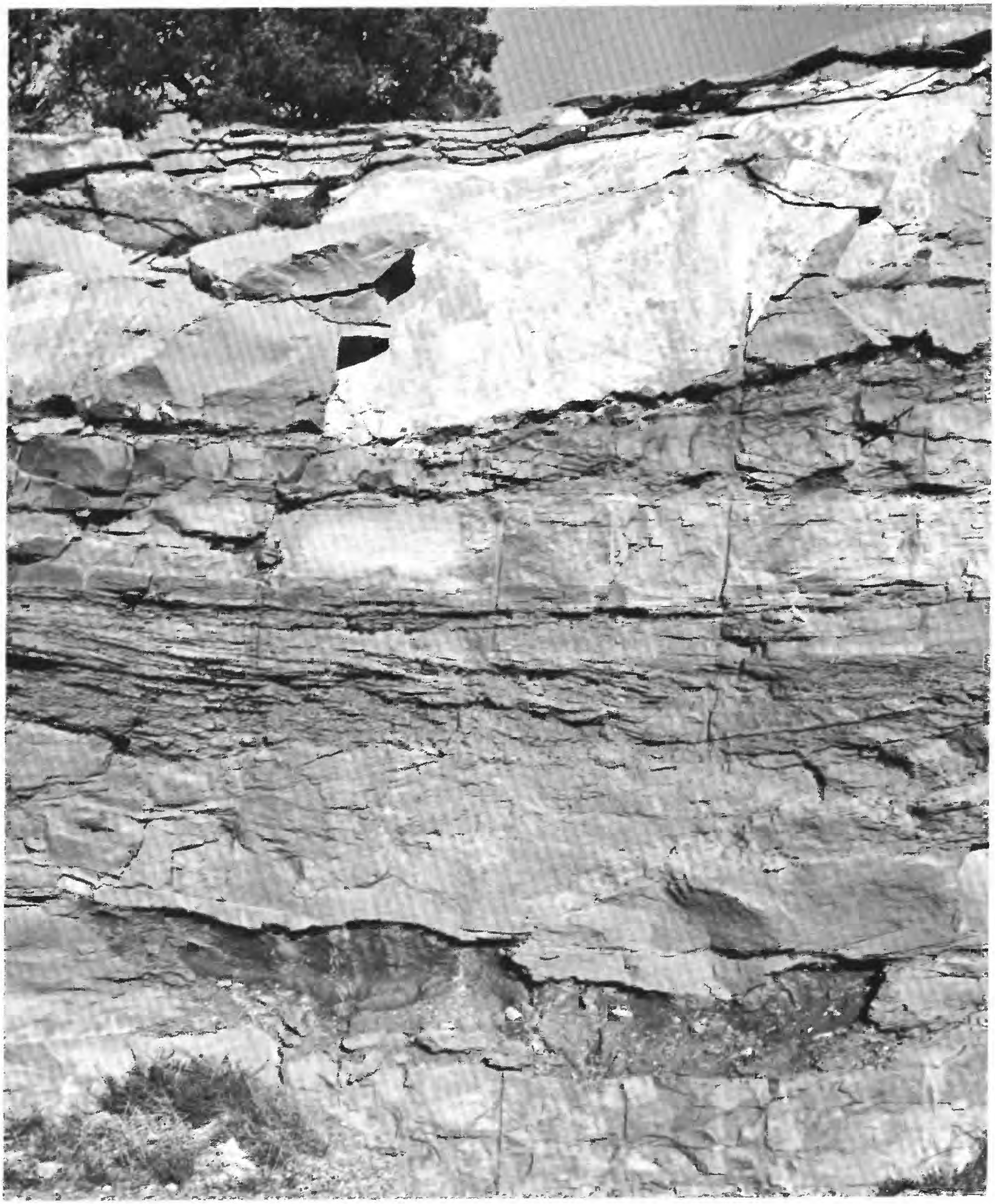

FIGURE 11.—Kayenta Formation in cut along Rim Rock Drive near elbow of Ute Canyon. Note irregular lens of red siltstone near base and irregular bedding of sandstones above.

The Kayenta Formation is typically a bench-former between cliffs of the Wingate Sandstone below and the Entrada Sandstone above (figs. 2, 7), but in some parts of the Colorado National Monument, where the bench is absent, the three formations form a single cliff (fig. 10). Most of scenic Rim Rock Drive in the monument is on a bench of the Kayenta, from which may be seen spectacular views of the canyons below. Because of its bench-forming character, the Kayenta generally crops out over greater areas than the thicker cliff-forming sandstone formations above and below, and covers many broad intercanyon mesas in and near Colorado National Monument, in Glade Park, and in East Park.

The Kayenta Formation has a greater range in thickness than any other formation in the Grand Junction area. Holmes found it to be 127 feet thick north of sec. 18, T. 11 S., R. 102 W., about 2 miles west of the area (see Black Ridge section at end of this report). The Kayenta ranges from about 60 to more than 80 feet thick in the western and central parts of the Colorado National Monument, but thins southeastward to 47 feet on the east side of No Thoroughfare Canyon in the NW¼ sec. 32, T. 1 S., R. 1 W., Ute P.M., to 16 feet along Ladder Canyon in the NW¼ sec. 30, T. 12 S., R. 100 W., becomes still thinner at the east end of East Park, and is absent entirely in and east of North East Creek canyon, where the Entrada Sandstone rests directly on the Wingate Sandstone (fig. 6). The southeasternmost featheredge of the Kayenta, therefore, is concealed somewhere within the 3-mile interval between the outcrop of the Kayenta at the east end of East Park and the outcrops of the Wingate and Entrada Sandstones in North East Creek canyon. The Kayenta also is absent on the southwestern flank of the Uncompahgre Plateau east of the SE cor. sec. 35, T. 15 S., R. 102 W., about 18 miles to the south-southwest from the featheredge indicated above (Cater, 1955).

The section that follows is not typical of the Kayenta in that the formation is thinner and not as conglomeratic as it is farther west, but it will serve to illustrate some details of the lithology.

Section of Kayenta Formation and Entrada Sandstone along perennial tributary of No Thoroughfare Canyon above large cottonwoods, in NW¼ sec. 32, T. 1 S., R. 1 W., Ute P.M.

[Measured by S. W. Lohman and W. H. Lohman, Aug. 22, 1949]

	Thickness (feet)
Jurassic:	
Summerville Formation (incomplete):	
Siltstone, red.	
Entrada Sandstone:	
Moab Member:	
Sandstone, buff to white, evenly to poorly bedded; some thin layers stained yellow by iron oxide; thin bedded and greenish white near top	50

Section of Kayenta Formation and Entrada Sandstone along perennial tributary of No Thoroughfare Canyon above large cottonwoods, in NW¼ sec. 32, T. 1 S., R. 1 W., Ute P.M.—Con.

	Thickness (feet)
Jurassic—Continued	
Entrada Sandstone—Continued	
Slick Rock Member:	
Sandstone, fine-grained, salmon-colored, hard, fairly evenly bedded; some grains of coarse sand scattered and in thin layers	22
Sandstone, similar to bed above but softer	40
Total Slick Rock Member	62
Total Entrada	112
Triassic(?):	
Kayenta Formation:	
Sandstone, medium-grained, gray, hard	3.0
Sandstone, conglomeratic, greenish, hard; pebbles of green and red shale	1.0
Siltsone and shale, red, largely concealed	4.5
Sandstone, fine- to medium-grained, gray, thin-bedded; some yellow specks of iron oxide; some pebbles of siltstone ¼–½ in. in diameter	2.0
Sandstone, fine- to medium-grained, buff to gray, hard, lenticular; in beds of varying thickness with thin shale partings between	36
Total Kayenta (rounded)	47
Triassic:	
Wingate Sandstone.	

Conditions of deposition.—Geologists who have worked with the Kayenta Formation seem to be in general agreement that it comprises fluvial deposits laid down during a short wet interval between longer and possibly drier intervals of dominantly dune formation (Wingate and Navajo Sandstones). In and near the Grand Junction area the Kayenta thins to extinction eastward toward the old Uncompahgre highland; this thinning suggests the highland as a general source area for the streams and the transported material. Detailed studies of current cross-stratification by F. G. Poole (oral communication, July 27, 1960) showed that throughout most of the Colorado Plateau the streams that deposited the Kayenta flowed in a southwesterly direction. Near Red Canyon Overlook, in the Colorado National Monument, a local northwesterly direction of flow (N. 78° W.) was indicated from Poole's studies, but this direction also is away from the old landmass.

A continental origin for the Kayenta Formation is indicated also by the fossils found to date, information on which is given immediately below.

Age and correlation.—Opinions as to the age of the Kayenta Formation (table 3) have fluctuated much like those concerning the age of the Wingate Sandstone, and much of what is given on pages 30, 31 applies also to the Kayenta and need not be repeated here. Most earlier workers considered the Kayenta to be of Triassic age, until Gregory (1917, p. 55, 56) assigned to it a Jurassic age, in part because of his miscorrelation of the Wingate Sandstone and his "Todilto Formation" [Kayenta Formation] with the lower and middle members, respectively, of the La Plata Sandstone of Cross, and perhaps in part because of the supposed unconformity at the base of the Wingate. Strata in the San Rafael Swell now known to belong to the Kayenta Formation were assigned to the Jurassic(?) by Gilluly and Reeside (1928, p. 72, 73), but with the statement that "The Glen Canyon Group may be Jurassic or Triassic ***", and this age assignment to the Jurassic(?) remained unchanged for many years. (See Harshbarger, Repenning, and Irwin, 1957, p. 25–31.)

No fossils have been found in the Kayenta Formation in or near the Grand Junction area, but the vertebrates *Protosuchus* and a new genus of tritylodont have been found from 10 to 8 feet below the top of the formation at the type locality near Kayenta, Ariz. (G. E. Lewis, written communication, July 25, 1960). In July 1960 a group of U.S. Geological Survey geologists [8] familiar with the Glen Canyon Group of the Colorado Plateau met at Denver to consider the age of the Kayenta and associated formations on the basis of the age indicated by these and other fossils and on stratigraphic relationships in the type area and in other parts of the Plateau. The group unanimously recommended that (written communication to George V. Cohee, Chairman, Geologic Names Committee, U.S. Geological Survey, July 28, 1960):

1. The Kayenta Formation be assigned to the Triassic(?) because of its content of Triassic(?) fossils and its partial equivalence to the Triassic(?) Moenave Formation.
2. The Navajo Sandstone be assigned to the Jurassic and Triassic(?) because it intertongues with the Jurassic Carmel Formation above and the Triassic(?) Kayenta Formation below.

Their recommendations also stated:

*** We probably would have suggested reassignment of the Kayenta and Moenave Formations and, hence, also of the lower part of the Navajo Sandstone, to the Triassic without query, except for the facts that:

1. There are still some differences of opinion regarding the age of some of the fossils involved.
2. The Kayenta is unfossiliferous in most areas and its synchroneity over the entire Colorado Plateau is not certain.

The recommendations were approved by the Geologic Names Committee on September 28, 1960, hence the age of the Kayenta Formation is now considered by the U.S. Geological Survey to be Triassic(?). The paleontologic and stratigraphic evidence supporting the changes in age assignments has been presented by Lewis, Irwin, and Wilson (1961).

[8] F. W. Cater, Jr., L. C. Craig, J. H. Irwin, G. E. Lewis, S. W. Lohman, E. D. McKee, F. G. Poole, J. D. Strobell, Jr., R. F. Wilson, and J. C. Wright.

Water supply.—The Kayenta Formation is not considered to be an aquifer, but neither is it thought of as completely separating, hydraulically, the two principal artesian aquifers—the Wingate and Entrada Sandstones. Although the Kayenta is largely sandstone, the sandstone is highly lenticular and well cemented and doubtless has a very low permeability, particularly in the direction normal to the bedding. Moreover, the sandstone beds are separated by or interbedded with lenses of siltstone of probably even lower permeability.

East of the featheredge of the Kayenta Formation between the southeast end of East Park and North East Creek, the absence of the Kayenta allows the Wingate and Entrada Sandstones to come in contact and form a single artesian aquifer (fig. 6). No wells have been drilled downdip from recharge areas of this combined aquifer, however, so the effect of this combination on the yield of wells is not known. Presumably the yield would depend in large part on the aggregate thickness of the two aquifers penetrated, as it does in wells where the Kayenta is present.

The flow from an opening at or near the base of the Kayenta in well 19 probably comes from the underlying Wingate Sandstone (p. 32).

JURASSIC SYSTEM

SAN RAFAEL GROUP

The San Rafael Group was named by Gilluly and Reeside (1928, p. 73) to include, from oldest to youngest, the Carmel, Entrada, Curtis, and Summerville Formations, from their excellent exposures in the San Rafael Swell, Utah. In the San Juan Mountain region, beds equivalent to the Summerville generally are included in the Wanakah Formation.

Later the Bluff Sandstone of the Four Corners region and the equivalent Junction Creek Sandstone of the San Juan region (Goldman and Spencer, 1941, p. 1759) were assigned to the San Rafael Group by Craig and others (1955, p. 133, 134), and the Todilto Formation also was assigned to the San Rafael Group (Harshbarger, Repenning, and Irwin, 1957, p. 38).

In the Grand Junction area the San Rafael Group is represented only by the Entrada Sandstone and the Summerville Formation, but the Moab Member of the Entrada at least in part probably is a time equivalent of the Curtis Formation (p. 45, 46).

EROSIONAL UNCONFORMITY AT THE BASE OF THE ENTRADA SANDSTONE

An erosional unconformity at the base of the Entrada Sandstone marks the absence from the Grand Junction area of parts of the Glen Canyon and San Rafael Groups (table 3), including much of the Entrada Sandstone, all the Carmel Formation and Navajo Sandstone, most of the Kayenta Formation west of

North East Creek, and all the Kayenta and possibly part of the Wingate Sandstone in and east of North East Creek Canyon. Slight irregularities on this erosion surface at the top of the Kayenta are shown in figure 12, and a somewhat smoother contact between the Entrada and the Wingate Sandstone is shown in figure 6. Figure 12 shows what may be a slight angular unconformity, but any angular discordance is masked by irregular and cross-stratification in the Kayenta. A slight angular unconformity between the Entrada and the Kayenta was reported, however, by L. R. Litsey (J. C. Wright and D. D. Dickey, written communication, July 9, 1960) in Tabeguache Canyon, Montrose County, Colo., in sec. 34, T. 48 N., R. 15 W., New Mexico P.M.

From studies of the San Rafael Group in Utah and parts of adjacent states, Wright and Dickey (written communication, July 9, 1960) found that in southwestern Utah the Carmel Formation intertongues with the underlying Navajo Sandstone but that elsewhere in the Colorado Plateau, including western Colorado, an erosional unconformity separates the San Rafael and Glen Canyon Groups. Their most convincing evidence of this erosional unconformity is on Bartlett Flat near the head of Seven Mile Canyon, in the northeastern part of T. 25 S., R. 19 E., Salt Lake Meridian, about 15 miles northwest of Moab, Utah, where the Navajo Sandstone is only about 150 feet thick in contrast to nearby areas where it is 250–350 feet thick and where a monadnock of the Navajo rises about 35 feet above the generally smooth erosion surface and extends into the overlying Entrada.

This erosion surface may extend eastward to the Black Canyon of the Gunnison, in the lower part of which the Entrada rests directly on the Precambrian complex and in the upper part of which the Wanakah Formation (equivalent to the Summerville Formation) rests directly on the Precambrian complex (Wallace R. Hansen, oral communication, July 10, 1960). This thinning and ultimate disappearance of strata against the flank of the old Uncompahgre highland may result in part from nondeposition near the old highland, but is clearly erosional farther west.

In the Grand Junction area there is undoubtedly an erosional unconformity at the base of the Entrada Sandstone, and there may be a slight angular discordance. Part of the missing strata seemingly was removed by erosion, but part may never have been deposited.

UPPER JURASSIC SERIES

ENTRADA SANDSTONE

Definition.—The Entrada Sandstone was named by Gilluly and Reeside (1928, p. 76) from Entrada Point in the northern part of the San Rafael Swell, Utah.

In the Moab, Utah, area, the uppermost massive crossbedded grayish-white sandstone of the Entrada was named the Moab Tongue of the Entrada Sandstone by Baker and others (1927, p. 787, 799) and was used as the Moab Member of the Entrada by Dane (1935, p. 19). The underlying and larger part of the Entrada remained unnamed until 1962, when the use of named members rather than "lower, middle, or upper members" became necessary to avoid confusion in correlating the twofold division of the Entrada Sandstone in the Grand Junction area with the generally threefold division in south-central Utah. Accordingly, the massive smooth-faced, cliff-forming sandstone beneath the Moab Member was named the Slick Rock Member after exposures at the town of Slick Rock, Colo., and the basal silty, earthy sandstone (formerly included in the Carmel Formation) was named the Dewey Bridge Member after exposures near Dewey Bridge, Grand County, Utah (Wright, Shawe, and Lohman, 1963). The silty, earthy Dewey Bridge Member closely resembles the entire Entrada at the type locality in the San Rafael Swell, but the Entrada becomes increasingly sandy eastward from the Swell.

The Moab is called a member in and east of Arches National Monument, where it rests directly on the Slick Rock Member, but west of this point, where it intertongues with the Summerville Formation, it is called a tongue (Wright, Shawe, and Lohman, 1963, fig. 2).

In the Grand Junction area only the Moab and Slick Rock Members of the Entrada Sandstone are present.

Character, distribution, and thickness.—Throughout the Colorado National Monument and adjacent parts of the area, the Entrada Sandstone forms a distinctive and colorful series of cliffs that are secondary in height and grandeur only to those of the Wingate Sandstone. The cliffs or steep slopes of the Entrada generally surmount the bench of the Kayenta Formation (fig. 7), but locally the Entrada, Kayenta, and Wingate form a single high cliff (fig. 10), and in and east of North East Creek Canyon the Entrada and Wingate form a single sandstone cliff (fig. 6). Although the Entrada normally forms cliffs or steep slopes, it disintegrates more rapidly in areas of greater precipitation and higher altitudes, and it crops out over broad, flat sandy areas in Glade Park and in the western part of East Park.

The Slick Rock Member of the Entrada Sandstone is the principal cliff-forming part of the formation in southwestern Colorado and adjacent parts of Utah, but locally the other members share in this expression. The generally unjointed smooth cliff faces and the salmon or pink color of the Slick Rock Member give it a distinctive and unmistakable appearance that readily

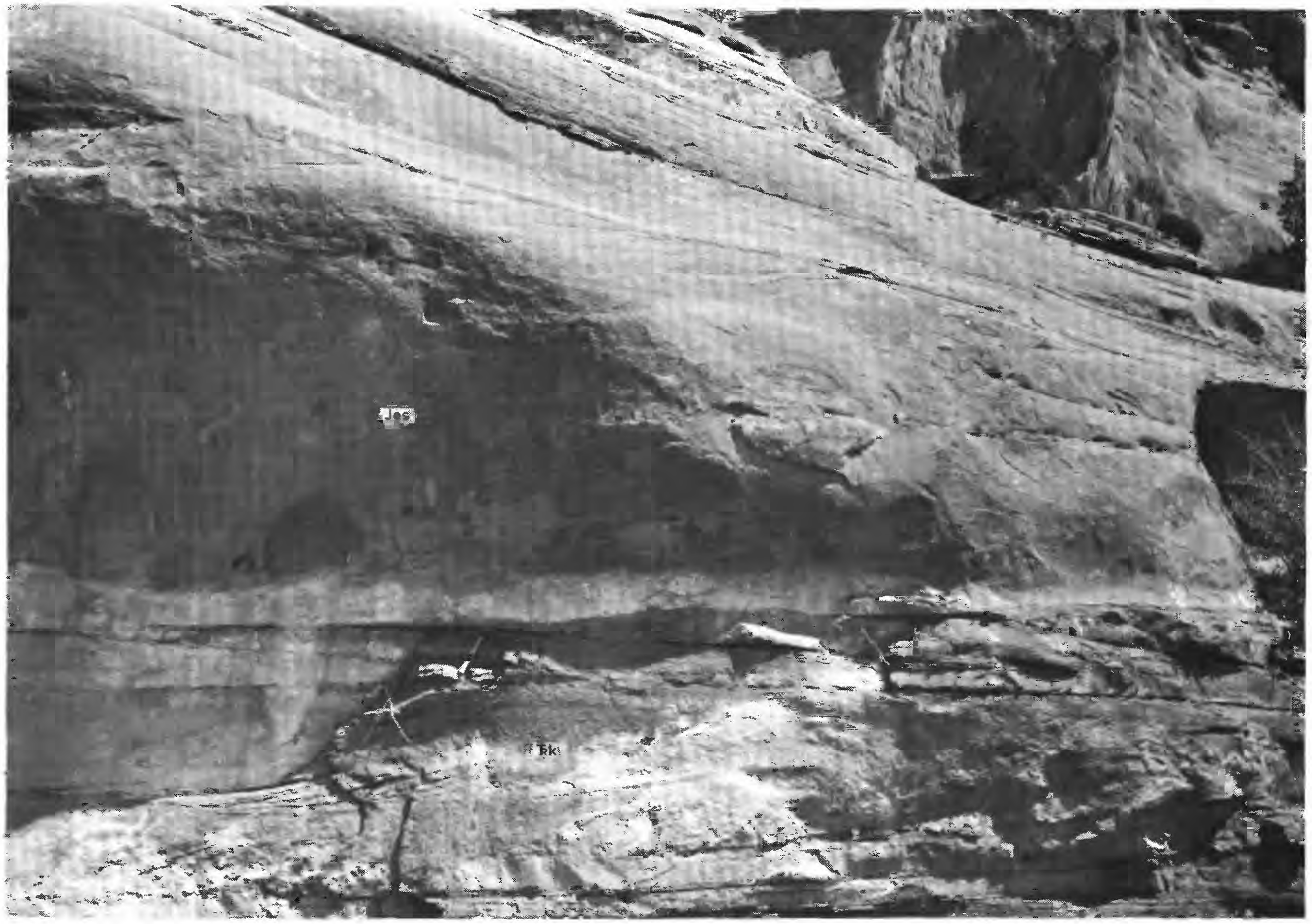

FIGURE 12.—Erosional unconformity between the Slick Rock Member of the Entrada Sandstone (Jes) and the Kayenta Formation (Ꞧk). Along Rim Rock Drive, Colorado National Monument, in the SE¼ sec. 13, T. 11 S., R. 102 W.

distinguishes it from the generally jointed and desert-varnish coated higher cliffs of the Wingate Sandstone (figs. 6, 12, 13). Locally the otherwise smooth cliff faces of the Entrada may be pockmarked by solution cavities ranging in size from a silver dollar to an automobile.

Individual beds in the Slick Rock Member generally range from a few feet to a few tens of feet thick, but some are less than a foot thick. Most of the beds, particularly the thicker beds in the lower part of the member, exhibit high-angle crossbedding, but some are evenly bedded.

The Slick Rock Member is a sandstone composed dominantly of fine- to very fine grained sand, generally a little medium-grained sand, and from less than 10 percent to as much as 30 percent silt. Most beds contain a small amount of clay, and some beds, particularly those near the base, contain a small proportion of coarse-grained sand in thin laminae or in scattered grains. One sample (table 4, fig. 14) contained more than 10 percent of these coarse grains. The coarse grains, which are well rounded and generally frosted and iron-stained, stand out conspicuously in the matrix of finer sand and are referred to as "Entrada berries" by many geologists who have worked in the Colorado Plateau. The secondary peak in the curve for sample 6 in figure 14 was caused by 10.2 percent of these coarse grains and only 1.8 percent medium-grained sand. The possible causes of this type of sorting have been discussed by Dane (1935, p. 100–102).

For the four samples of sandstone from the Slick Rock Member that were analyzed, the median grain diameters ranged from 0.077 to 0.173 mm (very fine to fine-grained sand), and the values of the Trask sorting coefficient, 1.4 to 1.6, indicate a well-sorted material. The degree of sorting is comparable to that of the samples of Wingate Sandstone but slightly less than that of the samples from the Moab Member.

Like the samples from the Wingate Sandstone and the Moab Member, the samples from the Slick Rock Member consist mostly of quartz grains, contain considerable feldspar, and range widely in their content of calcite cement (table 4). Sample 6 had the greatest content of cement and the lowest porosity and per-

FIGURE 13.—Slick Rock Member of Entrada Sandstone. In west arm of Ute Canyon, Colorado National Monument. Ꝗk, Kayenta Formation; Jes, Slick Rock Member. Moab Member and Summerville and Morrison Formations poorly exposed above cliff.

meability of the nine sandstone samples examined. Samples 4 and 6 contained a few grains of chert.

On the basis of microscopic examinations of thin sections of the four samples of sandstone from the Slick Rock Member, H. A. Tourtelot (written communication, July 14, 1960) stated:

Sample 3.—Grains are subangular to subrounded in cross section and are not markedly intersutured where they are in contact. Most grains of quartz and feldspar are surrounded by a highly birefringent rim several microns thick. This rim material appears to be sericite (possibly illite?) that has formed by alteration after the rock was deposited. Some feldspar grains were partly altered to sericite before deposition; others were partly altered to kaolinite and sericite after deposition. Red iron oxide is moderately abundant and occurs in the matrix clay.

Sample 4.—Grains are mostly subangular in cross section although grains larger than 0.1 mm are abundant. Microcline appears to be more abundant than in preceding slides. A number of the orthoclase grains appear to be in the process of altering to kaolinite in place. Other orthoclase grains appear to have been partly altered to sericite and calcite before deposition in this rock. Red iron oxide occurs in the matrix clay and only incidentally stains grains. In some of matrix areas, the iron oxide is accompanied by the tiny grains interpreted as siderite. Wherever sand grains are in contact, they have somewhat intersutured boundaries.

Sample 5.—Matrix clay is fairly evenly distributed through the rock and there is relatively little grain suturing. Both the matrix and calcite appear to have been somewhat leached. In other respects, the slide is similar to sample 6 except for the scattered large grains.

Sample 6.—The sandstone is poorly sorted [compared to the other 8 samples examined] with scattered well-rounded grains of quartz (one of chert was noted) as large as 1.0 mm in a ground mass of grains smaller than about 0.2 mm. Grains larger than about 0.1 mm are generally rounded in cross section and smaller grains are generally angular. The distribution of matrix is patchy, the packing of the sand grains varying from place to place in the slide. Where the grains are closely packed, suturing of grain boundaries is developed. This solution has reduced the amount of matrix clay in the rock. Calcite apparently was deposited after much if not most of the solution took place. Within the calcite patches are aggregates of a carbonate mineral with higher relief than calcite; this may be dolomite. Most grains of quartz and feldspar have a coating of red iron oxide that seems to penetrate the grain to a depth of a few microns. Red iron oxide also is present in the matrix. One fragment of rock was noted that consisted of tiny lathlike

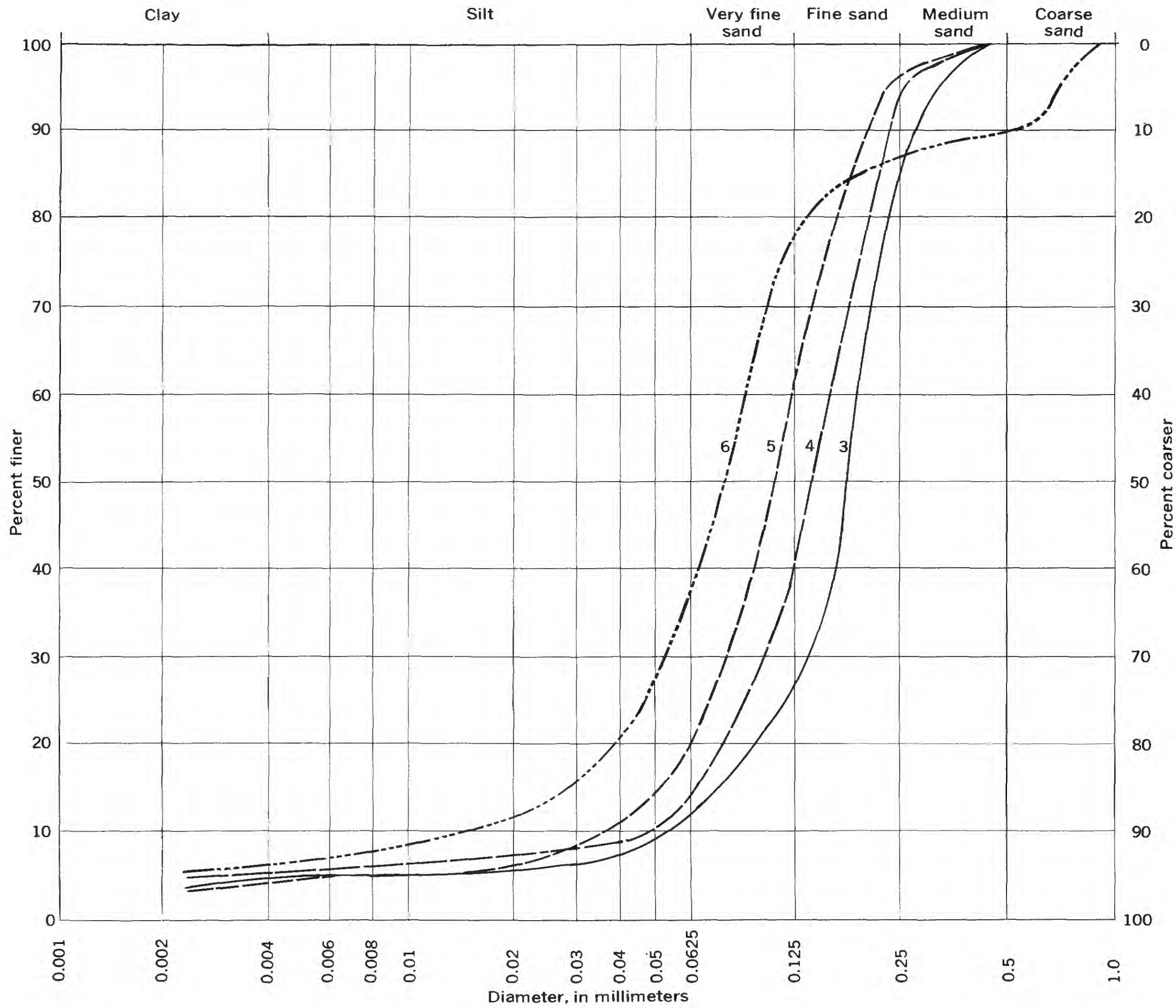

FIGURE 14.—Cumulative curves showing particle sizes of four samples of sandstone of the Slick Rock Member of the Entrada Sandstone. For locations of sampling points see table 4.

feldspar crystals in a heavily iron stained matrix. This fragment probably is of an effusive volcanic rock.

In the four samples of sandstone from the Slick Rock Member that were analyzed (table 4), the clay content ranged from 4.5 to 7.0 percent and consisted of 15 to 35 percent kaolinite and 65 to 85 percent mixed-layer clay, the latter consisting of from about 50 to 70 percent illite and from about 30 to 50 percent montmorillonite. The ability of such clay to soften the ground waters is discussed on pages 117, 118.

Although normally salmon colored or pink, the Slick Rock Member is nearly white or yellowish white locally in Glade Park, in most of sec. 13, T. 12 S., R. 102 W. Along the southwest end of Ute Canyon, about 2 miles downdip (northeast) from the Glade Park locality, the Entrada Sandstone has the mottled appearance shown in figure 15. Note that in figure 15 the Slick Rock Member retains its normal salmon color in the lower dark part of the outcrop but that the upper part seeminly has been leached to white—the same color as the overlying, normally white Moab Member—and that near the irregular color boundary are isolated leached and unleached spots. As a possible explanation for this color change by apparent leaching, it is postulated that the Slick Rock Member in Glade Park and in this part of Ute Canyon was originally all salmon colored and that, prior to draining of the beds by canyon cutting, the slow movement of artesian water downdip through the Entrada Sandstone may have leached out the salmon color. Seemingly, the

FIGURE 15.—Mottled salmon and white Slick Rock Member (Jes) of the Entrada Sandstone overlain by white Moab Member (Jem). In southwestern part of Ute Canyon, Colorado National Monument.

leaching was carried to completion in the outcrops in Glade Park but was only partly completed in Ute Canyon when the process was halted by draining during and after canyon cutting. The ferric iron compounds forming the red color in the Slick Rock Member could have been leached by a slightly acid water or reduced to ferrous iron compounds by some reducing agent in the water, although, of course, the chemical character of the long-absent water is not known.

At this point the reader may ask why the apparent leaching shown in figure 15 is confined to the upper part of the Slick Rock Member and does not extend into the lower part. Laboratory determinations of the coefficient of permeability of six samples of sandstone from the Entrada (table 4) suggest that the Moab Member is more permeable than the Slick Rock Member and that the upper part of the Slick Rock Member is more permeable than the lower part, and these determinations are in general accord with the results of flow tests and the experiences of local well drillers. Other things being equal, therefore, in any given period of time more water could have moved through the Moab Member and the upper part of the Slick Rock Member than through the lower part of the Slick Rock; hence it seems logical that the upper part could have undergone a greater amount of leaching. Moreover, when this area was covered by younger rocks, the only escape route for the water was upward through the overlying rocks or upward along fault planes farther to the northeast; thus, the movement had both an upward component and a downdip component.

In sharp contrast to the salmon-colored massive beds in the Slick Rock Member are the thinner, generally evenly bedded white to light-buff sandstone beds of the Moab Member. The beds generally range in thickness from 1 to several feet, and alternate somewhat in hardness so as to weather into a

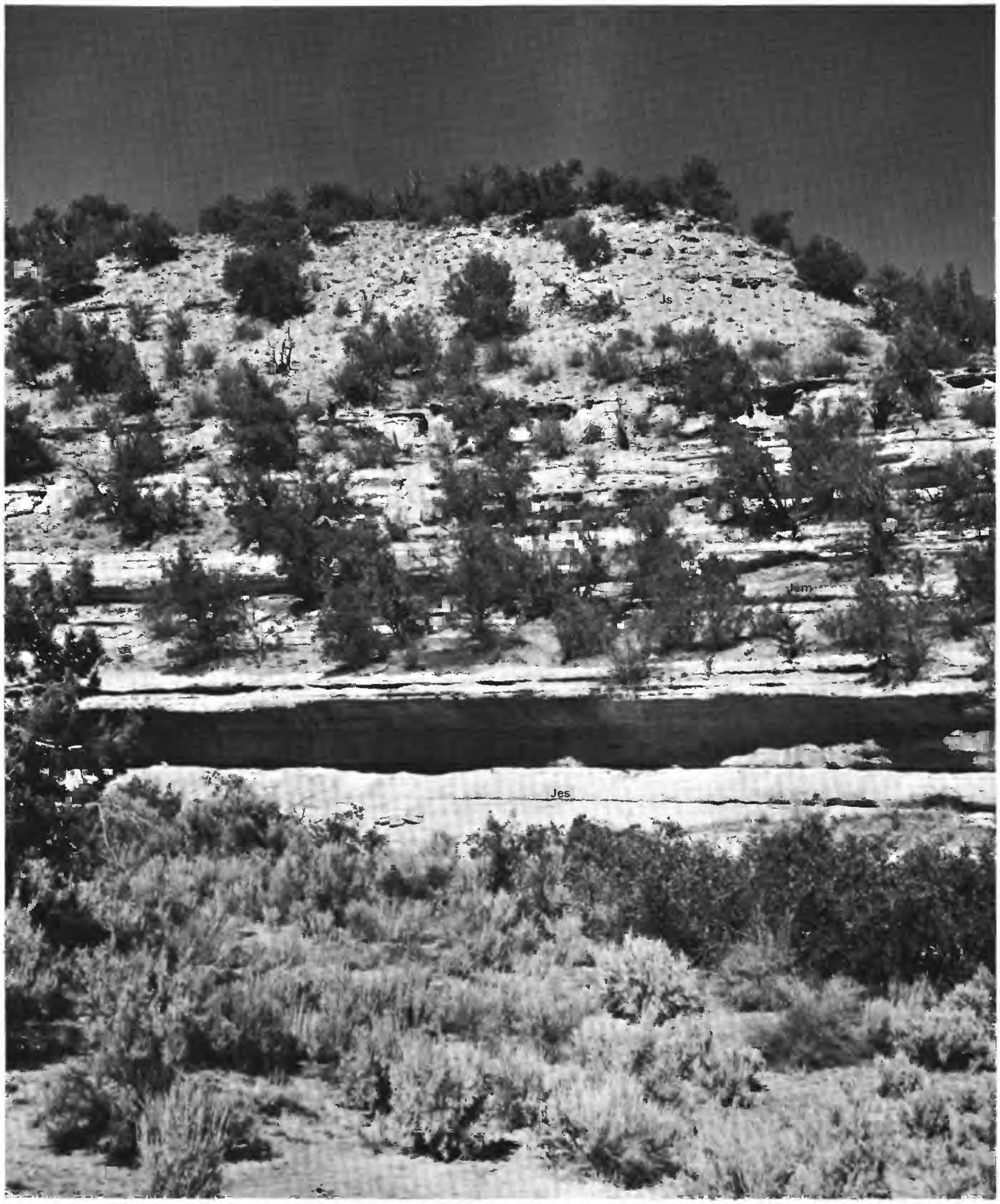

FIGURE 16.—Steplike weathering of Moab Member of Entrada Sandstone. In west arm of Ute Canyon, Colorado National Monument. Jes, Slick Rock Member of Entrada; Jem, Moab Member; Js, Summerville Formation.

series of steps or benches (fig. 16), some of which are overhanging, except locally where the entire unit may form a single cliff or ledge. Most of the strata are evenly bedded, but some exhibit low-angle cross-bedding and some of the uppermost beds have ripple marks whose crests are 1 to 1½ inches apart. In some places, where the overlying Summerville Formation has weathered back, the exposed upper surface of the Moab Member forms a flat, smooth, hard surface resembling concrete pavement. The largest exposures of this type seen in the area are on the dip slope just east of No Thoroughfare Canyon, mainly in sec. 13, T. 12 S., R. 101 W.

Table 4 indicates that the two samples from the Moab Member are dominantly fine-grained sand having median grain diameters of 0.13 and 0.137 mm (fig. 17), but that they also contain considerable very fine grained sand and small amounts of medium-grained sand, silt, and clay. The Trask sorting coefficients of these samples, which are lower than for any of the other samples analyzed, indicate well-sorted material, slightly better sorted than the samples of the Slick Rock Member or Wingate Sandstone.

As do the samples of the Slick Rock Member and the Wingate Sandstone, the two samples of sandstone from the Moab Member consist largely of quartz grains but contain 10 and 20 percent feldspar, respectively. The samples had higher porosity, lower

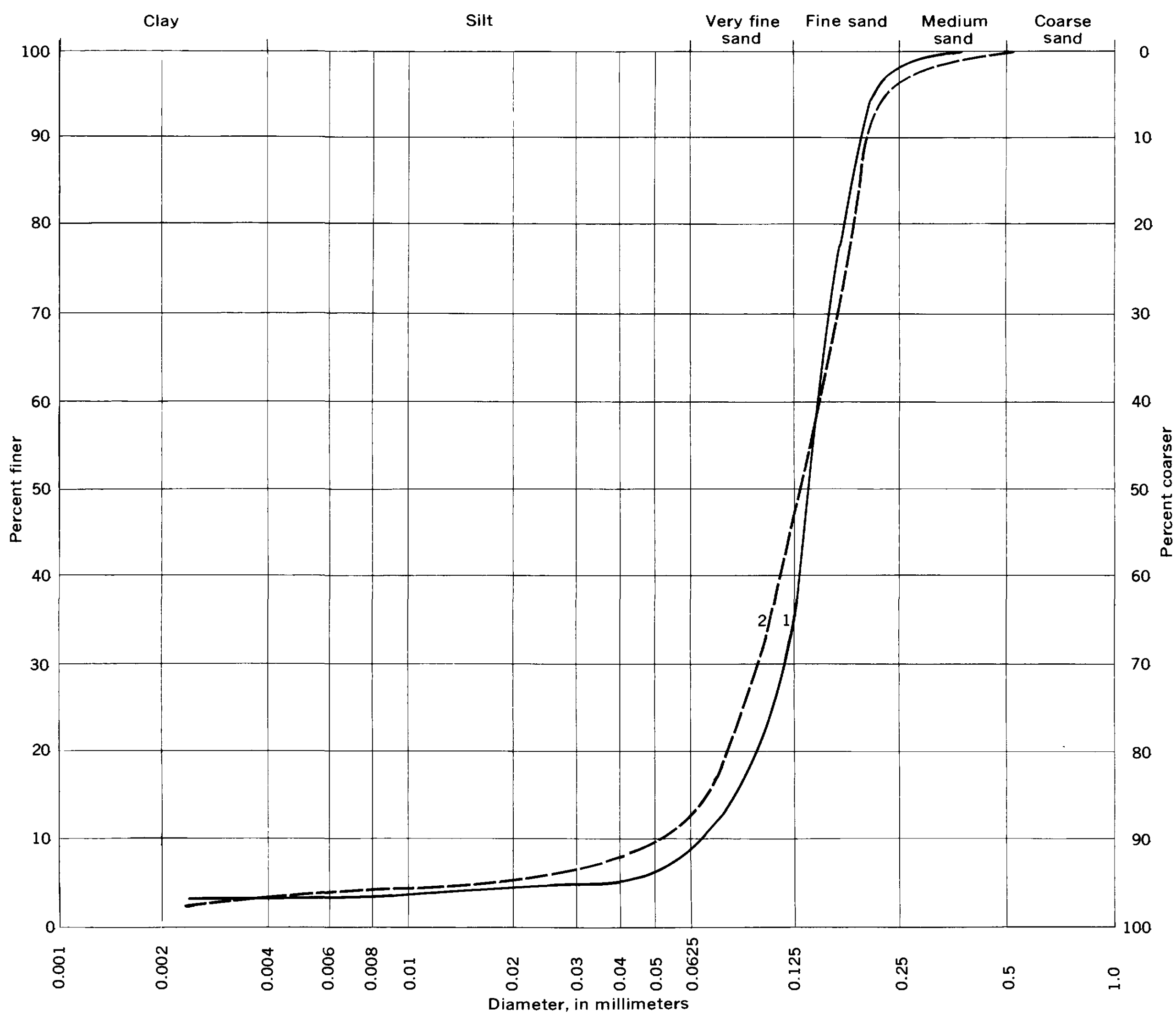

FIGURE 17.—Cumulative curves showing particle sizes of two samples of sandstone from the Moab Member of the Entrada Sandstone. For locations of sampling points see table 4.

content of cement, and higher permeability than most of the other samples tested. Sample 2 had the highest percentage of kaolinite of any of the samples tested.

On the basis of microscopic examination of slides of the two samples from the Moab Member, H. A. Tourtelot (written communication, July 14, 1960) stated:

> Sample 1.—The matrix of this rock is very patchy in its distribution but grains of quartz and feldspar in contact are not much intersutured. Sand grains range from subangular to subrounded in cross section. Some of the feldspar grains are much altered and now consist mostly of kaolinite and sericite. The altered material in some of these grains is indistinguishable from the matrix and may represent in-place alteration. Other grains appear to have been deposited in an altered condition. Red iron oxide is concentrated in the matrix, and in some of the paler patches are the tiny grains resembling siderite.
>
> Sample 2.—The visual impression made by this rock is quite different from the others. The sorting seems much poorer and the grains and matrix are more evenly mixed. The feldspar grains are prominently tabular in cross section and show little sign of alteration. The quartz grains are very clear and there is no suturing where the grains are in contact. The matrix clay seems to be almost entirely kaolinite. Red iron oxide is in patches in the matrix and mostly associated with calcite. Some of the tiny grains resembling siderite also are present. A few of the quartz and feldspar grains are bordered by a highly birefringent rim.

The Entrada Sandstone varies widely in thickness in the Grand Junction area, as it does throughout Colorado and Utah. It is 265–844 feet thick in the San Rafael Swell, the type area (Gilluly, 1929, p. 103), it thins eastward and is absent at the Black Canyon of the Gunnison, but it is present in central and eastern Colorado. Dane (1935, p. 98) found the Entrada to be 300 feet thick at the north end of Salt Valley and 295 feet thick near Dewey, both in Grand County, Utah, but to these thicknesses must be added the thickness of the Dewey Bridge Member of the Entrada, then regarded by Dane as the Carmel Formation (J. C. Wright, written communication, July 21, 1960), which would make a total thickness of the Entrada of about 470 feet in Salt Valley and 315 feet near Dewey. In the Grand Junction area the Entrada is from 100 to 200 feet thick in the western part but diminishes to about 60 feet along the Gunnison River Canyon in the southeast corner of the area. In general, the Moab Member makes up from one-third to one-half the total thickness.

The measured section that follows is typical of the Entrada Sandstone in the western half of the Grand Junction area. (See also measured sections at the end of this report.)

Section of Entrada Sandstone west of Fruita Canyon in SE¼ sec. 30, T. 1 N., R. 2 W., Ute P.M.

[Measured by S. W. Lohman and W. H. Lohman, Aug. 18, 1949]

	Thickness (feet)
Jurassic:	
Summerville Formation (incomplete):	
Siltstone and sandstone, red; base poorly exposed.	
Entrada Sandstone:	
Moab Member:	
Sandstone, medium- to fine-grained, buff to white; generally hard, but harder and softer beds alternate and weather to series of benches or steps except locally where entire interval may form single cliff or ledge; mainly evenly bedded in beds 1 to several feet thick, but some beds show low-angle crossbedding; top beds regularly ripple marked, 1–1½ in. between crests	42. 4
Sandstone, medium-grained, white to light-gray, friable; some bands stained light tan by iron oxide; forms recess below cliff	3. 1
Total Moab Member	45. 5
Slick Rock Member:	
Sandstone, medium-grained, pink, hard, evenly bedded; forms slight ledge	1. 8
Sandstone, medium-grained, pink, friable, evenly bedded; forms bench 10–15 ft wide	3. 6
Sandstone, medium-grained, salmon-colored, friable, evenly bedded; speckled with small white pellets of altered feldspar and few specks of biotite; forms several benches 1–4 ft thick separated by thin layers of soft sandstone	8. 3
Sandstone, medium-grained, pinkish-salmon, friable, evenly bedded; forms recess in cliff	. 6
Sandstone, medium- to fine-grained, salmon-colored streaked with light gray and buff, evenly bedded; harder and softer layers weather to alternating iron-stained ridges and reddish recesses on cliffs or slopes	10. 6
Sandstone, fine- to medium-grained, pink to salmon-colored to light-red, hard, crossbedded; some light-gray streaks 10–12 in. wide; well-rounded quartz grains of coarse-grained sand to fine-grained gravel sizes ("Entrada berries") scattered and in layers 1/16–½ in. thick, generally iron stained; steep-angle crossbedding extending 5 ft stratigraphically; base locally channeled into Kayenta Formation	75. 9
Total Slick Rock Member (rounded)[1]	101
Total Entrada (rounded)	146
Triassic(?):	
Kayenta Formation.	

[1] In an independently measured section about 1,800 feet east of this one, J. C. Wright and D. D. Dickey (written communication, 1960) measured only 69 feet of the Slick Rock Member. It is not known whether this variance is natural or is due to an undiscovered error in measuring one of the sections.

Conditions of deposition.—The high-angle cross stratification of most of the beds and the level bedding in others suggest that the Entrada Sandstone in this area is largely of eolian origin but is in part water-laid; a similar origin for the Entrada in Utah has been indicated (Gilluly and Reeside, 1928, p. 78; Stokes and Holmes, 1954, p. 37). The level-bedded Moab Member seems to be entirely water-laid in this area, water-laid in parts of Grand County, Utah (Dane, 1935, p. 102), and eolian at the type area near Moab, Utah (Baker, 1933, p. 49; Wright and Dickey, 1958, p. 179).

The statement quoted from H. A. Tourtelot on p. 29 and the comments that follow apply to both the Wingate and Entrada Sandstones and suggest that the Entrada also probably was derived in one or more stages from the old Uncompahgre highland to the east of the area. This proposal is in agreement with detailed studies of cross stratification of the eolian parts of the Entrada Sandstone in and near the Grand Junction area by F. G. Poole (oral communication, July 20, 1960), who found dips of cross strata of 16° to 17° and determined wind directions of S. 59° W. near the Coke Ovens and S. 74° W. at Red Canyon, both in the Colorado National Monument, but he found the wind direction to be N. 57° W. in Cactus Park, in the southwestern part of the area. This direction may have been only a local anomaly, however, for Poole found the direction to be S. 36° W. along Escalante Creek farther south in secs. 29–32, T. 15 S., R. 97 W., and southwesterly or southeasterly in most other parts of the Colorado Plateau.

Gilluly and Reeside (1928, p. 78) thought that the even bedding and continuity of single siltstone zones of the Entrada Sandstone in the western part of the San Rafael Swell suggested a marine origin, even though no fossils had been found. In the Grand Junction area the eolian and water-laid beds of the Slick Rock Member may include beds laid down along the margin or quite close to the sea under deltaic or littoral conditions (Wright and Dickey, 1958, p. 174). The eolian Moab Tongue of the type area may represent dunes just east of the Curtis sea, and the water-laid Moab Member in Grand County, Utah, and in the Grand Junction area may represent beach deposits laid down along the margin of the sea. Wright (1959, p. 64) indicated a generally northward to northwestward trend for the streams that brought in the material for these deposits, and in the Grand Junction area the trend seems to be northwestward or westward.

Age and correlation.—No fossils have been reported from the Entrada Sandstone except dinosaur footprints in the Moab Member near Moab, Utah (Baker, Dane, and Reeside, 1936, p. 8), but at the type locality in the San Rafael Swell the Entrada is well dated as Late Jurassic by its position between the fossiliferous Middle and Upper Jurassic Carmel Formation below and the Upper Jurassic Curtis Formation above (Gilluly and Reeside, 1928, p. 78).

The Entrada Sandstone was called the upper part of the La Plata Sandstone by Cross (1907, p. 644, 645) and Coffin (1921, p. 61, 62), and was believed by them to be correlative with part of the Flaming Gorge Group of Powell (Gilluly and Reeside, 1928, p. 78) and with part of the Sundance Formation. It was formerly considered correlative with part of the Nugget Sandstone, Twin Creek Formation, and Beckwith Formation (Baker, Dane, and Reeside, 1936, p. 7). It is called Entrada in central Colorado, in most of eastern Colorado and northern New Mexico, and on both sides of the Uinta Mountains, but has been called the Exeter Sandstone in northeastern New Mexico and the Panhandle of Oklahoma (Lee, 1902, p. 45–46), the Ocate Sandstone locally in north-central New Mexico (Bachman, 1953), and the Garo Sandstone in South Park, Colo. (Stark and others, 1949, p. 47). The name Exeter is no longer used in northeastern New Mexico, and the name Ocate has been abandoned.

The Slick Rock Member of the Entrada Sandstone in and near the Grand Junction area and the Dewey Bridge Member in nearby parts of Utah probably are correlative with the upper sandy member and medial silty member, respectively, of the Entrada in the Navajo Country of Arizona (Harshbarger, Repenning, and Irwin, 1957, p. 35–37). Near Green River, Utah, the nonmarine beds of the Dewey Bridge Member are abruptly transitional into the marine beds of the Carmel Formation (Wright, Shawe, and Lohman, 1963).

McKnight (1940, fig. 3, p. 90, 94–98) traced the Moab Tongue of the Entrada Sandstone across the area between the Colorado and Green Rivers, in eastern Utah, and found that it thins northwestward and ultimately disappears, that a thin red shale parting at the base of the Moab Tongue thickens northwestward at the expense of the Moab Tongue and becomes typical of the overlying Summerville Formation, that northwest of the featheredge of the Moab Tongue the Summerville Formation extends down to the massive Slick Rock Member of the Entrada, and that still farther northwestward the lower part of the Summerville grades laterally into the Curtis Formation on the west. Later work by J. C. Wright and D. D. Dickey (oral communication, Aug. 16, 1960; Wright, Shawe, and Lohman, 1963) has verified this relationship. Moreover, I have carefully compared the sandstone of the Curtis Formation at the type locality in the San Rafael Swell in Utah and elsewhere with that of the Moab Member in and near the Grand Junction area and, except for the presence of glauconite in the

Curtis and lack of this mineral in the Moab, have been impressed with the great similarily of their lithologic character, topographic expression, and general appearance. Accordingly, it seems highly probable that the Moab is of the same age as the Curtis.

Water supply.—The Entrada Sandstone is the most widely used and probably the most productive artesian aquifer in the Grand Junction area. According to the logs and casing records available, of the 48 wells listed in table 7, 25 obtain water solely from the Entrada, 10 obtain water from the Entrada and Wingate Sandstones, 1 obtains water from the Entrada and Morrison Formations, 1 from the Entrada, Wingate, and Morrison Formations, and 1 from the Entrada, Kayenta, and Wingate Formations.

The relatively impermeable overlying Summerville and Morrison Formations form confining beds or "aquitards" [9] that effectively keep the artesian water in the Entrada and underlying aquifers under considerable pressure and probably permit only very slow upward leakage. As noted on page 36, it is doubtful if the underlying Kayenta completely separates hydraulically the Entrada and Wingate Sandstones anywhere in the area, and in and east of East Creek Canyon, where the Kayenta is absent, the two sandstones form a single artesian aquifer.

The average values of the coefficients of transmissibility and storage of the Entrada Sandstone obtained from flow tests (table 6) on five wells were 150 gpd per ft (gallons per day per foot) and 5×10^{-5}, respectively. On this basis alone, the Entrada and other aquifers would be regarded as very poor aquifers, but in the arid Grand Junction area, which is practically devoid of any usable shallow ground water, wells tapping such aquifers are highly valued. Table 4 indicates that, on the basis of scanty sampling and testing, the Moab Member is considerably more permeable than the Slick Rock Member, and this fact is borne out by the experiences of well drillers in the area.

When first drilled and tested, several of the wells in the Entrada had static artesian heads of as much as 150 feet above land surface, and well 1 had a head of 169.5 feet. The heads of individual wells vary widely because of differences in surface altitude, transmissibility of the aquifer, depth of pentration of the aquifer, and interference from nearby wells.

Because of such high artesian heads, all wells in the Entrada except a few close to the outcrop flowed at the surface when first drilled. Most of the wells still flow or flow when not pumped, but a few wells have stopped flowing at the surface and have to be pumped. The reasons for the decline in head and, hence, in yield are discussed on page 113.

Despite such high initial artesian heads, the wells in the Entrada flow or flowed at rather small rates because of the low transmissibility of the formation. The original flows ranged from less than 10 to as much as 30 gpm and the drawdowns in head to as much as 150 feet. For example, in 1947, well 5 flowed 23 gpm with a drawdown of 149 feet, which indicates a specific capacity of only 0.15 gpm per foot of drawdown. In contrast, many irrigation wells in alluvium in other areas have specific capacities of more than 100 gpm per ft. To increase the yield, many wells in the Entrada are now equipped with pumps that yield 15–30 gpm, and a few are pumped intermittently at reported rates as high as 50 gpm.

As indicated in table 8, analyses of the 16 samples of water from the Entrada Sandstone indicate generally soft sodium bicarbonate water of good quality for domestic use and most other uses. In common with all the water analyzed, that from the Entrada has undergone softening by natural base exchange and become increasingly soft at increased distances from the recharge areas (p. 117, 118; fig. 46). The water from a few wells in the Entrada contains small amounts of H_2S (hydrogen sulfide) gas, which has a slightly unpleasant taste and odor to most people, but otherwise does not impair the usefulness of the water. The abnormally high content of sodium chloride (common salt) in the sample from well 1 is discussed on page 21.

CONTACT BETWEEN ENTRADA SANDSTONE AND SUMMERVILLE FORMATION

The contact between the generally bare, smooth pavement at the top of the Moab Member of the Entrada Sandstone and the generally reddish siltstone at the base of the Summerville Formation is one of the sharpest in the area, viewed either from the ground or on aerial photographs. It appears to be entirely conformable, as does the Summerville-Curtis contact in the San Rafael Swell (Gilluly and Reeside, 1928, p. 80).

SUMMERVILLE FORMATION

Definition.—The Summerville Formation was named by Gilluly and Reeside (1928, p. 80) "***from its excellent exposures on Summerville Point, just southeast of the head of Summerville Wash, in the north end of the [San Rafael] Swell."

Character, distribution, and thickness.—The thin-bedded Summerville Formation consists mainly of alternating beds of siltstone and sandstone, but it also contains beds of shale and mudstone and, near the top, generally at least one bed or lens of limestone.

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[9] Confining beds formerly were commonly called "aquicludes," which imply impermeability. Because no rocks are regarded as wholly impermeable, however, the term "aquitard," meaning materials retarding leakage of water, was suggested by John G. Ferris (written communication to Chief, Ground Water Branch, Feb. 15, 1952), and seems more appropriate.

The beds of siltstone range in thickness from a few tenths of a foot to 3 or 4 feet and are gray, blue gray, greenish gray, chocolate brown, reddish brown, and red. The mudstone associated with the siltstone is similar in color but generally breaks with conchoidal fractures. Some of the siltstone beds contain small concretions of greenish sandstone; others contain concretions of dove-gray limestone as large as 4 inches in diameter. The beds of shale are fissile, occur as thin partings in the siltstone or as separate beds, and generally are purple, red, or greenish-gray.

Most of the sandstone interbeds are less than a foot thick, but some are 3 or 4 feet thick. These beds are fine- to medium-grained, very hard, and maintain remarkably uniform character and thickness for hundreds of feet, in sharp contrast to the highly lenticular sandstone in the overlying Salt Wash Member of the Morrison Formation. Most of the sandstone beds are gray to yellow, but a few are greenish-gray or reddish-gray; some contain scattered small grains of black chert, and small grains of rose quartz were observed in one bed. Some beds of sandstone contain flattened pebbles of shale, most of which weather out on outcrops leaving holes that resemble fossil casts. Some beds of sandstone in the lower part are ripple marked, much like those in the underlying Moab Member of the Entrada Sandstone.

Generally the lowermost 10–20 feet of the Summerville Formation is red or reddish, a fact that has assisted well drillers in the area by alerting them that the main artesian aquifer—the Entrada Sandstone, is not far below. (See well logs at the end of this report.)

The Summerville Formation in the Grand Junction area resembles only slightly that of the type locality in the San Rafael Swell because of gradational changes. In the Swell it is much thicker, is dominantly chocolate brown, and contains gypsum and much less sandstone.

Although it is present throughout the area, the Summerville Formation is the least well exposed of any unit in the Grand Junction area. It is well exposed only in two cuts along Rim Rock Drive in Colorado National Monument; at and near Artists Point (fig. 18) and along the west fork of Ute Canyon. Elsewhere the Summerville forms a gentle to steep slope that is largely or wholly covered by slumping of the Summerville and the overlying Morrison Formation. For this reason, and also because it is very thin, the Summerville was not mapped separately and is included with the Morrison on plate 1.

The Summerville Formation is 163 to 331 feet thick in the San Rafael Swell (Gilluly and Reeside, 1928, p. 80), but it thins eastward and is reported to be only 37 to 58 feet thick in parts of Grand County, Utah (Dane, 1935, p. 103), and is 40 to 60 feet thick in the Grand Junction area. The section that follows is fairly typical as to both thickness and lithology. (See also measured sections at the end of this report.)

Section of Summerville Formation along Rim Rock Drive from Artists Point southward, Colorado National Monument, in SE¼ sec. 19, T. 11 S., R. 102 W.

[Measured by S. W. Lohman and W. H. Lohman, Aug. 17, 1949]

	Thickness (feet)
Jurassic:	
Morrison Formation (incomplete):	
Salt Wash Member (incomplete):	
Sandstone, medium-grained, buff, massive, iron-stained; pellets of shale in lower few inches; exposed part	10
Sandstone and siltstone, variegated purple, buff, and green; thin layers of green and purple shale	3.0
Limestone, gray	.2
Siltstone, green grading upward into purple	.7
Limestone, gray	.3
Siltstone, green	.3
Limestone, gray	.4
Siltstone, green	.5
Limestone, gray	.5
Siltstone, green	1.1
Limestone, gray, hard; thickness irregular	.5
Siltstone, greenish; scattered pebbles of gray limestone ½–1½ in. in diameter	2.5
Siltstone, purple, nodular	.4
Siltstone, greenish, nodular; some reddish bands	3.0
Concealed interval; probably greenish siltstone and thin-bedded sandstone	23.1
Sandstone, medium-grained, buff, hard, crossbedded; casts of shale pebbles near base; fairly persistent but splits into several beds laterally; where weathered, thin laminae are finely ripple marked	5.5
Total Salt Wash Member measured (rounded)	52
Summerville Formation:	
Siltstone and mudstone, blue-gray, reddish-brown, and greenish-gray; mudstone breaks with conchoidal fracture	3.6
Sandstone, fine-grained, gray	.4
Siltstone, gray	.3
Limestone, gray, hard, lenticular, irregularly bedded; ½-inch green shale parting near top; lenses out into shale 4 ft from section	.4
Siltstone, alternating reddish-brown and green	.9
Sandstone, fine-grained, gray, hard; black chert pebbles in lower 6 in.; thin greenish shale partings in upper part	1.3
Shale, red and greenish-gray	.1
Sandstone, fine- to medium-grained, yellow to gray, iron-speckled	.5
Siltstone, chocolate-brown, alternating with yellow and gray sandstone in beds 1–6 in. thick	2.8
Sandstone, fine-grained, yellow-gray; shale partings in lower third	1.0
Siltstone, alternating gray-green and reddish-brown	.8

Section of Summerville Formation along Rim Rock Drive from Artists Point southward, Colorado National Monument, in SE¼ sec. 19, T. 11 S., R. 102 W—Continued

	Thickness (feet)
Jurassic—Continued	
Summerville Formation—Continued	
Sandstone, fine- to medium-grained, gray; several thin shale partings	0.8
Sandstone, fine-grained, buff; in beds ¼-2 in. thick containing pellets of brown shale; alternating with fissile brown shale and siltstone in beds ½-2 in. thick containing green-blue shale partings	.9
Sandstone, fine-grained, greenish-gray, hard; Sandstone, fine-grained, greenish-gray, hard; several greenish shale partings	.7
Siltstone and shale, brown; and beds of sandstone ⅛-1 in. thick	1.8
Sandstone, medium-grained, light-buff, very hard; squeezed shale pebbles near base and middle, most of which weather out on outcrop. Basal 0.1 foot is coarse grained, gray, contains some grains of rose quartz and fine grains of black chert	3.4
Shale and siltstone, greenish-gray, fissile; some brown in upper half; 4-in. concretions of dove-gray limestone in lower half	17.9
Siltstone, red and few thin layers of greenish shale; 0.2-ft bed of very hard fine-grained greenish sandstone near top	2.8
Shale, bluish-purple, fissile	.3
Siltstone, red; 0.2-ft bed of brown silty limestone at middle; greenish sandstone concretions and thin bed of fine-grained sandstone near top	3.0
Shale, purple, fissile	.1
Sandstone, fine-grained, greenish	.4
Siltstone, red; ¼-in. bed of purple fissile shale at top	.6
Sandstone, medium-grained, reddish-gray	.3
Siltstone, red	1.2
Sandstone, yellow, hard; green shale partings	.2
Shale, purple, fissile	.2
Sandstone, fine- to medium-grained, light greenish-gray, very hard; few flat pellets of green shale	.8
Siltstone and sandy siltstone, red; thin layers of fissile red and green shale and ½-in. bed of blue shale at top; specks of biotite	3.1
Siltstone, red; base partly concealed	3.8
Total Summerville Formation (rounded)	54
Entrada Sandstone:	
Moab Member.	

Conditions of deposition.—The very thin bedded character, the uniform thickness of the beds, particularly the sandstone beds, and the ripple marks on some of these beds, all suggest deposition of the Summerville Formation in a body of quiet shallow water. Craig and others (1955, p. 133) regarded the Summerville Formation "* * * as a marginal marine deposit formed in relatively quiet shallow water." This "water" could have been a shallow arm of the Curtis or Summerville sea, in which the water-laid Moab Member was deposited earlier, or possibly brackish or fresh-water bodies bordering this sea. Wright (1959, p. 65, fig. 4) felt that the Summerville was laid down just above sea level on a broad aggradational river flood plain that drained northwestward toward the sea, while the partly equivalent Todilto Limestone was being deposited in a large saline lake to the southeast. If the Summerville had been deposited on a river flood plain, however, one would expect to find more evidence of channel scour and fill, but none has been observed in the Grand Junction area, and L. C. Craig (oral communication, Aug. 30, 1960) indicated that scour and fill structures are almost absent in the Summerville and that, where they have been observed, they are of small scale.

Because no fossils have been reported from the Summerville, possibly in part because of the oxidizing conditions in the red parts, its mode of origin cannot be determined with certainty.

Age and correlation.—Although no fossils have been reported from the Summerville Formation, it is well dated as Late Jurassic because of its position in the type area between the Curtis Formation, which contains Late Jurassic marine fossils, and the overlying Morrison, which has yielded many remains of Late Jurassic terrestrial vertebrates and some fresh-water invertebrates (p. 54, 55; table 5).

Baker, Dane, and Reeside (1936, pls. 2, 10, figs. 4, 6) understandably did not recognize the Summerville in sections measured at the Serpents Trail, in Colorado National Monument, and in Unaweep Canyon, for the Summerville is thin and very poorly exposed at both places. The Summerville had earlier been recognized in oil tests north of the area (Erdmann, 1934, p. 26) and was later traced by Holt (1940, p. 55) into the Grand Junction area and as far eastward as Iola, Colo. However, in the next exposures east of the Grand Junction area, in the Black Canyon of the Gunnison, beds equivalent to the Summerville are included in the Wanakah Formation (Wallace R. Hansen, oral communication, Sept. 1, 1960; see also Goldman and Spencer, 1941, p. 1756–1759). In the lower part of the Black Canyon of the Gunnison, the Wanakah also includes gypsum beds (Siebenthal, 1905, p. 401–403). In much of the Four Corners region, the upper part of the Summerville is replaced by the Bluff Sandstone. The Bluff Sandstone intertongues with the Cow Springs Sandstone of the Navajo Country, where the Cow Springs occupies the stratigraphic position of the Summerville Formation and the lower part of the overlying Morrison Formation (Craig and others, 1955, p. 133). The Curtis Formation occupies the entire Curtis and

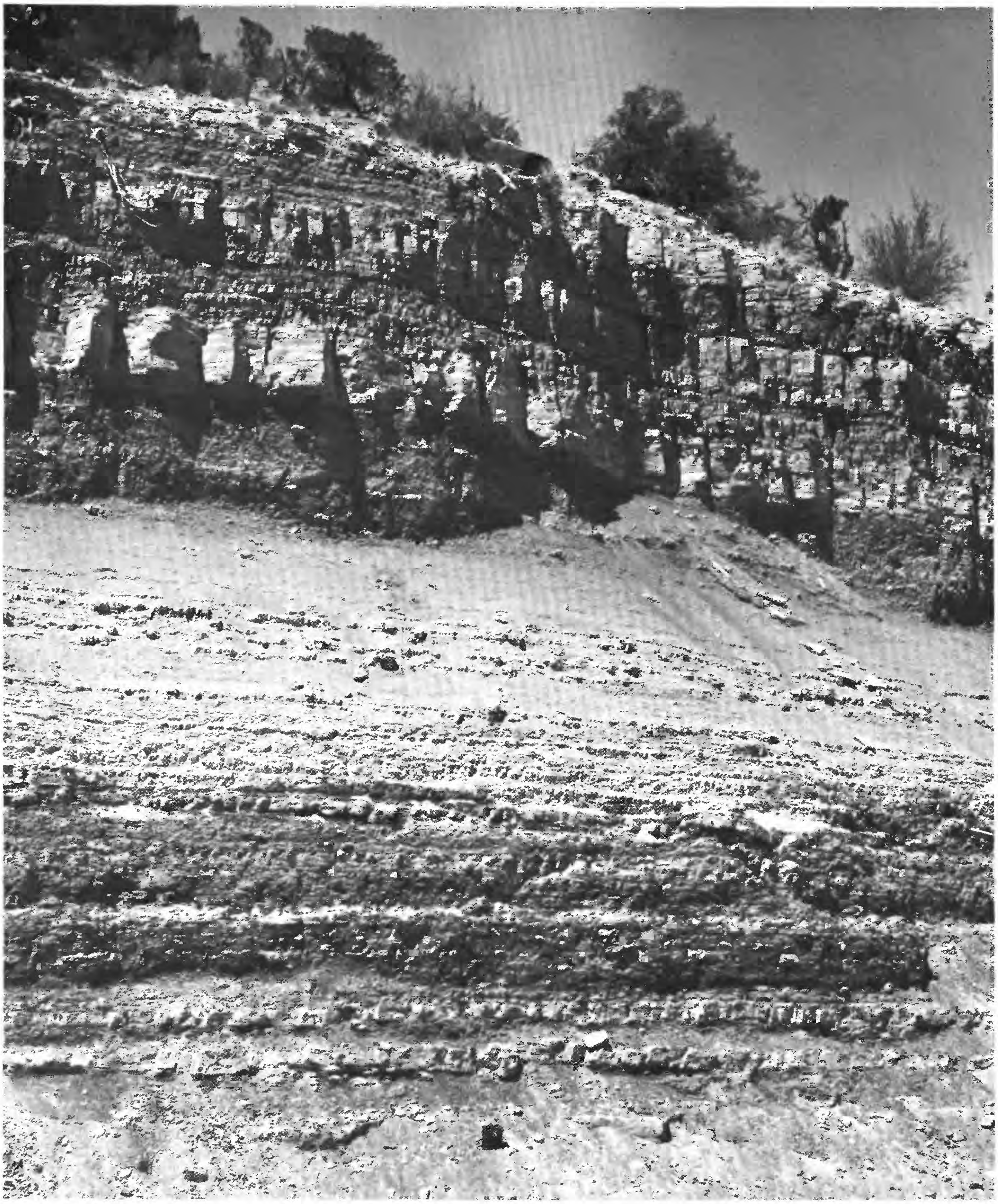


FIGURE 18.—Lower part of Summerville Formation. Along Rim Rock Drive at Artists Point, Colorado National Monument. Camera case is 7½ inches high.

Summerville intervals along the south flank of the Uinta Mountains (L. C. Craig, written communication, Oct. 26, 1960). In older reports describing the Grand Junction area the Summerville was included with the McElmo, Gunnison, or Morrison Formations (table 3).

Water supply.—The fine-grained materials of the Summerville Formation in this area have a very low permeability and yield no water to wells. Rather, the Summerville and the overlying Morrison Formation serve as confining beds, or aquitards (p. 46), that effectively prevent the escape of most artesian water from the underlying Entrada and Wingate Sandstones.

CONTACT BETWEEN SUMMERVILLE AND MORRISON FORMATIONS

In the San Rafael Swell, Utah, an angular and erosional unconformity has been described between the Morrison and Summerville Formations (Gilluly and Reeside, 1928, p. 81).

In the Grand Junction area, no angular discordance was observed but, at most of the few places where the contact is exposed, a slight erosional unconformity is suggested by an erosional surface at the base of a scour and fill sandstone unit which marks the base of the Morrison. For example, near Artists Point and in the western arm of Ute Canyon, in the Colorado National Monument, the erosional unconformity is between a highly lenticular, generally crossbedded fluvial channel sandstone of the Salt Wash Member of the Morrison Formation and thin persistent quiet-water deposits of the Summerville Formation.

On the other hand, locally, as in the section south of Fruita, the lowermost bed of the Salt Wash Member is a fossiliferous fresh-water limestone, the base of which seems quite conformable with the underlying beds of the Summerville.

Holt (1940, p. 55) considered the contact to be conformable and, on the basis of algaelike casts in a sandstone near the base of the Morrison, he believed that the basal beds of the Morrison were deposited in lagoons on the border of the Late Jurassic Curtis sea. Indeed, in the Grand Junction area the basal contact of the Morrison may be conformable, and the scour surface apparent at most exposures may represent only a minor break in time; certainly only a few feet of beds seem to have been removed by the scour, and the scour surface may be no more significant than any of the numerous scour surfaces within the Morrison Formation.

MORRISON FORMATION

Definition.—The Morrison Formation was named by Eldridge (Emmons, Cross, and Eldridge, 1896, p. 60) after exposures near the town of Morrison, Colo., but the name appeared in print 2 years earlier (Cross, 1894, p. 2). The name later was extended to include rocks in the San Rafael Swell, Utah, because of similarities in fauna and lithology of beds in that area to those of the type locality (Gilluly and Reeside, 1928, p. 81, 82), and it has since been used throughout the Colorado Plateau.

In the Four Corners region the Morrison Formation has been subdivided into four members on the basis of differences in lithology, which are, from bottom to top: Salt Wash Sandstone Member, named from exposures along Salt Wash, Grand County, Utah (Lupton, 1914, p. 127); Recapture Shale Member, from exposures near mouth of Recapture Creek, San Juan County, Utah (Gregory, 1938, p. 58); Westwater Canyon Sandstone Member, from exposures in the canyon of Westwater Creek, San Juan County, Utah (Gregory, 1938, p. 59); and Brushy Basin Shale Member, from exposures in Brushy Basin, San Juan County (Gregory, 1938, p. 59). Other units formerly included as members of the Morrison—the Todilto Limestone (Baker, Dane, and Reeside, 1936, p. 17), the Wanakah Formation, Bluff Sandstone, and Junction Creek Sandstone (Goldman and Spencer, 1941, p. 1750; Gregory, 1938, p. 58), were later generally considered as separate formations of the San Rafael Group in the local areas in which they occur (Harshbarger, Repenning, and Irwin, 1957, p. 38; Craig and others, 1955, p. 133). The lithologic terms in the names of the four members of the Morrison are not everywhere strictly applicable, generally are no longer used (Craig and others, 1955, p. 135–155), and are not used in the present report.

The Recapture and Westwater Canyon Members of the Morrison Formation are not recognizable very far north of the Four Corners region (Craig and others, 1955, figs. 20, 22, 29), and only the Salt Wash and Brushy Basin Members are present in the Grand Junction area.

Character, distribution, and thickness.—The Morrison Formation comprises a varied and colorful assemblage of beds of siltstone, mudstone, sandstone, a little conglomerate and limestone and, according to Robert A. Cadigan (oral communication, Sept. 26, 1960), contains a few shards of volcanic ash and some altered ash. In the lower and drier parts of the Grand Junction area the Morrison generally forms steep barren badlands (fig. 19), but at higher altitudes it is generally covered by brush or trees. The Morrison and Summerville Formations are much less resistant to erosion than the underlying and overlying formations and, hence, form moderate to steep slopes between resistant sandstone cliffs or ledges. For these reasons, there have been many landslides in the Morrison, some of which cover underlying older formations. The larger landslides are shown on plate 1. In many of the deeper canyons in the southeastern part of the area the steep canyon walls of the Morrison are strewn with and locally covered with small to very large blocks of sandstone from the overlying Burro Canyon Formation and Dakota Sandstone.

In the Grand Junction area the Salt Wash Member forms the lower one-third to one-half of the Morrison Formation; the Brushy Basin Member forms the rest.

In most of the eastern half of the mapped area and in much of the western half, the Salt Wash Member consists of alternating beds or lenses of siltstone or mudstone and highly lenticular sandstone, and a few beds of limestone—particularly at or near the base. The siltstone and mudstone, some of which are sandy, are mainly reddish brown, reddish gray, and light greenish gray. The sandstone consists mostly of fine- to medium- to coarse-grained quartz particles but contains some accessory minerals, and locally is conglomeratic. In the uranium-producing area southwest of the Uncompahgre Plateau, cores of sandstone from the Salt Wash Member taken below the water table contained pyrite, particularly associated with carbonaceous material, but above the water table the pyrite had been oxidized to limonite stains (Daniel R. Shawe, oral communication, Sept. 23, 1960). The sandstone is mostly crossbedded, but some is evenly bedded. These beds are poorly to well cemented and generally form ledges or low cliffs. Most of the sandstone is white or light gray, but some is light brown. Individual lenses may range in thickness from less than a foot to about 40 feet and in length from a few feet to a few hundred feet or yards (fig. 19). Groups of beds or lenses of sandstone locally attain a thickness of 70–80 feet.

Because of widespread vanadium- and uranium-ore deposits in the Salt Wash Member in areas southwest of the Uncompahgre Plateau, the Morrison has received more detailed study than any of the other Jurassic formations but, because of the absence of such ore deposits in the Grand Junction area (Fischer, 1942; Finch, 1955), only a few of these studies have reached as far north and east as the Grand Junction area.

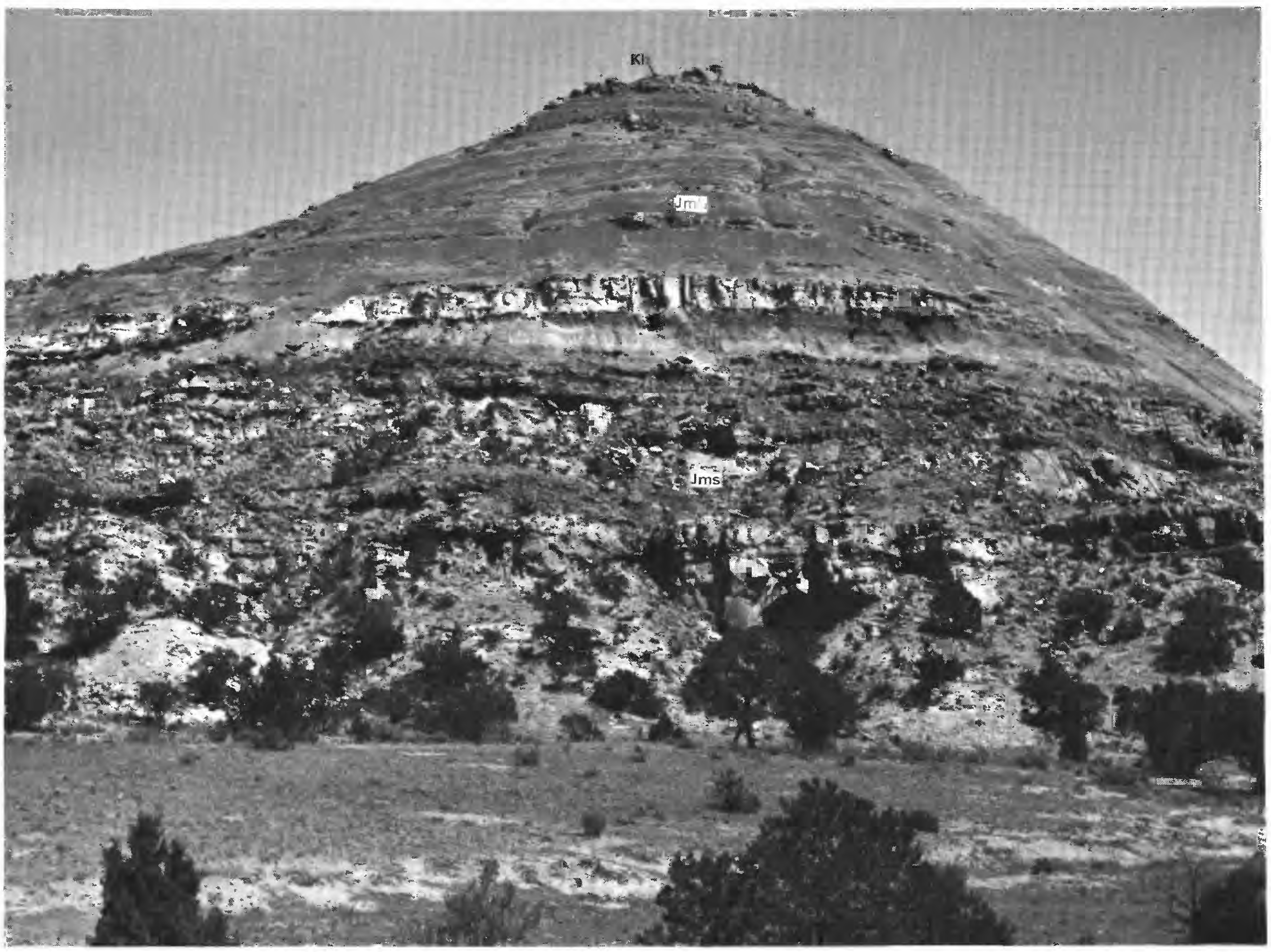


FIGURE 19.—Morrison Formation, showing highly lenticular sandstone in Salt Wash Member (Jms, lower third of Morrison) and generally fine-grained Brushy Basin Member (Jmb). Basal beds of Burro Canyon Formation (Kb) cap top of hill. Northeast of Ladder Creek in S½ sec. 19, T. 12 S., R. 100 W. (See Ladder Canyon section, p. 124–127.)

Craig and others (1955, fig. 21) found that the Salt Wash Member decreases in thickness northeastward from as much as 600 feet in southern Utah to only 200 to 300 feet in the Grand Junction area, where it begins to change from a dominantly sandstone and mudstone facies to a claystone and lenticular sandstone facies, and not far to the east and northeast of Grand Junction the Salt Wash is no longer recognizable as a member of the Morrison Formation. Lithofacies studies of the Salt Wash Member by Mullens and Freeman (1957, p. 514) indicated that in three sections of the Salt Wash in and near the Grand Junction area the average percentages of stream deposits were 20 at Ladder Canyon, 31 at east Unaweep Canyon, and 46 at Black Ridge west of the area (see measured sections at the end of this report), the rest of the member having been classed as flood-plain or lacustrine deposits. Actually, the range is even greater than indicated by these studies, for locally in the western half of the mapped area the Salt Wash Member may be nearly or entirely lacking in beds or lenses of sandstone and may resemble the overlying Brushy Basin Member. For this reason in the western half of the area and because the contact between the two members in the eastern half of the area generally is obscured by talus, the two members are not differentiated on plate 1 but are included with the underlying Summerville Formation.

Just to the north of the high bluff in the S½ sec. 32 T. 1 S., R. 1 N., Ute P.M. a sandstone lens in the Salt Wash Member attains a thickness of 30 to 40 feet within a short distance, persists to and beyond No Throughfare Canyon to the west, and continues under cover far enough to the northeast to supply water to wells 17, 18, and 24 (table 7).

The limestone beds of the Salt Wash Member are lenticular to fairly persistent, vary in number from place to place from one or two to five or six, and occur mostly near the base but locally as much as 60 to 80 feet above the base. Most of the beds of limestone are from less than 1 to 3 feet thick, but one bed 8.5 feet thick occurs in the SW¼ sec. 29, T. 1 N., R. 2 W., Ute P.M. Most of the limestone beds are light gray to dark gray, but one 10-inch bed of dense black limestone that emitted a petroliferous odor when freshly broken was observed in the SW¼SE¼ sec. 27, T. 11 S., R. 101 W. Locally the limestone contains fresh-water invertebrates or casts from which pellets of siltstone or mudstone have weathered out.

The Brushy Basin Member is dominantly siltstone and mudstone, but it contains thin beds of sandstone, limestone, and bentonitic mudstone. It is even more brightly colored than the Salt Wash Member and, although dominantly red, it includes beds of most other colors and shades including purple and green. A thin lens of limestone on Riggs Hill and another about a mile west of the Fruita Golf Course, both about 115 feet below the top of the Brushy Basin Member, are reported to contain fresh-water pelecepods as silicified casts or replaced by agate, jasper, or chalcedony (Holt, 1942, p. 456–460). Locally, as in the section given below, the base of the Brushy Basin Member is marked by a distinctive conglomerate containing rounded pebbles of black and red chert. Similar conglomerates containing pebbles of red, green, black, or white chert occur at the base of the Brushy Basin Member in many places to the south of the Grand Junction area (Lawrence C. Craig, oral communication, Sept. 8, 1960).

Studies by Craig and others (1955, fig. 29) indicate that the Brushy Basin Member decreases in thickness northward and northeastward from more than 400 feet in parts of southwestern Colorado and eastern Utah to 200 to 350 feet in the Grand Junction area, but then thickens northwestward to more than 600 feet locally in northwestern Colorado and northeastern Utah. Like the Salt Wash Member, the Brushy Basin Member is not recognizable in central and eastern Colorado, where the Morrison Formation has not been subdivided.

In addition to the fresh-water invertebrates noted above, the Morrison Formation in this area, as in many other areas, has yielded many bone fragments and several skeletons of dinosaurs, petrified wood (Minor, 1939), and so-called "gastroliths"—highly polished pebbles believed by some (Minor, 1937) to have been the gizzard stones of dinosaurs. On the other hand, Stokes (1942) found that many dinosaur remains have few or no associated "gastroliths" and that many "gastroliths" have no associated bones. Because he found most of them in the Brushy Basin Member, which contains bentonitic beds derived from volcanic ash, he thought that the "gastroliths" may have received their high polish by volcanic ash blown against them by wind. The vertebrates and invertebrates found in the Morrison in or near the area are listed in the section on "Age and correlation."

The Morrison Formation ranges in thickness from 800 to 900 feet in areas to the south and southwest to 500 to 600 feet in the Grand Junction area, and is 200 to 500 feet thick in eastern and central Colorado, respectively. In the sections beginning on p. 123 the range is 530 to 600 feet. The section that follows is fairly typical of the Morrison as to lithology but is thicker than other sections measured in or near the area, either because of local thickening or possibly because of the steepness of the slope and its effect on the accuracy of measurement. The beds described in the section as "shale" should more properly be called mudstone (R. P. Fischer, oral communication, Sept. 9, 1960).

Section of the Morrison and Summerville Formations between water gap of No Thoroughfare Canyon and top of hill to the northeast, in SW¼ sec. 32, T. 1.S., R. 1.W., Ute. P.M.

[Measured by Richard P. Fischer, May 21, 1944]

	Thickness (feet)
Cretaceous:	
Burro Canyon Formation (incomplete):	
Sandstone, medium- to coarse-grained, brown, partly conglomeratic; some shale. Estimated	80±
Shale, sandy, brown; thin brown sandstone beds	8
Sandstone, rather fine-grained, brown, rather evenly bedded	8
Total Burro Canyon exposed	96±
Jurassic:	
Morrison Formation:	
Brushy Basin Member:	
Shale, dominantly gray, some red, purple, and green; bentonitic; an occasional sandstone bed 3 in. to 3 ft thick	275
Shale, red, massive or blocky, slightly bentonitic	6
Conglomeratic sandstone, coarse-grained, white, massive, soft; contains rounded pebbles (dominantly black and red chert) as much as 1 in. across; laterally this bed is replaced by bed above	25
Total Brushy Basin	306
Salt Wash Member:	
Shale, sandy, dominantly red, some gray	22
Sandstone, light-gray, massive, soft; shale lenses	45
Shale, red and gray; sandy layers	25
Sandstone, medium-grained, light-gray to buff, massive and crossbedded; maximum thickness in line of section; thins laterally	44
Sandstone and shale; sandstone rather fine grained, hard, irregularly bedded and lenticular; interbedded with red and gray sandy shale	12
Shale, sandy, gray and red; thin-bedded sandstone and limestone layers	12
Sandstone, medium-grained, light-gray to buff, soft, lenticular; crossbedded with some poor ripple bedding	22
Shale, gray	2
Sandstone medium-grained, light-gray; forms ledge locally, but lenses out 300 ft laterally	6
Slope, mostly covered; dominantly sandy shale but thin discontinuous sandstone beds crop out in places, and nodular and thinly bedded limestone is in the lower half	44
Limestone, gray, dense, poorly bedded; forms ledge locally	2
Slope, mostly covered; gray shale, gray nodular to thinly bedded limestone, and light-gray, thinly bedded sandstone crop out in places	10
Sandstone, medium-grained, light-gray; forms ledge locally but lenses out 500 ft laterally	6

Section of the Morrison and Summerville Formations between water gap of No Thoroughfare Canyon and top of hill to the northeast in SW¼ sec. 32, T. 1.S., R. 1.W., Ute. P.M.—Con.

	Thickness (feet)
Jurassic—Continued	
Morrison Formation—Continued	
Salt Wash Member—Continued	
Sandstone, shale, and limestone; sandstone medium grained, light gray, lenticular (basal 6-foot bed lenses out about 100 ft to northeast); shale gray; limestone gray, dense, blocky, somewhat sandy or muddy, partly nodular but mostly poorly bedded	60
Total Salt Wash	312
Total Morrison	618
Summerville Formation:	
Sandstone, fine-grained, white to buff; contains coarse grains or fine pebbles of black chert(?); evenly and thinly bedded; some shale partings	7
Shale, light- to dark-gray, and nodular or irregular thin beds of gray limestone; grades upward into silty reddish-brown mudstone in top 2–3 ft	12
Sandstone, limy, gray, in 2–3-inch beds, interbedded with gray sandy shale in 4–6-inch layers (carnelian chert in sandstone bed near middle)	3
Mudstone, sandy, red and gray, poorly bedded; weathers blocky	6
Sandstone, fine-grained, white to light-red, thinly bedded, rather hard	.3
Sandstone or siltstone, fine-grained, red, poorly bedded; weathers blocky	1.5
Sandstone, medium-grained, mottled red and white, poorly bedded, quartzitic; forms ledge	1
Sandstone, fine-grained, red; has purple-red shaly seams and a few white fine-grained sandstone layers	2
Sandstone or siltstone, fine-grained, red, poorly bedded; weathers blocky	8
Total Summerville (rounded)	41
Entrada Sandstone (incomplete):	
Sandstone, fine-grained, white to light-gray, sparse medium to coarse grains; evenly but poorly bedded in upper part, crossbedded below. Exposed part	25±

Conditions of deposition.—The lithologic character, fresh-water invertebrates, petrified wood, and abundance of bones and bone fragments of terrestrial vertebrates in the Morrison Formation all attest to its undoubted continental origin.

Detailed studies by Craig and others (1955, p. 150–152) and by Mullens and Freeman (1957, p. 516–521) indicated clearly that the Salt Wash Member was deposited by streams that emanated from south-central Utah and flowed northward and eastward in an aggrading distributary system of braided channels which changed position on a broad alluvial fan by lateral migration. The finer grained beds represent flood-plain or lacustrine deposits, and the limestone beds probably were deposited in lakes. The deposits thin toward the old Uncompahgre highland but were deposited across the lower parts of this old landmass (Craig and others, 1955, fig. 21). The presence of shards of volcanic ash and of some altered ash in the Salt Wash Member indicates at least mild volcanic activity in nearby areas.

Similar studies of the Brushy Basin Member also suggest deposition in a fluvial and lacustrine environment in a similar distributary system of streams from the same general source area, but with less channel sand and more flood-plain deposits (Craig and others, 1955, p. 156, 157). The thin limestone beds probably were formed in lakes, and the bentonitic beds probably resulted from showers of volcanic ash in the source area.

Although the climate probably was fairly wet during all of Morrison time, the greater abundance of fossil-plant and dinosaur remains in the Brushy Basin Member suggests deposition under conditions of greater humidity than prevailed during deposition of the Salt Wash Member (Craig and others, 1955, p. 157). A large amount of vegetation would have been required to feed the dinosaur population indicated by the abundant remains.

Age and correlation.—Although originally defined as Jurassic on the basis of dinosaur remains (Emmons, Cross, and Eldridge, 1896, p. 60), the Morrison Formation was introduced into the Colorado Plateau as Jurassic(?) (Gilluly and Reeside, 1928, p. 60), probably on the basis of the angular and erosional unconformity between the Morrison and Summerville Formations in the San Rafael Swell. On the basis of additional fossil evidence over a wide area, the Morrison was and is regarded as Upper Jurassic (Baker, Dane, and Reeside, 1936, p. 9, 10).

Dinosaur remains were first discovered in the Grand Junction area in 1900 and 1901 when Elmer S. Riggs, then curator of the Field Columbian Museum, Chicago (now Chicago Natural History Museum), removed all but the forepart of a skeleton of *Apatasaurus excelcus* (fig. 20) from the Brushy Basin Member of the Morrison Formation on the southeast side of a hill one-quarter mile south of the Fruita bridge (Riggs, 1901a, 1903a). During the same period Riggs (1903b, 1904) removed part of the type skeleton of *Brachiosaurus altithorax* Riggs from the Brushy Basin Member on the south slope of what was later called Riggs Hill (pl. 1; fig. 21). Accounts of these finds, the dedication in 1938 of masonry monuments with brass plaques at the two localities, and quotations from Mr. Riggs, who was present for the occasion, are given by Look (1951, p. 55–57, 65, 66; 1955, p. 57, 58, 66, 67). One of these plaques is shown in figure 22.

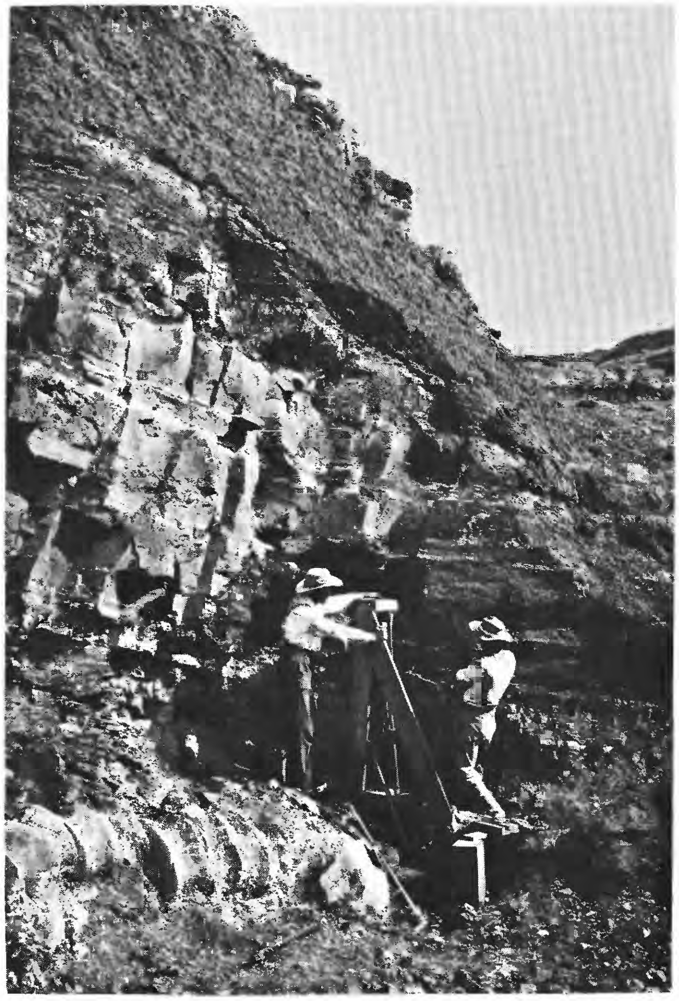


FIGURE 20.—Excavating vertebrae of *Apatasaurus excelcus* from Brushy Basin Member of the Morrison Formation. Southeast side of hill one-quarter mile south of Fruita bridge in NW¼ sec. 24, T. 1 N., R. 2 W., Ute P.M. Photograph, taken in 1900, reproduced by permission of the Chicago Natural History Museum.

Riggs (1901a) reported the presence of dinosaur bones or bone fragments throughout the upper part of the Morrison Formation (Brushy Basin Member) in the Redlands district of the Grand Junction area, mainly in the lower 150 feet but also within a few feet of the top. In addition to *Apatasaurus* and *Brachiosaurus*, Riggs also found remains of *Diplodocus*, *Camarasaurus*, and *Morosaurus* (Riggs, 1901b).

In 1937, Al Look and C. L. Holt (Look, 1951, p. 58–66; 1955, p. 60–69) found the closely associated remains of *Allosaurus* and *Stegosaurus* at the west end of Riggs Hill and, nearby, additional remains of *Brachiosaurus*. Despite careful attempts to protect these specimens, vandals and souvenir hunters have removed most of the remains of *Allosaurus* and *Stegosaurus*, which may have been nearly complete skeletons, but the remains of *Brachiosaurus* may still be intact (Al Look, oral communication, April 11, 1960). Additional information on vertebrate, invertebrate, and plant re-

FIGURE 21.—Excavating type specimen of *Brachiosaurus altithorax* Riggs from Brushy Basin Member of Morrison Formation. South side of Riggs Hill in NE¼ sec. 26, T. 11 S., R. 101 W. Photograph, taken in 1900, reproduced by permission of the Chicago Natural History Museum.

mains in the Morrison Formation in Grand County, Utah and other nearby areas is given by Stokes (1952a, p. 18, 19).

The invertebrate fossils that have been reported from the Morrison Formation in and near the Grand Junction area and the localities at which they were found are listed in table 5.

All the diagnostic fossils found in the Morrison Formation in and near this area indicate a Late Jurassic age for the formation.

In earlier reports describing the Grand Junction and adjacent areas the strata now comprising the Morrison and Summerville Formations were included in the McElmo Formation, Gunnison Formation, or McElmo Member of the Gunnison (table 3).

Water supply.—The Salt Wash Member of the Morrison Formation is third in importance among the four artesian aquifers of the Grand Junction area. Of the 48 wells listed in table 7, six obtain water from sandstone lenses in the Salt Wash Member and two obtain water from the Salt Wash and from older rocks. The drillers' logs of 19 of the wells indicate the finding of water in sandstone lenses at various positions in the Morrison, including a few in the Brushy Basin Member, but the lenses in the Brushy Basin seemingly were not very productive, for no wells are known to have been developed in them.

Although the sandstone lenses of the Salt Wash Member are highly lenticular, as would be expected of stream-channel deposits, the lenticularity is exhibited mainly in a general northwesterly direction approximately at right angles to the general trend of the streams that deposited these beds. That individual sandstone lenses extend in a general northeasterly direction for distances of several miles, in the direction of the former streams, is attested by the continued yield of wells that

FIGURE 22.—Brass plaque and monument marking the discovery of *Brachiosaurus altithorax* Riggs. Location same as given for figure 21.

TABLE 5.—*Fossils from the Morrison Formation in and near the Grand Junction area*

[All fossils but those described by Holt (1942) from table compiled by L. C. Craig; (written communication, 1960). × indicates presence of species in collection; A, abundant; C, common; U, uncommon; R, rare]

Fossil	Morrison Formation													
	Salt Wash Member						Brushy Basin Member							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Gastropods:														
Amplovalvata cyclostoma Yen	--	--	--	--	--	--	×	--	--	--	--	--	--	--
Gyraulis veternus (Meek and Hayden)	×	--	--	--	--	--	×	--	--	--	--	--	--	--
Lymnaea ativuncula White	--	--	--	--	--	--	×	--	--	--	--	--	--	--
morrisonensis Yen	--	--	--	--	--	--	×	--	--	--	--	--	--	--
Mesauriculstra morrisonensis ovalis Yen	--	--	--	--	--	--	×	--	--	--	--	--	--	--
Valvata scabrida Meek and Hayden [1]	--	--	--	--	--	--	--	--	×	×	--	--	--	--
Veviparus reesidei Yen	--	--	--	--	--	--	--	×	--	--	--	--	--	--
Vortifex stearnsi White [1]	--	×	--	--	--	--	--	--	--	--	--	--	--	--
Pelecypods:														
Hadrodon jurassicus Yen	×	--	--	--	--	--	--	--	--	--	--	--	--	--
Unio sp. undetermined	--	×	--	--	--	--	--	--	--	--	--	--	--	--
Vetulonaea faberi Holt	--	×	×	--	--	--	--	--	--	--	--	--	--	--
Charophytes:														
Aclistochara bransoni Peck	--	--	--	C	C	C	--	--	--	--	--	--	U	--
jonesi Peck	--	--	--	R	--	R	--	--	--	--	R	--	U	--
Aclistochara obovata Peck [2]	--	--	--	--	--	--	--	--	--	--	--	C	U	--
Charaxis sp	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Echinochara spinosa Peck	--	--	--	C	C	×	--	--	--	--	--	--	U	--
sp	--	--	--	--	--	--	--	--	--	--	--	--	U	--
Latochara collina Peck	--	--	--	--	C	--	--	--	--	--	--	--	--	--
concinna Peck	--	--	--	C	C	R	--	--	--	--	--	--	--	--
latitruncata (Peck)	--	--	--	R	C	R	--	--	--	--	C	C	A	--
Obtusochara madleri Peck	--	--	--	U	R	U	--	--	--	--	--	--	--	--
Praechara voluta (Peck)	--	--	--	C	--	C	--	--	--	--	--	R	C	--
sp. indet	--	--	--	--	C	--	--	--	--	--	--	--	R	--
Stellatochara arguta Peck	--	--	--	--	C	--	--	--	--	--	C	U	U	--
Ostracodes:														
Bairdiocypris sp	--	--	--	--	R	--	--	--	--	--	--	--	U	×
Metacypris pahasapensis (Roth)	--	--	--	C	C	C	--	--	--	--	--	C	A	C
sp	--	--	--	--	C	--	--	--	--	--	--	--	--	C
sp. indet	--	--	--	C	--	C	--	--	--	--	--	--	--	--
Paracypris cf. *P. acuminatus* Roth	--	--	--	--	--	--	--	--	--	--	--	--	--	A
cf. *P. simplus* Roth	--	--	--	C	C	C	--	--	--	--	--	C	C	C

[1] According to Yen (1952, p. 27) the *Vortifex stearnsi* White and *Valvata scabrida* Meek and Hayden of Holt (1942) are *Amplovalvata scabrida* Meek and Hayden (adult form) and *Viviparus reesidei* Yen, respectively.

[2] According to R. E. Peck (written communication) this species was mistakenly referred to the genus *Stellatochara* in Peck (1957).

1. Probably from lower part of member, in Gunnison River valley in the SE¼ sec. 26, T. 14 S., R. 98 W. (Yen, 1952, p. 28, locality 9).
2. From 80 feet above base of member; type locality on Ladder Canyon (Jacobs Ladder) road about 6 miles south of Grand Junction (Holt, 1942).
3. From lower part of member in gray calcareous shale in cut along Rim Rock Drive, about 3 miles south of headquarters, Colorado National Monument (Holt, 1942).
4. From 25-foot limestone and shale section at base of member, on road to Broughton Fruit Farm, in sec. 26, T. 14 S., R. 98 W., Delta County, Colo. (Peck, 1957, p. 12, collection D428).
5. From basal limestone and shale of member at Ladder Canyon section (p. 126), in sec. 19, T. 12 S., R. 100 W. Collected and identified by R. E. Peck.
6. From calcareous shale and thin limestone at base of member on south side of No Thoroughfare Canyon Road, in sec. 29, T. 1 S., R. 1 W., Ute P.M. (Peck, 1957, p. 12, collection D306).
7. From near Broughton Fruit Farm road, in sec. 35, T. 14 S., R. 98 W., Delta County, Colo. Collected by C. N. Holmes, identified by T. C. Yen.
8. From limestone in lower one-third of member about 5 miles west of Fruita, approximately sec. 15, T. 1 N., R. 3 W., Ute P.M. Collected by L. C. Craig, identified by J. B. Reeside, Jr.
9. From 6-inch limestone about 115 feet below top of member 2½ miles west of Fruita bridge; as silicified casts of agate, jasper, and chalcedony (Holt, 1942).
10. About 115 feet below top of member, on Riggs Hill in NE¼ sec. 26, T. 11 S., R. 101 W. (Holt, 1942).
11. From calcareous beds in lower one-third of member about 5 miles west of Fruita, approximately sec. 15, T. 1 N., R. 3 W., Ute P.M. Collected and identified by R. E. Peck.
12. From nodular limestone in middle of member about 5 miles west of Fruita, approximately sec. 15, T. 1 N., R. 3 W., Ute P.M. Collected and identified by R. E. Peck.
13. From nodular limestone near middle of member, about 25 feet above sample 12, about 5 miles west of Fruita, approximately sec. 15, T. 1 N., R. 3 W., Ute P.M. Collected and identified by R. E. Peck.
14. From near Broughton Fruit Farm road in sec. 35, T. 14 S., R. 98 W., Delta County, Colo. Collected by C. N. Holmes, identified by R. E. Peck.

tap such lenses in several parts of the Redlands. This fact does not imply that water is everywhere obtainable from such lenses in the Salt Wash Member, for most wells that obtained little or no water from the Salt Wash Member were drilled deeper to the Entrada Sandstone.

The sandstone lenses in the Salt Wash Member that supply wells in the area generally are only 30 to 50 feet thick, hence the yields are lower than those obtained from the much thicker Entrada or Wingate Sandstones, and range, by natural flow, from less than 1 to 5 gpm. Moreover, the intake areas of the lenses of the Salt Wash Member crop out at lower altitudes than those of the Wingate and Entrada Sandstones, and a lower artesian head in the Salt Wash results.

The coefficients of transmissibility and storage obtained from flow tests on wells 17 and 24 were 47 gpd per ft and 3×10^{-5}, and 36 gpd per ft and 4×10^{-4}, respectively (table 6). On October 21, 1947, the shut-in head of well 17 was 77.6 feet above land surface. Immediately after opening the valve the discharge was 0.92 gpm, which declined to 0.47 gpm after the well had flowed 3 hours and 51 minutes. Thus, the well had a specific capacity at the end of this flow period of only 0.006 gpm per ft. Despite such a low yield and low specific capacity, this well, when equipped with a small jet pump, has supplied the domestic needs for five houses.

The three samples of water from two wells in the Salt Wash Member that were analyzed (table 8, wells 17, 24) were soft sodium bicarbonate-sodium sulfate waters of good quality for domestic and most other uses. The samples contained much more sulfate than any of the other waters analyzed. No samples of sandstone from the Salt Wash Member in the Grand Junction area were collected for analysis, but the pyrite reported in the sandstone beds of the Salt Wash in the area southwest of the Uncompahgre uplift (p. 51) suggests that pyrite probably is present also in these beds in the Grand Junction area, the oxidation of which accounts for the high sulfate content.

The analyses of samples of water from two wells in the Salt Wash Member suggest that the waters have undergone an equal or greater degree of softening by natural base exchange than those from the Entrada and Wingate Sandstones (p. 117, 118). The altered volcanic ash reported in the Salt Wash would provide sufficient montmorillonite to accomplish the softening.

The samples of water from the Salt Wash Member have the highest sodium (alkali) hazards of any of the samples analyzed (fig. 47). This water probably would be harmful to certain plants and crops, but is satisfactory for domestic use.

CONTACT BETWEEN MORRISON AND BURRO CANYON FORMATIONS

Opinions have differed in regard to the character of the contact and duration of the interval between the Morrison and Burro Canyon Formations. Stokes (1944, p. 976) recognized an unconformity at the base of the Buckhorn Conglomerate of Utah (basal bed of Burro

Canyon Formation in southwestern Colorado) and its equivalents and believed that the unconformity marked "* * * regional uplift followed by a long period of still-stand and limited local sedimentation under conditions of arid or semi-arid climate." Young (1960a, p. 191) also indicated an unconformity at the base of his Cedar Mountain Formation (Burro Canyon of this report), which he believed represents a large part of Early Cretaceous time. On the other hand, most other workers who have examined this contact in many parts of the Colorado Plateau regard it as conformable and gradational, having no significant break in sedimentation (Craig and others, 1955, p. 160; Harshbarger, Repenning, and Irwin, 1957, p. 57; Simmons, 1957, p. 2523; Ekren and Houser, 1959, p. 192; Craig and others, 1961). In describing the Brushy Basin-Burro Canyon contact in the Slick Rock district, Colorado, Simmons (1957, p. 2523) stated:

> * * * Although the contact is commonly a disconformity marked by scours and sandstone-filled channels, the contact in many other places is gradational, marked by intertonguing of sandstone of the Burro Canyon with shale of the Brushy Basin. Also, in many places, thicker sandstones near the base of the Brushy Basin shale member resemble sandstones of the underlying Salt Wash sandstone member, whereas thicker sandstones near the top of the Brushy Basin resemble sandstones of the overlying Burro Canyon formation. These relations indicate that in the Slick Rock district deposition was essentially continuous from Morrison (Late Jurassic) into Burro Canyon (Early Cretaceous) time.

I have noted a similar intertonguing relationship in No Thoroughfare Canyon in the middle of sec. 21, T. 1 S., R. 1 W., Ute P.M., where a lens of Burro Canyon-like sandstone occurs near the top of the Brushy Basin Member.

In the Grand Junction area the contact generally is sharp, especially when viewed from a distance, but locally is somewhat indistinct. The basal bed or beds of the Burro Canyon are sandstone in most places, conglomerate in other places. The local channeling of the basal beds into the underlying Brushy Basin is similar to that of individual channel sandstone beds of the Salt Wash Member into underlying fine-grained beds. That there may be at least a short time lapse between the Morrison and Burro Canyon is suggested by the distinct change in character of sedimentation between the dominantly mudstone beds of the Brushy Basin Member and the sandstone or conglomerate of the Burro Canyon. Locally, however, as in No Thoroughfare Canyon, intertonguing between the two formations suggests a more gradual transition in sedimentation. All things considered, therefore, the contact in this area appears to be conformable.

A columnar section of rocks exposed in and near the Colorado National Monument (Lohman, 1960b, p. 87), which was prepared soon after the fieldwork began, incorrectly shows an unconformity at the base of the Burro Canyon Formation. Additional fieldwork showed this supposed unconformity to be a local condition of scour and fill, and proved that in most places the contact appears to be conformable, as shown in plate 2.

CRETACEOUS SYSTEM

LOWER CRETACEOUS SERIES

BURRO CANYON FORMATION

Definition.—The Burro Canyon Formation was namd by Stokes and Phoenix (1948) from exposures in Burro Canyon, sec. 29, T. 44 N., R. 18 W., New Mexico Meridian, in San Miguel County, Colo.

Character, distribution, and thickness.—The Burro Canyon Formation consists mainly of sandstone and shale or siltstone, but locally the sandstone, particularly at the base, may be conglomeratic, and thin lenticular limestone occurs in some sections. The pebbles in the conglomerate are mainly chert.

The Burro Canyon Formation has a wide range in thickness and lithology comparable to that of the Salt Wash Member of the Morrison Formation. In about the western half of the area the Burro Canyon is mainly green shale, but it includes a basal sandstone or conglomerate 15 to 50 feet thick and one or more additional lenticular beds of sandstone. The basal sandstone is medium grained, massive, crossbedded, and varies from greenish gray to buff. Generally it is more or less iron stained where exposed, and large talus blocks generally are darkly iron stained on all sides. In some places, as in the No Thoroughfare Canyon section, the green shale contains a thin lenticular bed of very hard green cherty sandstone that rings when struck by a hammer and breaks with a smooth conchoidal fracture. In some places this bed contains fossils resembling fern or wood, and poorly preserved shells. In this part of the area the Burro Canyon and the overlying Dakota Sandstone cap a continuous series of low cuestas along the Redlands, and cap a high mesa and its outliers called Black Ridge. The Burro Canyon and lower part of the Dakota are best exposed in the lower part of No Thoroughfare Canyon (fig. 23).

In about the eastern half of the area the Burro Canyon Formation is dominantly sandstone in most places, and locally is as much as 85 percent sandstone (fig. 24); the remainder consists mainly of green shale or siltstone, some red or purple shale, and, locally, thin gray nodular limestone. Here the Burro Canyon and the overlying Dakota Sandstone cap gently sloping mesas in large interstream areas and protect the underlying Morrison Formation from erosion. The Burro Canyon and Dakota also cap the crest and higher parts of Piñon Mesa, southwest of the area.

In and near No Thoroughfare Canyon the Burro Canyon Formation and Dakota Sandstone are well exposed and readily separable, but to the west the contact is obscured in most places by weathering or soil cover, and to the east the two units together crop out in nearly vertical cliffs; so hence the contact is virtually inaccessible and is superimposed on the Burro Canyon-Morrison contact. For these reasons the two formations are not differentiated on plate 1.

FIGURE 23.—Burro Canyon Formation and Dakota Sandstone in west side of No Thoroughfare Canyon, NE¼ sec. 21, T. 1 S., R. 1 W., Ute P.M. Basal sandstone of Burro Canyon and overlying green shale above road; white band half way up slope is basal conglomerate of Dakota overlain by lignitic shale, lignite, and sandstone.

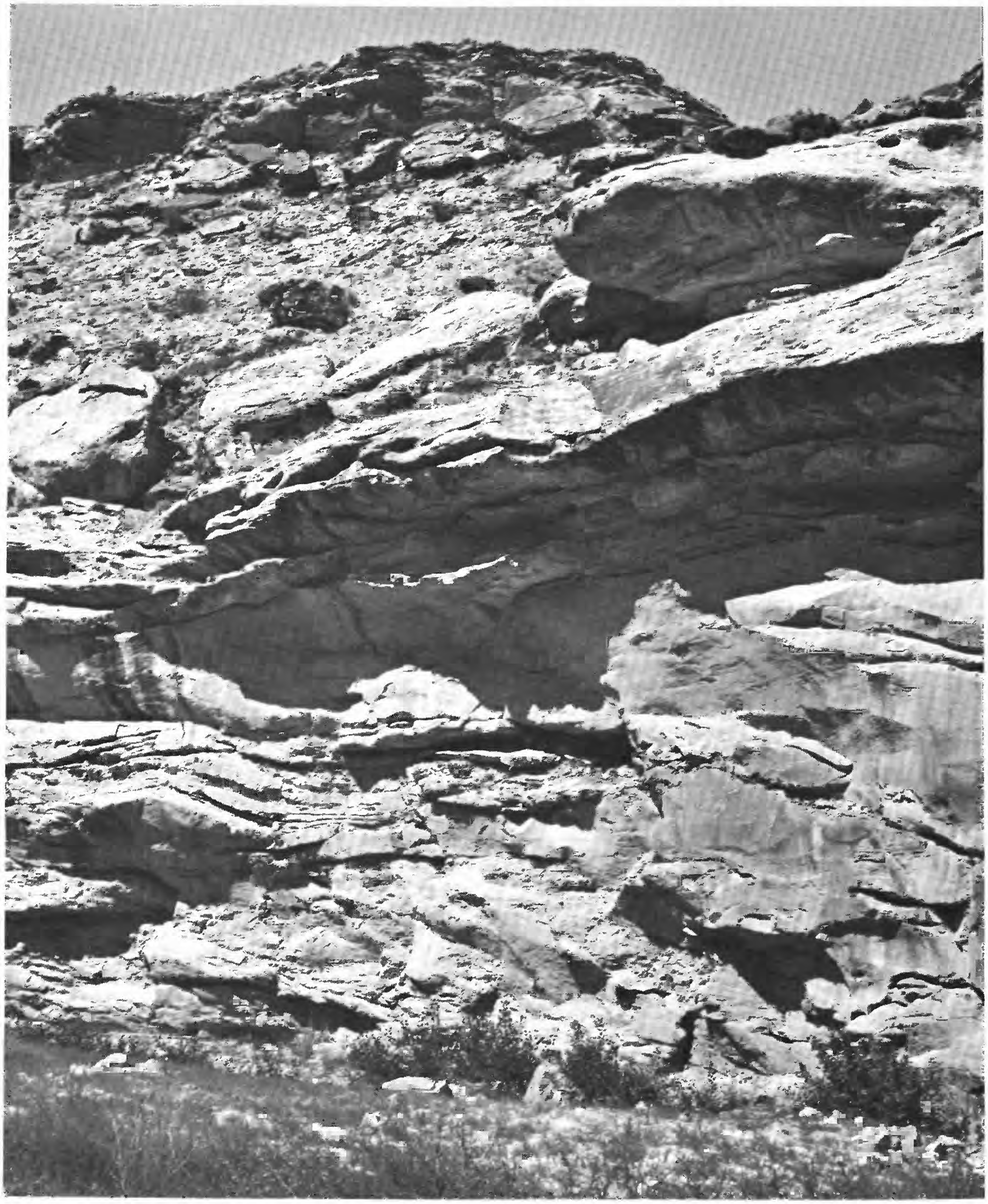


FIGURE 24.—Sandstone facies of Burro Canyon Formation. Looking west near mouth of East Creek Canyon, NE¼ sec. 33, T. 2 S., R. 1 E., Ute P.M.

No two sections of the Burro Canyon are similar or typical, because of the wide range in lithology and thickness. In the western part of the area, where more of the Burro Canyon was removed by erosion prior to deposition of the Dakota Sandstone, it is generally only 50–60 feet thick, but in the eastern part the sandstone facies is as much as 120 feet thick and in some places probably is even thicker. The following sections illustrate these differences. (See also measured sections at the end of this report.)

Section of Dakota and Burro Canyon Formations along west side of No Thoroughfare Canyon in NE¼ sec. 21 T. 1 S., R. 1 W., Ute P.M.

[Measured by S. W. Lohman and W. H. Lohman, Aug. 20, 1949]

	Thickness (feet)
Upper Cretaceous:	
Dakota Sandstone (incomplete):	
Shale, greenish and dark-colored; thin beds of soft sandstone; partly concealed to top of hill	17
Sandstone, medium-grained, buff, crossbedded; shale breaks near top	14
Shale, dark-colored, carbonaceous; thin seams of white sandstone and beds of greenish sandstone 2–12 in. thick; beds of lignite 1–4 in. thick at intervals and 6-inch bed of lignite at top overlying brownish carbonaceous shale containing many plant impressions	58
Conglomerate, coarse, white; matrix is coarse-grained crossbedded sandstone; pebbles are ¼–2 in. in diameter, but mostly ½–1 in. in diameter, and are mostly black or white chert; pink and purple streaks near top	41
Total Dakota exposed	130
Lower Cretaceous:	
Burro Canyon Formation:	
Shale, greenish, largely concealed; red streaks in uppermost 1 foot; 6-inch bed of hard, reddish and variegated flint clay at top which breaks with conchoidal fracture but also cleaves along bedding planes	15
Sandstone, medium-grained, dark-green, cherty, very hard; rings when struck by hammer; contains fossils resembling fern or wood, and poorly preserved shells; thickens to 7–8 ft northeastward	2.5
Shale, greenish, largely concealed	22.4
Sandstone, medium-grained, greenish gray to buff, massive, crossbedded; shale break 2 in. thick near top; ledge forming; basal bed locally iron stained; thickens to the south; basal sandstone channeled into underlying Morrison Formation	18.3
Total Burro Canyon (rounded)	58

Section of Dakota and Burro Canyon Formations along west side of No Thoroughfore Canyon in NE¼ sec. 21 T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)
Jurassic:	
Morrison Formation (incomplete):	
Siltstone and mudstone, variegated reddish and greenish.	

Section of Dakota and Burro Canyon Formations along old East Creek road in SW¼ sec. 30, T. 13 S., R. 99 W.

[Measured by S. W. Lohman and W. H. Lohman, Aug. 28, 1950]

	Thickness (feet)
Upper Cretaceous:	
Dakota Sandstone (incomplete):	
Largely concealed interval to top of mesa, mostly sandstone, some shale	20
Sandstone, fine-grained, white	6
Shale, dark-colored, lignitic	3
Sandstone, coarse-grained, and conglomerate; white; alternating layers of pebbly sandstone and coarse conglomerate; unit resembles basal conglomerate of Dakota in No Thoroughfare Canyon section	12
Concealed interval, mostly shale; one thick bed of sandstone	12
Sandstone, medium- to coarse-grained, and conglomerate; white, massive, crossbedded; pebbles mostly black chert	11.4
Sandstone; many pebbles of slightly coalified wood, shale, and black chert	.3
Shale, black, lignitic	2
Siltstone, sandy, light-gray, blocky; stained with iron oxide; thin beds of muddy sandstone	3.5
Sandstone, coarse-grained, white; stained buff on exposure; few zones of scattered pebbles of dove-gray to black chert; chert pebbles at base ½–3 in. in diameter	5.5
Total Dakota present (rounded)	76
Lower Cretaceous:	
Burro Canyon Formation:	
Siltstone, sandy, mainly pale-green with iron-stained zones and streaks, blocky; local cemented zones, beds, and concretions; one lens of speckled brownish-gray sandstone 1 foot thick	8.2
Sandstone, fine-grained, muddy, silty, yellow-brown	2.0
Siltstone, green, brown, and yellow-stained, lenticular	.4
Sandstone, fine-grained, muddy, silty, yellow-brown	5.4
Limestone, nodular	.4
Sandstone, gray, nodular, hard	.4
Limestone, gray, nodular, hard	.5
The three beds above grade laterally into a single limestone bed 0.8 ft thick, which then lenses to 3.5 ft thick by channeling into the siltstone below.	

Section of Dakota and Burro Canyon Formations along old East Creek road in SW¼ sec. 30, T. 13 S., R. 99 W.—Continued

	Thickness (feet)
Lower Cretaceous—Continued	
Burro Canyon Formation—Continued	
Siltstone, variegated green, olive-green, gray-green, and purple; 2-ft hard lime-cemented purple to buff-brown zone near base; purple near top, yellow and green in top 0.4 ft	8. 2
Sandstone, fine-grained, buff, hard, iron-stained; in beds 0.3–2 ft thick separated by partings and irregular lenses of greenish blocky sandy clay	26. 3
Sandstone, white, crossbedded, hard; scattered irregular zones of shale pebbles which weather out on exposure	10. 4
Sandstone, medium- to coarse-grained, white, lenticular; lenses out in 10 ft	. 9
Sandstone, white speckled with yellow and some dark iron oxide, crossbedded, hard; lower foot contains irregular zone of pebbles of light-green shale and brown to pale-green quartzite; next 2 ft above base contain a few similar pebbles; few scattered pebbles of black and white chert; base is channeled into shale below	14. 2
Shale, silty, green, lenticular; ranges in thickness from 0.3–1 ft for 20 ft, then grades into massive sandstone; thickness along section	. 4
Sandstone, mostly medium-grained, buff to gray-buff stained with iron oxide, well-rounded grains, massive, crossbedded; some beds coarse-grained; grades upward to fine-grained; irregular zone of clay pebbles 1–3 in. in diameter 1 ft above base; base rests on irregular scour surface	42. 4
Total Burro Canyon (rounded)	120
Jurassic:	
Morrison Formation (incomplete):	
Clay, green, some leached to chocolate and yellow, blocky; joints filled with fluffy white soluble salt having saline taste (sodium sulfate?)	1. 1
Sandstone, fine- to medium-grained, green, massive, nodular, soft; irregular limonite-stained streaks; becomes harder toward top	6. 2
Sandstone, fine-grained, light greenish-gray, slightly indurated; partly mottled by iron oxide	7. 3
Total Morrison measured	14. 6

Conditions of deposition.—The plant remains, the fresh-water invertebrates, and the lithologic characteristics of the Burro Canyon Formation are indicative of a continental origin. The sandstone beds and shale or siltstone beds are stream deposits, and the lenticular limestone beds probably were deposited in temporary lakes.

No fossils were observed in pebbles of the conglomerate in the Burro Canyon in the Grand Junction area, but Stokes (1944, p. 978–980) found abundant late Paleozoic fossils in pebbles from the Buckhorn Conglomerate in Utah and suggested that the pebbles were brought in by streams from the southwest and west. The pebbles suggest uplift of the source area with respect to the area of deposition.

Stokes (1944, p. 976–978; 1952b) suggested that the Burro Canyon Formation was laid down in an arid or semiarid environment, on the basis of its scanty fossil remains and because it is much thinner than the underlying Morrison Formation. According to Brown (1950, p. 47, 48), the fossil plants indicate that in Early Cretaceous and early Late Cretaceous time southwestern Colorado probably was a low-lying region not far above sea level.

Age and correlation.—Poorly preserved remains of plants and shells were observed in the Burro Canyon Formation in the Grand Junction area, but no identifiable fossils have been reported. On the basis of fossil plant remains, Brown (1950, p. 47) concluded that in southwestern Colorado the post-McElmo Formation (Burro Canyon of this report) and Dakota Sandstone of Coffin were Lower Cretaceous and Upper Cretaceous, respectively. Katich (1951, p. 2093, 2094) found Early Cretaceous invertebrate fossils in the equivalent Cedar Mountain Formation (Stokes, 1944, p. 958) in the western part of the San Rafael Swell. Additional invertebrate fossils and microfossils found in the Burro Canyon or its equivalents in several parts of the Colorado Plateau (Stokes, 1952a, p. 20, 1952c, p. 1768–1771; Mitchell, 1956, p. 110; Simmons, 1957, p. 2525–2528; Young, 1960a, p. 180–188) all attest the Early Cretaceous age of at least all but the basal sandstone or conglomerate of the Burro Canyon and equivalent Cedar Mountain. Although a thin sequence of beds comprising the uppermost part of the Brushy Basin Member of the Morrison Formation and the basal sandstone or conglomerate of the Burro Canyon or Cedar Mountain is undated because of lack of fossils, and hence may be Upper Jurassic or Lower Cretaceous, it seems reasonable to use the mappable contact at the base of this sandstone or conglomerate as the Jurassic-Cretaceous boundary, as suggested by Stokes (1952c, p. 1768).

In earlier reports on the area, the beds now included in the Burro Canyon Formation were called lower Dakota, Dakota, Dakota(?), or post-McElmo (table 3). Beds in Utah equivalent to the Burro Canyon of southwestern Colorado are included in the Cedar Mountain Group (Stokes, 1944, p. 958; 1952c, p. 1774; Simmons, 1957, p. 2528).

On the basis of supposed intertonguing between the Burro Canyon or Cedar Mountain Formations and the overlying Dakota Sandstone, Young (1960a, p. 157, 158) has proposed that the name Burro Canyon be dropped and replaced by the older name Cedar Mountain, that the name Dakota Sandstone be dropped and replaced by his Naturita Formation, and that his Dakota Group be used to include his Cedar Mountain and Naturita Formations. In the absence of any such supposed intertonguing in the Grand Junction area and because of its apparent absence elsewhere (Craig and others, 1961), there seem to be insufficient reasons for making the changes proposed by Young.

Water supply.—Only wells 14 and 36 are known to obtain water from the Burro Canyon Formation or Dakota Sandstone or both, but water in one or both of these units was also found in the drilling of wells 11 and 17, and perhaps also in others. No analyses of water from these formations are available because wells 14 and 36 were drilled long after the water samples were collected. Several attempts were made to collect a sample from a well formerly in the NE¼NE¼SW¼ sec. 25, T. 1 S., R. 1 W. Ute P.M., that obtained water from one or both of these formations, but each time the pump was reported inoperable. Later the well was destroyed during the realignment and widening of U.S. Highway 50. The waters from this well and from well 36 were reported satisfactory for domestic use, but in most other wells tapping these formations the water was reported to be salty and in some wells to contain H_2S (hydrogen sulfide). The salt water and perhaps also the H_2S probably come from the Dakota Sandstone, which is partly of marine origin, but the sandstone of the Burro Canyon Formation is of continental origin and should be expected to contain at least small amounts of fresh water.

The sandstone beds of the Burro Canyon Formation and Dakota Sandstone are tightly cemented, lenticular, and generally thin, hence they yield only small amounts of water, generally under insufficient artesian head to flow at the surface. Because of the small yields and local salty water at least in the Dakota, these two formations are unimportant as sources of water and rank last in importance among the four artesian aquifers of the area.

EROSIONAL UNCONFORMITY BETWEEN BURRO CANYON FORMATION AND DAKOTA SANDSTONE

The nature of the contact between the Burro Canyon Formation and the Dakota Sandstone, like many other stratigraphic problems on the Colorado Plateau, has been the subject of some dispute. Carter (1956, p. 1679–1680, 1957, p. 311–313) described the contact in the Mt. Peale 1 quadrangle of eastern Utah as a disconformity and as an extremely undulatory erosion surface, and he found blocks of Burro Canyon in the basal conglomerate of the Dakota. In tracing this contact into New Mexico and Arizona, Craig and others (1955, p. 161) noted that the contact at the base of the Dakota becomes an angular unconformity at the top of successively older rocks. Similarly, Harshbarger, Repenning, and Irwin (1957, p. 57) found that near Showlow, Ariz., the Dakota rests on the Upper Triassic Chinle Formation or rocks of Early Triassic age, and that at McNary, Ariz., the Dakota rests on Paleozoic rocks. Despite such evidence of a widespread erosional unconformity which becomes an angular unconformity to the south, Young (1960a, p. 176) contended that the Burro Canyon and Dakota intertongue (Craig and others, 1961).

In the Grand Junction area there is an erosional unconformity at the base of the Dakota Sandstone. Pre-Dakota erosion has removed all but 58 feet of the Burro Canyon Formation in No Thoroughfare Canyon, whereas 120 feet of the Burro Canyon remains in East Creek Canyon. (See sections, p. 61, 62.) The basal conglomerate and sandstone of the Dakota is white because of abundant white interstitial clay. A sample of the white sandstone from near the base of the Dakota in No Thoroughfare Canyon was examined by X-ray and microscopic methods by H. A. Tourtelot (oral communication, Aug. 30, 1962). The interstitial clay is kaolinite. None of the grains of kaolinite could be interpreted as a result of postdepositional alteration of feldspar or other aluminum silicate minerals. The kaolinite thus seems to be a result of pre-Dakota weathering as suggested by Leopold (1943, p. 56) for parts of Arizona and New Mexico and by L. C. Craig (written communication, Oct. 26, 1960) for many places in the southern part of the Colorado Plateau.

Mr. Tourtelot also examined a sample of the 6-inch bed of flint clay just below the basal conglomerate of the Dakota in No Thoroughfare Canyon. The clay appears laminated but breaks with a conchoidal fracture and is composed of about 90 percent kaolinite and 10 percent quartz. Most of the kaolinite is in a ground mass of highly oriented clay particles, but some of it is in discrete grains made up of well-developed books and "worms" of kaolinite crystals. These grains may represent original feldspar grains that were altered in place, and the bed may be a remnant of a deeply weathered zone on a pre-Dakota surface. The laminated appearance and high degree of orientation of the clay particles does not seem consistent with such an origin, however, and suggests the need for further study.

UPPER CRETACEOUS SERIES

DAKOTA SANDSTONE

Definition.—The Dakota Sandstone was named (as the Dakota Group) by Meek and Hayden (1862, p. 419, 420) from exposures in back of the town of Dakota, Dakota County, Nebr. The use of the name was later extended over a wide area, and the name was used in the Colorado Plateau by various earlier workers as

Dakota Group, Dakota Formation, Dakota(?) Sandstone, and, finally, Dakota Sandstone (table 3).

Character, distribution, and thickness.—The only completely exposed sections of the Dakota Sandstone known in the Grand Junction area are at the top of inaccessible cliffs along the gorge of the Gunnison River. Elsewhere the upper part of the Dakota is mostly eroded away except where small patches of the overlying Mancos Shale remain, and in such places exposures generally are poor.

The lower part of the Dakota is well exposed in No Thoroughfare Canyon (fig. 23), where it comprises a basal conglomerate or conglomeratic sandstone 41 feet thick overlain by carbonaceous and lignitic shale, lignite, and buff sandstone. (See section, p. 61.) The basal bed changes laterally from a conglomerate to a coarse-grained crossbedded sandstone containing only a few thin layers of conglomerate. The basal bed is conglomeratic; the pebbles range in diameter from ¼ to 2 inches but are chiefly ½–1 inch, and are mostly black or white chert, but some are quartzite.

This basal bed of the Dakota Sandstone is white, which readily distinguishes it from other conglomerate or sandstone beds in the Dakota or the Burro Canyon Formation in this part of the area. The reason for the whiteness of this bed is given in the section on the Erosional unconformity between Burro Canyon Formation and Dakota Sandstone.

The shale ranges from gray to brown or black, depending upon the content of carbonaceous material, and contains thin seams or beds of white and green sandstone, beds of lignite, and many plant impressions. The overlying beds of sandstone are mostly medium grained, crossbedded, and buff to light brown. Most of them are lenticular, particularly near the top (fig. 25), but some maintain a fairly uniform thickness for hundreds of feet.

Like the Burro Canyon Formation, the Dakota Sandstone becomes sandier eastward in the area, where, as in East Creek Canyon, it locally contains as many as three white sandstone or conglomerate beds that resemble the basal conglomerate in No Thoroughfare Canyon. (See section along East Creek road, p. 61.) Here the basal sandstone contains at the bottom chert pebbles as large as 3 inches in diameter, and some of the overlying sandstone beds contain pebbles of slightly coalified wood.

The Dakota Sandstone crops out over the same area and in similar manner as the Burro Canyon Formation and forms the surface over large interstream tracts in the eastern part of the area. The softer beds have been stripped from most of these dip slopes, which are capped by resistant sandstone.

Lignite coal formerly was mined from the Dakota Sandstone at several places along the east side of the Gunnison River Valley but, owing to the high content of ash, no coal has been mined for many years (Woodruff, 1912, p. 569). Most of the coal beds are 6 inches thick or less, but Woodruff (1912, p. 567) reported a 17-inch bed near the mouth of the Gunnison River and a 20-inch bed along the river a few miles southeast of the area.

Incomplete thicknesses of the Dakota Sandstone in the two sections measured were 76 and 130 feet. The total thickness is not known but probably exceeds 200 feet.

Conditions of deposition.—The basal sandstone or conglomerate and some overlying beds of the Dakota Sandstone appear to be near-shore fluvial deposits. The carbonaceous shale and lignite coal beds probably formed in coastal swamps or lagoons. Some of the upper sandstone beds appear to be beach deposits; similar deposits have yielded marine invertebrates near Delta, Colo. (Weeks, 1925, p. 19, 20; Young, 1960a, p. 185; Fisher, Erdmann, and Reeside, 1960, p. 25). Near Grand Junction, a species of *Inoceramus* and a gastropod fragment were reported from carbonaceous shale near the top of the Dakota (Fisher, Erdmann, and Reeside, 1960, p. 25). Slight oscillations of the land above and below sea level are indicated by alternate layers of beach deposits and coastal swamp or lagoonal deposits. Finally, the land sank below sea level for a long period of time during which the overlying Mancos Shale was deposited.

According to Brown (1950, p. 48), some of the ferns found in shale associated with coal beds suggest a relatively warm and moist environment at the beginning of the Late Cretaceous. The development of kaolinite at and near the base of the Dakota also suggests a moist environment.

Age and correlation.—Inasmuch as the deposits forming the Dakota Sandstone were laid down in and near a gradually transgressing sea, they are not everywhere of the same age. In most of the eastern and northern parts of the basin of deposition the Dakota or its equivalents are of Early Cretaceous age, but the deposition was progressively later toward the south and west. Thus, near Crawford, Colo., only about 25 miles east of Delta, Young (1960a, p. 188) found evidence that most of his Naturita Formation (Dakota) may be of Early Cretaceous age, whereas he (1960a, p. 185, 186) reported Late Cretaceous marine invertebrates from the upper part of his Naturita (Dakota) near Delta and Montrose, Colo., and at several localities farther west. Katich (1951, p. 2094) reported Early Cretaceous marine fossils from the Dakota in east-central Utah, but on the basis of subsequent collections supposedly from the same locality Young (1960a, p. 187) indicated the Dakota in that area to be of Late Cretaceous age. According to Katich (Craig and others, 1961, p. 1590), however, Young's collections were obtained ½ to 1 mile farther west. Partly on the basis of the fossils and perhaps partly on the basis of the supposed intertonguing between his Naturita (Dakota) and Cedar Mountain Formation, Young considered his Naturita to be of both Early and Late Cretaceous age, but mainly of Early Cretaceous age.

On the basis of fossil plants from several parts of southwestern Colorado, Brown (1950, p. 47) assigned the entire Dakota Sandstone to the Late Cretaceous. From consideration of the fossil plants and marine invertebrates found in nearby parts of the Colorado Plateau, J. B. Reeside, Jr. (oral communication, June 1955), W. A. Cobban (oral communication, Oct. 5, 1960), and Fisher, Erdmann, and Reeside (1960, p. 25) indicated that the entire Dakota in the Grand Junction area is of Late Cretaceous age. Moreover, the Dakota intertongues with the overlying Upper Cretaceous Mancos Shale in this area (fig. 25).

For the above reasons, I consider the Dakota Sandstone in the Grand Junction area to be of Late Cretaceous age, but I realize that there may be some doubt about the age of the lower, generally unfossiliferous part of the formation here and in other parts of the Colorado Plateau. The widespread erosional unconformity at the base of the Dakota, which becomes also an angular unconformity farther south (p. 57, 58), suggests that the interval between Burro Canyon and Dakota times may have been considerable; this implication tends to weaken the doubt about the Late Cretaceous age of the lower part of the Dakota. This opinion is in agreement with the findings of Fisher, Erdmann, and Reeside (1960, p. 25, 26): "The writers are inclined to believe that in the Book Cliffs region [of Utah and Colorado] a Cenomanian Dakota Sandstone rests unconformably on the Aptian Cedar Mountain Formation or the Burro Canyon Formation and that equivalents of the post-Aptian Lower Cretaceous beds are missing." Moreover, the thin fluvial deposits in the lower part of the Dakota were covered by the initial deposits of the transgressing Late Cretaceous Mancos sea.

Because the Dakota Sandstone is of Early Cretaceous age in the type area and in many other parts of its basin of deposition, the Upper Cretaceous Dakota Sand-

FIGURE 25.—Contact between Dakota Sandstone and Mancos Shale. Northwest bank of ephemeral stream in SE¼SE¼ sec. 14, T. 11 S., R. 101 W. Dakota Sandstone: Kd1, carbonaceous shale and lignite; Kd2, lenticular crossbedded marine sandstone, 3-4 feet thick; Kd3, tongue of lignite, 10 inches thick. Mancos Shale: Km1, tongue of olive-gray marine shale, 1½ feet thick; Km2, olive-gray marine thin-bedded sandstone and shale. Arrow points to contact mapped.

stone of the Grand Junction area correlates with a host of named Upper Cretaceous units elsewhere, the details of which are complex and beyond the scope of this paper. (See Cobban and Reeside, 1952; Fisher, Erdmann, and Reeside, 1960, p. 24.)

Water supply.—The occurrence of ground water in the Dakota Sandstone and Burro Canyon Formation is discussed on p. 63, for the two formations are not readily separable in most drillers' logs. They are unimportant as sources of water and rank last among the four artesian aquifers of the area.

During the drilling of well 5, a pocket of natural gas was found in the top of the Dakota Sandstone at a depth of 718 feet. Despite precautions taken to keep fire away from the vicinity, the gas was ignited by a spark from the drill bit and the resulting explosion and fire consumed most of the wooden parts of the drilling machine and warped many of the metal parts. The gas, in noncommercial amount, probably was methane (marsh gas) from the carbonaceous material in the Dakota.

CONTACT BETWEEN DAKOTA SANDSTONE AND MANCOS SHALE

In the Grand Junction area the contact between the Dakota Sandstone and the Mancos Shale appears to be conformable and gradational to the extent that in some places it is difficult to locate with certainty, and locally the two formations intertongue (fig. 25). The intertonguing relations shown in figure 25 suggest a transgression of the sea in late Dakota time and early Mancos time, which covered the coastal swamp with beach sand and then with deeper water mud, a slight regression of the sea that allowed the formation of another coastal swamp, and then a final transgression of the Mancos sea which allowed the accumulation of sand and mud.

MANCOS SHALE

Definition.—The Mancos Shale was named by Cross (1899) for outcrops in the Mancos Valley and around the town of Mancos, in Montezuma County, Colo. It is the youngest pre-Quaternary formation in the Grand Junction area.

Character, distribution, and thickness.—The Mancos Shale is a thick drab sequence of mainly fissile shale containing a few sandy zones and thin sandstone beds and some chalky shale. Some of the drillers' logs of wells indicate thin beds of limestone in the Mancos. The shale is largely olive gray to lead gray, but some is gray black and the chalky beds are light buff or cream colored.

The Mancos Shale underlies the entire Grand Valley, a large valley just to the east of the Gunnison River gorge, and forms most of the Book Cliffs and the base of towering Grand Mesa; it crops out along a narrow belt and in patches in the Redlands just south of the Colorado River and in scattered patches west of the Gunnison River. The two large valleys owe their origin to the ease with which the thick soft Mancos Shale has been eroded.

Only the lower part of the Mancos is present in the area mapped. The middle part is mostly concealed beneath the soil of irrigated land in the Grand Valley but is largely exposed along the sides of partly dissected pediments in the large valley east of the Gunnison River that is traversed by U.S. Highway 50. The latter area contains the only good exposures of the Mancos in the area mapped. The excellent exposures of the upper part of the Mancos in the Book Cliffs and at the base of Grand Mesa are protected from rapid erosion by the capping basal beds of sandstone of the overlying Mesaverde Group (fig. 26).

The weathered surface of the Mancos Shale is intricately carved and pitted by rain and rivulet erosion, which is strikingly displayed on the steep slopes of the Book Cliffs (fig. 26). When wet, the surface of the Mancos becomes sticky and very slippery, even though the very low permeability of the shale generally permits wetting to a depth of only a small fraction of an inch. Unimproved roads on the Mancos Shale become virtually impassable when wet.

No sections of Mancos Shale were measured, and the thickness of the Mancos in the mapped area is not known. From logs of oil tests near Grand Mesa, the total thickness of the Mancos is reported to be about 3,800 feet (A. D. Zapp, oral communication, Apr. 1960). Wells 1 and 5 penetrated 643 and 638 feet of Mancos, respectively, and several other wells penetrated more than 300 feet. Probably not more than about 700 feet of Mancos is present in the area mapped.

Conditions of deposition.—The Mancos Shale is clearly of marine origin and contains marine fossils at many places. Some of the sandy or the thin sandstone beds in the Mancos are attributed by Young (1960a, p. 192, 193) to slight uplifts above sea level in parts of the Colorado Plateau resulting in the shedding of coarser material from uplifted areas into adjacent parts of the Mancos sea. Young (1955, p. 182) also suggested that the Mancos was deposited as mud in the shallow water of the Late Cretaceous sea beyond the sand-mud transition line.

Age and correlation.—The marine fossils collected from the Mancos Shale in and near the Grand Junction area (Weeks, 1925, p. 23–25; Fisher, Erdmann, and Reeside, 1960, p. 26–31) are all of Late Cretaceous age. The fossils and stratigraphic studies (Cobban and Reeside, 1952, chart 10b; Weimer, 1960, fig. 3; Fisher, Erdmann, and Reeside, 1960, table 1, p. 24) indicate that the Mancos in the Grand Junction area contains

FIGURE 26.—Mount Garfield, a prominent point on the Book Cliffs. Looking north from U.S. Highways 6 and 24 west of Palisade. Slopes are Mancos Shale; ledge about halfway up slope is a landslide deposit; capping beds of sandstone at crest are basal beds of Mesaverde Group. Infrared photograph.

strata equivalent to units in eastern Colorado and western Kansas, including the Graneros Shale, Greenhorn Limestone, Carlile Shale, Codell Sandstone Member of the Carlile, Niobrara Formation, and the lower part of the Pierre Shale. Similarly, such studies (Cobban and Reeside, 1952, chart 10b; Young, 1955, pl. 3; and Weimer, 1960, fig. 3) have shown the equivalence of the Mancos in the Grand Junction area to Upper Cretaceous strata in several parts of central Utah.

Water supply.—In the Grand Junction area, as in most other places, the Mancos Shale is not water bearing. A few shallow wells in the Grand Valley have obtained small amounts of unconfined ground water from either the weathered zone of the Mancos or the alluvium filling former arroyos in the Mancos, or from both, but the water generally is of very poor quality owing to the high content of sodium sulfate and bicarbonate. The high content of salt in the Mancos is borne out by the many white efflorescent patches of alkali on both unirrigated and irrigated surfaces, the high salt content of return flow in ditches that drain irrigated areas, and the abundance of salt grass and salt cedar along such drainage ditches.

In rural areas underlain by the Mancos Shale, virtually all domestic water and some stock water is hauled from the nearest public water supply or from some of the wells that tap the principal artesian aquifers described above.

POST-MANCOS MESOZOIC AND TERTIARY EVENTS

The post-Mancos Mesozoic and Tertiary events that affected the Grand Junction area were depositional, deformational, and erosional. Deposits of these ages that once covered the area and are still preserved to the north and east in the Uinta Basin section of the Colorado Plateaus Province have all been eroded from the mapped area; they will be discussed only briefly.

By the end of Mancos time the Grand Junction area was buried beneath thousands of feet of marine mud that was eventually compacted into about 3,800 feet of shale. Then began a series of uplifts slightly above sea level and subsidences slightly below sea level which resulted in the intertonguing of marine shale of the Mancos and littoral marine sandstone, lagoonal deposits, and coal swamps of the overlying Mesaverde Group. Young (1955, p. 199, 200) recognized several successive four-fold cyclothems of this type and several more complex sequences which he called megacyclothems. Continued uplift caused the final withdrawal of the sea to the east, for the upper part of the Mesaverde Group is of continental origin, as are all subsequent deposits in and near the area. Northeast of Palisade the Mesaverde Group is about 2,300 feet thick (Young, 1960b, p. 85, 86). According to Hunt (1956a, p. 63), "At the close of Late Cretaceous time the area covered by the Colorado Plateau must have stood at, or near, sea level because it was a coastal plain."

The area was uplifted still higher at about the close of the Cretaceous, for part of the Mesaverde Group was removed by pre-Tertiary erosion (Erdmann, 1934, p. 64; Young, 1960b, p. 86) and an angular unconformity at the base of the Tertiary has been noted in several parts of the Colorado Plateau to the south and west of the Grand Junction area (Hunt, 1956a, p. 57). Deformation that accompanied this uplift formed the ancestral San Juan Mountains to the southwest and several ranges of the Rocky Mountains to the east and northeast (Burbank, 1933, p. 283–288), and uplift of the Uinta Mountains and the Uncompahgre Plateau (arch) may have begun at this time or slightly later (Hunt, 1956a, p. 57, 75). In and near the Grand Junction area this uplift, erosion, and gentle deformation created a large inland basin in which were deposited a thin sequence of fluvial sediments of Paleocene age, formerly called "Plateau Valley beds" by Patterson (1936, p. 398), and the thick fluvial Eocene Wasatch Formation. These Paleocene beds later were included in the lower member of the Wasatch Formation by Donnell (1961). The combined thickness of the deposits now included in the Wasatch is about 5,500 feet in the middle of the Piceance Creek Basin, only about 1,000 feet on the slopes of Lands End, the westernmost promontory of Grand Mesa, and probably was less than 1,000 feet in the Grand Junction area, which was near the southern margin of the basin (John R. Donnell, oral communication, Apr. 1960). The "Plateau Valley beds" have yielded *Titanoides* and other primitive mammals of late Paleocene age (Patterson, 1939).

In early and middle Eocene time the northern part of the Colorado Plateau was downwarped to form a huge lake, called Uinta Lake or Green River Lake, the possible extent of which has been depicted by Hunt (1956a, fig. 56), who showed the ancestral Uncompahgre arch as a peninsula extending northwestward into this lake. In this large lake, which covered the northeastern part or perhaps all the Grand Junction area, was deposited a thick sequence of very remarkable sediments known as the Green River Formation, including papery shale, sandstone, marlstone, oolite, algae reefs, and many beds of lean to rich oil shale. The character, origin, and microfossils of this assemblage and the probable climate that prevailed during its deposition have been described by W. H. Bradley (1929, 1931). Donnell (1957, p. 255) estimated that in the part of the Piceance Creek Basin northwest of the Colorado River alone, the Green River Formation contains nearly one trillion barrels of oil, and later studies indicated an estimate of more than one trillion barrels (John R. Donnell, oral communication, Oct. 20, 1960). The Green River Formation is about 3,890 feet thick in the Piceance Creek Basin; it thins to not more than 800 feet at Lands End, on the western tip of Grand Mesa, and probably was not more than 400 feet thick in the Grand Junction area, which was near the southern shore of ancient Uinta Lake (John R. Donnell, oral communication, Apr. 1960).

While Eocene deposits were accumulating in the Piceance Creek Basin in and northeast of the Grand Junction area, intrusion and extrusion of volcanic rocks occurred to the south and east of the area; these events are recorded by beds of tuff in the Green River Formation.

According to Hunt (1956a, p. 77), the Uinta or Green River Lake disappeared in middle Eocene time in part because of filling and perhaps in part because of uplift. Except for thick basalt flows of post-Green River age, remnants of which still cap Grand and Battlement Mesas and the Roan cliffs, this filling probably ended deposition for a long period of time in and near the Grand Junction area, but fluvial sediments of later Tertiary age were deposited in northern Colorado and Wyoming.

Renewed uplift and folding in many parts of the Colorado Plateau, including the Grand Junction area, occurred in post-Green River time, for the Green River Formation and underlying rocks were folded to form the Uinta and Piceance Creek structural basins and the intervening Douglas Creek anticline. According to John R. Donnell (oral communication, October 24, 1960), beds of the Wasatch are vertical or slightly overturned along the Grand Hogback monocline at several places between Rifle and Meeker, and beds of the Green River dip as much as 25° in the northwestern part of the Piceance Creek basin about 10 or 15 miles east of Rangely, Colo. According to Larsen and Cross (1956, p. 244), the San Juan Mountain region also suffered a major deformation after the deposition of the Eocene beds, which they suggested probably occurred in early Miocene or Oligocene time. Although the Uncompahgre arch probably began to rise at about the close of the

Cretaceous, it seems reasonable to assume that additional uplift and attendant folding and faulting of the Uncompahgre arch took place in post-Green River time when the Douglas Creek anticline and adjacent synclinal basins were formed and the White River uplift was further raised with steepening of the Grand Hogback monocline. The monoclines and faults on the northeast flank of the northwestward-plunging Uncompahgre arch, most of which traverse the Grand Junction area, are discussed under "Structure."

Events of Oligocene and Miocene times were not recorded in the Grand Junction area, except for the outpouring of lava sometime after the Green River deposition, but late Tertiary vulcanism occurred in the San Juan Mountains, in parts of central Colorado, and in distant parts of the Colorado Plateau. According to Larsen and Cross (1956, p. 62), no volcanic rocks were erupted in the San Juan Mountains region from early Paleocene time to about middle Miocene time, but eruptions began about middle Miocene time and continued intermittently into Quaternary time. Hunt suggested (1956a, p. 85 and fig. 61) that during late Miocene to middle Pliocene time the Colorado Plateau rose (epeirogenically), was tilted northeastward so as to impound drainage, and that sediments such as the Miocene(?) Browns Park Formation of northwestern Colorado were deposited in virtually all the basins and valleys of the Plateau. If any sediments were laid down in valleys of the Grand Junction area at this time or during any part of the Oligocene and Miocene interval, they were removed by subsequent erosion; the net effect of this interval on the area was extensive removal of older rocks by erosion.

Hunt (1956a, p. 67, 68) suggested that the course of the Colorado River from Rifle to Grand Junction could have been established by superposition on the lavas of post-Green River age, remnants of which now cap Grand and Battlement Mesas and the Roan Plateau, and which presumably once covered a wide area; he also implied that the old course through Unaweep Canyon also resulted from this superposition. From studies farther upstream, Ogden Tweto (oral communication, May 1961) thought that the river may have been established prior to extrusion of the lavas, which seems to be a logical time for establishment of the old course of the river. The streams probably greatly deepened their channels without regard to hardness of rocks or underlying structure during the epeirogenic uplifts in late Miocene to middle Pliocene time. It seems likely that Unaweep Canyon was cut down to and probably into the Precambrian core of the Uncompahgre Plateau during this interval (fig. 28*A*).

Hunt (1956a, p. 68) suggested further that the new course of the Colorado River between what is now Grand Junction and the mouth of the Dolores River was established by superposition on deposits at least as old as the Browns Park Formation. However, this reach crosses and is cut into the Uncompahgre arch, which seems an unlikely place to expect a basin in which such material could have been deposited. In the section that follows I shall attempt to show that the piracy resulting in this new course of the river probably took place by normal headward erosion of a tributary in soft Mancos Shale, possibly aided by renewed uplift of the Uncompahgre arch.

LATEST TERTIARY AND EARLY QUATERNARY EVENTS

Until perhaps Pliocene time, the Grand Junction area and adjacent parts of the Colorado Plateau continued to be eroded by the ancestral Colorado River and its tributaries, the courses of which had been previously established. Evidence that differential uplift of the Uncompahgre arch may have been renewed in Pliocene time was found by F. W. Cater (written communication, Dec. 1960). Then, probably also in Pliocene time, occurred major drainage changes in the courses of the Colorado and Gunnison Rivers, followed by renewed uplift of the Uncompahgre arch, which together profoundly affected the later erosional pattern of the area and made possible the cutting of the Grand Valley and the magnificent canyons in and near the Colorado National Monument.

UNAWEEP CANYON

An anomalous deep canyon crosses the Uncompahgre Plateau between the towns of Whitewater and Gateway, Colo., known as Unaweep Canyon, the northeastern end of which is shown on plate 1. (See the Moab, Utah-Colorado, topographic map prepared by the Army Map Service.) The inner gorge of this canyon, which is cut in hard Precambrian rocks and is nearly vertical walled, is from 1,000 to 1,200 feet deep and from ¼ to ½ mile wide in most places and nearly a mile wide locally. The entire canyon, including the gentler sloping walls of the overlying Mesozoic sedimentary rocks, is about 2,000 feet deep just east of the crest of the Plateau where the width at the top of the canyon is about 4 miles. Later erosion by West Creek has deepened the canyon to 3,300 feet at the crest of the Plateau about 10 miles northeast of Gateway, where the width at the top is about 5 miles.

About 11 miles east of the crest of the Uncompahgre Plateau, in the southeast corner of T. 14 S., R. 100 W., is a very gentle drainage divide in the bottom of the steep-walled inner gorge. At the divide, Unaweep Canyon is about 1,000 feet deep. The crest of the divide has an altitude of about 7,000 feet and stands about 2,500 feet above Grand Junction and Gateway, on opposite sides of the Uncompahgre Plateau. From this divide, East Creek flows northeastward about 20 miles to join the Gunnison River at Whitewater (fig. 27) and West Creek flows southwestward about 25 miles to join the Dolores River at Gateway. The two small streams are ephemeral near their headwaters, but become perennial farther downstream except for periods when their flows are diverted for irrigation.

That such an immense canyon could not have been cut by such small streams flowing in opposite directions was recognized as early as 1875 by A. C. Peale and Henry Gannett, members of the Hayden survey. They each correctly concluded that the canyon was cut by a large river which had since abandoned the canyon, but Peale (1877, p. 58, 59) attributed the cutting to the Gunnison River alone, whereas Gannett (1882, p. 785) attributed it to the Grand (Colorado) River. They both attributed the cause of the drainage change solely to renewed uplift of the Uncompahgre Plateau (arch), however, and did not mention the obvious additional possibility—stream piracy.

In a brief guidebook article, Stokes (1948, p. 39 and fig. 9) suggested that Unaweep Canyon formerly was occupied by the Colorado River; he attributed the drainage change to piracy, with which I agree, but he did not tell the complete story which, I believe, involved two successive major piracies, renewed differential uplift of the Uncompahgre arch soon after the two major piracies, and at least one minor piracy (Lohman, 1961a).

Figure 28*A* shows my concept of the major drainage and topographic features just prior to the piracy of the ancestral Colorado River, and is similar to that of Stokes (1948, p. 39, fig. 9a). At this time, probably in the Pliocene, the river had cut more than 1,000 feet through Precambrian granite, gneiss, and schist in Unaweep Canyon. Because this was the hardest rock encountered by the degrading river between Glenwood Canyon, Colo., and Grand Canyon, Ariz., downcutting by the ancestral Colorado in and above Unaweep Canyon was greatly retarded for a long period of time. Not so with the tributary shown at the left, however, which, though carrying much less water than the master

FIGURE 27.—Unaweep Canyon. Looking southwest from rim of inner gorge 5 miles northeast of drainage divide (see fig. 28*D*).

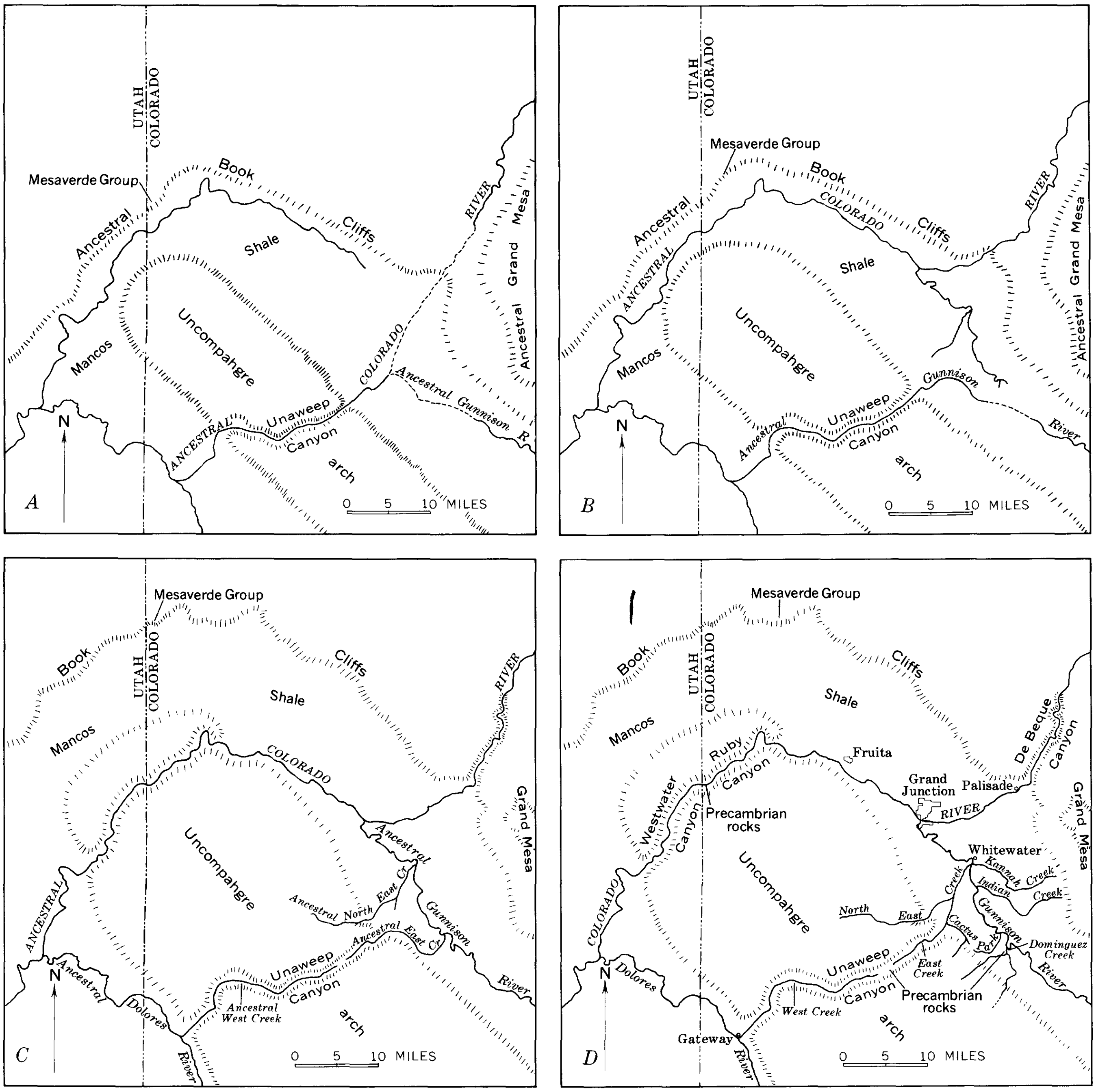


FIGURE 28.—Sketch maps of a part of western Colorado and eastern Utah showing probable drainage pattern and topographic features at four successive stages of development. Solid drainage lines taken from Moab and Grand Junction, Utah-Colorado, topographic maps of the Army Map Service; dashed drainage lines are hypothetical. *A*, just prior to piracy of ancestral Colorado River; *B*, after piracy of ancestral Colorado River and just prior to piracy of ancestral Gunnison River; *C*, after piracy of ancestral Gunnison River; and *D*, present drainage pattern, after renewed uplift of the Uncompahgre arch and piracy of East Creek.

stream, had only the soft Mancos Shale to cut. At this time the band of Mancos Shale extended much farther up the flanks of the northwestward-plunging Uncompahgre arch than at present, and some higher parts of the plateau may still have been covered by the Mancos. Note also that the ancestral Book Cliffs and Grand Mesa were then somewhat closer to the plateau.

PIRACY OF THE ANCESTRAL COLORADO RIVER

The tributary shown at the left on figure 28*A* continued to cut headward until only a low divide of shale separated it from the ancestral Colorado River. Then, probably during an unusually large flood, the ancestral Colorado breached its banks and spilled over into the headwaters of the tributary. With this enormously increased supply of water at its disposal, the tributary cut down rapidly into the soft Mancos Shale, captured the waters of the ancestral Colorado, and isolated the ancestral Gunnison River (fig. 28*B*). Note also that soon after capture of the ancestral Colorado, a tributary was cutting southward into the soft shale and was about to capture the ancestral Gunnison. The position of the three streams shown in figure 28*A* indicates that both rivers could not have been captured simultaneously.

That the interval between piracies of the two rivers probably was short is suggested by the considerable differences in their downcutting abilities and discharge rates. The new channel of the ancestral Colorado was cut down rapidly through the soft Mancos Shale, whereas that of the ancestral Gunnison still lay in the hard Precambrian rocks in Unaweep Canyon. Assuming that the relative discharge rates, but not necessarily the actual rates, probably were similar to the present relative discharge rates, the ancestral Colorado probably carried about 64 percent of the former combined flow and the ancestral Gunnison about 36 percent (E. J. Tripp, oral communication based on 26 years of Geological Survey records, 1934–59; Dec. 27, 1960).

PIRACY OF THE ANCESTRAL GUNNISON RIVER

Figure 28*C* depicts my concept of what the drainage pattern may have been sometime after piracy of the ancestral Gunnison River by the newly formed and rapidly downcutting ancestral Colorado River. The divide between ancestral East and West Creeks had had time to migrate from a point near the ancestral Gunnison River to the northeastern end of Unaweep Canyon, but was still migrating slowly southwestward. Meanwhile, ancestral North East Creek had cut its channel deeper and farther west, and a short tributary was cutting southwestward toward ancestral East Creek

At this stage in the development of the area, a superposed master stream and one of its larger superposed tributaries had been captured by a subsequent tributary, which in general followed the strike of the soft Mancos Shale around the end of the northwestward-plunging Uncompahgre arch; but other changes were to take place.

Additional evidence that Unaweep Canyon once carried water from drainage basins east of the Uncompahgre Plateau was afforded by F. W. Cater (written communication, Dec. 1960), who found basalt pebbles in high terrace gravel along West Creek about 4½ miles above Gateway. He stated that "The gravels of the Dolores River and its terraces above Gateway seem to lack such pebbles—at least none were found after considerable search." He believed it likely that the terrace gravel containing basalt was deposited by ancestral West Creek rather than by the ancestral Colorado River, probably from the reworking of older gravel deposited farther upstream by the ancestral Colorado. Inasmuch as basalt pebbles generally disintegrate fairly rapidly during stream transportation, it seems likely that those found near Gateway were derived from tributaries of the ancestral Colorado and Gunnison Rivers that drained nearby basalt-capped Grand and Battlement Mesas.

RENEWED UPLIFT OF THE UNCOMPAHGRE ARCH

The Uncompahgre arch seemingly was uplifted both before and after abandonment of Unaweep Canyon by the ancestral Colorado and Gunnison Rivers, and the earlier uplift may have aided the two stream piracies. F. W. Cater (written communication, Dec. 1960) called attention to the fact that the divide between East and West Creeks is about 2,500 feet higher than the Dolores River at Gateway. He believed that relatively little downcutting has taken place along this part of the Dolores and upstream areas since abandonment of Unaweep Canyon, that this gradient (about 100 feet per mile) is far greater than that likely to be found on any large river and, therefore, that most of this difference in altitude must be the result of differential uplift of the Uncompahgre arch after abandonment of Unaweep Canyon; as further supporting evidence concerning relatively recent uplift of the Uncompahgre Plateau, Cater cited the fact that the upland surface of the Plateau is eroded only to about the same stratigraphic level (Dakota Sandstone) as the adjoining mesas at much lower altitudes to the southwest (and to the northeast)—that is, the topographic and stratigraphic displacements are about equal—a condition not likely to exist if the last uplift had occurred much earlier. To this I might add that the higher parts of the Plateau have a relatively mature topography whereas the lower flanks on all sides, which have suffered postuplift erosion, have a very youthful topography. Before citing the evidence in and north of the Grand Junction area that supports and augments Cater's views, it seems desirable to attempt to determine the time of the uplift or uplifts, and hence also the time of the preceding stream piracies, by considering the evidence from nearby areas.

Atwood and Mather (1932, p. 25–27) presented evidence that late in the Cenozoic Era the San Juan Mountains underwent several successive episodes of uplift and crustal warping, the first of which marked the transition from Pliocene to Pleistocene time. Shoemaker (1954, p. 66) cited evidence of renewed deformation at about the same time in the Defiance and Zuni uplifts. Although the evidence in and near the Grand Junction area is less complete than that in the San Juan Mountain region, it seems probable that the renewed uplift of the Uncompahgre arch occurred at about the same time as the deformation in the San Juan Mountains—latest Pliocene or earliest Pleistocene; that the two major stream piracies occurred before, in the Pliocene; and that additional uplift may have occurred during Pleistocene time. I agree with C. B. Hunt (written communication, July 1964) that renewed uplift probably caused homoclinal shifting of the ancestral Colorado River down the dip of the northwestward-plunging Uncompahgre arch. If so, the position of the ancestral Colorado River in Ruby and Westwater Canyons should have been drawn somewhat to the southeast of where they are placed in figure 28*A–C*.

The divide between East Creek and West Creek, noted by Cater as being about 2,500 feet above the Dolores River at Gateway, is also about the same height above the Colorado River at Grand Junction, the evidence on the southwestern side cited from Cater for renewed uplift of the Uncompahgre Plateau applies equally well, therefore, to the northeastern side. I am in agreement with Cater that most of the uplift seems to have occurred along faults and faulted monoclines bordering the southwestern and northeastern sides of the Plateau, but some of the uplift probably occurred also by additional tilting of strata. That the uplift of the Plateau was fairly uniform and that both flanks were deformed about equally is suggested by the fact that the gradient of West Creek for the first 2½ miles west of the divide (Peale, 1877, p. 58), which I believe is virtually unchanged since abandonment by the ancestral Colorado and Gunnison Rivers, is the same as that of the Colorado River between Grand Junction and the mouth of the Dolores River—about 4.4 feet per mile.

It is not certain how much of the 2,500 feet suggested by Cater is due to renewed localized uplift of the Uncompahgre arch and to normal erosion since the major piracies and the uplift or uplifts. Scattered bits of information in and northeast of the Grand Junction area suggest certain possible answers. In the absence of detailed topographic maps and detailed study of areas to the northeast, it is difficult to fit all the pieces together, but an attempt will be made.

Remnants of dissected pediments are well preserved along the south side of the Colorado River valley between Silt and De Beque, Colo. These pediments, which were cut on the Eocene Wasatch Formation and are veneered with surficial deposits, are known locally as mesas, and represent at least two former relatively mature valley levels that have since been cut off abruptly on the north side by the Colorado River. The abrupt northern edges of Grass Mesa and Taughenbaugh Mesa, respectively south and southwest of Rifle, stand 800 and 400 feet above the Colorado River, but if the pediment surfaces are projected northward at the same slope, the projections are 600 and 300 feet above the river.[10] Similarly, the northwestern edges of High Mesa south of the town of Grand Valley and a lower mesa east of De Beque stand about 1,050 and 625 feet, respectively, above the river, but projected surfaces stand about 650 and 350 feet above the river.[11] Before dissection, the pediments probably had slightly concave upward surfaces rather than linear slopes; thus the actual heights above river level probably were greater than indicated above and may have been 600 to 800 and 300 to 400 feet, respectively. Locally one or more lower pediments are visible, and there is evidence of at least one higher pediment.

It is possible that the well-developed pediments 600 to 800 feet above the present river represent a mature valley formed while the ancestral Colorado River was temporarily base-leveled by the hard Precambrian rocks in Unaweep Canyon and that, after the two major stream piracies in Pliocene time, dissection of this surface began by the accelerated downcutting of the river. Ruby and Westwater Canyons (fig. 28*D*) also have been cut about 600 to 800 feet below the Uncompahgre Plateau.

Finally, another mature valley seemingly was developed at the level of the pediments now 300 to 400 feet above the present river. Dissection of this lower valley surface may have been caused by slight epeirogenic uplift that accompanied the greater local renewed uplift of the Uncompahgre arch in late Pliocene or early Pleistocene time. Of course, the two old valley levels may have been dissected as a result of two successive periods of uplift, major climatic changes, or other causes. The possible causes postulated above, however, seem to be more in keeping with the available evidence. The less well-preserved pediment above the 600- to 800-foot level may reflect an earlier uplift (Pliocene?), and those below the 300- to 400-foot level may reflect later uplifts during Pleistocene time.

In the Grand and Gunnison River valleys of the Grand Junction area are several levels of well-preserved pediments cut on the Mancos Shale, the most striking of which are in the Gunnison River valley between Delta and Grand Junction, and which are capped with about 15 feet of basalt cobbles derived from Grand Mesa. The higher pediments, at altitudes of about 6,000 feet, are too far from the Colorado or Gunnison Rivers to determine the projected heights above the present river level, but they may be correlatives of the 600- to 800-foot surface near Rifle and Grand Valley.

[10] See U.S. Geological Survey topographic map of the Rifle 7½-minute quadrangle.

[11] See U.S. Geological Survey topographic map of the Grand Valley 15-minute quadrangle.

A remnant of a well-preserved lower pediment, which now contains a small airfield, is along the drainage divide just south of Orchard Mesa. This pediment represents an old valley level about 500 feet above the present Colorado River and may be correlative with the lower 300- to 400-foot level farther up the Colorado River. Because it lies athwart the supposed course of the ancestral Colorado River shown by a dashed line in figure 28*A*, all that can be said of this surface with reasonable certainty is that it was formed after the two major stream piracies.

The ledge about halfway up the slope of Mt. Garfield, shown in figure 26, was examined by John H. Stewart (written communication, Dec. 29, 1961), who found it to be a remnant of an old landslide deposit consisting of jumbled masses of Mancos Shale and sandstone from the overlying Mesaverde Group. He found that the base of these deposits rests on a flat, nearly horizontal surface of Mancos Shale that suggests the surface of an earlier valley. This surface is now about 400 feet above the Colorado River and seems to be correlative with the 300- to 400-foot level just discussed. Inasmuch as the Book Cliffs have receded northward since this old surface was dissected, the landslide deposits doubtless once extended farther south and to a somewhat lower level.

Most of the youthful topography on the northeastern flank of the Uncompahgre Plateau, including the deep cliff-walled canyons of Colorado National Monument, lies within about 1,700 feet above the present Colorado or Gunnison Rivers. This interval may include the 600 to 800 feet of erosion since the formation of the higher pediments upstream and 900 to 1,100 feet of additional uplift on the northeastern flank of the Uncompahgre arch. Similarly, the difference in altitude of 2,500 feet between the divide in Unaweep Canyon and the river at Grand Junction may include 600 to 800 feet of erosion and 1,700 to 1,900 feet of additional uplift near the axis of the Uncompahgre arch.

QUATERNARY EVENTS AND DEPOSITS

PIRACY OF EAST CREEK

Ample evidence indicates that, after the two major stream piracies, ancestral East Creek joined the ancestral Gunnison River along the course shown in figure 28*C*, but that later, probably in the Pleistocene, East Creek was captured by a tributary of North East Creek to form the present drainage pattern shown in figure 28*D* (fig. 29).

A small patch of terrace deposits containing cobbles and pebbles of basalt, quartzite, granite and other crystalline rocks covers the crest of a small hill in Cactus Park in the NE¼ NW¼ sec. 6, T. 14 S., R. 99 W. This material is about 800 feet below the divide in Unaweep Canyon, and therefore it probably was not deposited by the ancestral Colorado or Gunnison Rivers. At least the basalt and probably also the other rock types, however, were brought into Unaweep Canyon by these rivers; later, they probably were reworked and carried back to the northeast by ancestral East Creek when it flowed generally northeastward and locally southeastward through what is now a broad alluviated valley known as Cactus Park. The terrace deposits are now about 200 feet above the new channel of East Creek 0.6 mile to the west.

A very gentle divide in the NE¼ sec. 16, T. 14 S., R. 99 W. now separates the two parts of beheaded ancestral East Creek, one part draining westward to East Creek and the other draining first southeastward then northeastward to the Gunnison River. The divide is in Cactus Park, which is rimmed on the north by a steep slope of the Morrison Formation capped by the Burro Canyon Formation and Dakota Sandstone (fig. 29). This broad valley or park formerly occupied by ancestral East Creek and believed to mark also the approximate former course of the ancestral Gunnison River (fig. 28*A*, *B*) is at least in part of structural origin, as it is just south of the East Creek monocline.

Additional evidence of this piracy and of renewed uplift of the Uncompahgre arch is afforded by changes in gradient along East and North East Creeks. From the divide in Unaweep Canyon to the SW¼ sec. 1, T. 14 S., R. 100 W., East Creek has a gradient of about 80 feet per mile. In the 2-mile alluviated stretch of its canyon below this point, the gradient is only about 50 feet per mile, but in the next 2 miles extending to its confluence with North East Creek, the gradient is about 350 feet per mile. From this confluence to the mouth, North East Creek has a gradient of about 110 feet per mile. The reach of East Creek having a gradient of about 350 feet per mile is the former tributary of ancestral North East Creek that captured East Creek (fig. 28*D*). It seems likely also that the steep gradient of this 2-mile reach and the reach below was caused at least in part by the preceding renewed uplift of the Uncompahgre arch.

Studies of the alluvium in East Creek canyon in sec. 1, T. 14 S., R. 100 W., by Hunt (1956b, p. 66; see middle of fig. 29) made in connection with an archaeological investigation of the Taylor site in this canyon (p. 79) afford some evidence that the piracy of East Creek probably occurred in Pleistocene time. He indicated three successive deposits of alluvium: (1) The oldest and thickest alluvium is compact, clayey, and limy, and contains fresh water shells; its top is about 25 feet above the creek; (2) an intermediate sandy alluvium that fills a wide deep arroyo cut into (1) and that overlies (1) to depths of 1 to 10 feet; and (3) the

FIGURE 29.—Oblique aerial photograph of the mouth of Unaweep Canyon, looking northeast. A, East Creek; B, former course of East Creek and Gunnison River, in Cactus Park; C, new course of East Creek; D, terrace deposits containing pebbles and cobbles of basalt; and E, Gunnison River. Lower slopes of Grand Mesa in background. Geologic features may be identified by comparison with appropriate part of plate 1, viewed toward the northeast. Scale variable. Photograph by Master Sergeants M. M. Friedman and C. M. Fetterman, Lowry Air Force Base, U.S. Air Force.

youngest gravelly and sandy alluvium that fills to a depth of about 6 feet an arroyo cut into (2). Hunt believed (1) to be late Pleistocene in age, (2) to be pre-Christian era in age, and (3) to be early historic in age. If the oldest alluvium, laid down after the new course of East Creek had cut down about 200 feet, is of late Pleistocene age, the piracy must be older, possibly early or middle Pleistocene.

Glade and East Parks are mature surfaces at comparable altitudes and are just above and south of the principal folds and faults and the youthful canyons, some of which have been cut several hundred feet below this surface. Possibly these surfaces were formed at the time the higher pediments 600 to 800 feet above the present river were formed. The canyons southwest of the major folds and faults have gentle gradients, caused in part by temporary base leveling of many of the canyons on the hard Precambrian rocks. Alluvium was deposited in some of these canyons, including the upper parts of Monument and No Thoroughfare Canyons, the lower part of Ute Canyon, and the part of East Creek Canyon just described. This temporary base leveling and alluviation may have occurred at the time the lower pediments 300 to 400 feet above the present rivers were formed. If Hunt's dating of the older alluvium is correct, a late Pleistocene age for the lower surface is suggested.

The abrupt steepening of stream gradients along the major faults and folds could be explained either by renewed folding and faulting after the lower surface was formed or by the exhuming of previously formed structures by later erosion. It is not known how much of the major folding and faulting was post-Green River and pre-Pliocene and how much was Pliocene or latest Pliocene-earliest Pleistocene, but it seems unlikely that significant movement could have occurred after the lower level was formed, for competent beds, such as the Wingate Sandstone, are bent along the monoclines without significant breakage. The facts that hard Precambrian rocks are at or near the surface in the canyon bottoms just southwest of the major faults and folds, and softer sedimentary rocks are just to the northeast, could explain the steepened stream gradients across the structures by the more rapid erosion of the softer rocks.

CANYON CUTTING

After the two major stream piracies and the renewed uplift or uplifts of the Uncompahgre arch, rugged cliff-walled canyons were cut along the flanks of the arch. In the Grand Junction area, most of these canyons are within the interval about 1,700 feet above the Colorado or Gunnison River, but some are within an interval about 2,000 feet above these rivers. The most spectacular canyons are in and near Colorado National Monument (pl. 1). These canyons are in a youthful stage of development and are still being cut headward.

Inasmuch as most of these canyons are occupied only by small ephemeral streams having small drainage areas, the question might be asked as to how such large, deep canyons could have been cut by small streams that carry water only for short periods after heavy rains or rapid snow melts. The actual cutting seems to be largely the result of several other processes of erosion; the streams are involved mainly as sewers in which the products of other forms of erosion are carried to the Colorado River and thence to Lake Powell (earlier, Lake Meade, and the Gulf of California).

In the Grand Junction area, as in other parts of the Canyon Lands section of the Colorado Plateaus Province, the character of the canyon walls seems to be governed by several factors: the climate, which in turn is dependent upon the altitude; the character and hardness of the rocks; the presence or absence of joints; the relative positions of layers of hard and soft rocks; freezing and thawing; and the amount of sunshine the canyon walls receive. In the Grand Junction area, two principal types of canyons are affected by some or all these factors, but the canyons differ geologically and morphologically: (1) the generally U-shaped cliff-walled canyons in and adjacent to the Colorado National Monument, which are floored with Precambrian rocks or the Chinle Formation and whose steep to vertical walls are formed by the Wingate Sandstone, not the Navajo Sandstone, as indicated by Buss (1956, p. 20), and locally also by the overlying Kayenta Formation and Entrada Sandstone; and (2) the generally V-shaped canyons in the southeastern part of the area that are cut in or through the soft Morrison Formation beneath a dip slope capped by the more resistant Burro Canyon Formation and Dakota Sandstone.

The U-shaped cliff-walled canyons are in an arid to semiarid climate, where the annual precipitation ranges from less than 10 to a little more than 10 inches per year (p. 11). When first cut, the canyons are narrow gorges having steep gradients, but when the flat surface of the old erosion surface on the hard Precambrian rocks is reached in places of low dips, downcutting is arrested, the gradient is lessened, and the cliff walls tend to recede from the stream, leaving a cliff-walled almost flat-bottomed canyon. Recession of the cliffs of Wingate Sandstone is caused in part by undercutting of the soft underlying siltstone of the Chinle Formation by wind and locally by streams, which allows slabs of the overlying sandstone to fall, disintegrate, and be carried away as sand by the streams. The Wingate forms vertical or nearly vertical cliffs only where protected above by the more resistant lower sandstone lenses of the Kayenta Formation and where the Wingate faces in a direction toward the sun most of the year—generally southward, southeastward, or southwestward. The Entrada Sandstone forms a secondary line of lower cliffs above the bench of the Kayenta Formation around many of the canyons, but locally the Wingate, Kayenta, and Entrada form a single cliff on sun-facing exposures (fig. 10).

As pointed out by W. C. Bradley (1958) and some earlier workers, exfoliation of cliff faces along joints parallel to the cliffs but not related to regional structure or jointing may result from expansion of thin layers of rock after the sideward release of confining pressure from the weight of overlying rocks. Such a process may be effective but does not seem to have been the sole cause of the vertical-walled cliffs in or near the Grand Junction area because the sun-facing cliffs are vertical to nearly vertical, whereas many northward-facing cliffs bearing equal loads of rock are low-angled enough to hold talus and to be climbed (fig. 30). These facts suggest that other processes must be responsible, at least in part, for the nearly vertical sun-facing cliffs.

The summer sun heats the cliff faces until they are hot to the touch, but the cliffs cool rapidly at night. In the winter the southward-facing cliffs are likewise alternately heated and cooled, but the northward-facing cliffs receive little or no sun. This alternate heating and cooling, called insolation, has been held to cause alternate expansion and contraction of layers of rock parallel to the cliff faces that break off by exfoliation, but this process has been considered by others to be ineffective as a cause of rock weathering (Blackwelder, 1933, p. 111, 112). Heating and cooling of rocks in the laboratory reported thus far has been tried mainly on granite (Tarr, 1915; Griggs, 1936, p. 796), for which repeated dry heating and cooling had no effect until temperatures much higher than sun-heated surfaces were reached. Repeated wetting and drying of marble and other rocks seem to have been more effective in causing rock disintegration (Blackwelder, 1933, p. 103), and repeated cycles of heating and then cooling by a fine spray of water caused noticeable disintegration of granite within 10 days, including "cracks of the exfoliation type" (Griggs, 1936, p. 795). Summer thundershowers that fall upon sun-heated cliff faces in the Grand Junction area, therefore, may assist in the weathering process.

If incipient exfoliation cracks are formed by pressure release or possibly by insolation of moist cliff surfaces or other causes, repeated freezing and thawing may be chiefly responsible for prying loose thin slabs of rock to produce the nearly vertical, generally sun-facing cliffs. In the winter the sun-facing cliffs may be heated to temperatures well above freezing by day, then cooled to below freezing temperatures at night. Inasmuch as the rocks and the mesa surfaces dip northeastward, southward-facing cliffs generally receive less drainage than northward-facing canyon walls; however, even small amounts of water from melting snow above would be sufficient to allow this daily prying action by frost in cracks or in the outer wetted layers of porous sandstone. On the contrary, the generally northward-facing canyon walls are in deep shadow during much of the winter, and even though such slopes receive and hold more water, they remain frozen during long cold spells and usually do not undergo daily repetitions of freezing and thawing.

The generally northward-facing canyon walls receive much more runoff, retain snow and moisture for long periods, may remain frozen for long periods, undergo solution and chemical weathering, and generally weather into steep to gentle slopes that hold at least thin patches of talus. Some of the gentler slopes develop soil and hold sparse vegetation. Many of the northward-facing slopes are gentle, whereas the opposite walls of the same canyons generally are inaccessible vertical cliffs. The contrast between southeastward- and northwestward-facing canyon walls of Red Canyon is shown in figure 30, and the contrast is still greater in canyons having more nearly northward- and southward-facing walls.

Sideward recession of the cliffs in North and East Entrances of Monument Canyon left but a narrow wall separating two canyons. The wall was later breached in two places and a central pier known as Independence Monument (fig. 2) was left. This erosional remnant also will eventually disappear.

In some parts of the area, closely spaced groups of monoliths are separated by vertical joints along which weathering proceeded more rapidly. The Coke Ovens (fig. 7) and Pipe Organ (fig. 2) in Colorado National Monument were formed in this manner.

At higher altitudes, where precipitation is greater and the climate ranges from semiarid to subhumid, the effects of moisture, vegetation, and chemical weathering become predominant and all canyon walls tend to be less abrupt.

At the lower altitudes of the Grand Junction area, the siltstone and mudstone of the Morrison Formation weather rapidly into almost barren badlands, but at higher altitudes the weathered slopes are covered by brush and timber. Canyons in the southeastern part of the area, such as the lower parts of Ladder Creek, Bangs, North East Creek, and Gunnison River canyons have cut into or through the Morrison and Summerville Formations to form V-shaped canyons rimmed by nearly vertical cliffs of the Burro Canyon Formation and Dakota Sandstone, both of which are dominantly sandstone in this part of the area. The steep walls of these canyons are strewn with very large to small blocks of sandstone that have fallen from the cliffs above. Because these blocks are much more resistant to erosion than those of the Wingate and Entrada Sandstones, which disintegrate rapidly, they tend to protect the canyon walls from additional erosion.

MINOR STREAM PIRACIES

In addition to the piracies of the Colorado and Gunnison Rivers and of East Creek, several piracies of small ephemeral streams have taken place in and near the Grand Junction area, and the stage is set for others to take place in the future. Most of these piracies seem to have occurred in the eastern half of the area along streams that have breached the Burro Canyon Formation and Dakota Sandstone to form the caprock of the dip slope, and have then cut into the underlying Morrison Formation.

One such piracy has taken place at about the middle of sec. 33, T. 12 S., R. 100 W.; the details of this piracy are shown in the upper part of the left stereoscopic pair in figure 36. Note that the captured stream has cut down to a lower level than the next stream to the right, which ultimately will be captured also.

The trellis pattern of Bangs Canyon may have involved some minor piracies long ago, but no evidence for this was found. More likely this pattern has a structural control, which may be a northwestward-trending joint or group of joints. A careful search for a northwestward-trending fault was made both in the

FIGURE 30.—Red Canyon, Colorado National Monument. Looking northeast from Red Canyon Overlook. Canyon mouth frames Grand Junction; Battlement and Grand Mesas form left and right skylines. Note nearly vertical southeastward-facing cliff on left, more subdued northwestward-facing slopes on right.

field and on steroscopic pairs of aerial photos, but no displacement could be found.

East and North Entrances of Monument Canyon are now separated only by two low divides and, because East Entrance has a much larger drainage basin, it may eventually capture some of the drainage of North Entrance.

TERRACE DEPOSITS

Terrace deposits cap many of the bluffs along the Colorado River Valley in the Redlands northwest of the bridge carrying Colorado Highway 340, and also cap the part of Orchard Mesa generally north of Orchard Mesa Canal 2. The deposits include coarse gravel and small cobbles, but very few exposures are available from which to study the material. The contact between the terrace deposits and underlying bedrock is visible only in a few artificial cuts; elsewhere gravel from the deposits covers the contacts and much of the bedrock below. For this reason, and because they are unimportant as sources of water, the terrace deposits were considered "transparent," and only the underlying bedrock formations are shown on plate 1.

The deposits on the Redlands have been drained on several sides, hence contain little or no water. The more extensive terrace on Orchard Mesa is irrigated, and contains some return flow from irrigation. The water is too highly mineralized for most uses, and no shallow wells were observed.

Terrace gravel is shown on plate 1 only in sec. 6, T. 14 S., R. 99 W. This small patch was mapped because of its importance in deciphering the capture of East Creek; the gravel is described on page 74.

PEDIMENTS AND PEDIMENT DEPOSITS

The pediments cut on the Mancos Shale in and east of the northeastern part of the area, and the deposits they contain, were noted on page 73.

Much of the Redlands underlain by the Morrison and Summerville Formations is a pediment cut mainly on the Morrison but in part on younger formations. The surficial deposits are very thin in most places and absent entirely in many places, so the deposits were considered "transparent" and are not shown on plate 1. Parts of the pediment have a thin soil that is used for crops or orchards.

LANDSLIDE DEPOSITS

Landslide deposits occur in many places in the area, particularly in and below steep slopes underlain by the Morrison Formation, but only those large enough to cover extensive areas of older formations are shown in plate 1. Those shown in and west of Colorado National Monument are jumbled masses of the Morrison. Those in Ladder Canyon are made up largely of Precambrian and Triassic rock and include some talus from these units.

ALLUVIUM

Only the principal deposits of alluvium are shown on plate 1. Not shown are narrow strips of thin alluvium along some of the tributary streams and a veneer of soil over large areas in Glade and East Parks and the Grand Valley.

The patches of alluvium shown in the upper ends of Monument and No Thoroughfare Canyons and the lower part of Ute Canyon may be correlative in age with that in East Creek Canyon (p. 74, 75), where Hunt (1956b, p. 66) found three stages of alluvium which he believed ranged in age from late Pleistocene to early historic. Arroyos similar to the ones mentioned by Hunt are found in the alluvium of No Thoroughfare Canyon, but the alluvium in Monument and Ute Canyons has not been dissected as deeply.

ARCHAEOLOGY

Considerable evidence indicates that the Grand Junction area was inhabited by prehistoric people. Two sites in the area and one just outside the area have been explored and named, and several other known sites remain to be explored.

The Taylor site (Wormington and Lister, 1956, p. 35–64) is on the Alva Taylor Ranch in Unaweep Canyon, in the NW¼ sec. 1, T. 14 S., R. 100 W. The artifacts were found in alluvium in front of and beneath an overhanging ledge of the Wingate Sandstone. Six hearths, a core biface, knives, scrapers, drills, choppers, hammerstones, milling stones, handstones, bone awls, tubular bone beads, projectile points, animal bones, and charcoal were found. No pottery was found in the deposits, but sherds of more recent age used by Ute Indians were found nearby. The age of the alluvium is discussed on pages 74, 75.

The Alva site (Wormington and Lister, 1956, p. 69–77) is 2 miles southwest of the Taylor site in a tributary canyon on the west side of Unaweep Canyon, just southwest of the map border. Artifacts found 150 feet above the canyon bottom at the base of a cliff of Wingate Sandstone included projectile points, knives, drills, milling stones, handstones, petroglyphs, and bits of fur, hide, split fiber, and string, but no pottery.

The two Little Park Caves (Wormington and Lister, 1956, p. 119–122), excavated by Al Look, of Grand Junction, are near the head of No Thoroughfare Canyon at the base of a cliff of the Wingate Sandstone in the NE¼ sec. 29, T. 13 S., R. 101 W. Mr. Look obtained projectile points, knives, milling stones, manos, awls, part of a sandal, part of a coiled basket, reed matting, corn cobs, corn, acorns, and animal bones, but no pottery.

The three sites that have been explored and studied seem to belong to a variant of the Desert Culture named the Uncompahgre Complex that may date back to the first few millenia preceding the beginning of the Christian era (Wormington and Lister, 1956, p. 81).

Look (oral communication, Apr. 11, 1960) has found other caves and sites in the area that have not yet been excavated, including several other caves in No Thoroughfare Canyon in sec. 28, T. 13 S., R. 101 W., near the Little Park Caves; several caves in Ladder Canyon in sec. 36, T. 12 S., R. 101 W.; and several hearths, bits of charcoal, and scattered artifacts on top of the mesa in the eastern part of the same section.

Well-preserved petroglyphs have been found on a slab of Wingate Sandstone on the southeast side of No Thoroughfare Canyon in the SE¼NE¼ sec. 31, T. 1 S., R. 1 W. Ute P.M. (Pat H. Miller, Chief Park Naturalist, Colorado National Monument, written communication, Dec. 1961).

RECENTLY INHABITED CAVES

There are three adjacent large caves at the base of the cliff of Wingate Sandstone on the north wall of a canyon containing a tributary of Clarks Wash, in the northern part of sec. 27, T. 12 S., R. 102 W., along the main road about 3 miles west of Glade Park Post Office. The middle cave, which contains a small one-room frame house and other improvements, was occupied for about 40 years prior to 1958 by Mrs. Laura Hazel Miller (fig. 8), after which the aged lady moved to Grand Junction to live with her daughter. A large cave just to the west was used to store boxes, cartons, and household goods, and another large cave just to the east formerly was fenced to shelter domestic animals. Mrs. Miller lived alone most of this time, but had a dog for companionship the last few years she inhabited the cave.

Mr. Look (oral communication, Apr. 11, 1960) thinks it likely that these caves may have been inhabited by prehistoric people.

POSSIBLE FUTURE STREAM PIRACIES

After abandoning its course in the hard Precambrian rocks of Unaweep Canyon, the Colorado River once again has cut down about 15 feet into the hard Precambrian rocks at two places in Ruby Canyon, just east of the Utah State line (fig. 28*D*), and has cut into these rocks in Westwater Canyon, in Utah. The south side of the Gunnison River has also reached Precambrian rocks at the mouth of Dominguez Creek (fig. 28*D*). Thus, once again, downcutting by the two rivers is being retarded by hard rocks. In the future, when Ruby and Westwater Canyons have developed deep inner gorges in hard rocks similar to that of Unaweep Canyon, and the Book Cliffs and adjacent belt of Mancos Shale have retreated farther to the north, Ruby and Westwater Canyons may be abandoned through capture of the Colorado River by a subsequent tributary cutting around the northwestward-plunging Uncompahgre arch. Similarly, when a deep gorge in Precambrian rocks has been cut by the Gunnison, a tributary, such as Indian Creek or Kannah Creek, could cut headward to the east of the canyon and capture the Gunnison above the Canyon. Of course, other possible future events, such as renewed mountain building or pronounced climatic changes, could alter, hasten, or prevent such events.

GEOLOGIC STRUCTURE

GENERAL FEATURES

The principal geologic structures in or near the Grand Junction area are the Uncompahgre arch, a northwestward-plunging anticline whose axis is at the crest of the Uncompahgre Plateau and Piñon Mesa, a few miles to the southwest; and the Piceance Creek basin, a broad deep synclinal basin whose axis crosses the Colorado River at the town of Grand Valley. The Grand Junction area occupies a part of the northeastern flank of the Uncompahgre arch in which the rocks dip gently to the northeast.

The northeastern flank of the Uncompahgre arch is deformed by a series of major monoclines and faults generally parallel or nearly parallel to the northwestward-trending arch, and by some minor folds and faults that trend in various directions. These structural features have been given the names shown in plate 1 to assist in their identification and description. Some evidence of several successive periods of deformation was found, but many of the details are obscure.

Kelley (1955, p. 801) defined a monocline as "* * * a double bend involving a local steepening in otherwise less steeply inclined layers," and noted (p. 793) that monoclines are the principal structural features of the Colorado Plateau. Most of the features of monoclines listed by Kelley (p. 794, 795) as characteristic for the Colorado Plateau are characteristic also for the Grand Junction area, except the general form of asymmetrical monoclines as noted below.

The major monoclines in the Grand Junction area are asymmetrical, but some of the minor monoclines are symmetrical. The asymmetrical monoclines all have a sharp upper bend[12] (convex upward) whose axis can be mapped, and a gentle lower bend (concave upward) whose axis generally cannot be accurately placed. (See particularly Ladder Creek monocline, pl. 1 and fig. 36, and p. 87). Kelley (1955, p. 794) regarded this form as anomalous on the Plateau, where he reported most asymmetrical monoclines to have sharp lower bends and gentle upper bends.

For most of the symmetrical monoclines, such as the East Creek monocline, it was practicable to map only the middle axis along the greatest angle of dip, but for part of the symmetrical North East Creek monocline the upper, middle, and lower axes were mapped.

The monoclines in the Grand Junction area are considered the result of lateral compression from the southwest, or northeast.

All the faults in the Grand Junction area seem to be dip slips—no strike-slip displacements were observed. Most of the faults are vertical or nearly vertical normal faults, but in at least two places the Redlands fault is reverse (p. 87).

Two major structure systems in the mapped area appear to be related, each of which comprises several alternating monoclines and faults alined end to end and each of which has some closely associated structures. The first structure system includes, from northwest to southeast, the Flume Canyon fault, a short unnamed monocline, Kodels Canyon fault, Lizard Canyon monocline, and Redlands fault; the second includes the Ladder Creek monocline, Bangs Canyon fault, and East Creek monocline. The two systems are connected tangentially near the top of the Serpents Trail by the northward-plunging Ladder Creek monocline.

The two systems, which contain the greatest and most abrupt vertical displacements in the area, do not appear at first glance to be alined, but the perfect alinement of the central part of the Redlands fault with the northwestern part of the Bangs Canyon fault is probably more than coincidental. Elsewhere, the trends of the two systems deviate considerably.

The major structures are both concave and convex away from the Uncompahgre arch—two types of trends noted by Kelley (1955, p. 794) in other parts of the Colorado Plateau.

The principal structures have a profound effect on the artesian systems of the area. In general, the principal structures allow drainage of strata to the southwest and provide recharge facilities for aquifers to the northeast. (See p. 100.) For this reason the structures were "walked out" to determine whether the artesian aquifers are cut off from recharge at any point.

[12] Kelley (1955, p. 791, 792) has followed the usage of Busk (1929, p. 7) in terming the upper part of a monocline an anticlinal bend and the lower part a synclinal bend. I am opposed to such usage because there is a reversal in direction of dip in both anticlines and synclines, whereas in a monocline there is no change in direction but merely a double change in the amount of dip.

Only along part of the Bangs Canyon fault are the aquifers so cut off, and even here recharge may possibly take place downward along the fault.

METHODS OF REPRESENTING STRUCTURE

The geologic structure of the Grand Junction area may be visualized in several ways from plate 1, which shows the locations and directions of movement of the faults, the locations and types of folds, the relative dips on each side of monoclinal axes, and the attitude of the strata in many places by dip and strike symbols. The dips and strikes observed in the field are shown by a different symbol from those determined photogrammetrically using the Kelsh Plotter. For the latter, only dips of 10° or more are shown because of the greater chance of error in determining low dips, particularly those of from 1° to 5°. Although it was possible to read low dips directly on the tilting platten, the vertical ground control generally was not adequate to insure removing all unwanted tilt from the Kelsh plates; and this lack of control affected the accuracy of determining dips of low angle proportionately greater than for dips of high angle.

The structure is also depicted in plate 1 by structure contours drawn on the top of the Entrada Sandstone. This stratigraphic horizon was chosen: (1) because it is the most sharply defined contact in the area, viewed either on the ground or on aerial photographs, and (2) because the Entrada Sandstone is the most important artesian aquifer in the area, hence the depth to the top of the Entrada is of considerable interest to well drillers and well owners, and has been one of the principal questions directed to the Geological Survey. The solid-line contours depict the configuration of this stratum where it is covered by varying thicknesses of younger formations and hence is reachable by drilling; the dashed-line contours represent the inferred position of the stratum before it was removed by erosion.

In areas of solid-line contours the approximate depth to the Entrada Sandstone may be determined at any locality by subtracting the altitude indicated by the contour, or interpolated between adjacent contours, from the altitude of the surface of the ground. This procedure will be greatly facilitated in the future when large-scale topographic maps of the area become available, but at present (1962) the surface altitudes in most of the area must be determined by ground surveys or approximated by reading the small-scale Grand Junction topographic map prepared by the Army Map Service.

The accuracy of the structure contours varies with the accuracy in determining the altitudes of the many control points (not shown) and with the stratigraphic position of the control points. The contours are most accurate near water wells whose surface altitudes were determined by instrumental leveling and which have accurate well logs (see table 7), as in parts of the Redlands and Orchard Mesa and a small part of the Grand Valley. Contours could not be drawn for large areas of the Grand Valley that lack wells deep enough to reach the Entrada Sandstone or other recognizable formation contacts above the Entrada. The topographic maps of the Colorado National Monument and a part of the Gunnison River Valley were of considerable help in determining the altitudes of control points in these small areas. Elsewhere, altitudes of control points were determined photogrammetrically by placing the floating dot of the platten of the Kelsh plotter on some point of known altitude, such as a bench mark of the U.S. Coast and Geodetic Survey, and then in turn at many points on the geologic contacts used for control. Differences in scale readings between successive positions of the floating dot multiplied by a model constant gave the differences in altitude. Bench marks were available only in the small areas having topographic maps, along the Denver and Rio Grande Western Railroad in the Grand and Gunnison River Valleys, and along part of Colorado Highway 141 southwest from Whitewater. An attempt was made to extrapolate, as far as possible, from these bench marks, but the vertical control was not adequate to insure proper leveling of all models. The contours were therefore omitted entirely from the southwestern part of plate 1, including much of Glade Park, where the control was poor and the dips are nearly horizontal. The extreme flatness of Glade Park is well shown in figure 35. Contours also were omitted from an area about 3 miles southwest of Grand Junction for the reasons given under "Jacobs Ladder fault complex," page 89.

Contours based upon stratigraphic control points other than from well logs are most accurate along the line of outcrop of the top of the Entrada Sandstone. Elsewhere, the thickness of strata above or below this top was subtracted from or added to the altitudes of the control points, and variations in thickness of the formations in different parts of the area were taken into account. Control points were taken, in order of decreasing accuracy, on the top of the Entrada Sandstone, Wingate Sandstone, Morrison Formation, or Dakota Sandstone.

The structure contours are based mainly on equal spacing between control points of determined altitude, but partly on the observed or photogrammetrically determined dip and strike of the strata. The general strike is parallel to the contour lines, and the dip is at right angles to the contours in the direction toward the next contour of lower altitude. The tangent of the average angle of dip between any two successive contours may be determined by dividing the contour interval (200 feet) by the horizontal distance between the contours, in feet, using the scale on the map or any scale of 1:31,680 ratio. The angle is then obtained from a table of tangents or from the proper scale of a slide rule. For example, between two contours 3,850 feet apart, the tangent of the average angle of dip is about 0.052 and the average dip about 3°.

The structure contours are considered generally accurate to within less than half a contour interval (100 feet) and locally accurate to within less than a quarter contour interval (50 feet), although exceptions may be found in parts of the area when large-scale topographic maps become available.

Only one cross section is given on plate 1 as only small areas are shown on large-scale topographic maps.

DETAILS OF STRUCTURE

STRUCTURAL FEATURES IN NORTHERN PART OF COLORADO NATIONAL MONUMENT

In and northwest of the northern part of Colorado National Monument is a series of monoclines and associated faults. The principal deformation here was upward bending or movement on the south side of a sinuous line of connected monoclines and normal vertical faults.

The Flume Canyon fault, which extends northwestward beyond the western edge of the map, has a maximum throw, or displacement, of about 300 feet in Flume Canyon, but the throw decreases both northwestward and southeastward from this canyon. The fault dies out and merges with an unnamed short symmetrical monocline in the east side of Devils Canyon. In the next canyon to the east the monocline merges with the Kodels Canyon fault, which has a maximum throw of about 350 feet in the west side of Kodels Canyon (fig. 31). This fault begins to die out eastward in Fruita Canyon as a faulted monocline (fig. 32), east of which it merges with the sharp upper bend of the asymmetrical Lizard Canyon monocline (fig. 33), which becomes more symmetrical farther to the southeast. This structure in turn becomes the Redlands fault southeastward from East Entrance of Monument Canyon.

The Lizard Canyon monocline has two upper bends the higher of which is shown on plate 1 as the Fruita Canyon "monocline," although actually only one complete monocline is involved.

FIGURE 31.—Looking west along Kodels Canyon fault in Kodels Canyon, Colorado National Monument. In NW¼ sec. 31, T. 1 N., R. 2 W., Ute P.M. Wingate Sandstone is displaced its full thickness of about 350 feet.

FIGURE 32.—Eastern end of Kodels Canyon fault on west side of Fruita Canyon, Colorado National Monument. In NW¼ sec. 32, T. 1 N., R. 2 W., Ute P.M. No visible displacement except for considerable thinning of Wingate Sandstone. High cliff of Wingate Sandstone at left rests on slopes of Chinle Formation. Piñon- and juniper-covered slope near middle is Kayenta Formation resting on thinned Wingate Sandstone. Entrada Sandstone forms low cliffs on right.

FIGURE 33.—Lizard Canyon monocline. Looking southeastward across Lizard Canyon and North Entrance of Monument Canyon from point on Rim Rock Drive in NE¼ sec. 32, T. 1 N., R. 2 W., Ute P.M. Note sharp upper bend on right, gentle lower bend on left. Strata range from Chinle Formation in canyon on right to Burro Canyon Formation capping low hogback on left.

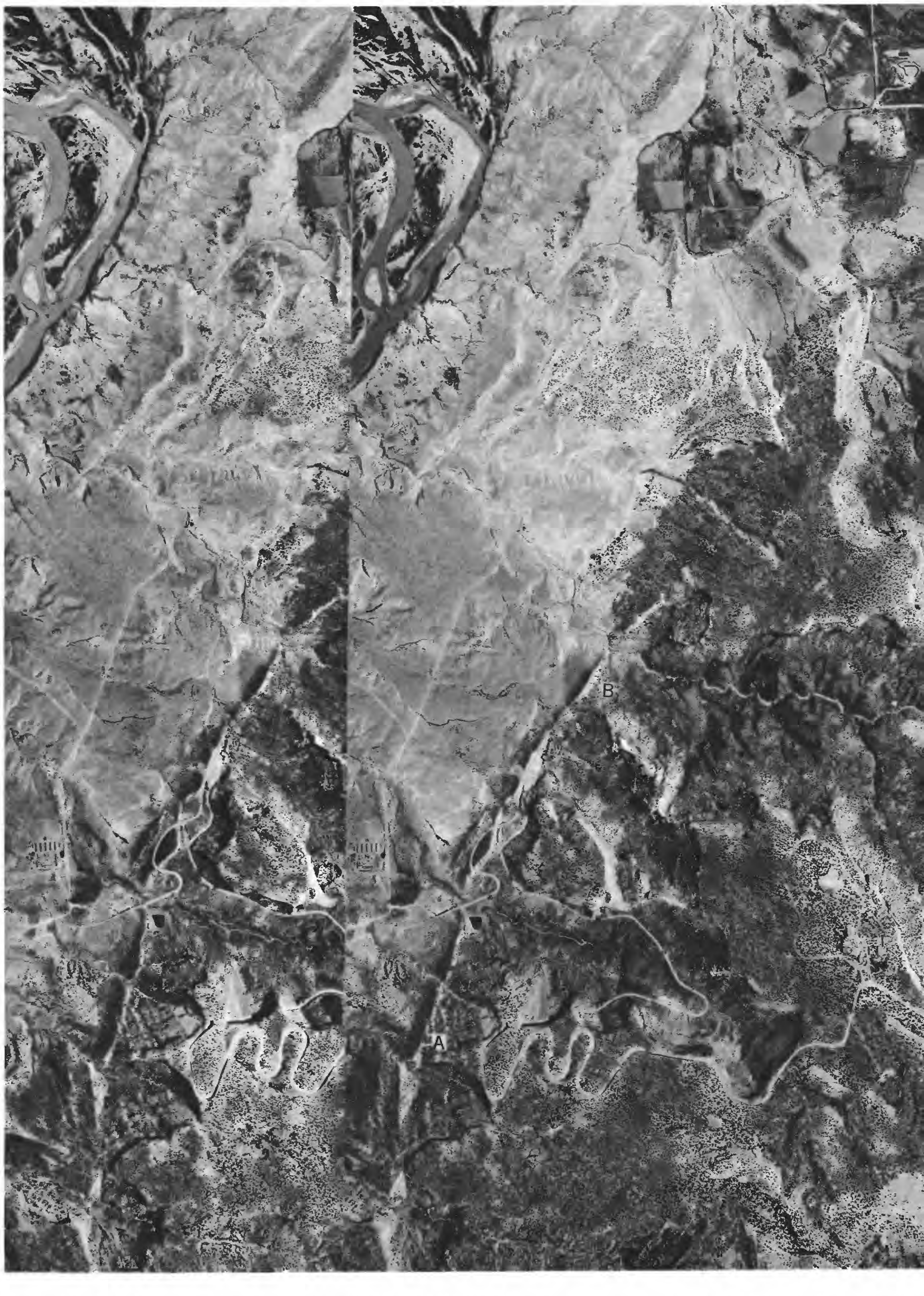
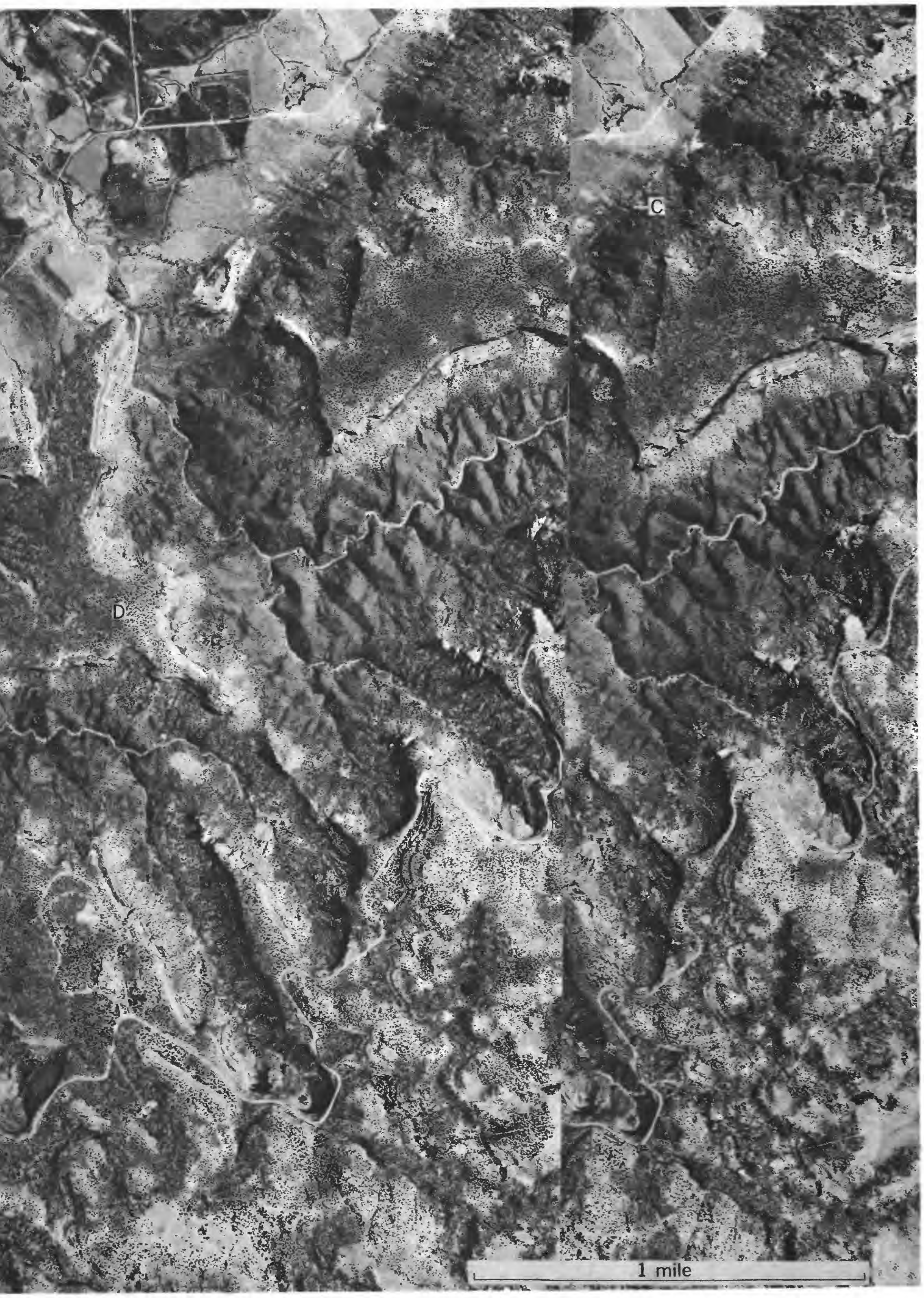


FIGURE 34.—Geologic structural features at north end of Colorado National Monument. Approximate scale 1:25,000. The three stereoscopic
may be identified by comparison with the appropriate part of plate 1, orienting map with north to the left. A, Kodels Canyon
Conservation Service.



wed in turn without optical aids by those accustomed to this procedure, or by use of a simple double-lens stereoscope. Geologic features
nd of Lizard Canyon monocline; C, Redlands fault; and D, upper bend of Fruita Canyon "monocline." Photographs by U.S. Soil

The Kodels Canyon fault, Lizard Canyon monocline, and eastern part of the Fruita Canyon "monocline" are well shown in the left two stereoscopic pairs of figure 34 (p. 84).

The Flume Creek monocline is a nearly symmetrical monocline that enters the area from the northwest. It extends farther southeastward than shown on plate 1, but could not be accurately placed farther than shown because much of the structure is obscured by a pediment

The symmetrical Devils Canyon monocline merges northwestward into a short normal fault that is tangential to the Flume Canyon fault. Southeastward it curves toward the Lizard Canyon monocline, then dies out. Possibly this monocline and short fault were formed later than the main structures, and their formation may have been accompanied by renewed deformation along the main structures.

Another minor monocline, part of which is visible near the top of the left stereoscopic pair in figure 34, closely follows the 4,000-foot contour along hogbacks of the Burro Canyon Formation and Dakota Sandstone. Its axis is difficult to place accurately and is not shown on plate 1.

REDLANDS FAULT

The Redlands fault is one of the principal structural features of the area and, together with the three main structures to the northwest, played a major role in setting the stage for the cutting of the spectacular deep canyons of the Colorado National Monument. The northwestern part of this fault is clearly shown in the right two stereoscopic pairs in figure 34, and the southeastern part is shown in figure 35. The fault has a maximum throw of about 700 or 800 feet in the SE¼ sec. 21, T. 11 S., R. 101 W., but dies out in scissors

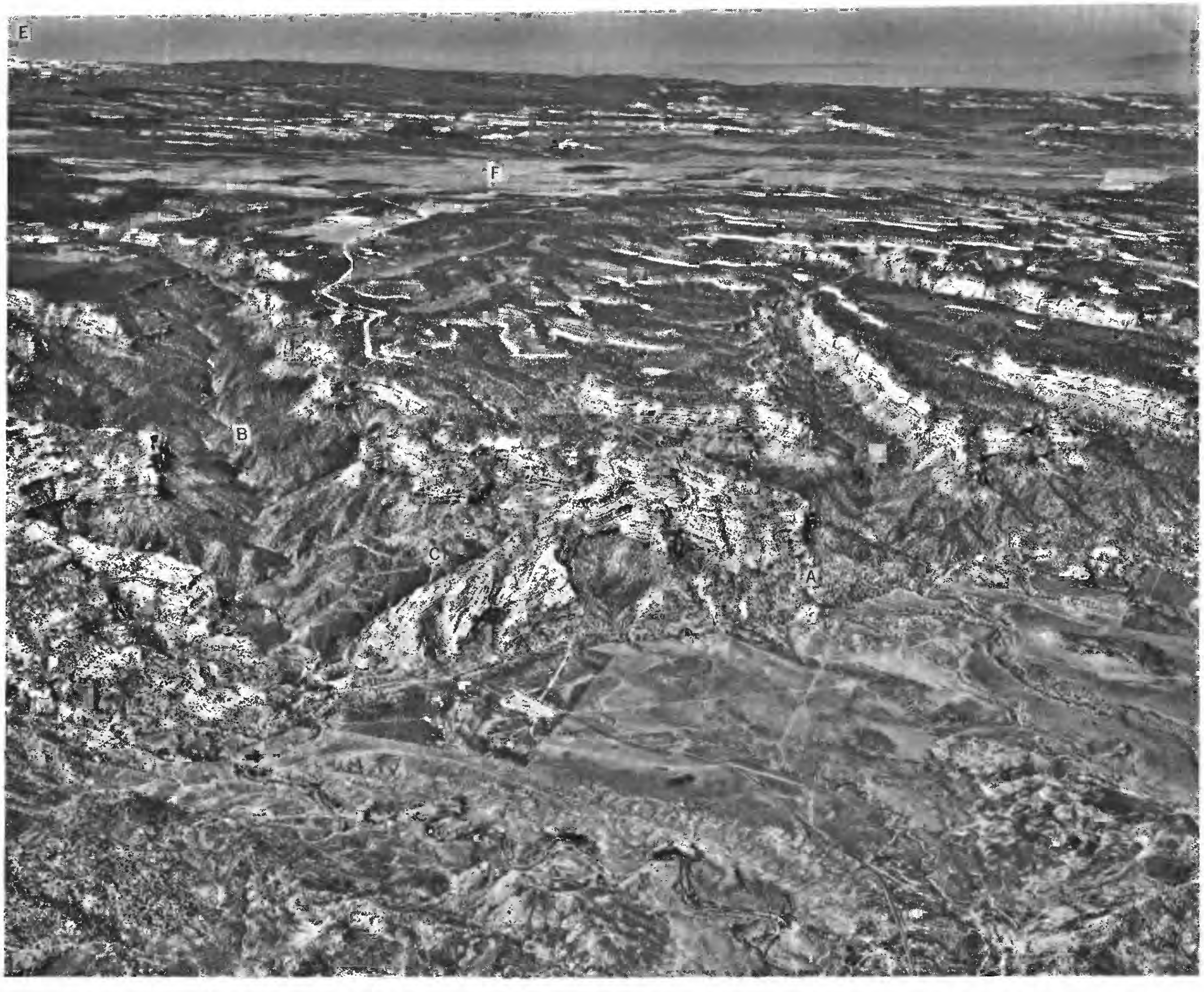


FIGURE 35.—Oblique aerial photograph of the southeastern part of Colorado National Monument, looking southwestward. A, Redlands fault; B, No Thoroughfare Canyon; C, old Serpents Trail; D, Red Canyon; E, Piñon Mesa; and F, Glade Park. Geologic features may be identified by comparison with appropriate part of plate 1. Scale variable. Photograph by Master Sergeants M. M. Friedman and C. M. Fetterman, Lowry Air Force Base, U.S. Air Force.

fashion at each end. It is a vertical or nearly vertical normal fault throughout its 6-mile length, except at and near the mouth of Gold Star Canyon and at the mouth of a small canyon in the SE¼SW¼ sec. 30, T. 1 S., R. 1 W., Ute P.M., where it is a reverse fault that dips about 45 degrees to the southwest. Along the cross section shown in plate 1, the dip is about 60 degrees to the southwest, as the fault plane gradually becomes steeper northwest of Gold Star Canyon. The fault originally may have been normal throughout, but during some period of renewed deformation, compressive forces from the southwest or northeast may have rotated the fault from the vertical to its present inclined position, in the manner suggested by Kelley (1955, p. 798). The strata on the downthrown side of the Redlands fault have been dragged upward steeply (figs. 34, 35), and as a result, the Chinle, Wingate, Kayenta, and Entrada Formations (pl. 1) were squeezed considerably thinner. One or more vertical faults may lie roughly parallel to and northeast of the Redlands fault, including the parts having reverse dip, but none could be positively identified and mapped.

In many places adjacent to the Redlands fault the updragged strata are vertical, but they have relatively low dips a short distance to the northeast. If the Redlands fault is a sharply faulted monocline (though proof of such structure is lacking), the lower bend is much sharper than the now eroded upper bend—a condition not found in any of the known asymmetrical monoclines in the area (p. 80). It is here regarded simply as a fault with steeply updragged strata on the northeastern side.

LADDER CREEK MONOCLINE

The southeastern part of the asymmetrical Ladder Creek monocline has the sharpest upper bend of any monocline in the Grand Junction area. As shown in plate 1 and in the left stereoscopic pair in figure 36, the dip changes abruptly from about 3° on the southwest to 80° on the northeast, much like a bent hinge, though no displacement by faulting is visible. Southeastward the upper bend merges with a normal fault which dies out against the Bangs Canyon fault. Viewed from the north (fig. 37), the high escarpment formed along the sharp upper bend could be mistaken for a fault, but a view southeastward along strike from the side of the canyon on the right skyline reveals no displacement.

To the northwest, the upper bend of the Ladder Creek monocline becomes much more gentle, the strike swings gradually north, and the axis plunges northward. If the strike of the beds as shown by the contours, but not necessarily all the dip, represents the strike produced by an early period of deformation, the northern part of the Ladder Creek monocline may be the result of later renewed deformation, and later additional bending may have occurred in the southeastern part of this structure.

BANGS CANYON FAULT

The short Bangs Canyon fault has a throw of about 1,000 feet—the greatest of any fault in the Grand Junction area. The northeastern half of the fault is shown in the right stereoscopic pair of figure 36. The fault drag on both sides of the fault suggests that the structure may be a faulted monocline, although the drag could have resulted from faulting alone. Erosion along the fault has produced a fault valley transverse to the principal drainage, which is occupied by subsequent tributaries and low intertributary divides. The fault seems to be normal and nearly vertical, although its angle cannot be observed.

Northwestward the Bangs Canyon fault disappears beneath landslide debris in Ladder Creek Canyon and dies out. To the southeast it merges with the symmetrical East Creek monocline. Between the southeastern end of the fault and the northwestern curving end of the North East Creek monocline is a triangular synclinal block cut off on the southeast by a short cross fault. The apparent updrag on the upthrown side of this part of the Bangs Canyon fault is anomalous and not explainable by me.

EAST CREEK MONOCLINE

The East Creek monocline is the longest uninterrupted fold in the mapped area. It is a symmetrical monocline that has only small vertical displacement in the northwestern part but considerable displacement where it crosses East Creek Canyon and parallels Cactus Park. Northwest of East Creek it is generally parallel to the regional strike, but southeast of East Creek, from where it begins to plunge southeastward, it deviates 25°–30° from the regional strike and is crossed by several structure contours. This deviation suggests that the southeastern part of the fold probably is younger than the principal uplift of the Uncompahgre arch and that it may be younger than the northwestern part of the fold.

The East Creek monocline has been mistaken for a fault by some who viewed it only on aerial photographs, but no faulting is evident when it is followed on foot.

The lower bend of the East Creek monocline is visible in figure 29 in the high bluffs just beyond Cactus Park.

NORTH EAST CREEK MONOCLINE AND CACTUS PARK FAULT

The North East Creek monocline splits off from the Bangs Canyon fault at a rather high angle, then swings around to become more nearly parallel to parts of the East Creek monocline. The upper, middle, and lower axes are mapped in one area; elsewhere only the middle axis can be followed readily. It crosses or is crossed by a small normal fault on the west side of North East

FIGURE 36.—Ladder Creek monocline and Bangs Canyon fault. A, upper bend of Ladder Creek monocline; B, small fault terminating monocline; C, Bangs Canyon fault; D, piracy of small ephemeral stream. Scale about 1:30,000. For suggestions on stereoscopic viewing, see figure 34. Photographs by U.S. Soil Conservation Service.

FIGURE 37.—Ladder Creek monocline. Looking southeast from point in SE¼ sec. 30, T. 12 S., R. 100 W. Col in left skyline is formed by Bangs Canyon fault. Note updrag of beds on left (or downthrown) side of fault and downdrag on right (or upthrown) side.

Creek Canyon and may be later or earlier than the fault, for exposures are poor at the crossing and the throw of the fault is small.

The East Creek monocline merges southeastward into the Cactus Park fault. The vertical, normal character of this fault is clearly visible where it crosses Colorado Highway 141. Here the fault lies between the Entrada Sandstone to the north and the Wingate Sandstone to the south. The Cactus Park fault may be continuous with the Deer Run monocline and associated fault, but in the intervening area the strata either are poorly exposed or covered by alluvium.

DEER RUN MONOCLINE

The symmetrical Deer Run monocline, which merges southeastward into a normal vertical fault, is nearly parallel to the East Creek monocline. Like the East Creek, the Deer Run monocline plunges southeastward and deviates 25°–30° from the regional dip; this deviation suggests a later origin than the principal uplift of the Uncompahgre arch.

GLADE PARK AND LADDER CREEK FAULTS

The Glade Park and Ladder Creek faults are so nearly alined as to suggest that they might be continuous. However, they die out toward each other and, in the intervening area, no evidence of displacement could be observed in the field or on aerial photographs.

The Glade Park fault and the western part of the Ladder Creek fault, which appear to be normal, are the only principal faults in the area having the downthrown side on the south. However, the throw is small—probably less than 25 feet. Despite their small throw, the two faults produce zones of weakness that allowed more rapid erosion of canyons tributary to No Thoroughfare and Ladder Creek Canyons.

The Ladder Creek fault is rotational east of the Ladder Creek monocline, where the direction of throw is reversed, and the rocks are downthrown on the south side. Here, also, the Ladder Creek fault either curves abruptly toward the southeast (as shown on pl. 1) or is joined by another fault. A small area between this and another small fault has been dragged upward and forms a small syncline.

The ages of the Glade Park and Ladder Creek faults relative to the principal structures of the area are not known.

JACOBS LADDER FAULT COMPLEX

The Jacobs Ladder fault complex is an area of complex but minor faulting and some minor folding, about 3 miles southwest of Grand Junction. On plate 1 the structure contours are omitted for this small area for it is not certain whether the structures extend deep enough to reach and include the Entrada Sandstone. The visible part of the structures involve the competent Burro Canyon Formation and Dakota Sandstone and the upper part of the incompetent Morrison Formation, and they may have resulted from crumpling and breaking of the brittle beds by one of the later or latest periods of deformation. This mode of origin is suggested in part by the small throw of the faults and in part by the haphazard trends of the structures at various angles to the major structural features of the area.

The faults and folds in this complex were difficult to map for several reasons, and I am not certain that they are correctly portrayed. Some of the mudstone and siltstone beds in the Burro Canyon Formation closely resemble similar beds in the Morrison Formation; moreover, fault slices of either or both are strewn with blocks of sandstone to the extent that parts of the area are a jumbled mixture. I have attempted to show the principal structures and lineaments, but others could be added.

It is perhaps significant and more than coincidental that the Jacobs Ladder fault complex occupies the focal point of the outwardly concave Ladder Creek monocline, but their relation, if any, is not known.

UNAWEEP ANTICLINE

The Unaweep anticline, which is traceable for 2 miles, is the longest observed in the area and is, in fact, the only anticline observed except for a short one in the southeastern end of the Jacobs Ladder fault complex. The Unaweep anticline has a barely perceptible reversal in direction of dip and plunges gently to the northwest; thus the 4,200-foot structure contour crosses its axis as shown in plate 1.

Although the axis of the Unaweep anticline is parallel to the regional dip, its gentleness suggests that it may have formed in a late period of deformation and that possibly it is associated with the Jacobs Ladder fault complex.

JOINTS

Considering the repeated periods of deformation that have affected the Grand Junction area, the competent rocks, with few exceptions, are remarkably free of regular joint systems or patterns such as are common in many other parts of the Colorado Plateau. Certain formations contain more joints than others, so the joints will be considered by separate formations or by groups.

The hard crystalline rocks of the Precambrian complex (fig. 27) and the hard well-cemented beds in the Kayenta, Summerville, Morrison, Burro Canyon, and Dakota Formations are cut irregularly by joints, most of which are vertical, but no regular patterns or systems of joints are readily apparent. Vertical joints in the sandstone and conglomerate of the Burro Canyon Formation and Dakota Sandstone allow large blocks of rock to fall into the canyons, particularly in the eastern part of the area.

The Wingate Sandstone contains vertical joints in many places, but many cliff faces of the Wingate contain few joints (fig. 10) except for those parallel to cliff faces (p. 76, 77). In parts of the Colorado National Monument, however, notably in Monument Canyon, the Wingate is cut by local systems of vertical joints which are clearly visible from the air or on aerial photographs and which have allowed the formation of several of the named erosion features. One local system of northward-trending vertical joints connects the Squaw Fingers and the Coke Ovens (fig. 7) and the intervening ridge, but does not extend to ridges to the north or south. Another longer set of northwestward-trending vertical joints, which connects the Kissing Couple and Pipe Organ and cuts the three intervening ridges, is clearly shown at the middle of the right stereoscopic pair of figure 34. Most of these joints disappear northwest of the Pipe Organ but one or more joints extend far enough northwestward to separate Sentinel Spire from the main cliff.

The pronounced linearity of Red Canyon (figs. 30, 35) and the two long arms of Ute Canyon probably is due to jointing.

A notable feature of the Entrada Sandstone, particularly the Slick Rock Member, is the almost total absence of joints for long distances along cliff faces (figs. 12, 13). The reason for the general absence of joints from the Entrada and their presence in strata both above and below is puzzling.

SUMMARY OF TECTONIC EVENTS

The rocks in and near the Grand Junction area reveal the results of several periods of deformation extending over much of geologic time. The various times of uplift and deformation have been discussed and documented at intervals in pages 20–76, but inasmuch as this information is scattered throughout many pages it seems appropriate at this point to summarize these events briefly, particularly the principal tectonic events and their bearing on the geologic structure of the area.

The recorded tectonic history of the area began well back in Precambrian time, when deeply buried sediments and possibly also associated igneous rocks were metamorphosed by intense heat and pressure into schists and gneisses. Later in the Precambrian these rocks were intruded by granite, pegmatite, and locally by other rock types. The now vertical or nearly vertical position of the once horizontal or gently inclined structures in these old rocks indicates the intensity of deformation.

The late Precambrian and early Paleozoic events probably included several periods of uplift and erosion alternating with periods of subsidence and deposition. From Early Pennsylvanian to Late Pennsylvanian or Permian time the Uncompahgre-San Luis geanticline or highland was uplifted and subjected to erosion until Late Triassic time, when the Chinle, Wingate, and Kayenta Formations were deposited.

A period of erosion and probable uplift in Jurassic time is recorded by the erosional unconformity at the base of the Entrada Sandstone. Deposition, with minor interruptions, again became dominant until about the end of Early Cretaceous time, when minor uplift and erosion occurred. The area subsided beneath the sea in Late Cretaceous time but rose above sea level before the end of the Cretaceous and was uplifted still higher near the close of the Cretaceous. The first uplift of the Uncompahgre arch and possibly some of the folds and faults may have begun at this time or slightly later. The broad form of the plunging arch developed at this time and gave a general northeastward dip to the sedimentary rocks of the Grand Junction area.

The Uncompahgre arch doubtless received renewed uplift and deformation in post-Green River time because the Wasatch and Green River Formations in the Piceance Creek basin to the north were deformed.

There is evidence of epeirogenic uplift and tilting of the Colorado Plateau during late Miocene to middle Pliocene time and of renewed differential uplift of the Uncompahgre arch in Pliocene time, again in late Pliocene or early Pleistocene time, and perhaps still later.

Evidence ranges from scanty to lacking as to the relative amount and degree of deformation that occurred in the area in Late Cretaceous, post-Green River, late Tertiary, or late Pliocene and early Pleistocene times, but some speculations seem warranted.

The total structural displacement of the Uncompahgre arch between the summit of Piñon Mesa and Grand Junction is about 5,000 feet. If 1,600 to 1,900 feet of this displacement took place in late Pliocene or early Pleistocene time, after the abandonment of Unaweep Canyon about 3,100–3,400 feet of the total displacement must have occurred as the result of the several earlier periods of deformation. Much of this may have occurred during the deformation in post-Green River time.

GROUND WATER

GENERAL PRINCIPLES OF OCCURRENCE AND MOVEMENT

No one report or small group of reports covers adequately the occurrence and movement of ground water, but as a starter the interested reader is referred to Meinzer (1923a, b), Tolman (1937), Jacob (1950), and Todd (1959). This report will discuss the occurrence and movement of ground water in the Grand Junction area, mainly the artesian water, and brief mention will be made of such fundamentals as are necessary for a basic understanding of the subject.

The rocks of the earth's crust generally contain many open spaces that may be saturated with ground water, or underground water, as it is called by some. In the sedimentary rocks of the Grand Junction area such openings are the voids or interstices between grains of sand in the sandstones and between grains of sand or pebbles in the alluvium of the stream valleys. The porosity of a rock is the ratio of the volume of the interstices to the total volume of the rock; it is expressed as a percentage or decimal fraction. In the sandstone aquifers, or water-bearing formations, of the area, the porosity has been reduced by deposition of cementing material, generally calcite, but locally has been increased by jointing or faulting.

The "permeability" of a rock may be defined as its capacity for transmitting fluid under head, and is measured by the rate at which the rock will transmit a given fluid, such as water, through a given cross sectional area under a given difference of head per unit of distance. The "coefficient of permeability" [13] used by the Geological Survey may be expressed as the number of gallons of water a day, at 60°F, that is conducted laterally through each square foot of water-bearing material (measured at right angles to the direction of flow), under a hydraulic gradient of 1 foot per foot. It has the inconsistent units of gallons per day per square foot (gpd per sq ft). (See table 4.) For analyzing field tests involving flow through the entire thickness of aquifers, it is generally more convenient to use the coefficient of transmissibility of Theis (1935, p. 520), which he expressed as "***T=coefficient of transmissibility of aquifer, in gallons a day, through each 1-foot strip extending the height of the aquifer, under a unit gradient—this is the average coefficient of permeability (Meinzer) multiplied by the thickness of the aquifer." It is expressed in the inconsistent units gallons per day per foot (gpd per ft). Both definitions are based upon Darcy's Law, which states that the rate of movement of water through porous media is proportional to the hydraulic gradient:

$$q=-k\frac{dh}{dl}$$

in which q=velocity of movement; k=constant of proportionality, which is the hydraulic conductivity; and $\frac{dh}{dl}$=hydraulic gradient, expressed as a change in head (dh) over a given change in flow length (dl).

Ground water occurs either as unconfined water or as confined, or artesian, water. Because aquifers have greatly differing storage properties in the two modes of occurrence (and in intermediate types), the two modes of occurrence will be taken up separately.

[13] The coefficient of permeability, P, used by the Geological Survey has the fundamental dimensions of a velocity, $[l/t]$, hence should more properly be called an "hydraulic conductivity" in that it depends upon the permeability of the medium to only one fluid—relatively pure water at a stated or implied temperature. A true unit of permeability has the dimensions of area $[l^2]$, and is independent of the type of fluid flowing through the medium unless the fluid and medium interact chemically. Hence, the true permeability of a porous medium, generally called the intrinsic permeability, is independent of such fluid properties as viscosity or density (Todd, 1959, p. 51).

UNCONFINED GROUND WATER

Unconfined ground water occurs in aquifers that are not separated from the atmosphere by strata of lower permeability (fig. 38). Actually, few aquifers are wholly unconfined, for in sedimentary rocks the permeability parallel to the bedding planes generally is much greater than at right angles to these planes, and this reduced vertical permeability provides varying degrees of confinement.

When a well is sunk into an unconfined aquifer, the water level in the well remains, for a time, at the same altitude at which it was first found in drilling, but of course this level may fluctuate later in response to many factors. This level is one point on the water table, which may be defined as that "surface", within the zone of saturation, at which the pressure is everywhere atmospheric (see Hubbert, 1940, p. 897). As shown in figure 38, the zone of saturation extends somewhat above the water table, and includes the zone of complete capillary saturation (Terzaghi, 1942, p. 347) or the capillary stage (Versluys, 1917). The thickness of this zone depends upon the grain size of the material, and for grains of uniform size is greater for fine-grained material than for coarse-grained material. The two zones above the zone of complete capillary saturation are only partly saturated, hence are said to be in the zone of aeration. The pressure in the several zones with respect to atmospheric pressure is shown in the left-hand column of figure 38.

Pumping a well in an unconfined aquifer causes actual unwatering of the material within an inverted, roughly cone shaped volume, called the cone of depression, by simple gravity drainage toward the low point at the well. The area of the top of this cone is called the area of influence. When pumping ceases, the cone gradually refills with water. The ratio of the volume of water that thus drains by gravity from the volume of the cone of depression in an unconfined aquifer to the latter volume is called the specific yield, and is generally expressed as a percentage or decimal fraction. Not all the water is drained from such material by gravity, for a part is held by molecular attraction of the rock particles. Thus the specific yield is equal to the porosity minus the specific retention—the latter representing the amount held or retained by molecular attraction. In most unconfined aquifers, the specific yield ranges from about 10 to about 30 percent, or 0.1 to 0.3.

Note in figure 38 that observation wells A and B penetrate a reduced thickness of saturated material but are still partly submerged. Well C is too shallow to reach the saturated material while the pumped well is in operation; it has been literally dried up.

In the Grand Junction area, unconfined aquifers generally yield but little water or water of poor quality, or both; hence very little time in the field was devoted to unconfined aquifers, and no wells tapping them are included in table 7. Unconfined aquifers in the area include the alluvium along the Colorado and Gunnison Rivers and larger tributaries (pl. 1); the terrace deposits

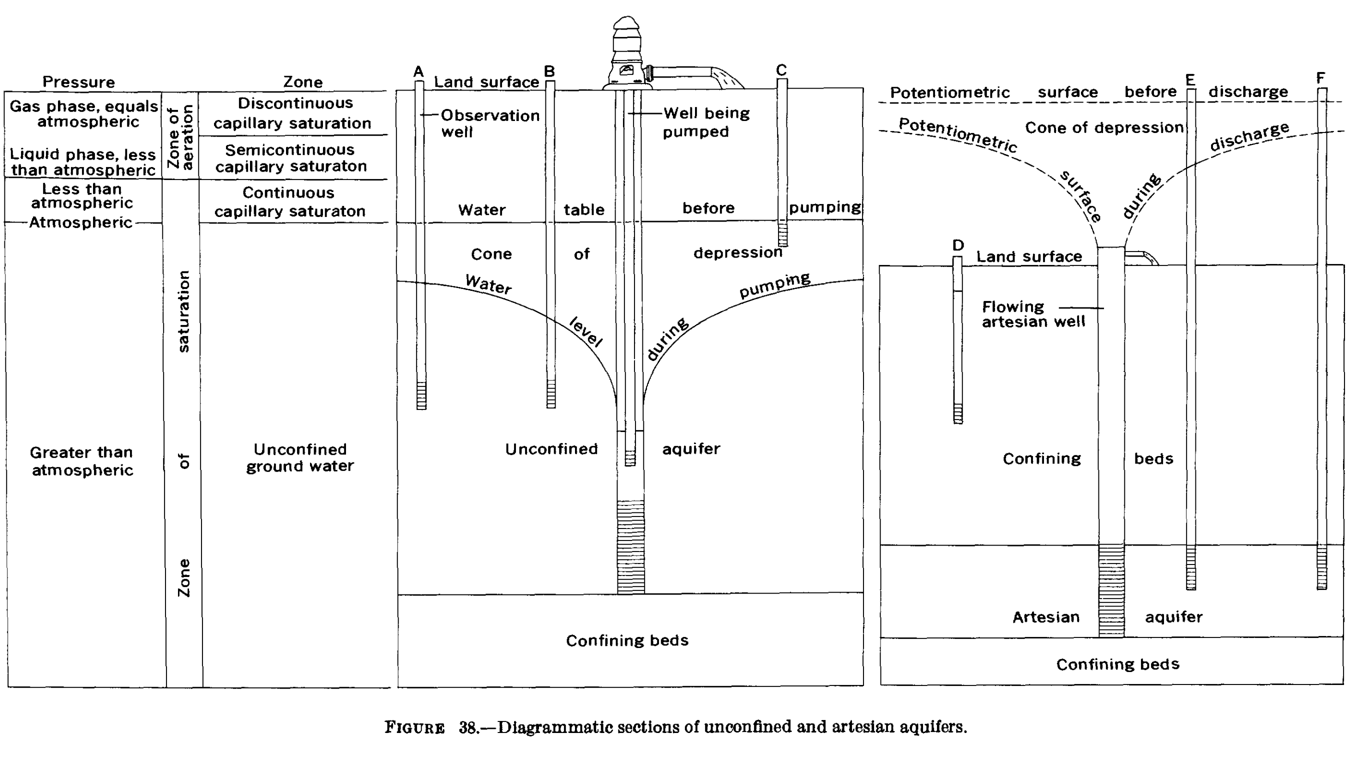


FIGURE 38.—Diagrammatic sections of unconfined and artesian aquifers.

on Orchard Mesa that have been saturated by return flows from irrigation; soil and weathered rock in the Grand Valley, Redlands, and Glade Park; and deposits that fill arroyos in parts of the Grand Valley.

Where thick, the alluvium along the principal streams probably would yield considerable water to properly constructed wells, but the water probably would be too hard for domestic or public supplies. It would be suitable chemically for irrigation, but irrigation water from the rivers is abundantly available at lower cost.

Most of the Grand Valley is almost devoid of shallow ground water, and such meager supplies as are obtainable locally from soil, weathered rock, arroyo fill, or from the terrace deposits on Orchard Mesa, are too highly mineralized for most ordinary uses. The materials have been saturated by irrigation water and return flows from irrigation—waters that have picked up large quantities of dissolved mineral matter from the weathered marine Mancos Shale (p. 67).

Shallow unconfined ground water may be available locally in irrigated parts of the Redlands, but it too would be of poor quality for similar reasons, though probably not as highly mineralized as the waters that have leached the Mancos Shale.

The weathered and locally soil-covered Entrada Sandstone forms the surface of much of Glade Park and yields small supplies of unconfined ground water of reported good quality to a few ranch wells in localities removed from the canyons of the Colorado National Monument. The strata in Glade Park are nearly flat lying, but dip to the northeast just enough that near these canyons all or nearly all water has drained out of the strata. At points more distant from the canyons, at least the lower part of the Entrada contains sufficient water to supply small domestic or stock needs.

A well in the NE¼NE¼ sec. 31, T. 12 S., R. 101 W. in Glade Park is reported to be 350 feet deep and has a reported water level 270 feet below land surface. The water in this well, which is reported to be of good quality, probably comes from the Wingate Sandstone.

CONFINED, OR ARTESIAN, GROUND WATER

Confined, or artesian, water is ground water that is confined beneath a relatively impermeable or less permeable stratum and that rises above the point at which it is first found in wells. Inasmuch as no rock stratum is regarded as wholly impermeable, confining beds vary in permeability and hence in their ability to confine artesian aquifers. (See p. 46.)

As shown in figure 38, there is no unwatering by gravity drainage of an artesian aquifer in the vicinity of a discharging well, such as occurs in an unconfined aquifer, if the water level during discharge remains above the top of the aquifer. Thus, observation wells E and F and the flowing well penetrate a fully saturated aquifer during discharge of the flowing well. Well D taps a higher aquifer and therefore is unaffected by the discharging well in the lower aquifer if the confining beds are of negligible permeability.

The "potentiometric surface" is an imaginary surface above the aquifer, and in figure 38 is also above the land surface, to which water from an artesian aquifer would rise in a pipe. The term "potentiometric surface" means head- or potential-indicating surface, and is used in this report instead of the term "piezometric surface." If this surface is above the top of the aquifer, the latter is an artesian aquifer and a well tapping the aquifer is an artesian well. If the potentiometric surface is above the land surface, a well tapping the artesian aquifer is a flowing artesian well.

Note that discharge of the well by natural flow has produced a cone of depression in the potentiometric surface similar in shape to the cone of depression in the water table of the unconfined aquifer. The rate of growth and areal extent of the two types of cones of depression are quite different, however, as will be explained under "Interference between Wells," page 110.

Although ground water is stored in the natural openings in an artesian aquifer, as in an unconfined aquifer, the release of water from artesian storage is accomplished in a manner entirely different from the gravity drainage or unwatering of an unconfined aquifer, and an artesian aquifer remains saturated while releasing stored water.

For example, consider a sandstone artesian aquifer overlain by 500 feet of confining beds composed of shale and sandstone and having an average density of about 2.4—a condition common to part of the Grand Junction area. Then the top of the aquifer supports a load of rock of about 520 lb per sq in. A part of this load is supported by the sandstone aquifer and a part by the water, which is under artesian pressure and hence is pushing upward and downward against the confining beds. When the artesian pressure is reduced, as in the vicinity of a discharging artesian well, the ability of the aquifer to support the load of rock is reduced by an amount proportional to the reduction in artesian pressure; as a result, the aquifer is compressed a little and some water which is thereby released or forced out of artesian storage moves toward and out of the well. Simultaneously, reduction in artesian head allows the water to expand slightly and thus releases additional water from storage.

The compressibility and elasticity of artesian aquifers was first recognized by Meinzer and Hard (1925, p. 90–93) and the theory was developed qualitatively by Meinzer (1928). The first quantitative determinations of the amount of water released from storage in artesian aquifers were made possible as a result of the formulation by Theis (1935), through analogy with the mathematical theory of heat conduction, of an equation for the nonsteady-state flow of ground water through permeable media to a discharging well, which is

$$s=\frac{Q}{4\pi T}\int_{\frac{r^2S}{4Tt}}^{\infty}\left(\frac{e^{-u}}{u}\right)du \qquad (2)$$

in which s is the drawdown in water level at distance r from a well discharging at constant rate Q from an extensive homogeneous and isotropic aquifer having a coefficient of transmissibility T and a coefficient of storage S, after a period of discharge t. The coefficient of storage S, which is a dimensionless constant, was defined by Theis (1938, p. 894) as "* * * the volume of water, measured in cubic feet, released from storage in each column of the aquifer having a base 1 foot square and a height equal to the thickness of the aquifer, when the water table or other piezometric surface is lowered 1 foot." The coefficient of storage is proportional to the thickness of the aquifer, and for most artesian aquifers ranges from about 10^{-6} to about 10^{-3}—much less than the specific yield of unconfined aquifers. Thus, if in the Entrada Sandstone in the Grand Junction area, which has an average coefficient of storage of about 5×10^{-5}, the head is lowered 150 feet in an area of 1 square mile (about 27.9 million square feet), about 210,000 cubic feet or about 1.57 million gallons of water is released from artesian storage by compression of the aquifer and expansion of the water.

The amount of compression in cemented sandstones, such as the principal artesian aquifers in the Grand Junction area, is small compared to the amount of plastic deformation in unconsolidated aquifers that contain appreciable amounts of clay and is probably an elastic type of compression. A method for determining the compression of elastic artesian aquifers of this type has been published (Lohman, 1961b).

ARTESIAN AQUIFERS

CHARACTER

The four artesian aquifers in the Grand Junction area, which are all sandstones, are, in order of importance and productivity: (1) the Entrada Sandstone, (2) the Wingate Sandstone, (3) lenticular sandstone beds in the Salt Wash Member of the Morrison Formation and in some places in the Brushy Basin Member, and (4) the Dakota Sandstone and sandstone in the Burro Canyon Formation. The last two units are classed together because they are generally not readily separable in drillers' logs. The outcrop areas of these aquifers are shown on plate 1, and detailed descriptions of the lithologic character, distribution, thickness, and water supply of the aquifers are given in pages 17–79 Additional measured sections of the strata and drillers' logs of many of the wells are given at the end of this report.

DEPTHS TO AQUIFERS AND AREAS OF POTENTIAL DEVELOPMEN

The depths to artesian aquifers vary widely according to the aquifer being sought in drilling, the geologic structure, the location, and the surface altitude.

The four principal aquifers contain water under artesian pressure only in areas northeast of the principal faults and monoclines (pl. 1) where they are overlain by younger relatively impermeable strata that serve as confining beds. Southwest of these structures the up-faulted or up-folded strata have been largely drained by the many deep canyons. Within the area northeast of the principal faults and monoclines the outcrops of the Wingate and Entrada Sandstones are close together along the southwest border, and the two sandstones are continuous in the subsurface to the northeast; hence, both these aquifers are available to wells throughout the potentially productive area. The lenticular sandstone beds in the Salt Wash Member of the Morrison Formation crop out from half a mile to perhaps a mile farther to the northeast in the Redlands and at varying distances in the area southeast from the Redlands. The Dakota Sandstone and Burro Canyon Formation have a much smaller area for potential development of artesian water—the area covered by the Mancos Shale.

Within the area of potential development of artesian water, the approximate depth to the top of the Entrada Sandstone may be determined from the structure contours on plate 1, if the surface altitude of the well site is known, by the procedure explained on page 81. Because the strata dip northeastward, they lie progressively deeper toward the northeast. If sufficient water is not obtained in the Entrada after penetrating its full thickness, additional water may be obtained by drilling through the underlying Kayenta Formation, where present (p. 35), and into or preferably through the underlying Wingate Sandstone. The ranges in thickness of these strata, where known in the area, are given in the detailed formation descriptions.

According to my interpretation of formation tops in drillers' logs, the top of the Entrada has been reached at depths ranging from 188 to 1,555 feet, but mostly at 600 to 800 feet. Depths of more than 1,500 feet were reached in the two wells (1 and 5) farthest from the outcrop.

Although only 8 of the 48 wells obtain water wholly or in part from sandstone beds in the Morrison Formation, the occurrence of water in one or more of these beds was noted by drillers in 19 of the logs. Most of the water-bearing sandstone lenses are in the Salt Wash Member, but a few seem to be in the Brushy Basin Member. These lenses are at varying and unpredictable heights above the top of the Entrada Sandstone; moreover, they are discontinuous and hence are not found everywhere. Thus, the finding of water in sandstone lenses of the Morrison is a matter of chance, and generally has resulted in wells that were planned to reach the continuous Entrada Sandstone, but in which sufficient water to satisfy the owner was found at shallower depth in the Morrison.

Water in the Dakota Sandstone and Burro Canyon Formation generally is found at depths of less than 100 feet in or just northeast of the outcrop area (pl. 1), but the top of the Dakota was reached at depths of more than 700 feet in wells 1 and 5. The water generally is too poor in quality for ordinary uses (p. 63).

HYDROLOGIC PROPERTIES

FIELD FLOW TESTS

THEORY

To determine both the coefficients of transmissibility and storage from discharging-well tests by use of equation (2), (p. 94), or simplified approximate forms of this equation (Cooper and Jacob, 1946), it is customary and very advantageous, though not absolutely necessary, to measure water levels in one or more nearby observation wells. Methods of testing that require the simultaneous use of more than one well were not practicable in the Grand Junction area: (1) because of the high cost of drilling observation wells to the required depths (600–1,600 feet), (2) because most wells are too far apart, and (3) because the continuous demand for the water precluded the practicability of shutting in more than one well at a time. Moreover, the equations referred to apply to steady-state or nonsteady-state movement of ground water to wells of constant discharge rates and variable drawdowns, whereas, when a flowing artesian well is shut in long enough for the artesian head to become virtually static and then the well is allowed to flow, the nonsteady-state movement of water is under conditions of constant drawdown and variable discharge. For these flow conditions to a single flowing artesian well, equations were developed for an exact graphical solution for even very small periods (t) of flow (Jacob and Lohman, 1952, p. 560) and for simpler approximate graphical solutions which give equally accurate results for slightly longer periods of flow (Jacob and Lohman, 1952, p. 563, 566, 567). The equations for the approximate, or straight-line, solutions are

$$T=\frac{2.30}{4\pi d(s_w/Q)/d\log_{10}(t/r_w^2)} \tag{3}$$

and

$$S=2.25T(t/r_w^2)_0 \tag{4}$$

or

$$S=\frac{2.25T(t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/\Delta(s_w/Q)]} \tag{5}$$

in which T=coefficient of transmissibility (in consistent units), s_w=drawdown (constant), Q=flow rate (variable), t=time between beginning of flow and flow measurement, r_w=radius of part of well through aquifer, $(t/r_w^2)_0$ is taken at the point $(s_w/Q)=0$, and $\Delta(s_w/Q)$ is the change in s_w/Q for one log cycle of t/r_w^2. For the units of Q and T commonly used by the Geological Survey (p. 91), equations (3), (4), and (5) may be written

$$T=\frac{264}{\Delta(s_w/Q)} \tag{6}$$

$$S=2.1\times10^{-4}T(t/r_w^2)_0 \tag{7}$$

or

$$S=\frac{2.1\times10^{-4}T(t/r_w^2)}{\log_{10}^{-1}[(s_w/Q)/\Delta(s_w/Q)]} \tag{8}$$

in which T is in gallons per day per foot, s_w and r_w are in feet, t is in minutes, and Q is in gallons per minute. Using semilogarithmic paper, values of s_w/Q are plotted on the linear scale against corresponding values of t/r_w^2 on the logarithmic scale (fig. 45). The slope of the resulting straight line [$\Delta(s_w/Q)$ per log cycle of t/r_w^2] gives the value of T by use of equations 3 or 6. Extrapolation of the straight line to the point $s_w/Q=0$ gives the value of S by use of equations 4 or 7, or S may be determined for any point on the straight line, as within the data region, by use of equations 5 or 8.

Equations 3–8 are valid under the condition that

$$u=\frac{r_w^2S}{4Tt}\leq \text{about } 0.01$$

where u is the lower limit of integration in equation 2 and the r is changed to r_w. This condition is satisfied very early in flow tests of artesian wells, because r_w^2 and S are very small. In the wells tested in the Grand Junction area the maximum value of r_w is 0.42 ft for which r_w^2 is only 0.18 ft^2 (table 6). Using this value of r_w^2 and average values of the other terms, to solve the above equation for t, in minutes

$$t=\frac{(7.48\text{ gal. ft}^{-3})(0.18\text{ ft}^2)(5\times10^{-5})(1{,}440\text{ min day}^{-1})}{(4)(150\text{ gal day}^{-1}\text{ ft}^{-1})(0.01)}$$

$$=0.016\text{ min.}$$

Thus, for these or comparable values, equations 3–8 are valid for all discharge measurements after about 0.02 minute of discharge; the earliest discharge readings made in any of the flow tests were from 0.5 to 1 minute after discharge began.

As a check on the values of T obtained by flow tests using equations 3 or 6, recovery tests were made using an equation formulated by Theis (1935, p. 522)

$$T=\frac{2.30\ Q}{4\pi s}\log_{10} t/t' \qquad (9)$$

in which Q is the weighted average discharge, t is the time since discharge started, t' is the time since discharge stopped, and s is the residual drawdown in the gradually recovering water level. In units used by the Geological Survey, equation 9 may be written

$$T=\frac{264\ Q}{s}\log_{10} t/t'. \qquad (10)$$

Even though equations 9 and 10 are based upon nonsteady-state flow to wells of constant discharge, they may be used to determine T by the recovery in head of a shut-in artesian well that previously has been discharging at declining rates of natural flow. At sufficiently large relative values of t (small values of u), other things being equal, the ratios of discharge to drawdown (Q/s) of two wells—one having constant discharge, the other having constant drawdown—approach equality (Jacob and Lohman, 1952, p. 561, fig. 2). Equations 9 and 10 are solved graphically on semilogarithmic paper by plotting values of s on the linear scale against corresponding values of t/t' on the logarithmic scale, then determining Δs for one log cycle of t/t' (fig. 41), whence

$$T=\frac{264\ Q}{\Delta s}. \qquad (11)$$

FIELD PROCEDURES

Flow and recovery tests were made at 11 of the flowing artesian wells (table 6) and repeated measurements of shut-in artesian head were made at these and other wells during the period 1946–52.(table 7). Tests could not be made at the other wells during that period because of physical difficulties or lack of owners' permission. Similarly, it was found impracticable to remeasure heads or to make tests of wells drilled after 1952, all of which were equipped with pumps.

Static and recovering heads were measured using an ink-well mercury gage, which I designed and built for this purpose, construction details for which have been published. (See footnotes 1, 2, p. —). The detailed field procedures for running the flow and recovery tests have also been published (Jacob and Lohman, 1952, p. 564, 565). Typical setups for these tests are shown in figure 39. Only the lower section of the gage, which reads heads as high as 66.5 feet of water, is shown in figure 39*A*: the extension shown in figure 39*B* extends the range to 134 feet of water. Heads of more than

A

B

FIGURE 39.—Typical setups for flow and recovery tests on artesian wells. *A*, well 45, in Entrada and Wingate Sandstones; and *B*, well 29, in Entrada Sandstone. Lower section of gage is 5 feet high.

134 feet were read by adding a length of glass tubing to the top section and measuring the rise above 134 feet.

RESULTS

The results of the flow and recovery tests are given in table 6, and details of the wells tested are given in table 7. Typical graphical solutions of flow and recovery tests are shown in figures 40 and 41.

The effective well radius, r_w, was the most difficult quantity to evaluate accurately and, inasmuch as it appears as r_w^2 in the equations, a slight error in r_w has considerable effect upon the accuracy of S, but does not effect T. In the Grand Junction area, values of r_w were obtained by careful inspection of the drilling and casing records and, where possible, by questioning the drillers as to the size of bit used, the amount of bit wobble suspected, and the possibility of and probable amount of caving. Reasonably accurate values of r_w generally are more readily determined for open holes in

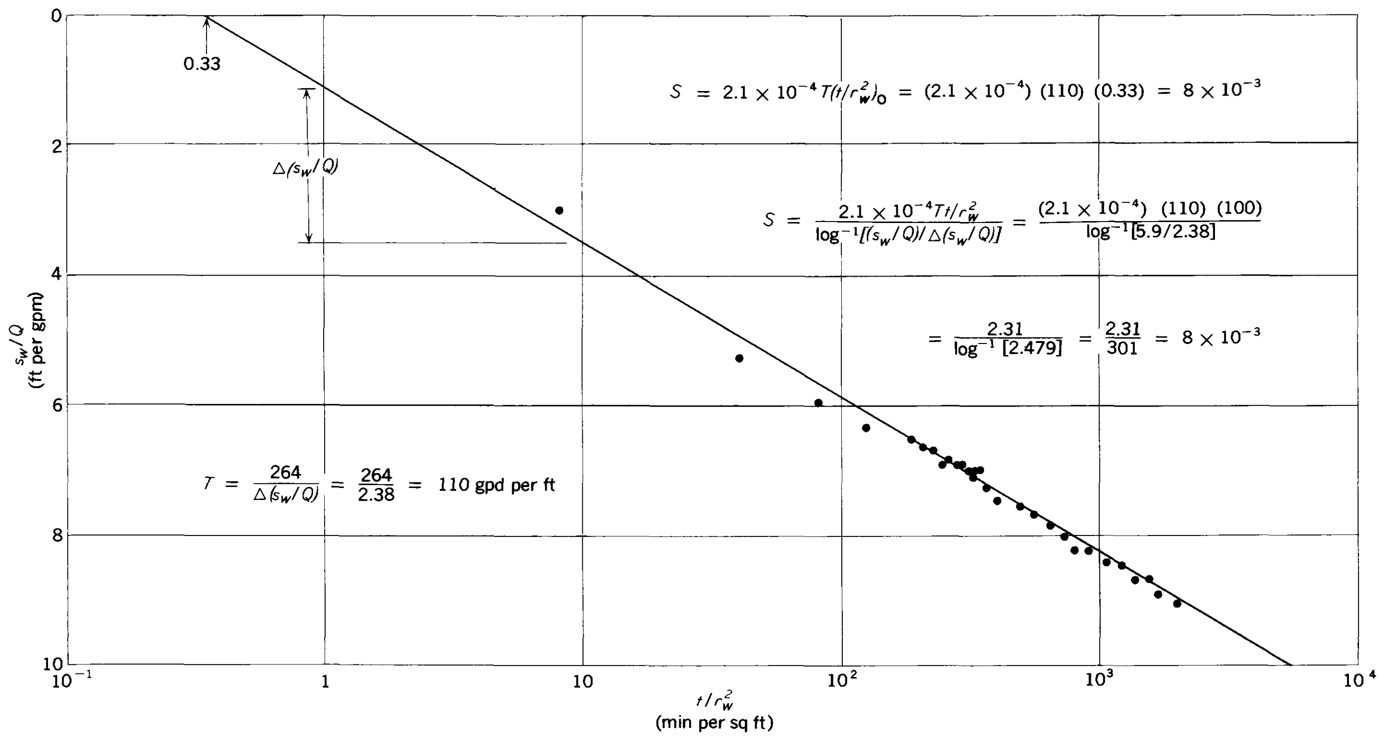


FIGURE 40.—Curve of s_w/Q versus $\log_{10} t/r_w^2$ for well 45 and solutions for T and S.

TABLE 6.—*Results of flow and recovery tests of artesian wells*

Well (pl. 1, table 7)	Geologic source	Open hole radius, r_w (feet)	Flow rate (gpm)		Duration of test (min)		Draw-down, s_w (feet)	Specific capacity at time t_1 (gpm per ft)	T(gpd per ft)		S (equation 8)	Percent penetration of aquifer	Remarks
			Start	End	Flow (t_1)	Recovery (t_2)			Flow method (equation 6)	Recovery method (equation 11)			
1	Entrada Formation	0.17	6.2	3.8	106	....	166.77	0.02	33	....	7×10^{-5}	100	Aquifer possibly partly plugged with drilling mud; recovery test not made.
5	do	.21	75	23.1	130	132	150.54	.15	120	110	(1)	100?	
16	do	.17	14.3	9.0	285	203	78.15	.12	240	230	5×10^{-6}	40±	Tested when depth was 865 feet; later deepened to 1,117 feet.
17	Morrison Formation	.25	.92	.47	236	120	70.76	.007	9.2	47	3×10^{-5}	100?	Poor test; head in three sand beds below land surface but head in main aquifer above land surface; well seal may leak.
23	Entrada Formation	.28	11.0	6.1	225	60	50.67	.12	150	150	5×10^{-5}	100	Recovery test stopped by thunderstorm.
24	Morrison Formation	.18	5.4	2.3	200	169	62.77	.04	36	35	4×10^{-4}	?	Do.
28	Entrada Formation	.28	7.3	4.9	114	82	92.33	.05	90	80	1.4×10^{-5}	50±	
29	do	.28	12.5	6.9	150	110	89.09	.08	120	125	8×10^{-5}	60±	
31	Entrada and Wingate Formations.	.42	41.2	23.4	260	310	118.82	.20	300	290	1.6×10^{-4}	100?	
33	Morrison and Entrada Formations.	.32	3.29	2.20	239	116	9.00	.22	490	320	6×10^{-6}	40±	Head in Morrison below land surface; head in Entrada above land surface.
45	Entrada and Wingate Formations.	.25	34.8	11.4	120	69	104.31	.11	110	110	8×10^{-3}	50±	

[1] Indeterminate.

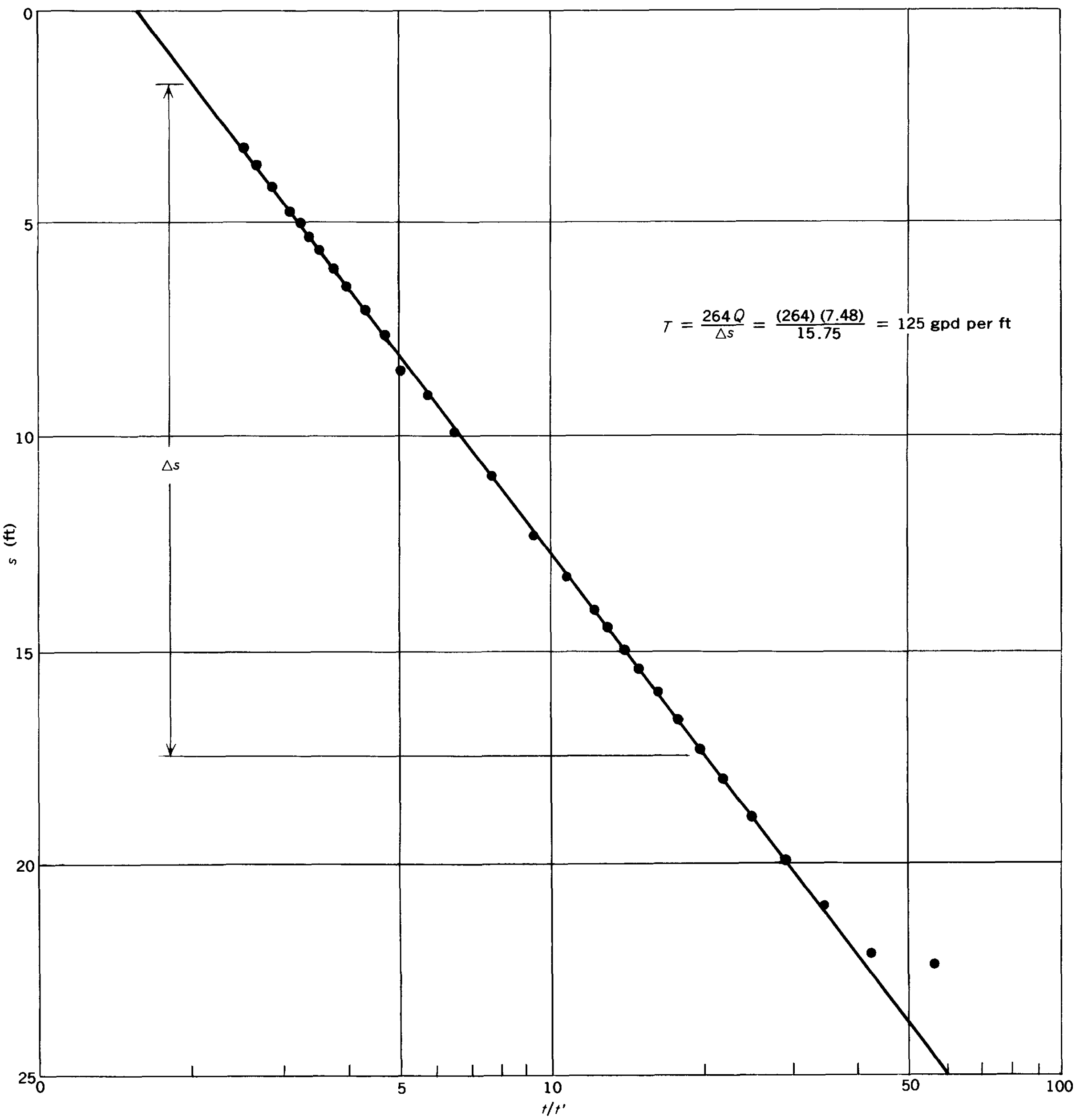


FIGURE 41.—Recovery curve of s versus $\log_{10} t/t'$ for well 29 and solution for T.

consolidated sandstone, such as those in the Grand Junction area, than for wells in unconsolidated material. Nevertheless, the considerable range in the values of S (table 6) suggests that some of the values of r_w may be in error, but this range is due in part to different percentages of penetration of the aquifers and to variations in the thicknesses of the aquifers. No reasonable value for S could be determined for well 5; the value of S for well 45 (fig. 45) seems too high, and values for wells 16 and 33 seem low.

For flowing artesian wells in which r_w cannot be determined, S cannot be determined either, but T can be determined by the following simplified forms of equations 3 and 6:

$$T = \frac{2.30}{4\pi s_w d(1/Q)/d \log_{10} t} \tag{12}$$

$$T = \frac{264}{s_w \Delta(1/Q)}. \tag{13}$$

The wide range in flow rates is the result of many factors, including the thickness, character, and permeability of the aquifer; construction of the well; amount of shut-in artesian head, which in turn is dependent in part upon the length of time the well was shut-in; and upon the relative heads in several aquifers that supply some wells. For these reasons the specific capacities of the wells (gallons per minute per foot of drawdown) are more meaningful indices of the actual capacities of the wells to produce water by either natural flow or pumping. In general, these are approximately proportional to the values of *T*.

Most of the wells were shut-in only from 13 to 15 hours prior to a flow test, for the owners generally would not release their wells from service for longer periods. Longer shut-in periods doubtless would have allowed some additional recovery in head (see Remarks column for well 28, table 7), but probably would not have affected appreciably the results of the tests.

The duration of the flow and recovery tests varied widely and, indeed, no prescribed uniform period was deemed necessary. The numerical example given above indicates that all discharge or recovering head measurements made after about 0.02 minute of discharge or recovery are valid; the duration of the test, therefore, need simply be long enough to obtain a straight-line plot. The discharges and recovering heads change rapidly at first, but at the end of from 1 to 4 hours they change so slowly that waits of 30 minutes or more may be needed to detect any measurable change. When such a condition is reached, the test may be stopped. Some tests were cut short by thunderstorms, by fluctuations in atmospheric pressure, or by the owners' need for the water, but generally sufficient data had been obtained from which to determine *S*. The short duration of the tests assists in avoiding the spread of the cone of depression to nearby boundaries in the aquifer, such as other flowing wells.

For tests involving observation wells hundreds of feet from a discharging well, however, many hours or days may be needed for artesian aquifers, and many days or weeks may be required for testing some unconfined aquifers.

The principal results of the tests are the values of *T* and *S* given in table 6. The values of *T* by the flow and recovery methods are considered to be in close agreement except for wells 17 and 33, and well 1 at which no recovery test was made.

In plotting the data from the flow test of well 17, it was found that the slope decreased abruptly after a discharge period of 18¾ minutes; this abrupt decrease suggested the possible presence of a nearby boundary, that is, that a new source of water entered the flow system and affected the discharge at that time. Computation of the distance to this supposed source boundary gave the surprising answer, 1.4 feet—virtually at the well. The character of this supposed boundary is not known, but possibly it is a well seal (driller's record indicates a steel compression seal) that leaks slightly when the head is above a certain height but closes when the head is reduced. If so, some water may have been escaping into higher strata during the first 18¾ minutes of discharge, at which time the seal closed and the rate of decline in discharge at the well head was reduced. Similarly, the recovery curve shows an abrupt decline in rate of recovery after about 21 minutes of recovery, which suggests that the leak was resumed at that time by the effect of the increased head on the well seal. The driller's log indicates several sandstone aquifers below the well seal at 571 feet, which are above the main aquifer and which have artesian heads below land surface. These aquifers could have received water through the well from the main aquifer, in which the head was 76 feet above the surface. All these factors may have contributed to the poor agreement between the average values of *T* determined by the two methods.

Inasmuch as the curves for flow and recovery tests for well 33 have no changes in slope, the discrepancy in *T* values by the two methods may result from the fact that this well also taps sandstone aquifers in the Morrison Formation having heads below land surface, whereas the principal aquifer, the Entrada Sandstone, had a head 9.9 feet above land surface. The value of *T* for well 1 (33 gpd per ft) seems much too small for the Entrada Sandstone, and may have resulted from plugging of the aquifer with drilling mud and the mud in the water. The upper 1,200 feet of this well was drilled by the cable-tool method, and the lower 439 feet was drilled by the hydraulic-rotary method, in which prepared drilling mud was used. During the flow test, considerable mud came up with the water—so much, in fact, that the greater density of the water and mud doubtless reduced the flow rate, and hence the value of *T*, appreciably. Because of the discharge of mud, the well was not again shut-in for a recovery test, in order to allow as much of the mud as possible to be discharged from the well.

Excluding the value of *T* for well 1, the average value of *T* for the other five wells in the Entrada Sandstone that were flow tested was 150 gpd per ft, and the logarithmic average of the values of *S* was 5×10^{-5}. This low value of *S* suggests that the porosity of the Entrada in the subsurface may be less than it is in outcrops (table 4) and that the effect of the expansion of water alone forms an appreciable part of the coefficient of storage.

Well 31 is the only well tested that completely penetrated both the Entrada and Wingate Sandstones, for which the *T* and *S* values of 300 gpd per ft and 1.6×10^{-4} seem to be of the right order of magnitude. If so, the Wingate, which is generally more than twice as thick as the Entrada, has about the same values of *T* and *S* and a permeability about half that of the

Entrada. This is suggested also by the laboratory determinations given in table 4.

LABORATORY DETERMINATIONS

The mineralogical composition and physical and hydrological properties of nine samples of the Entrada and Wingate Sandstones are given in table 4. The relations among sorting, porosity, permeability, and content of cement are discussed in the sections on these formations (p. 24, 25). Even though few samples were tested, the results are valuable in considerations of well construction and well performance.

The average permeabilities of outcrop samples parallel to bedding planes, 6.6 gpd per sq ft for the Entrada Sandstone and 1.6 gpd per sq ft for the Wingate Sandstone, are higher than the permeabilities of the beds in the subsurface as indicated by the flow and recovery tests, which suggest that they may be as low as about 1 gpd per sq ft for the Entrada and about 0.5 gpd per sq ft for the Wingate. Possibly some of the cementing material has been removed from the outcrop by solution, but probably the samples were not sufficiently representative of the entire formations and were insufficient in number.

The laboratory tests indicate that on the basis of a few samples, the Moab Member is more permeable than the Slick Rock Member, and the entire Entrada Sandstone is more permeable than the Wingate Sandstone. This observation is in accord with statements of drillers that the largest flows were in the upper part of the Entrada, even though the flow increased as wells were drilled deeper into the Entrada or into or through the Wingate. This situation is also in accord with some of the flow and recovery tests for wells in the Entrada Sandstone, in some of which higher T values were obtained for wells that penetrate only the upper part of the Entrada than in some that penetrated the entire formation. Most of the differences in T and specific capacity, however, probably resulted from local variations in permeability or conditions of the well faces.

The ratios of permeabilities parallel to the bedding and those normal to the bedding range from 1.25 to 35 and average 7.3. This range is to be expected in bedded sedimentary rocks, and demonstrates the desirability for wells to fully penetrate the aquifers for maximum yields of water. In wells that penetrate only part of an aquifer, water is obtained almost wholly from the part penetrated, because the water in the lower part is greatly hindered from moving upward to the well by the low vertical permeability.

RECHARGE

The areas in which the aquifers contain artesian water are discussed on page 94. Along the southwestern edges of these areas the sandstones crop out and receive water (recharge) from precipitation on the outcrops or from streams that cross the outcrops. Such outcrop areas are said to be recharge, or intake, areas, where water enters the aquifers and moves slowly down the dip of the strata beneath the overlying confining beds toward lower areas of natural discharge (p. 103 and fig. 44) or artificial discharge, as through wells.

Although some water may enter the outcrops of the aquifers directly from precipitation, the amount probably is very small. The outcrop areas have an arid to semiarid climate, and most of the scanty precipitation falls as rain in the summer, mostly during afternoon thundershowers. The bare sandstone outcrops generally are hot or warm before such thundershowers, and consequently much of the rain that falls upon them evaporates rather quickly, but a small part of the water from summer rains and a part from rain or snow in cooler seasons may seep in.

Most of the recharge probably takes place where the outcrops are crossed by streams. In parts of the Redlands the Dakota Sandstone and Burro Canyon Formation are overlain by irrigated land or crossed by irrigation canals and by drainage ditches, which carry return flows from irrigated areas. Such sources probably help recharge the sandstones in these formations but, except for the canals, such water is of an undesirable chemical character because of the content of dissolved minerals leached from the soil. Some of the sandstone beds in the Morrison Formation may be recharged from such sources in other parts of the Redlands, but most of the thicker lenticular sandstone beds in the Salt Wash Member crop out southwest of and higher than the irrigated areas, or along hills or ridges between irrigated areas.

The recharge areas for the Entrada and Wingate Sandstones, the two major artesian aquifers, are along their northeasternmost outcrops at or near the places where the solid-line structure contours on plate 1 become dashed lines. Along imaginary lines connecting these places, the outcrops of the Entrada and, a short distance to the south, the outcrops of the Wingate are crossed by many ephemeral streams and by two perennial streams—the Gunnison River and North East Creek. To the southwest, where the structure contours are dashed, the Entrada and generally also the Wingate have been partly or wholly removed by erosion.

Inasmuch as the Kayenta Formation is absent in the southeastern part of the area, the structure contours southeast of Bangs Canyon represent not only the top of the Entrada Sandstone but also the top of a single artesian aquifer comprising the Entrada and Wingate Sandstones. Excellent recharge facilities to this aquifer are provided where the outcrops are crossed by the

Gunnison River and covered by associated saturated alluvium. However, no wells deep enough to reach the Entrada are known in areas generally downdip from this point, as in the vicinity of Whitewater. Moreover, because of the gentle gradient of the Gunnison River, Whitewater is only about 100 feet below the recharge area nearly 5 miles to the south; consequently artesian wells drilled in the vicinity of Whitewater probably would not flow at the land surface because of the head loss between the two points.

The outcrops of the combined Entrada and Wingate Sandstones are crossed also by ephemeral East Creek at an altitude of about 5,800 feet and by perennial North East Creek at an altitude of about 6,800 feet. As shown on plate 1, these two recharge areas are, respectively, about 900 and 1,900 feet above outcrops along the Gunnison River just a few miles to the northeast; it seems likely that at least part of the water from one or both of these recharge areas may move toward the Gunnison River valley and be discharged from outcrops on the west side of the valley at points above the area where the Gunnison River recharges the same aquifer. The outcrops appeared dry when viewed from the accessible east side of the valley, but any discharge would soon drain most of the strata far back from the outcrop. However, a part of the recharge from East and North East Creeks may contribute to the aquifer in areas directly downdip (at right angles to the structure contours) and farther to the north or northwest. Recharge from these two streams, however, probably does not reach the vicinities of any of the artesian wells.

No recharge points to the Entrada and Wingate Sandstones are known within the mapped area between North East Creek and Ladder Creek, with the possible exception of a small outcrop area in the NE¼ sec. 16, T. 13 S., R. 100 W., along the Bangs Canyon fault, and along outcrops about 25 miles southwest.

If the plane of the Bangs Canyon fault is relatively impermeable, the fault would prevent recharge from the small outcrop area. If even slightly permeable, however, it might transmit small amounts of water downward to the aquifers on the north side of the fault, from the outcrop area and from small ephemeral streams that cross the fault.

The Entrada and Wingate Sandstones crop out northeast of the axis of the Uncompahgre arch along the north wall of Unaweep Canyon, about 25 miles southwest of the Bangs Canyon fault. The strata extend for some distance along the outcrops and dip only about 2° to the northeast, but some water may enter the outcrops from small tributaries of West Creek and reach the mapped area. Such water may be discharged at downstream low points, such as along East and North East Creeks, however, and may not reach the area of potential development in the Grand Junction area.

Plate 1 shows that the principal recharge points for that part of the Entrada and Wingate Sandstones and sandstone beds in the Morrison Formation that supply water to the wells are the northeasternmost outcrops of these aquifers crossed by Ladder Creek, No Thoroughfare Canyon, and the many small ephemeral streams between No Thoroughfare Canyon and the western border of the mapped area about 3½ miles southwest of Fruita. Although each of these streams contributes some recharge, the most important is No Thoroughfare Canyon, which has the largest drainage area and is most nearly updip from the area of greatest development by wells.

The recharge area of the Entrada Sandstone in No Thoroughfare Canyon is shown in figure 42, that for the Wingate Sandstone is a few hundred feet upstream, and that for the principal sandstone lenses in the Morrison Formation is about half a mile downstream. After a severe thundershower in the headwaters region, the stream may attain a depth of several feet for a few hours, then subside rapidly. The coarse alluvium, which may be about 20 feet thick, remains saturated for several days to a week or more after the surface runoff ceases, and thus provides a large volume of water resting on and against the aquifers. Because of the low permeability of the aquifers and the fact that the aquifers in the recharge areas are full of water, however, the rate of intake is very slow.

The Redlands fault was "walked out" in detail not only to map it and the upturned sediments on the northeast side, but to determine if the Entrada and Wingate Sandstones are cut off by the fault at any point and thus are deprived of possible recharge. In a few places the lower part of the Wingate is cut off by the fault, but elsewhere the Entrada and Wingate are continuous along the fault. The two sandstones are thinned by shearing, squeezing, and possible minor faulting, which have increased the porosity and permeability sufficiently that they can readily receive water from the many ephemeral streams that cross the outcrop. However, the amount of water taken in is limited by the low permeability of the rock below the sheared and broken outcrops.

The possibility that some variations in artesian head may have resulted from variations in recharge rates is discussed on page 113.

VELOCITY OF ARTESIAN WATER

Some well owners and drillers in the Grand Junction area have asked how fast the artesian water moves from the outcrop, or recharge, areas to the wells. The average velocity can be determined from known or

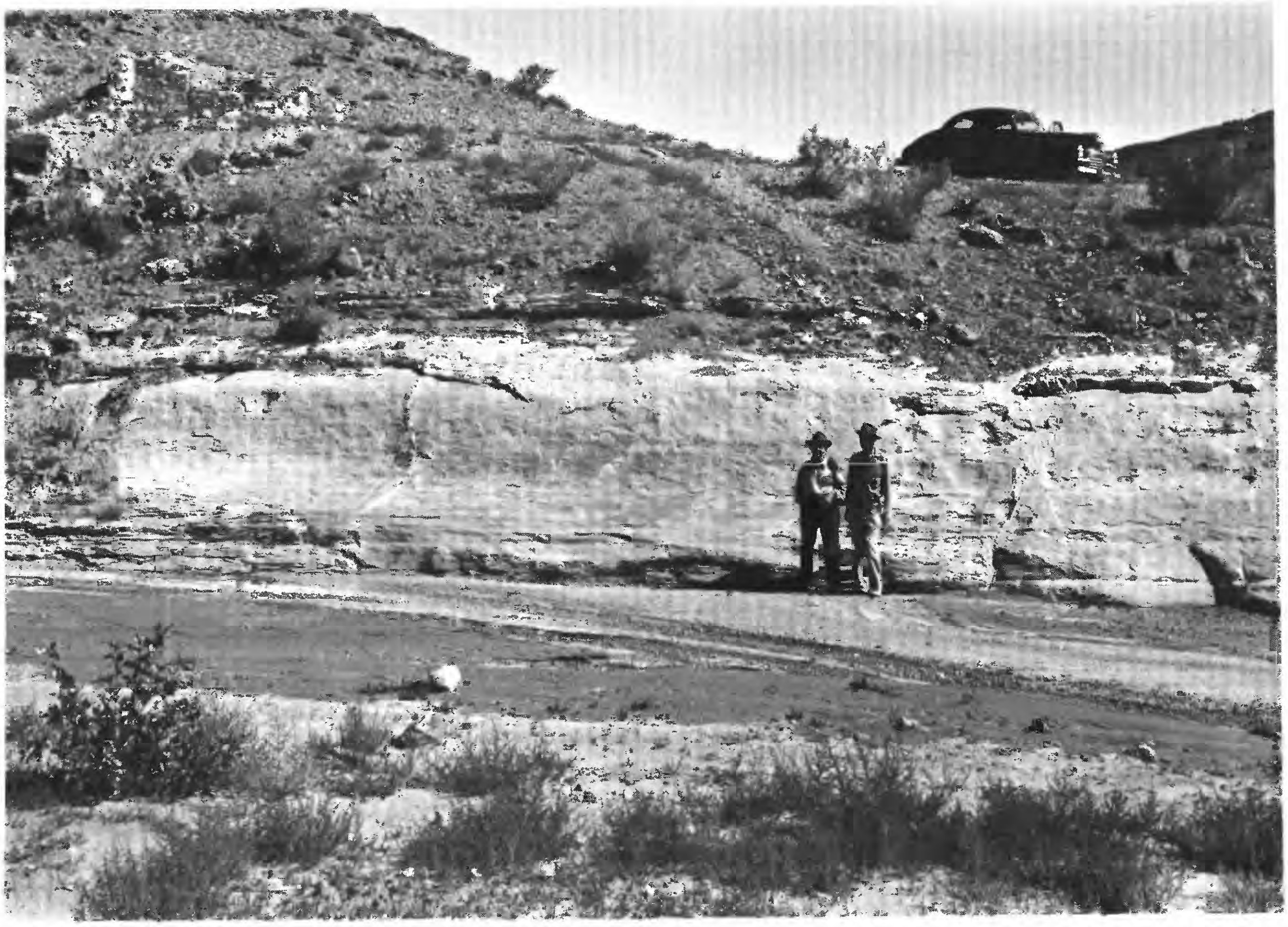


FIGURE 42.—Recharge area of Entrada Sandstone in No Thoroughfare Canyon. Looking north across meander of stream near large cottonwoods in NW¼ sec. 32, T. 1 S., R. 1 W., Ute P.M. Water in saturated alluvium, several days after flow in stream, is feeding water slowly into Entrada both downward and northward. Entrada dips 7° N.E., away from camera.

assumed factors, using the equation (Wenzel, 1942, p. 41):

$$v=\frac{PI}{7.48\ \theta} \tag{14}$$

in which v=velocity, in feet per day; P=coefficient of permeability, in gallons per day per square foot; I=hydraulic gradient, in feet per ft; 7.48=number of gallons in 1 cu ft; and θ=porosity, as a decimal fraction.

As an example, assume that all the water that reaches well 5 comes from the outcrop of the Entrada Sandstone at the mouth of No Thoroughfare Canyon, that there are no other wells, that the well is shut in, and that the head is 150 feet above land surface (as in 1947, table 7) or at an altitude of 4,765 feet. The outcrop mentioned has an altitude of about 5,100 feet and is about 6.2 miles or 32,800 feet from the well; the hydraulic gradient under these conditions would be (5,100−4,765)/32,800=about 0.01 ft per ft. The average coefficient of permeability of the Entrada Sandstone from the flow tests is about 1 gpd per sq ft, and the average porosity from laboratory tests of a few samples (Table 4) is 22 percent. However, as noted on page 100, the average permeability of the outcrop samples was greater than indicated by the flow tests, consequently the porosity of the aquifer in the subsurface probably is considerably less than at the outcrop, perhaps only about half as much, or about 10 percent. Using equation (14)

$$v=\frac{(1\ \text{gal day}^{-1}\ \text{ft}^{-2})(0.01)}{(7.48\ \text{gal ft}^{-3})(0.1)}=0.013\ \text{ft per day.}$$

This velocity, which is only about 5 feet per year, is the average velocity under the assumed conditions to a shut-in well; the velocity in more permeable parts of the aquifer might be several times as great, and that in less permeable parts might be a small fraction of this rate. The average velocity while the wells are discharging would be greater than this amount.

Under the assumed nondischarging conditions, therefore, about 6,500 years would be required for water following an average flow path in the Entrada Sandstone to move from the assumed recharge area to well 5, and about 3,000 years would be required for water to move to the large group of wells in the eastern part of the Redlands and the western part of Orchard Mesa. The oldest wells in the area have been discharging only about 50 to 60 years and the greater velocity under discharging conditions has not appreciably hastened the transit of the water.

The very slow average velocity of the water indicates that probably most of the water obtained from artesian wells in the area to date has come from artesian storage in the manner discussed on pages 93, 94.

NATURAL DISCHARGE

The water taken in by the artesian aquifers at the recharge areas described above moves very slowly downdip northeastward toward the axis of the Piceance Creek basin, where the Entrada Sandstone is estimated to lie more than a mile below sea level and where the other aquifers, if present, lie at comparable depths. Water also moves southwestward toward this axis from outcrops north of the Grand Hogback monocline. Not all the water moving toward the axis of this structural basin reaches the axis, however, or there could be no such movement. Even though the confining beds have very low permeabilities, the upper surfaces of the aquifers have areas of many thousands of square miles; in the aggregate a significant amount of water may thus escape upward to the surface. Any permeable fault planes or fault zones within this large area also would allow the escape of water. Over a long period of time the aggregate rate of such natural discharge by upward movement is equal to the aggregate rate of recharge, except for the trifling amount of water that has been discharged from wells.

Because the rate of such upward movement of water is so small and is distributed over such a large area, no surface evidence of escaping water, such as moist or wet rocks, was noted. The rate of upward movement seemingly is too small to saturate the overlying rocks, and such water as may reach the surface probably is in a gaseous state.

Inasmuch as the water discharged at the surface cannot be detected by ordinary means of measurement, as by discharge measurement of streams, such an artesian basin may be regarded for all practical purposes as a closed artesian basin that is not measurably contributory to the streams. It might be said, however, that streams are robbed of water by the recharge of the aquifers along tributaries that cross the outcrops of the aquifers, but the amounts of such losses also are too small to measure by ordinary stream-gaging procedures for they are probably less than the error of such measurements.

ARTESIAN WELLS

Artesian wells are defined technically on page 93; there now remain to be considered several practical aspects of such wells in the Grand Junction area.

721-906 O-65—10

TABLE 7.—*Records of artesian*

All wells were drilled by cable-tool method except wells 9, 24, 40, and 43, and lower
Well: Parentheses around number indicate that analysis of water is given in table 8.
Location: Location based on Ute principal meridian and base line are designated
Depth: All are reported depths.
Finish: O, open hole; P, perforated casing above open hole.
Geologic source: TRw, Wingate Sandstone; TRk, Kayenta Formation; Je, Entrada
and Burro Canyon Formation.
Discharge: F, natural flow; P, pumped; E, estimated; M, measured; R, reported.
Method of lift: F, natural flow; J, jet pump; N, none; ST, submersible turbine;
Use of water: D, domestic; H, hauled; I, industrial; N, none; P, swimming pool;
ceding H indicates number of 1,100-gallon tank trucks filled per day.
Water level: Measured water levels given in feet and tenths of feet, reported water
Remarks: H_2S=hydrogen sulfide gas; logs referred to are given in pages 130–142; aquifer tests

Well (pl. 1)	Location	Owner	Driller	Year drilled	Depth (feet)	Diameter (inches)	Depth of casing (feet)	Finish (method and feet)
	T. 1 N., R. 1 W.—U.							
(1)	SW¼SE¼ sec. 29	Appleton Pomona Elementary School.	H. L. Morgan and A. R. Chvilicek.	1949	1,639	12–4⅛	1,487	O, 152
	T. 1 N., R. 2 W.—U.							
2	NW¼NE¼ sec. 29	Mrs. Gladys Starks	D. S. Isaacs	1956	684	8⅝–6¼	519	P, 123 O, 165
3	NE¼NE¼ sec. 32	Keith Young	do	1955	655	8–6	114	O, 536
4	SW¼NW¼ sec. 33	D. E. and Thelma L. Isaacs	do	1957	500	14–8	200	O, 300
	T. 1 S., R. 1 E.—U.							
(5)	NW¼NW¼ sec. 18	Lloyd Files	Mesa Drilling Co	1946	1,615	8¼–5	1,264	P, 351
6	NE¼SW¼ sec. 29	C. M. and E. E. Chrismore	H. L. Morgan	1954	1,560	8–4½	1,400	O, 160
	T. 1 S., R. 1 W.—U.							
7	SW¼NW¼ sec. 5	Gobbo Brothers	J. D. Pinkerton	1955	1,215	8–5	1,130	O, 85
8	SW¼SW¼ sec. 7	B. A. Reed	D. S. Isaacs	1955	853	8–3	853	P, 80
9	SE¼SW¼ sec. 7	George Standifird	F. B. Dykes	1955	891	6–5½	891	P, 49
10	NW¼SE¼ sec. 10	W. R. Hall	J. B. Sloss Drilling Co.	1956	1,176	10¾–5½	1,115	O, 61
(11)	NW¼SW¼ sec. 15	Western Meat Packers	H. L. Morgan	1950	978	8–5	852	O, 126
(12)	NW¼SE¼ sec. 16	Mrs. John Vogel	do	1950	1,397	14–6	890	O, 507
13	SE¼SE¼ sec. 16	Melvin Seevers	D. S. Isaacs	1955	560	8–5	560	P, ?
14	SE¼SE¼ sec. 16	do	do	1955	61	8–6	61	P, 20
(15)	SE¼SE¼ sec. 16	O. L. Hermans	H. L. Morgan	1951	956	?–5¼		O, P
(16)	NE¼NE¼ sec. 21	J. Lewis Ford	Deepened by J. D. Pinkerton.	1940	1,117	?–4	865	P, 30 O, 235
(17)	SE¼NE¼ sec. 21	A. W. Meens	H. L. Morgan	1947	573	8¼–4	573	O, 102
18	SE¼NE¼ sec. 21	Mrs. Mattie Morton	D. S. Isaacs	1956	523	8–5	523	P, 53
(19)	NE¼SE¼ sec. 21	Frank Prinster, Jr	H. L. Morgan	1952	996	8–5¼	996	O, 262
(20)	NE¼NW¼ sec. 22	Austin Redd	Mesa Drilling Co. and Fred Sturm.	1947	925	8¼–6⅝	804	O, 121
(21)	SW¼NW¼ sec. 22	Mesa County Junior College		1938	927			
(22)	SE¼NW¼ sec. 22	Amos A. Bruner	Mesa Drilling Co	1947	810	?–6½	742	O, 68
(23)	NW¼ SW¼ sec. 22	Austin Redd	H. L. Morgan	1947	869	10–6⅝	680	O, 189
(24)	NW¼ SW¼ sec. 22	H. D. McCallum	Sturm and Billstrom	1946	665	4⅜	545	O, 120

wells in the Grand Junction area

part of well 1, which were drilled by hydraulic-rotary method.

by U.; other locations are based on 6th principal meridian and base line.

Sandstone; Jm, Morrison Formation (Salt Wash Member); Kdb, Dakota Sandstone

T, turbine. All pumps electrically operated.
S, stock. Number preceding D indicates number of houses connected; number pre-

levels given in feet.
referred to are given in table 6; geologic symbols are explained above in "Geologic source."

Geologic source	Discharge (gpm)	Date of measurement, estimate, or report	Method of lift	Use of water	Measuring point			Distance to water level above (+) or below (−) measuring point (feet)	Date of measurement or report	Remarks
					Description	Distance above (+) or below (−) land surface (feet)	Height above mean sea level (feet)			
Je	F 3.8 M F ½ E	7-19-50 4-18-60	F	D	Top collar on 12-in. casing.	0.0		+169.5	7-19-50	Water contains H_2S; see log and aquifer test.
Je, Jm	F 3 E P 50± R	4-18-60 4-18-60	F, ST	N				(+)		May later supply houses; water contains H_2S; see log.
R̄w, Je, Jm	F ½ E P 14± R	6-17-55 4-18-60	F, T	1D, 10H				(+)		Average discharge given; pump capacity for short periods 50 gpm; see log.
R̄w, Je	P 16 R	5-57	ST	D						Water level reported at surface; see log; well about 350 ft, to east is 762 ft deep and reached Entrada at 225 ft.
Je	F 21 R F 23 M P 16 R	6- 1-47 7- 8-47 4-14-60	F, ST	7D, 10H	Top lower part of bushing.	+1.5	4,615.7	+150.5 +115.0 +103.0 + 96.3	7- 8-47 9-22-48 7-26-49 7-21-50	Natural gas in Kdb at 730 ft; 3 gpm water in Jm at 1,218 ft; see log and aquifer test.
R̄w, Je	F 2½ R P 25± R	10-15-54 4-19-60	F, ST	D, S				(+)		See log.
Je	F 12 R F 9 R P 45 R	9- 2-55 1-59 4-60	F, ST	3D, 30H				(+)		Well flowed salt water from Kdb at 559 ft; see log.
Je	F 1½ R P 12 R	10- 3-55 4-14-60	F, ST	16D, 6H				(+)		See log.
Je	F 1± R P 10½ R	11-23-55 11-23-55	F, ST	13D				(+)		Do.
Je	F 5 R P 20 R	5-19-56 4-14-60	F, ST	4D, 18H				+155	5-19-56	Flowed 3 gpm from Jm at 861 ft; see log.
Je	F 12 R P 15 R	12- 4-50 4-18-60	F, ST	I	Top 5 in. casing	+.9		+101.2 + 42+	8-23-52 4-18-60	Flowed 2 gpm of salt water from Kdb at 191 ft; see log.
R̄w, Je	F 5.2 R F 9 R P 8½ R	10-19-50 7-53 4-18-60	F, ST	D, P	Top concrete well enclosure, north side.	+.9		+ 48.2	5-23-52	1950 flow from Je when well 1,001 ft deep; 1953 flow after well deepened to 1,397 ft through R̄k, R̄w, and 4 or 5 ft of R̄c; flow increased from 3.3 to 7 gpm at 1,031 ft in R̄w, then gradually to 9 gpm in next 50 ft; see log.
Jm	F 1± R P 8½ R	6-17-55 4-18-60	F, ST	6D				(+)		
Kdb	F 2½ R P 15 R	4-55 7-27-56	J	N				+ 3	7-27-56	Water reported salty and to contain H_2S; 4-18-60 reported filled to within 29 ft of surface.
Je	F 5 E P 5± R	8-22-55 4-19-60	ST	1D	Top 5¼-in. casing, north side.	.0		+ 34.4 (−)	8-22-55 4-19-60	Temp. 62° F.; flow diminished to 3 gpm then stopped flowing prior to 4-19-60.
R̄w, Je	F 12 R F 9.0 M F 2.3 M P 35 R P 20± R	3- 8-40 7-18-46 7- 5-50 7-25-55 4-18-60	ST	1D, 25-30H	Top L on top casing	−1.6	4,679.4	+ 81.8 + 45.9 − 54	7-18-46 10-22-47 7-25-55	Well in Je at depth 865 prior to deepening 7-25-55; see aquifer test and analysis of water for Je only; see log.
Jm	F 0.5 M	10-21-47	J	5D	Top 4-in. T on casing	−1.05	4,639.2	+ 76.6 + 80.2 + 82.1 + 57.3	10-21-47 7-26-49 7-19-50 8-24-52	Water in Kdb at 119 ft, see log and aquifer test.
Jm	F 5 R	5-10-56	J	2D				(+)		See log.
R̄w, R̄k, Je	F 13 R	6- 1-52	F	6D	Top concrete well box, north side.	−1.0		+ 53.8	8-23-52	Flowed 3½ gpm from Jm at 515 ft, 2 gpm from Je at 769; flow increased to 8½ gpm in 3-ft crevice in R̄k at 940–943 ft, then to 13 gpm in R̄w; see log.
Je	F 11.9 M P 30 R	10-23-47 4-19-60	F, ST	60D, 1-2H	Top 7-in. collar	+1.15	4,555.6	+134.0 +123.4 +122.5	9-22-48 7-27-49 7-21-50	Flow of about 10 gpm from Jm at 555–590 ft available between two casings but not used; see log.
Je	F 15.1 M	6-13-46	F, ST	D, S	Land surface	.0	4,637.7	+ 50+	8-31-45	See log.
Je	F 30 R P 50 R	4- 4-47 4-14-60	F, T	15D, 18H	Top 6-in. T	+1.1	4,567.0	+154.6 +125.7 +117.0	7-11-47 9-23-48 7-27-49	In August 1960 well still flowed after periods of non-pumping ranging from ½ hour to 24 hours; see log.
Je	F 6.1 M F ½ R P 23 R	7- 9-47 1958 4-14-60	ST	60D	Top low part of 4-in. plug.	+2.1	4,720.9	+ 50.7 + 39.7 + 30.8 + 23.0 + 11.2 −100±	7- 9-47 10-24-47 9-23-48 7-20-50 8-21-52 4-60	See log and aquifer test.
Jm	F 2.3 M	7-23-46	F	2D	Top cap on casing	+2.6	4,660.7	+ 62.8 + 84.6 + 55.1 + 78.8 + 71.0 + 81.5 + 61.1	7-24-46 7- 8-47 10-24-47 9-23-48 7-26-49 7-20-50 8-24-52	See aquifer test.

TABLE 7.—*Records of artesian*

Well (pl. 1)	Location	Owner	Driller	Year drilled	Depth (feet)	Diameter (inches)	Depth of casing (feet)	Finish (method and feet)
	T. 1 S., R. 1 W.—U.—Con.							
(25)	SW¼ SW¼ sec. 23	Raymond Balcom	T. N. Johnson	1945	855	5½–4		O
(26)	NE¼ SW¼ sec. 24	Holly Sugar Co.	Eureka Oil Co.	Before 1926.	1,660			
(27)	SW¼ NW¼ sec. 25	McCoy Co.	H. L. Morgan	1949	913	10–4	850	O, 63
(28)	SW¼ NW¼ sec. 25	Artesia Heights	C. T. Wilson	1946	940	10–4	936?	O, 4?
(29)	NW¼ NE¼ sec. 26	S. W. Collins	J. W. Moore	1945	870	8¼–6⅝	766	O, 104
(30)	NE¼ NW¼ sec. 26	Nellie L. Jones	Billy Doyle	1936	1,050	6–4	850	P, 200
(31)	NW¼ NW¼ sec. 26	City of Grand Junction		1903–04	1,213	10–?		
(32)	NW¼ SE¼ sec. 26	Joseph King	Kennedy and H. L. Morgan	1942	850	6–5½	550	O, 300
(33)	SW¼ NW¼ sec. 29	Gene Files	C. T. Wilson	1946	575	8–7¾	550	P, 100 O, 25
34	SE¼ SW¼ sec. 30	Welby Schrader	do	1946	444	6	80	O, 364
35	SE¼ SE¼ sec. 30	National Park Service (Colorado National Monument).	H. L. Morgan	1954	258	8–6	190	O, 68
	T. 11 S., R. 101 W.							
36	S½ sec. 14	Truman Evans	D. S. Isaacs	1955	130	8⅝–6⅝	130	P, 50
37	NE¼ NW¼ sec. 15	Albert Stassen	do	1959	1,030	12–6	720	P, 31 O, 310
38	SW¼ SE¼ sec. 15	Myron Ferree	J. D. Pinkerton	1955	579	6–5½	350	O, 330–350
39	NW¼ SW¼ sec. 16	K. C. Merling	D. S. Isaacs	1958	250	10–5½	200	P, 177–200 O, 50
40	SW¼ SE¼ sec. 16	G. M. McKeel	Morgan Drilling Co.	1959	475	5½		
41	SW¼ NE¼ sec. 21	M. A. Taylor and J. C. Perryman	J. D. Pinkerton	Before 1955.	350±			
42	NW¼ SW¼ sec. 22	J. L. Daily	H. L. Morgan	1959	310			
43	NE¼ SE¼ sec. 22	Welby Schrader	F. B. Dykes and J. D. Pinkerton.	1955	393	6	393	P, 263–387
44	NW¼ SE¼ sec. 22	L. C. Hoggett	D. S. Isaacs	1957	350	8–5	286	O, 64
(45)	NW¼ SE¼ sec. 23	M. Humphries estate	Mesa Drilling Co.	1946	922	8½–4½	585	O, 337
46	SE¼ NE¼ sec. 27	J. A. Watson	J. D. Pinkerton and D. S. Isaacs.	1957	232	8–6	180	P, 173–180 O, 52.
47	N½ sec. 27	W. V. Stone	H. L. Morgan	1952	610	8–5	290+	
48	SE¼ SW¼ sec. 35	J. O. Boyle	J. D. Pinkerton	1955	105	6⅝–4½	105	P, 20

HISTORY OF DEVELOPMENT

The first deep wells in the Grand Junction area reportedly were drilled in the hope of finding oil or gas, but when water was found instead, they were completed as flowing artesian wells. Statements of old residents (Carl M. Bennett, Director of Public Works and Planning, city of Grand Junction, written communication, Nov. 7, 1946) indicated that well 31 was drilled in 1903 or 1904, and this well may have been the first flowing artesian well in the area. According to fragmentary records obtained from the Grand Junction office of the Public Service Co. of Colorado, well 26 was drilled prior to 1926; it could have been put down earlier than well 31. Additional wells, listed in records dated 1934–35 from the same source but which may later have been abandoned or plugged or both, include the following. all in T. 1 S., R. 1 W., Ute P.M.: D. and R. G. W. R. R. well 1, in the NW¼ sec. 23; Ketchum well, in the NE¼ sec. 23; old 1 well (704 feet deep), in the SW¼ sec. 13; North 8th Street well (1,010 feet deep), in the NE¼ sec. 14; and Holly Sugar Co. well 2, in the NE¼ sec. 24. Drilling dates for these wells are not available, but any of the wells could have been the first well drilled.

wells in the Grand Junction area—Continued

Geologic source	Discharge (gpm)	Date of measurement, estimate, or report	Method of lift	Use of water	Measuring point: Description	Measuring point: Distance above (+) or below (−) land surface (feet)	Measuring point: Height above mean sea level (feet)	Distance to water level above (+) or below (−) measuring point (feet)	Date of measurement or report	Remarks
Je	F 16 R F 14 R F 11.3 M P 33 R	1-19-45 7-46 10-21-47 4-18-60	F, ST	15H				+150±	1-19-45	See log.
T̄Rw, Je	F 8.1 M	7-26-46	F	S	Top highest part of L.	+1.6	4,576.2	+ 13.6	7-26-46	Head and flow greatly reduced by water leaking upward around outside of casing; drilled as oil test; see log.
Je	F 10± R	12-12-49	F, J	D	Top concrete slab in front lawn.	.0		+ 92.9	7-20-50	See log.
Je	F 16 R F 4.9 M	8-15-46 9-22-48	F	D	Top 12-in. collar	+0.5	4,641.7	+111.2 + 93.4 +130.5 +107.4 + 85.7	7-10-47 9-22-48 7-26-49 7-20-50 8-21-52	Water in Kdb at 200–300 ft; first two water levels measured after shut in of 12 hours, others after shut in of several weeks; see log and aquifer test.
Je	F 9 R F 6.9 M P 18 R	4-45 7-25-46 4-14-60	F, J	4D, H	Top casing	+1.8	4,630.9	+ 89.1 + 70.7	7-25-46 7-10-47	Small flow from Jm at 575 ft cased off; see log and aquifer test.
T̄Rw, Je	F 12.3 M F 10.9 M	5-47 10-21-47	F, ST	D, 12H	Land surface	0	4,626.0	+138	1936	See log.
T̄Rw, Je	F 36 R F 23.4 M F 15.8 M F 5± E	1908 11-46 10-23-47 4-11-60	F	H	Top concrete cistern, northwest corner.	+1.7	4,621.8	+119.5	7-16-46	Attempts to shut in well between periods of use resulted in leak through casing to surface, reducing head and flow; drilled as oil test; see log and aquifer test.
Je	F 7.6 M P 10± R	10-23-47	F, T	2D	Top 3-in. T	+1.5	4,685.2	+ 70.2 + 73.5 + 65.0 + 39.8	9-23-48 7-27-49 7-20-50 8-22-52	Well deepened 50 ft after 1948 head measurement.
Je	F 2.2 M F 0 M	7-17-46 4-14-60	N	N	Top welded cap on casing.	+2.4	4,862.8	+ 9.9	7-17-46	Water believed moving from Je into Jm through perforated casing; see log and aquifer test.
T̄Rw			N	N	do	+1.5	5,042.7	− 40± − 47.4	7- 3-46 9-11-47	
Je	P 15 R	4-14-60	T	D	Land surface	.0		− 32	1959	See log.
Kdb	P 10 R	1-17-55	J	D						
T̄Rw, Je	F 2 R F 2 M	5-20-59 7-19-60	F	D, S						Water in Kdb at 75 and 137 ft, Jm at 373 ft, see log.
Jm	F 1 R F ½ E	5-21-55 6-18-55	F	D				(+)		Temporarily plugged at 350 ft, ended in Jm at 579, may drill deeper to Je.
Je			ST	S				− 50±	1958	
Je ?	F 1½ R F 1-2 E	5-59 7-19-60	F	D						
Je ?			J	D				(−)	6-18-55	
Je	F 2 R F 1½ R	6-15-59 4-18-60	F	D				(+)	4-18-60	
Jm	F 5 R F 3 E	9-20-55 4-14-60	F, J	S				(+)	4-14-60	See log.
Je	F 1 R F 1 E	9- 4-57 4-18-60	F	D				(+)	4-18-60	Do.
T̄Rw, Je	F 15 R F 11.4 M P 12½ R	4-15-46 10-22-47 4-18-60	F, ST	D, H	Top casing	+1.4	4,690.3	+ 43.6 +101.7 + 88.3 + 93.4 + 92.5 + 89.7	7-19-46 7- 9-47 9-24-48 7-27-49 7-20-50 8-22-52	First head measurement before leaky casing repaired, later measurements after repair; see log and aquifer test.
Je	F 2 R F ½ R P 15 R	4-26-57 4-18-60 4-18-60	F, ST	D				(+)	4-18-60	
T̄Rw, Je	F 3 R F 0 R	until 1954. after 1954.	J	D	Land surface			− 30±	4-14-60	
T̄Rw			J	D				(−)	4-18-60	

Of the 48 wells listed in table 7 and shown on plate 1, only 14, or 29 percent, had been drilled when this investigation began in the summer of 1946. At that time all but one well (34), which is near the outcrop, were flowing and were thought by most of the owners to be virtually inexhaustible. The desire of other property owners for similar flowing wells plus the natural growth of Grand Junction and suburban areas such as the Redlands and Orchard Mesa led to the drilling of 27 additional wells, or 56 percent of the total, during the ensuing 10-year period 1947–56. Long before the end of this period, interference between wells had caused considerable decline in artesian head, particularly in the areas of greatest well densities; flows had reduced or stopped, some well owners had installed pumps, and the enthusiasm for putting down similar wells had diminished somewhat. Thus, from 1956 to 1960 only 7 additional artesian wells, or 15 percent of those listed, were drilled.

CONSTRUCTION

Forty-three of the 48 wells listed in table 7 were drilled by the cable-tool method, and 5 wells were drilled all or in part by the hydraulic-rotary method.

In the cable-tool, or percussion, method, a heavy string of tools attached to a steel cable, is alternately and rapidly raised and dropped upon the bottom of the hole. The tools comprise a sharpened removable steel drill bit at the bottom, a long steel shaft for weight, and a set of sliding jars at the top to permit lifting the bit with a jerk to free it from the hole or accumulated rock fragments. Water is introduced into the hole periodically until water is reached in drilling. The water lubricates the bit and allows removal of rock fragments and water by bailing at intervals. Steel casing is lowered or driven into the hole to keep pace with the drilling, for many soft rocks tend to cave unless cased.

In the hydraulic-rotary method, a sharpened drill bit is rotated rapidly against the bottom of the hole and is thrust against the bottom either by the weight of the hollow steel drill pipe alone or by added hydraulic thrust. The rock fragments loosened by the bit are continuously washed to the surface by a stream of fluid pumped under pressure down the hollow drill stem, through nozzles in the drill bit, and back up the drill hole to a pit at the surface. The fluid serves also to cool and lubricate the bit. Generally a prepared drilling mud containing bentonite is used, but well 24 was drilled using clear water from an adjacent irrigation ditch. Use of muds of higher viscosities and densities than water permits lifting larger and heavier rock fragments and also coats the inside of the drill hole with a layer of mud, and thus tends to prevent caving. If little or no caving is experienced, some wells drilled by this method are not cased until after full depth, or an artesian flow, is reached. Well 1 was drilled to a depth of 1,200 feet by the cable-tool method, then completed to the total depth by the hydraulic-rotary method.

Generally it is not possible to complete wells as deep as most of those in the Grand Junction area by the cable-tool method with only one casing, because friction generally prevents driving one casing more than a few hundred feet. Drilling is therefore generally begun at a diameter larger than the finished well is planned, such as 8, 10, 12, or 14 inches; then when a larger casing cannot be driven deeper, a smaller bit is used below the bottom of the first casing, followed by a casing of smaller diameter. Most of the wells for which casing records are available contain two separate casings, but a few contain one to four casings. In table 7, the largest and smallest known casing or hole diameters are given. In completing the flowing artesian wells in the Grand Junction area, it was necessary to seal one or more of the strings of casing against the rock at some point above the top of the artesian aquifer to prevent upward escape of water between the casing and rock wall or between two casings. Many different types of commercial or homemade well seals were used, and some such seals were augmented by gravity or pressure cementing of the annular space between one or more outer casings and the rock wall. In some wells, cement forms the only seal. In spite of such precautions, in a few of the wells water is leaking to the surface around the outer casing. In a few of the older wells such leaks may be due to weakening and eventual puncturing of the casings by rusting.

The lower parts of the wells extending into or through the artesian aquifers were finished in one of several different ways. Most of the holes into or through the aquifers are simply uncased open holes, for the sandstone beds generally are sufficiently cemented to remain open with little or no sanding. In a few wells, perforated pipe extends into or through the aquifer to deter or prevent possible sanding or collapse. Two of the wells are finished with well screens surrounded by gravel to prevent possible sanding or caving. Screening and gravel packing generally are essential only in some unconsolidated aquifers.

Before most of the flowing artesian wells were equipped with pumps, the inner casing served to conduct the water to the surface. Generally a threaded reducer or bushing was welded to the top of the inner casing so that suitable pipe connections could be made, and this procedure facilitated connections to the wells for making flow and recovery tests (fig. 39).

YIELD AND SPECIFIC CAPACITY

The measured flows and specific capacities of wells on which flow tests were made are given in table 6 and discussed on page 99; the measured or reported yields by natural flow or by pumping of most of the 48 wells are given in table 7.

Before pumps were installed, most of the wells yielded water solely by natural flow. Wells having sufficiently large artesian heads generally were connected directly to home water systems or to elevated storage tanks (fig. 39), but some having small heads and flows were allowed to flow into cisterns from which water was pumped when needed. Under such conditions the wells were operated at nearly constant drawdowns and gradually diminishing discharge rates, and the reference points below which the drawdowns occurred were the heights above land surface to which the water would rise when the wells were shut-in.

The left end of each curve in figure 43*A* shows the drawdown after 30 days of discharge for stated rates of discharge from a flowing artesian well 6 inches in diameter ($r_w=0.25$ ft) tapping the full thickness of the Entrada Sandstone and having average values of T and S of 150 gpd per ft and 5×10^{-5}. Under these average conditions, after 30 days continuous discharge a well flowing 10 gpm would have a drawdown of 150 feet, and one flowing 20 gpm would have a drawdown of 300 feet. Inasmuch as only four wells in the area had initial artesian heads of as much as 150 feet above land surface (wells 1, 5, 10, and 22), and no wells had heads as high as 300 feet, the reader may wonder as to the meaning of these figures. We may assume, for example, either that a well having a head 150 feet above land surface was pumped at 20 gpm and that the water level declined to a point 150 feet below land surface, for a total drawdown of 300 feet, or that a well whose water level was just at land surface was pumped at 20 gpm and that the water level declined to a point 300 feet below land surface, again for a drawdown of 300 feet. In either example, 10 gpm per 150 ft or 20 gpm per 300 ft=a specific capacity of about 0.07 gpm per ft (p. 99). This average value of specific capacity for the Entrada Sandstone is smaller than some of the values given in table 6, which were computed after only 2 or 3 hours of discharge while the discharge rates were still declining slowly, whereas the average values shown in figure 43*A* were computed for 30 days of continuous discharge. After periods of discharge longer than 30 days, the specific capacity would be slightly less than the value given.

For wells that obtain water from the full thicknesses of both the Entrada and Wingate Sandstones, for which the values of T and S are about twice that for the Entrada alone (p. 99), or about 300 gpd per ft and 10^{-4}, the same discharge would produce only half the drawdown, or the same drawdown would produce twice the yield. Under this condition the specific capacity after 30 days of discharge would be 20 gpm per 150 ft=0.13 gpm per ft.

In many parts of the country, a well having a specific capacity of only a small fraction of 1 gpm per ft would be considered a dry hole, for many wells have specific capacities of tens, hundreds, or thousands of gallons per minute per foot. However, in the arid Grand Junction area, much of which is devoid of usable shallow ground water, artesian wells of such low specific capacities are highly valued.

During the decade 1947 through 1956, when most of the wells were drilled, interference of two types between wells became increasingly acute: (1) drawdown interference (the discharge of one well causes the artesian head to decline in a nearby well); and (2) declining natural flows, which are proportional to available artesian heads. This interference brought about the installation of pumps to restore well yields to those of earlier flows and, by 1960, 36 of the 48 wells were equipped with pumps, and a few other wells were to be equipped. Natural flows may have actually stopped in only a few wells on hills in the most heavily developed part of the area, but the flows of many wells had diminished to very small rates.

Figure 43 shows that within the range of about 5 to 40 gpm in artesian wells in which there is no dewatering of the aquifer the relation of drawdown to discharge is theoretically linear. Thus, within limits of the aquifers and wells, whether a given quantity of water can be obtained is determined by the drawdown, which in turn is determined by the capacity of the pump, the power available, and the depth of the pump below the water level. In figure 43, the discharge rates of 5 to about 40 gpm are realistic continuous pumping rates for the better wells in the Entrada Sandstone; those of about 50 to 100 gpm are unrealistic pumping rates inasmuch as pumping at such rates for only 30 days would dewater most wells and partly or wholly dewater the aquifer in the vicinity of the well. Therefore, the higher rates are included in the graphs simply to illustrate their impossibility.

In 1960 most of the wells equipped with pumps were yielding as much or more water as the same wells formerly yielded by natural flow, but of course the heads were considerably lower, and the cost of pumping at a given rate gradually increased as pumps were lowered or larger pumps and motors were installed. As is brought out in more detail below, this pumping has intensified the declines in artesian head.

ARTESIAN HEAD

INTERFERENCE BETWEEN WELLS

There is considerable difference in the rate of spread of the cone of depression around a discharging well in an artesian aquifer and one in an unconfined aquifer. In an unconfined aquifer an appreciable quantity of water drains slowly by gravity from the material within the spreading cone of depression. In a reasonably elastic artesian aquifer such as the Entrada Sandstone however, the actual pressure change travels through the aquifer with the speed of sound in the aquifer; the cone of depression and the area of influence (area in which measurable drawdown occurs) enlarge rapidly, but at a lesser and gradually diminishing rate. This phenomenon may be illustrated by a simple comparison. A simplified solution of equation 2 for values of u of 0.01 or less is (Cooper and Jacob, 1946, p. 527):

$$s=\frac{2.30Q}{4\pi T}\log_{10}\frac{2.25\ Tt}{r^2S} \tag{15}$$

Solving equation (15) for r^2 gives

$$r^2=\frac{2.25Tt}{S\log_{10}^{-1}\left[\frac{4\pi Ts}{2.30Q}\right]}. \tag{16}$$

For a given set of conditions all terms except r^2 and S may be considered constant; then, using k as a constant of proportionality,

$$r^2=\frac{k}{S}.$$

Multiplying both sides of this equation by π gives

$$\pi r^2=\frac{k'}{S}=A \text{ (area of influence).} \quad (17)$$

Equation 17 may be used to compare the area of influence in an unconfined aquifer (A_2) having a specific yield or storage coefficient of, say, 0.20 with that in the Entrada Sandstone (A_1) having an average storage coefficient of 5×10^{-5}, assuming that T, Q, and s are the same for both aquifers and that t is also the same and long enough that $u\leq0.01$. Then

$$\frac{A_1}{A_2}=\frac{\dfrac{k'}{5\times10^{-5}}}{\dfrac{k'}{0.20}}=\frac{2\times10^4}{5}=4\times10^3.$$

This result means that, under the assumed conditions, and all other things being equal, the area of influence in the artesian aquifer is 4,000 times larger than that in the unconfined aquifer.

The Theis equation 2 may be used to determine the amount of drawdown interference any one well exerts upon any other well under actual or assumed conditions of T, S, discharge (Q), distance (r), and time (t); however, if many mutually interfering wells are involved the problem becomes extremely complex, particularly with flowing wells of gradually declining discharge, and will not be dealt with here. The solution of the exponential definite integral in equation 2 is an infinite series, values of which have been computed for corresponding values of u (Wenzel, 1942, facing p. 89). If the value of the integral is represented by $W(u)$, the W function of u, then equation 2 may be written

$$s=\frac{Q}{4\pi T}W(u) \quad (18)$$

in which $u=\frac{r^2S}{4Tt}$, and all terms are as previously defined. In units used by the Geological Survey, equation 18 may be written

$$s=\frac{115Q}{T}W(u) \quad (19)$$

in which

$$u=\frac{1.87r^2S}{Tt}.$$

As an example, consider two wells 1 mile apart in the Entrada Sandstone, that the Entrada is of infinite extent (it is sufficiently extensive for the problem at hand), that it is homogeneous and isotropic (again the actual conditions of the problem reasonably approximate the assumption), that no other wells are discharging, and that there is no regional upward or downward trend in artesian head; then determine the amount of drawdown a well discharging 10 gpm will produce on a second nondischarging well at the end of 30 days of discharge.

$$u=\frac{(1.87)(5{,}280^2)(5\times10^{-5})}{(150)(30)}=5.8\times10^{-1}$$

From Wenzel's table (1942, facing p. 89) the value of $W(u)$ for this value of u is found to be 0.473. Then, using equation (19)

$$s=\frac{(115)(10)}{150}(0.473)=3.6 \text{ feet}$$

In this manner, many values were computed in preparing figure 43, which shows, by families of semilogarithmic curves, the drawdowns at various times and distances from wells discharging at stated rates from the Entrada Sandstone alone or from the Entrada and Wingate Sandstones. The curves in figure 43 apply generally to about the western two-thirds of the area, where the Entrada and Wingate Sandstones have average thicknesses of about 150 and 330 feet, respectively. In about the eastern one-third of the area, where the two sandstones are thinner and form a single artesian aquifer, the drawdowns would be somewhere between those shown on A, B, and C of figure 43.

Figures 43 A, B, and C are similar except for the duration of discharge (t), which ranges from 30 to 365 days, and except that figure 43A also shows the expected drawdown after 30 days in a well 6 inches in diameter (r_w=0.25 ft), at the left end of each curve.

To compare the effect of time on the drawdown interference at distance from a discharging well, note that for a discharge rate of 20 gpm from the Entrada Sandstone the interference at 1,000 feet is about 50 feet at the end of 30 days, 77 feet at 180 days, and 88 feet at 365 days. At the same discharge rate, the drawdown interference at a distance of 1 mile is about 1 foot at 30 days, about 8 feet at 180 days, and about 10 feet at 365 days. For wells penetrating both the Entrada and Wingate Sandstones, the corresponding drawdowns, read on the right-hand scales, are only half as much.

Figure 43D shows how the drawdown at a point 1,000 feet from a discharging well increases with time of discharge. A similar family of curves could be constructed for any other point within the cone of depression.

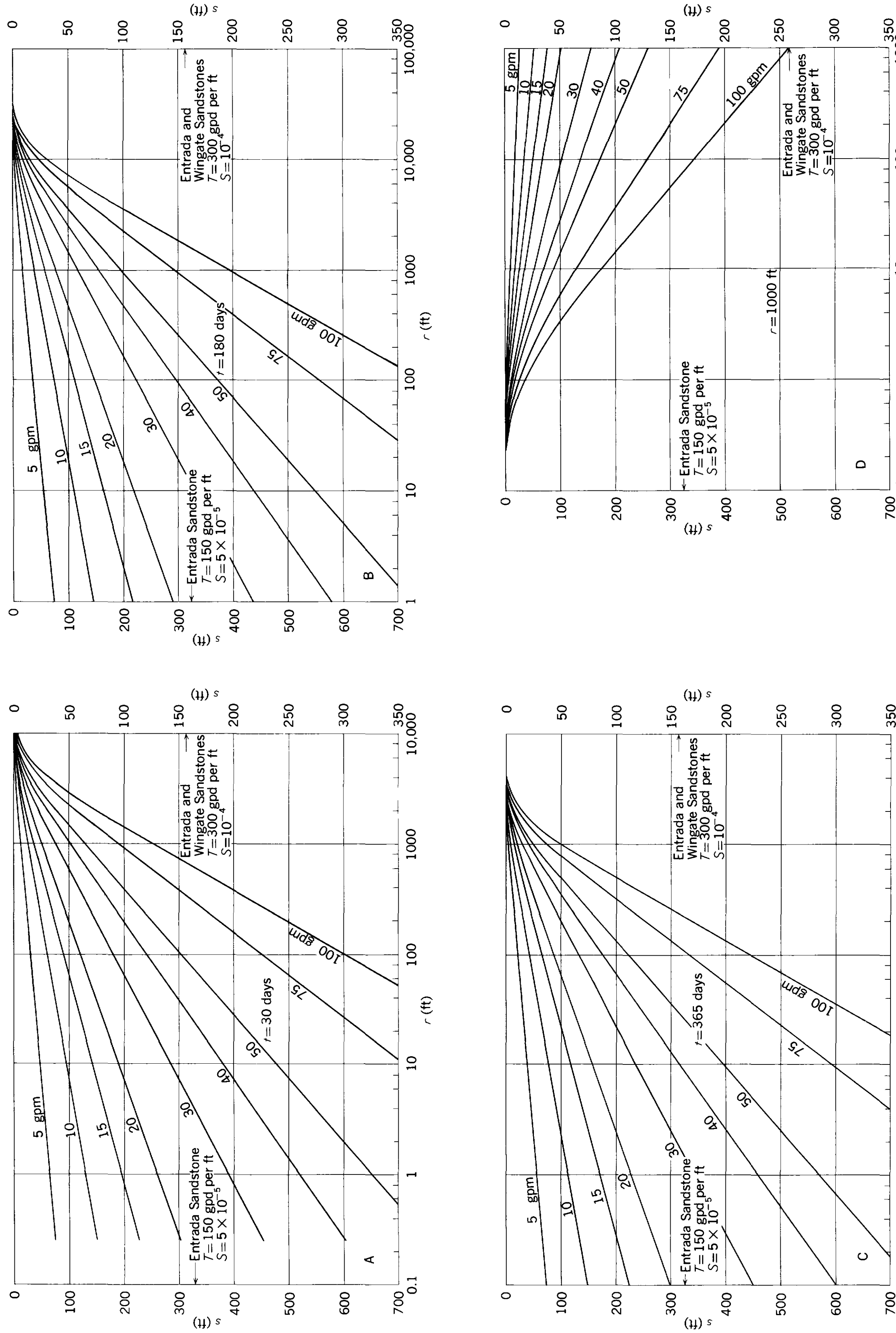


Figure 43.—Families of semilogarithmic curves, showing the drawdowns produced at various distances from a well discharging stated amounts of water from the Entrada Sandstone or from the Entrada and Wingate Sandstones, at various or stated durations of discharge. *A*, at end of 30 days' discharge; *B*, at end of 180 days' discharge; *C*, at end of 365 days' discharge; and *D*, at r=1,000 feet for various periods of discharge.

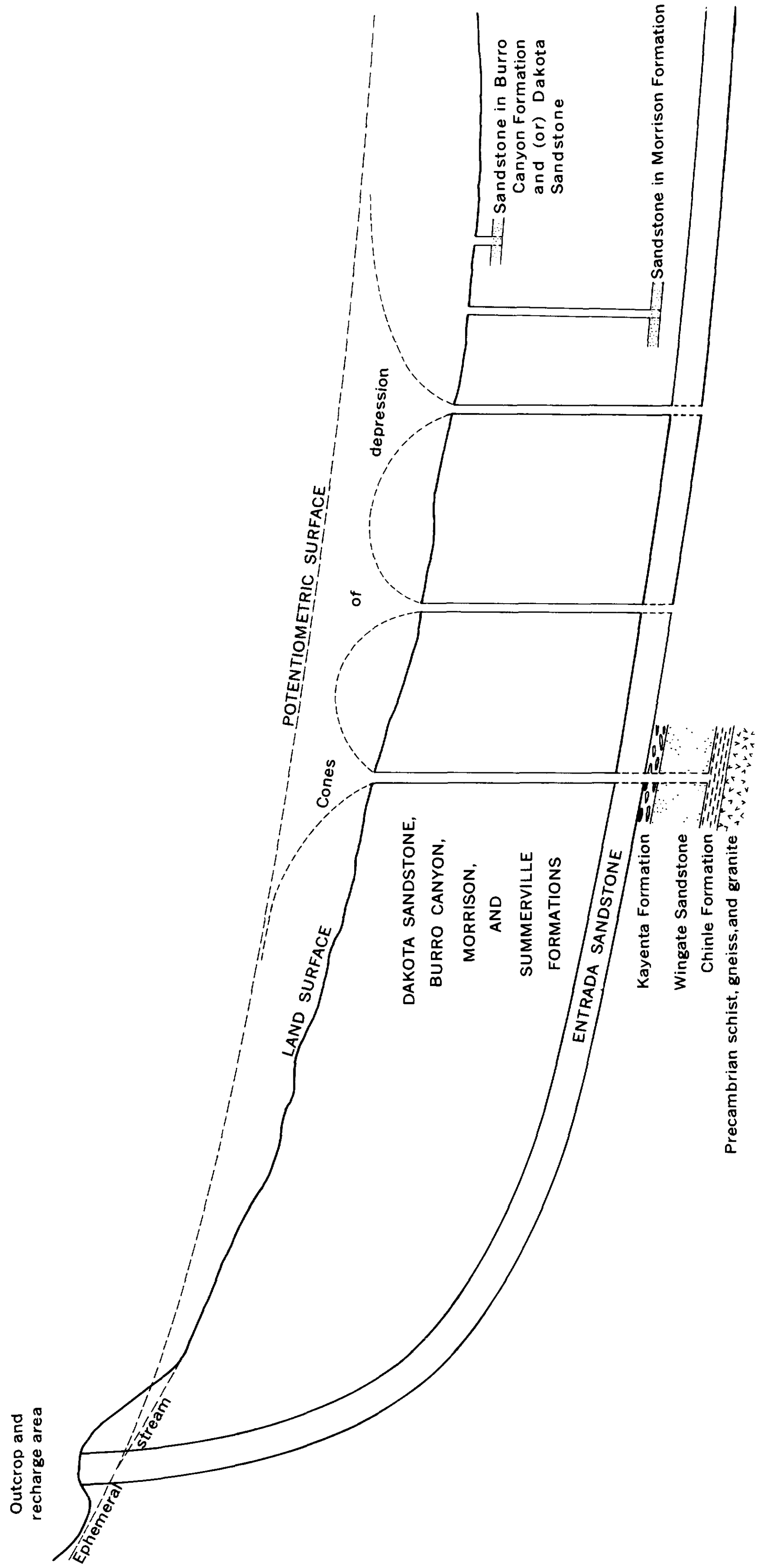


FIGURE 44.—Diagrammatic cross section of the Grand Junction artesian basin. Vertical exaggeration about 9 to 1.

It should be clear from inspection of the curves in figure 43 that there is considerable drawdown interference between wells in the same aquifer or aquifers in the Grand Junction area, particularly in the most intensely developed areas. This mutual drawdown interference caused corresponding declines in rates of flow and caused some wells to stop flowing at the surface.

Figure 44 shows diagrammatically how cones of depressions of nearby discharging wells in the same aquifer intersect because of mutual drawdown interference. Note also that no interference results between wells tapping the Entrada Sandstone or Wingate Sandstone, or both, and wells tapping a sandstone in the Morrison Formation and sandstones in the Dakota Sandstone or Burro Canyon Formation, or both.

DECLINES AND FLUCTUATIONS IN HEAD

Artesian heads were measured about annually in 11 wells from 1946 through 1952 (fig. 45), after which most

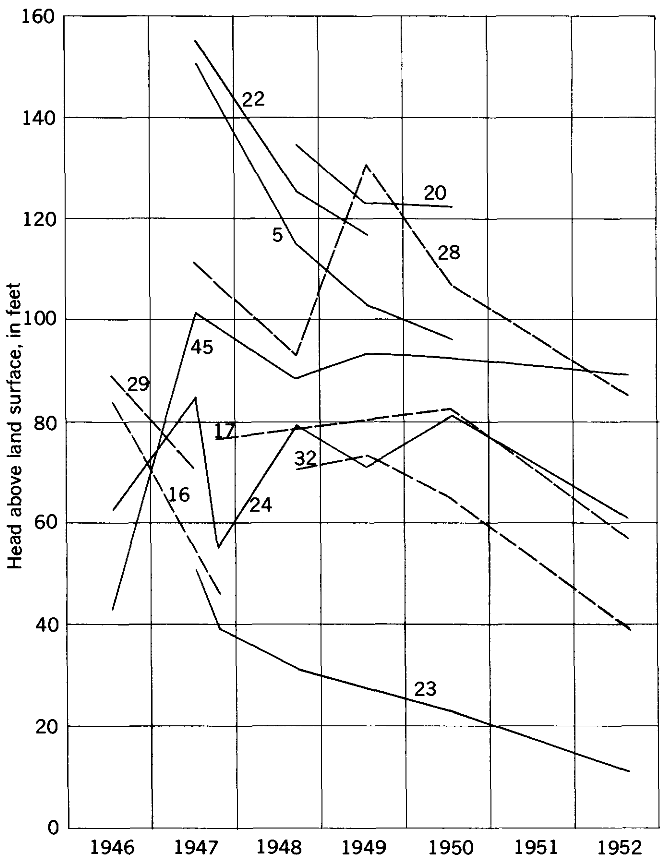


FIGURE 45.—Fluctuations in artesian head in 11 wells, 1946 through 1952. Wells are described by number in table 7 and shown on plate 1.

of the wells were equipped with pumps and additional measurements generally could not be made. These measured water levels (artesian heads) and some reported water levels are given in column 18 of table 7.

As shown in figure 45, the last heads measured in each well except well 45 are lower than the first measured heads. According to statements of well owners, the pronounced downward trend from 1950 to 1952 continued after 1952 at an accelerated rate because of the increased number of wells and withdrawal of water.

The trend in head in wells 5, 16, 20, 22, 23, and 29 was downward throughout the period of measurement. Some of the fluctuations during the first 4 or 5 years of record for other wells are explainable—others can only be surmised.

The head in well 28 in 1947 and 1948 was measured after shut-in periods of 12 hours, whereas the much higher head in 1949 was measured after a shut-in period of 2 months and those in 1950 and 1952 after periods of several days. The longer shut-in periods allowed more nearly complete recovery of artesian head, but it was not practicable to shut in other wells for more than about 12 hours.

A leaky well seal was indicated during the 1946 measurement of head in well 45 by water that came up around the casing. The 1947 measurement, made after the defective well seal had been repaired, was about 85 feet higher.

The rise in head between 1946 and 1947 in well 24 may have resulted from recharge to the sandstone in the Morrison Formation from the Entrada Sandstone in well 33, which taps both sandstones and which is only about 2 miles upgradient from well 24. If so, however, the decline in head in well 24 between July 8 and October 24 cannot be explained. The rises in head in well 24 in 1947, 1948, and 1950 and in well 17 in 1950 may be the result of additional recharge preceding these measurements. Such possible recharge most likely resulted from precipitation in the headwaters of No Thoroughfare Canyon, an area for which no precipitation records are available. Variations in recharge rates more likely would have affected the artesian heads in wells 17 and 24 than those in the other wells for which head measurements were made, however, because at that time they were the only two wells in a rather large area that tapped a sandstone in the Morrison Formation, whereas such possible variations in recharge rates would tend to be obscured in the many wells in the Entrada Sandstone because of greater discharges and greater interference between wells.

The rise in head in well 32 from 1948 to 1949 probably resulted from deepening the well an additional 50 feet after the 1948 measurement.

CHEMICAL QUALITY OF ARTESIAN WATER

The usefulness of water for various purposes depends in large part upon its chemical quality. To determine the chemical quality of the artesian waters in the Grand

Junction area, 26 samples of water were collected from 23 artesian wells during the period 1946–55, and were analyzed in the laboratories of the U.S. Geological Survey, at Albuquerque, N. Mex., or Salt Lake City, Utah (table 8).

Of the 26 samples collected for analysis, 16 are from the Entrada Sandstone, 5 are from 4 wells in the Entrada and Wingate Sandstones, 2 are from 1 well in the Entrada, Wingate, and Kayenta Formations, and 3 are from 2 wells in the Morrison Formation. No samples of water were obtained from the Burro Canyon Formation or Dakota Sandstone because during the sampling period the only well tapping these formations was a nonflowing well having an inoperable pump, and this well was later destroyed. Wells listed in table 7 that tap these formations were drilled after the sampling period. However, some idea of the chemical character of water from these two formations was obtained from drillers and owners, and the results are given on page 63.

The artesian water of this area originated from the rain or snow (meteoric water) that fell on or upstream from the recharge areas. Originally this water was as pure as distilled water, except for small amounts of dissolved atmospheric gases and particles of dust. As soon as the water came in contact with the rocks, however, it began to dissolve and take up soluble minerals. The amount and kind of dissolved minerals in the water, as sampled from the wells, depends upon the chemical character of the soils and rocks with which the water came in contact and the length of time the water was in contact with the atmosphere, soils, and rocks. The chemical character of the sedimentary rocks that form the artesian aquifers depends in part upon the source areas and types of the rocks and upon the environment in which they were deposited.

Inasmuch as most of the recharge to the principal artesian aquifers in the developed part of the Grand Junction artesian basin probably comes from ephemeral streams that cross the outcrop areas, the initial solution of rock and soil minerals began in the overland runoff to, and the flow in, such temporary streams. The surface runoff came in contact with rocks of many types, including the igneous and metamorphic rocks of the Precambrian complex and most of the younger sedimentary rocks except the Mancos Shale, but the time of transit from the point of precipitation to the recharge areas was relatively rapid. Nevertheless, the time in transit generally was sufficient for the water to take up more nearly equilibrium concentrations of atmospheric gases, to take up additional amounts of carbon dioxide gas (CO_2) from organic matter in the soils, and to dissolve some minerals from the soil and rocks. The dissolved CO_2 thus taken up formed carbonic acid (H_2CO_3), a weak acid that dissolves carbonate rocks, such as the thin limestones in the Morrison Formation, and the calcite cement (calcium carbonate, $CaCO_3$) in the sandstone beds. Thus, by the time the water reached the recharge areas, it contained in solution at least small amounts of dissolved minerals, including some calcium and bicarbonate ($Ca+HCO_3$), and lesser amounts of some or many of the other constituents listed in table 8.

After such dilute solutions of minerals reached and entered the outcrops of the artesian aquifers, the exceedingly slow movement through the aquifers allowed ample opportunity for additional solution of rock minerals and exchange of certain ions between the solution and some of the rock minerals. By the time the water reached and was discharged from the wells, it had the properties and mineral constituents listed in table 8.

The temperature of ground water in shallow unconfined aquifers generally approximates the mean annual air temperature, which is 52.1°F at Grand Junction and 51.3°F at Fruita, but at greater depths within the earth the rocks and their contained water become progressively warmer. Thus, as indicated in table 8, the temperatures of water in the deeper artesian aquifers range from 62° to 77°F, and are approximately proportional to the depth.

The laboratory procedures for analyzing natural water, the expression of analytical results, and the significance of properties and constituents of natural water have been treated in considerable detail by Hem (1959, p. 24–149). The significant properties and constituents of the water in relation to the geology and hydrology of the area and the usefulness of the water are discussed briefly below.

The principal dissolved ionic mineral constituents given in table 8 are expressed both in parts per million (ppm) and in equivalents per million (epm). A part per million is a unit weight of a mineral constituent in a million unit weights of water. An equivalent per million is a unit combining weight of a constituent in a million unit weights of water, and is calculated by dividing the concentration in parts per million by the chemical combining weight of the constituent (for conversion factors, see Hem, 1959, p. 32). The equivalents per million are useful in comparing analyses of different waters by constructing vertical bar graphs, such as those shown in figure 46. The positively charged ions, such as calcium (Ca^{++}) are called cations; the negatively charged ions, such as bicarbonate (HCO_3^-) are called anions.

CHEMICAL CONSTITUENTS IN RELATION TO AQUIFERS AND USE OF WATER

The discussion that follows has been adapted in part from Hem (1959, p. 35–149) and others.

TABLE 8.—*Analyses of water from artesian wells in the Grand Junction area*

[Analyzed in the laboratories of the U.S. Geological Survey, at Albuquerque, N. Mex., or Salt Lake City, Utah. Dissolved constituents given in parts per million; reacting values (in italics) given in equivalents per million. Geologic source: ₸w, Wingate Sandstone; ₸k, Kayenta Formation; Je, Entrada Sandstone; Jm, Morrison Formation (Salt Wash Member). Iron in solution, except as indicated. Dissolved solids calculated]

Well (pl. 1; table 7)	Location	Depth (feet)	Geologic source	Date of collection	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$ (all carbonate hardness)	Percent sodium	Specific conductance in micromhos per cm[3] at 25°C	pH
1	*T. 1 N., R. 1 W.—U.* SW¼ SE¼ sec. 29	1,639	Je	8-24-50	72	17	[1] 0.04	1.8 *.09*	1.0 *.08*	496 *21.57*	2.4 *.06*	970 *15.90*	16 *.53*	60 *1.25*	140 *3.95*	1.8 *.09*	0.1 *.00*	0.50	1,210	8	99	1,930	8.3
5	*T. 1 S., R. 1 E.—U.* NW¼ NW¼ sec. 18	1,615	Je	7-8-47	77	10	.57	3.8 *.19*	1.9 *.16*	280 *12.17*	5.0 *.13*	609 *9.98*	35 *1.17*	53 *1.10*	13 *.37*	.6 *.03*	0 *.00*	----	703	18	96	1,100	8.3
11	*T. 1 S., R. 1 W.—U.* NW¼ SW¼ sec. 15	978	Je	8-23-52	65	13	.07	2.7 *.13*	1.0 *.08*	129 *5.61*	1.0 *.03*	258 *4.23*	22 *.73*	45 *.94*	6.0 *.17*	.4 *.02*	.0 *.00*	.26	347	10	96	564	8.8
12	NW¼ SE¼ sec. 16	[2] 1,001	Je	8-23-52	65	15	.49	8.2 *.41*	3.4 *.28*	98 *4.26*	1.9 *.05*	250 *4.10*	----	39 *.81*	4.6 *.13*	.3 *.02*	.1 *.00*	.11	294	34	85	468	8.2
15	SE¼ SE¼ sec. 16	956	Je	8-22-52	62	16	1.1	13 *.65*	5.0 *.41*	87 *3.78*	2.5 *.06*	246 *4.03*	----	38 *.79*	4.6 *.13*	.3 *.02*	.2 *.00*	.11	289	53	77	457	8.0
16	NE¼ NE¼ sec. 21	[2] 865	Je	7-25-46	70	20	.36	17 *.85*	5.8 *.48*	[3] 91 [3] 3.95		257 *4.21*	----	43 *.90*	5.2 *.15*	.3 *.02*	.1 *.00*	.06	309	66	[4] 75	487	----
17	SE¼ NE¼ sec. 21	573	Jm	8-24-50	64	11	[1] .22	2.0 *.10*	.6 *.05*	326 *14.18*	1.8 *.05*	461 *7.56*	29 *.97*	241 *5.02*	25 *.71*	1.5 *.08*	.8 *.01*	.50	865	8	99	1,350	8.3
19	NE¼ SE¼ sec. 21	996	₸w, ₸k, Je	8-23-52	64	14	[1] .42	14 *.70*	6.7 *.55*	173 *7.52*	1.6 *.04*	276 *4.52*	12 *.40*	162 *3.37*	15 *.42*	.5 *.03*	.1 *.00*	.16	535	62	85	836	8.4
				6-18-55	64	18	.17	8.8 *.44*	3.4 *.28*	232 *10.09*	2.6 *.07*	323 *5.29*	4 *.13*	229 *4.77*	20 *.56*	.8 *.04*	.0 *.00*	----	678	36	93	1,060	8.3
20	NE¼ NW¼ sec. 22	925	Je	8-24-50	69	16	[1] .28	5.6 *.28*	3.0 *.25*	109 *4.74*	1.4 *.04*	262 *4.29*	----	38 *.79*	6.4 *.18*	.4 *.02*	.2 *.00*	.07	309	26	89	481	8.3
21	SW¼ NW¼ sec. 22	927	Je	7-26-46	([5])	17	.46	20 *1.00*	6.7 *.55*	[3] 80 [3] *3.48*		248 *4.06*	----	40 *.83*	4.2 *.12*	.3 *.02*	.1 *.00*	.06	291	78	[4] 69	464	----
22	SE¼ NW¼ sec. 22	810	Je	7-10-47	70	16	.24	26 *1.30*	8.4 *.69*	72 *3.15*	6.8 *.17*	261 *4.28*	----	42 *.87*	5 *.14*	.3 *.02*	0 *.00*	----	305	100	59	467	8.2
23	NW¼ SW¼ sec. 22	869	Je	7-9-47	65	16	.24	29 *1.45*	8.1 *.67*	74 *3.20*	7.8 *.20*	269 *4.41*	----	44 *.92*	6 *.17*	.4 *.02*	0 *.00*	.04	318	106	58	488	8.0
24	NW¼ SW¼ sec. 22	665	Jm	7-25-46	63	11	.23	2.2 *.11*	.8 *.07*	[3] 323 [3] *14.05*		370 *6.06*	39 *1.30*	292 *6.08*	26 *.73*	1.0 *.05*	.1 *.00*	.73	878	9	[4] 99	1,370	----
				8-24-50	63	12	[1] .06	1.8 *.09*	.4 *.03*	323 *14.05*	1.3 *.03*	370 *6.06*	35 *1.17*	296 *6.16*	26 *.73*	1.0 *.05*	.4 *.01*	.30	880	6	99	1,360	8.5
25	SW¼ SW¼ sec. 23	855	Je	7-25-46	71	14	.05	3.8 *.19*	1.8 *.15*	[3] 121 [3] *5.24*		238 *3.90*	18 *.60*	43 *.90*	5.5 *.16*	.3 *.02*	.1 *.00*	.11	325	17	[4] 94	515	----
26	NE¼ SW¼ sec. 24	1,660	₸w, Je	7-26-46	75	16	.05	1.8 *.09*	.7 *.06*	[3] 201 [3] *8.74*		363 *5.95*	40 *1.33*	58 *1.21*	13 *.37*	.5 *.03*	.1 *.00*	.37	510	8	[4] 98	818	----
27	SW¼ NW¼ sec. 25	913	Je	8-24-50	69	14	[1] .08	1.6 *.08*	.7 *.06*	145 *6.31*	1.0 *.03*	212 *3.47*	53 *1.77*	48 *1.00*	6.0 *.17*	.3 *.02*	.1 *.00*	.40	374	7	97	588	8.5
28	SW¼ NW¼ sec. 25	940	Je	7-10-47	65	11	.05	3.8 *.19*	2.5 *.21*	159 *6.92*	3.6 *.09*	258 *4.23*	48 *1.60*	57 *1.19*	13 *.37*	.3 *.02*	0 *.00*	----	426	20	93	684	8.4
29	NW¼ NE¼ sec. 26	870	Je	7-25-46	66	18	.11	4.6 *.23*	3.1 *.25*	[3] 113 [3] *4.91*		239 *3.92*	14 *.47*	41 *.85*	4.5 *.13*	.3 *.02*	.1 *.00*	.11	316	24	[4] 91	495	----
30	NE¼ NW¼ sec. 26	1,050	₸w, Je	7-25-46	([5])	17	.10	7.0 *.35*	3.8 *.31*	[3] 108 [3] *4.71*		238 *3.90*	12 *.40*	44 *.92*	4.5 *.13*	.3 *.02*	.1 *.00*	.09	314	33	[4] 88	495	----
31	NW¼ NW¼ sec. 26	1,213	₸w, Je	7-25-46	69	19	.10	16 *.80*	8.5 *.70*	[3] 92 [3] *4.00*		267 *4.38*	----	45 *.94*	5.8 *.16*	.3 *.02*	.1 *.00*	.18	318	75	[4] 73	505	----
				6-18-55	69	19	.19	15 *.75*	8.0 *.66*	110 *4.78*	3.3 *.08*	289 *4.74*	----	55 *1.15*	9.2 *.26*	.6 *.03*	.1 *.00*	----	362	70	76	579	7.9
32	NW¼ SE¼ sec. 26	850	Je	8-24-50	69	17	[1] .11	8.6 *.43*	4.8 *.39*	102 *4.44*	2.2 *.06*	254 *4.16*	----	39 *.81*	6.2 *.17*	.3 *.02*	.2 *.00*	.04	306	41	83	466	8.5
33	SW¼ NW¼ sec. 29	575	Je	7-25-46	62	23	[6] 2.7	36 *1.80*	8.2 *.67*	[3] 78 [2] *3.40*		278 *4.56*	----	51 *1.06*	8.0 *.23*	.3 *.02*	.1 *.00*	.04	342	124	[4] 58	543	----
45	*T. 11 S., R. 101 W.* NW¼ SE¼ sec. 23	922	₸w, Je	7-25-46	67	13	.05	1.2 *.06*	1.0 *.08*	[3] 194 [3] *8.43*		335 *5.49*	44 *1.47*	57 *1.19*	14 *.39*	.5 *.03*	.1 *.00*	.46	490	7	[4] 98	798	----

[1] In solution at time sample collected.
[2] Well later deepened to depth and formation given in table 7.
[3] Sodium plus potassium.
[4] Includes a small but undetermined quantity of potassium.
[5] Sampling point too far from well for temperature measurement.
[6] Includes 2.3 ppm precipitated in sample before analysis.

Silica.—Most natural water contains only from 1 to about 30 ppm of silica (SiO_2), but some contains as much as 100 ppm. The silica content of the 26 samples from the Grand Junction area ranged from 10 to 23 ppm—well within the normal range.

Iron.—If slightly alkaline water, such as that collected from the Grand Junction area, contains much more than about 0.5 ppm of iron (Fe), the excess may precipitate as iron oxide (Fe_2O_3)—a reddish sediment that may stain cooking utensils, porcelain fixtures, or laundry.

Only 3 of the 26 samples analyzed contained more than 0.5 ppm of iron, and only 1 sample (well 33) contained sufficient iron to form a precipitate between the time of collection and the time of analysis. Petrographic examination of some outcrop samples of both members of the Entrada Sandstone and the Wingate Sandstone (p. 24, 25, 39, and 40) revealed tiny grains of siderite ($FeCO_3$), a ferrous iron carbonate that is slightly soluble in water containing dissolved carbon dioxide. Well 33 is closer (0.9 mile) to the outcrop area than any other well sampled; this position suggests that some ferrous iron, possibly from siderite, remains in solution near the outcrops. Farther downdip, where all the dissolved carbon dioxide has been used up in dissolving carbonate, the solubility of the siderite may be less; this lower solubility may explain in part the generally lower iron content of the waters.

Calcium and magnesium.—Calcium (Ca) and magnesium (Mg) are the principal hardness-forming constituents of natural waters, for insoluble precipitates are formed when soap is added to water containing these cations; a part of the soap is thus used nonbeneficially.

Most of the samples from wells 3 miles or more from the outcrops contained very little calcium and magnesium, and were therefore low in hardness. However, the generally low content of these constituents probably resulted from ionic exchange of calcium and magnesium in the water with sodium in minerals in the aquifer. This exchange, known as natural softening by base exchange, is discussed more fully under "Hardness," pages 117, 118.

Sodium and potassium.—Sodium (Na) and potassium (K) together are the most abundant cations in the 26 samples, although the content of sodium far exceeds that of potassium. In most samples the sodium is accompanied by nearly equivalent amounts of bicarbonate, but the sample from well 1 contains some chloride also (see "Chloride," below, and fig. 46), and the samples from the Morrison Formation contained an appreciable amount of sulfate (see "Sulfate," below, and fig. 46).

Bicarbonate and carbonate.—Bicarbonate (HCO_3) is the most abundant anion in the 26 samples, and 15 of the samples contained 4 to 53 ppm of carbonate (CO_3). The concentrations of these two constituents together with the abundance of sodium cause the slightly alkaline character of the water, as indicated by the pH of 7.9 or larger.

Sulfate.—The content of sulfate (SO_4) is low in samples from the Entrada Sandstone and in most samples from the Entrada and Wingate Sandstones, but the three samples from two wells in the Morrison Formation contained 241 to 296 ppm of sulfate. The sulfate in these samples probably came from the near-outcrop oxidation of pyrite, an iron sulfide (FeS_2) occurring in sandstone beds of the Salt Wash Member of the Morrison in areas southwest of the Uncompahgre uplift (p. 51).

Chloride.—The chloride (Cl) content of all samples was very low except that from well 1, which contained 140 ppm (fig. 46). A possible explanation for the content of chloride in water from this well is given on page 21.

Fluoride.—Although fluoride (F) generally occurs only in small amounts in natural water, it is desirable to know its concentration in water that is likely to be used by children. The recommended limits of fluoride in milligrams per liter (approximately equal to parts per million) for the Grand Junction area are: lower limit, 0.9, optimum limit, 1.2, and upper limit, 1.7 (U.S. Public Health Service, 1961, p. 943). Fluoride concentrations above the upper limit may cause the dental defect known as mottled enamel on the teeth of children who drink the water during the period of formation of the permanent teeth.

All but four of the samples from the Grand Junction area contained less than the lower limit of fluoride. Three samples from two wells in the Morrison Formation contained 1.0 to 1.5 ppm of fluoride, or less than the upper limit, and one sample from the Entrada Sandstone (well 1) contained 1.8 ppm, just greater than the recommended upper limit of 1.7.

Nitrate.—Nitrate (NO_3)-rich water may cause cyanosis of infants (blue babies) when the water is used in the preparation of babies' formulas. All the samples of artesian water from the Grand Junction area contained less than 1.0 ppm of nitrate—far below the limits for cyanosis. The significance of high nitrate concentration on the possible sanitary character of natural waters is discussed on page 120.

Boron.—Boron (B) is necessary to most plants but is toxic to some plants in amounts as small as 1.0 to 2.0 ppm in water used for irrigation. All the samples analyzed had less than 1.0 ppm of boron, and only three contained as much as 0.50 to 0.73 ppm.

Dissolved solids.—The residue left after a natural water has evaporated consists of mineral constituents that were in solution, with which may be included some organic material and some water of crystallization. Water containing less than 500 ppm of dissolved solids generally is considered satisfactory for domestic use, and in many areas water containing as much as 1,000 ppm of dissolved solids is considered satisfactory, provided it is not excessively hard or corrosive. Some water containing 1,000 ppm or more dissolved solids contains enough of certain constituents to produce a noticeable taste or to make the water unsuitable in some other respects.

Fourteen of the 16 samples of water from the Entrada Sandstone contained less than 500 ppm of dissolved solids, and of the two samples having more than 500 ppm, only one (well 1) contained more than 1,000 ppm (1,210 ppm). The water from well 1 is very soft, however, and except for a slight excess of fluoride and a small content of hydrogen sulfide gas (H_2S, p. 120), is satisfactory for most domestic uses.

Four of the seven samples of water from wells tapping both the Entrada and Wingate Sandstones or the Entrada, Wingate, and Kayenta Formations contained less than 500 ppm of dissolved solids, the other three contained 510 to 678 ppm.

The three samples from two wells in the Morrison Formation contained 309 to 880 ppm.

Hardness.—The hardness of water is the property that generally receives the most attention, particularly in water for domestic, municipal, or certain industrial uses, and is most commonly recognized by its effects when soap is used with the water in washing. Calcium and magnesium cause nearly all the hardness and also contribute to the formation of most of the scale formed in steam boilers and in other vessels in which water is heated or evaporated.

The hardness or softness of a water is somewhat relative, for water considered hard in one area would be considered soft in some other areas. In most areas, however, water containing less than about 50 ppm of hardness is considered soft, and its treatment for removal of hardness generally is not necessary. Hardness between 50 and 150 ppm does not seriously interfere with the use of water for most purposes except that it increases the consumption of soap and, hence, may require softening for use by laundries and some other industries. Water having hardness of more than 150 ppm generally requires softening for most purposes.

The water from most artesian wells in the Grand Junction area is highly valued because of its softness. Seventeen samples from 16 artesian wells had a hardness of less than 50 ppm, of which 8 had a hardness of 10 ppm or less. Only three samples (wells 21, 22, and 33) had a hardness of 100 to 124 ppm. In all the samples the hardness was caused by calcium and magnesium bicarbonate, a type of hardness known as carbonate hardness.

In all the water analyzed the relative softness is attributed to natural softening by base exchange, by which Ca^{++} and Mg^{++} ions in the water are exchanged for Na^{+} ions in certain minerals in the aquifers; part or most of the hardness-producing calcium and magnesium is thus removed from the water and it is made softer. Exchange of these cations may be brought about by zeolites, a family of hydrous silicate minerals, some of which are used in commercial water softners, or by some of the clay minerals. Microscopic studies of thin sections (p. 24, 25, and 39) failed to reveal any zeolite minerals in outcrop samples of the Entrada and Wingate Sandstones, but the particle-size analyses (table 4) indicate from 2.5 to 7.0 percent clay, and additional clay minerals probably are included in the 5.6 to 45.4 percent silt-size particles. X-ray determinations of the approximate composition of the clay fractions indicated that 20 to 60 percent of the clay in the nine samples is kaolinite and that the balance is a mixed-layer clay composed of illite and montmorillonite in the approximate proportions given in table 4. The cation-exchange capacities of these three clay minerals are given in table 9. For a discussion of the mechanism of cation exchange in clay minerals, the reader is referred to Moore (1960, p. B-44-B-46).

TABLE 9.—*Cation-exchange capacity of 3 clay minerals, in milliequivalents per 100 grams, for water of pH=7*

[From Grim (1953, p. 129)]

Mineral	Cation-exchange capacity
Kaolinite	3- 15
Illite	10- 40
Montmorillonite	80-150

Table 4 indicates that there is an ample supply of these clay minerals in the Entrada and Wingate Sandstones to soften the water by cation exchange. No mineralogical studies were made of sandstones in the Morrison Formation, but the samples of water analyzed (wells 17 and 24) are very soft and suggest that a comparable or even greater amount of softening has taken place. The Morrison is known to contain altered volcanic ash—a common source of montmorillonite.

As shown in figure 46, there is almost a linear decrease in hardness (50 times the sum of Ca and Mg in epm) between well 33, which is 0.9 mile northeast of the recharge area in No Thoroughfare Canyon, and well 5, which is about 6 miles northeast of the same recharge area. This decrease is to be expected for, other things (such as the amount and kind of clay in the aquifer), being equal, the water from wells at greater distances from the outcrop has been in contact with the clay minerals for proportionately greater periods of time. At some distance greater than 6 miles from the recharge area, therefore, the hardness probably has been reduced even more. At distances closer to the recharge area than those for which analyses are available (less than 0.9 mile), the hardness is probably greater than that for the water from well 33 (128 ppm). Well 33 taps both the Entrada and Morrison Formations, but the head of water in the Morrison is below land surface, whereas the water from the Entrada flowed at the surface when the sample was collected; hence, the sample probably came entirely from the Entrada.

The hardness of water from well 1 is less than half that of water from well 5, even though well 1 is 1.3 miles closer to its recharge area. However, the two wells are about 5½ miles apart along the strike of the Entrada Sandstone, whereas the other wells whose water analyses are shown in figure 46 are almost on a line between the recharge area and well 5. Clay minerals in the Entrada near well 1 in the northwestern part of the area may be of slightly different composition or may be more abundant than in the central part of the area, southwest of well 5.

Water from some wells that tap both the Entrada and Wingate Sandstones, such as well 45, is softer than that from wells in the Entrada alone at a comparable distance from the recharge area. As indicated in table 4, the samples of Wingate Sandstone had a greater content of silt and clay than most of those from the Entrada, hence, probably contain more of the clay minerals.

Wells 19, 24, and 31 were resampled from 3 to 9 years after the first water samples were collected. The samples obtained later were softer and contained somewhat more dissolved solids, but the changes in concentration were different in the water from each of the three wells. The ages of the wells at the time of first sampling may have had an important bearing upon subsequent changes in the quality of the water.

Inasmuch as the first water samples from wells 19 and 24 were obtained a few weeks after the wells were completed, they were of relatively stagnant water released from artesian storage within small cylindrical volumes of the aquifers. The second set of samples, collected 3 (well 19) and 4 (well 24) years later, after the cones of depression had greatly enlarged, represented water that had moved at a slightly faster rate from much larger cylindrical volumes of the aquifers. The reasons for the reduction in hardness of about 40 percent, by the decrease in content of calcium and magnesium and increase in content of sodium, are not known, but certain speculations seem warranted.

The physical and hydrologic properties and the chemical composition of the aquifers and their contained minerals, such as clay, probably vary from place to place within the cones of depression, as elsewhere. In turn, the water varies somewhat in chemical composition from place to place within the cones of depression and elsewhere, as indicated in table 8. The samples collected after the cones of depression had enlarged were mixtures of waters of somewhat different composition from all parts of large volumes of the aquifers, so would not be expected to be of the same composition as the relatively stagnant water sampled soon after the wells were drilled. Moreover, the increased velocity of the water moving toward the wells may have accelerated the softening by allowing more of the residual calcium and magnesium ions to come in contact with clay minerals and be exchanged for sodium ions.

The reduction in hardness of the water from well 19, which taps the Entrada, Wingate, and Kayenta Formations, may have resulted in part also from the fact that a greater proportion of the flow in 1955 (second sample) may have come from the Wingate Sandstone because of less drawdown interference in this less intensely developed aquifer.

The first sample from well 31 was obtained more than 40 years after the well had been drilled; the well was reported to have flowed continuously during this long period and the cones of depression in the two aquifers (Entrada and Wingate Sandstones) had become very large before the first sample was collected. The second sample, collected 9 years after the first, was almost identical in chemical composition to the first sample, and had only 5 ppm less hardness. This similarity suggests that thorough mixing of waters from all parts of the cones of depression had occurred before the first sample was collected.

Percent sodium, and sodium-adsorption ratio.—When soils containing exchangeable Ca^{++} and Mg^{++} ions are irrigated with water in which the percentage of Na^{+} to $Ca^{++}+Mg^{++}+Na^{+}$ is considerably above 50, such soils take up sodium in exchange for calcium and magnesium and tend to deflocculate; they thus become impaired in tilth and permeability. The percentage of sodium given in table 8 ranges from 58 to 99, and in 19 of the 26 samples it is 75 or more.

A better method of expressing the suitability of water for irrigation involves computation of the sodium-adsorption-ratio, SAR (U.S. Salinity Laboratory Staff, 1954), from the following relation, in which ion concentrations are expressed in equivalents per million.

$$\mathrm{SAR}=\frac{Na^{+}}{\sqrt{\frac{Ca^{+2}+Mg^{+2}}{2}}} \qquad (20)$$

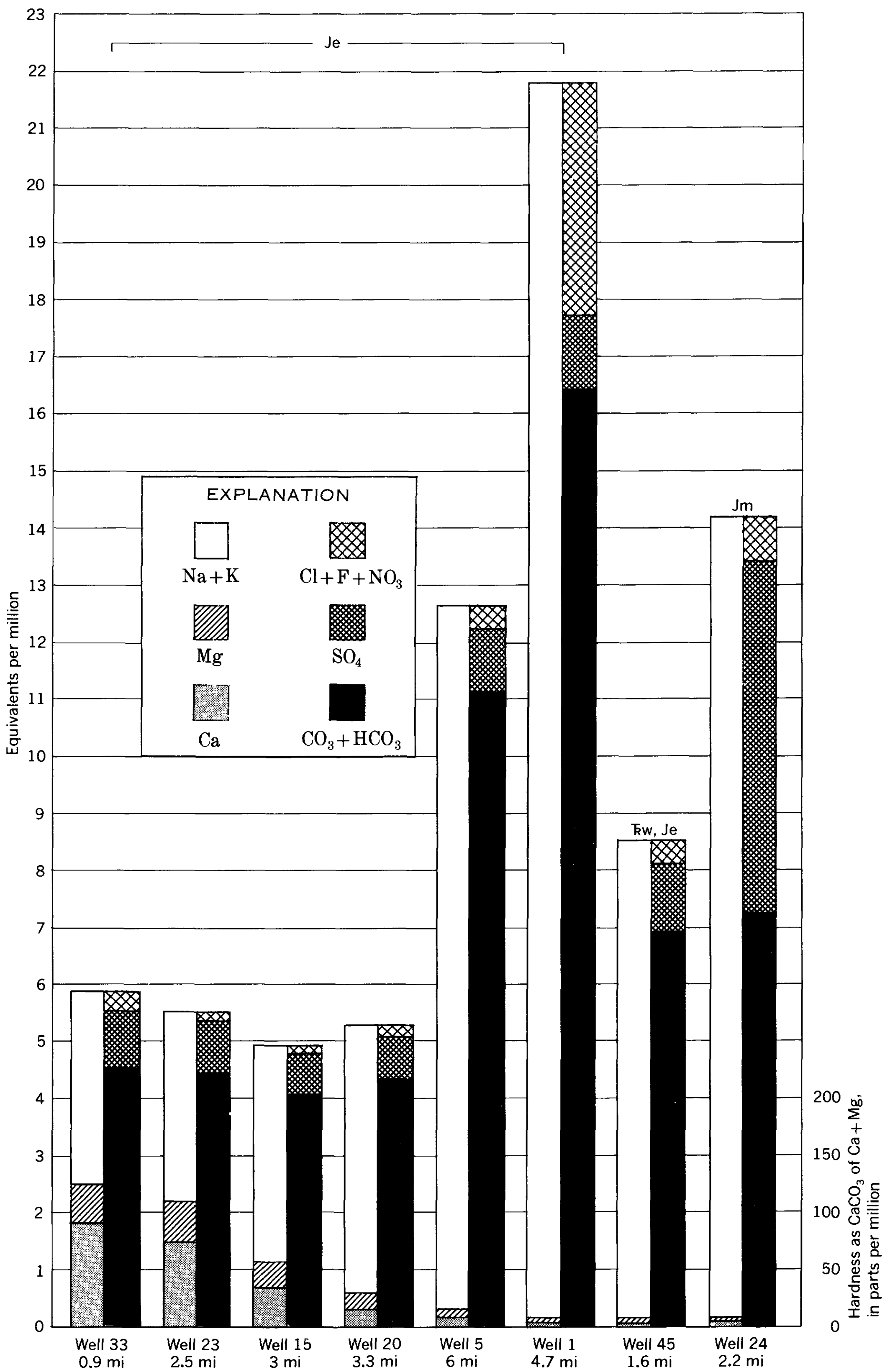


FIGURE 46.—Analyses of samples of typical water from the three principal aquifers in the Grand Junction area, and relation of softening by base exchange of water from the Entrada Sandstone to distance from the recharge area. Je, Entrada Sandstone; Ʀw, Je, Wingate and Entrada Sandstones; and Jm, Morrison Formation.

and then plotting the SAR values against the specific conductance in the manner shown in figure 47.

According to figure 47, the 26 samples of artesian water range from medium to high in salinity hazard and from low to very high in sodium (alkali) hazard. The samples having the highest hazard ratings of both types were from wells 17 and 24 in the Morrison Formation and from well 1 in the Entrada Sandstone.

Although most of the water from artesian wells in the Grand Junction area is used for drinking and cooking, for which it is well suited, some has been used for small plots of lawn, shrubs, and garden crops, and, as shown in figure 47, some of the water may be injurious to certain soils and crops. For the tolerances of various crops to water of various degrees of sodium and salinity hazards the reader is referred to the report of the U.S. Salinity Laboratory Staff (1954).

Specific conductance.—The specific electrical conductance is the ability of a fluid or substance to conduct an electric current, and is the reciprocal of the electrical resistance. It is expressed in micromhos per cm^3 at 25° C., which is the same as $\frac{1}{\text{megohms}}$ per cm^3 at 25° C. The specific conductance is a measure of the number of ions in solution, hence is approximately proportional to the amount of dissolved solids in solution. The specific conductance, which is easily and quickly determinable in the field or laboratory, is very convenient for preliminary sampling to determine the ranges in concentration to be expected or as a check on laboratory analyses. For most natural water, the specific conductance times a factor ranging from 0.55 to 0.75 is equal to the concentration of dissolved solids in parts per million.

Hydrogen-ion concentration (pH).—The hydrogen-ion concentration is expressed as the pH, which is the reciprocal of the logarithm (base 10) of the hydrogen-ion concentration in moles per liter. A neutral water has a pH of 7.0, which indicates an equal number of H^+ and OH^- ions; an alkaline water has a pH of more than 7.0, which indicates a preponderance of OH^- ions; and an acidic water has a pH of less than 7.0, which indicates a preponderance of H^+ ions.

Of the samples for which the pH was determined, the values range from 7.9 to 8.8 and indicates that these samples are slightly alkaline. This range is to be expected, for these waters are dominantly bicarbonate and carbonate of sodium, which hydrolize to form nearly completely dissociated NaOH and only slightly dissociated H_2CO_3, so that the number of OH^- ions in solution exceeds the number of H^+ ions.

Hydrogen sulfide.—A small amount of hydrogen sulfide gas (H_2S) gives a slightly unpleasant odor and taste to the water from wells 1 and 2 in the Entrada Sandstone, and was reported in the water from well 14 in the Dakota Sandstone and Burro Canyon Formation. In the small amounts present, the hydrogen sulfide in the water is harmless, and all or most of it can be removed by aeration, as is done at well 1.

Hydrogen sulfide is not unusual in water from the Dakota Sandstone because of the associated lignite coal and lignitic beds which chemically reduce some of the sulfate to sulfide. Hydrogen sulfide in water from the Entrada Sandstone, however, is unusual in this area, and not readily explicable unless sulfate-reducing bacteria were introduced during the drilling of these wells and this does not seem likely.

SANITARY CONSIDERATIONS

The water from some wells, particularly shallow wells in unconfined aquifers that are not properly sealed at the surface, may be contaminated with micro-organisms by entrance or percolation of surface water or drainage from sources of contamination such as barnyards or privies. Such contaminated water commonly has an abnormally high concentration of nitrate.

The artesian wells in the Grand Junction area generally are adequately protected against the possibility of such contamination (see "Construction," p. 107, 108), and all the water samples analyzed contained very small amounts of nitrate (table 8).

USE OF ARTESIAN WATER

USE IN 1960

The use of water indicated for each artesian well in table 7 is as of 1960. The water from most of the wells was used for domestic purposes, either by the owner alone, by the owner and from 2 or 3 to as many as 60 other nearby homes connected by pipeline to the well and storage system, or by hauling to homes equipped with storage cisterns or tanks. In most, but not all, homes supplied with artesian water, the water was used for household purposes only, for most of the residents have access to water from irrigation ditches for use on lawns, shrubs, and gardens. However, some of the artesian water is used for watering small tracts of lawn or other vegetation.

From 1 to as many as 30 tankloads of water per day are hauled from 13 of the wells, and the water from several wells is used entirely in this manner. The standard tank used by water haulers in the Grand Junction area holds 1,100 gallons. In 1960 and for several preceding years, a standard charge of $3.00 per tank load of water was made for deliveries within short distances, and a nominal additional mileage charge was added for deliveries to more distant points.

In 1960, three wells were used entirely for watering stock, three were used for domestic and stock needs,

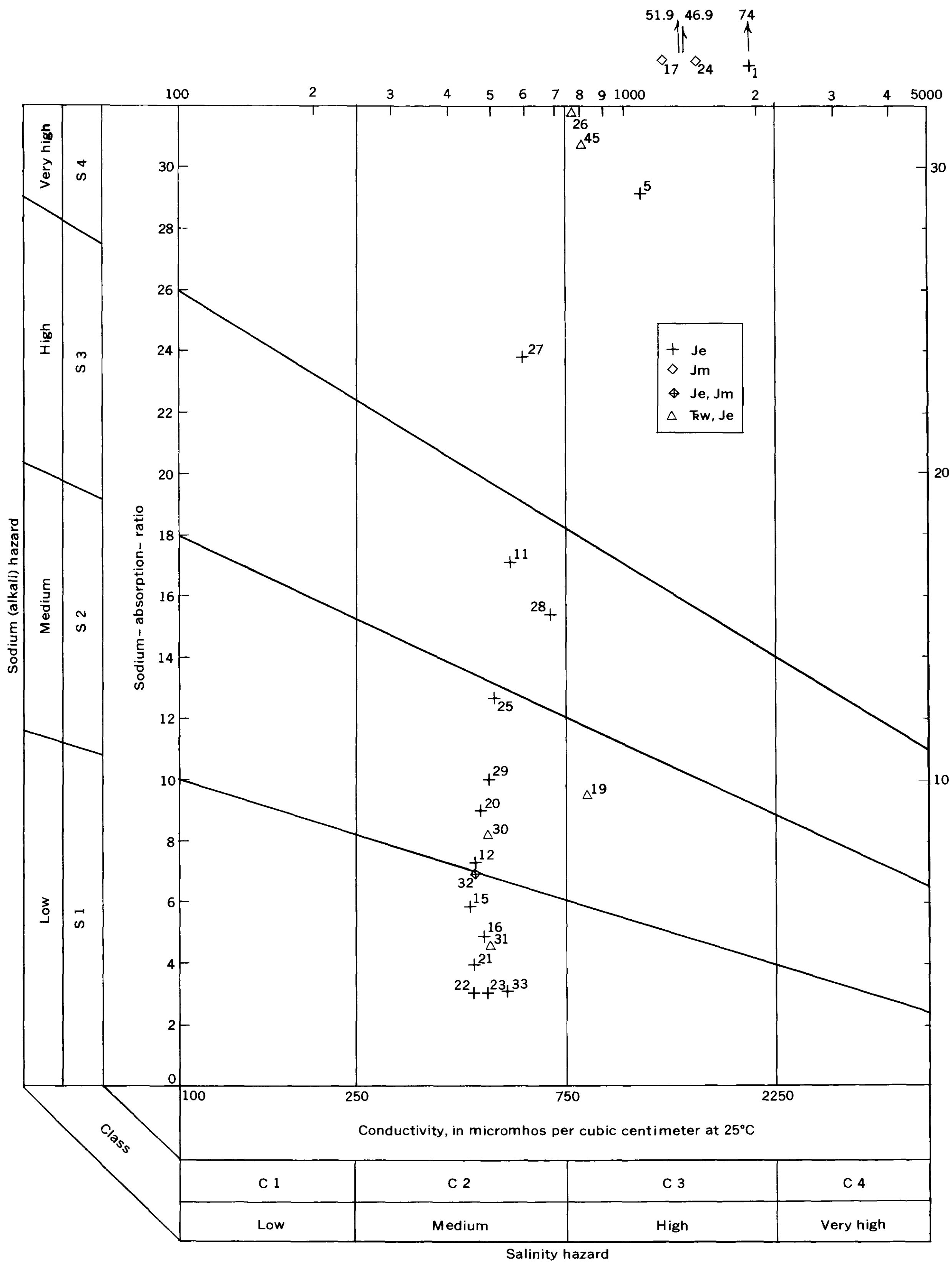


FIGURE 47.—Diagram showing the suitability of waters from artesian wells in the Grand Junction area for irrigation. Adopted from U.S. Salinity Laboratory Staff (1954).

one (11) was used by a meat-packing plant, and one domestic-supply well (12) also was used to fill a swimming pool. Four of the wells were not in use.

POSSIBILITIES OF DEVELOPMENT OF ADDITIONAL ARTESIAN WATER

In the sections on "Interference between wells" and "Declines and fluctuations in head," it was made apparent that the principal artesian aquifers—the Entrada Sandstone, and to a lesser extent also the Wingate Sandstone—have been intensively developed in parts of the Grand Junction area. The extent of such development, particularly in the eastern part of the Redlands and the western part of Orchard Mesa, is shown by the close groupings of wells on plate 1.

Two large areas underlain by the two principal aquifers are undeveloped or only slightly developed, and would yield additional artesian water to wells, preferably spaced more than a mile apart. One area is the southwestern side of the Grand Valley and the Redlands in Ranges 2 and 3 West (Ute P.M.) in and northwest from the northwestern part of the area and extending northwestward to or beyond Loma. Properly constructed wells into these aquifers in all or most of this area should have sufficient artesian head to flow at the land surface. The other area comprises the southwestern side of the Grand Valley, parts of Orchard Mesa, and the lower part of the Gunnison River valley in R. 1 and 2 E. (Ute P.M.). In the Grand Valley, Orchard Mesa, and along the Gunnison River below about the mouth of Bangs Canyon, the head should be high enough to produce flows at the land surface, but in much of the lower Gunnison River valley including the part traversed by U.S. Highway 50, the head probably is insufficient to reach the land surface. The reasons flows at the surface probably cannot be expected in the vicinity of Whitewater are given on page 101

Sandstone lenses in the Morrison Formation are not fully developed as aquifers, and they are not amenable to planned development for the reasons given on page 95.

The sandstones in the Dakota Sandstone and Burro Canyon Formation are tapped by very few wells but, because of the generally poor quality of the water (p. 63), very little additional development of water from these formations is likely or anticipated.

PUBLIC WATER SUPPLIES

Grand Junctions and Fruita have municipal water supplies piped from distant surface-water sources. The water for Grand Junction comes from impounding reservoirs on Kannah Creek and North Kannah Creek about 16 miles southwest of the city. These creeks drain a part of the western flank of Grand Mesa. The Grand Junction system also supplies water to the West Orchard Mesa District and the communities of Clifton and Whitewater. Fruita is supplied from stream- and spring-fed reservoirs on Piñon Mesa, about 22 miles to the south. The pipeline traverses the northwestern part of Colorado National Monument and supplies water to the facilities in the headquarters area. Water for the facilities at the No Thoroughfare Canyon entrance is obtained from well 35.

Some water is hauled to rural residents from the municipal supply systems of Grand Junction and Fruita, and also of Palisade, which is about 10 miles northeast from Grand Junction.

The Colbran Project of the U.S. Bureau of Reclamation (1961), construction of which began in 1961, supplies irrigation water to 2,310 acres of new land and supplemental water to 18,340 acres of irrigated land, all in Plateau Creek valley north of Grand Mesa; it generates electrical energy for use in west-central Colorado and provides 20 cfs (cubic feet per second) of water to the Ute Conservancy District for piping domestic water to several towns and most rural residents in the Grand Valley. A secondary adjudication provides an additional 50 cfs at certain times. The water comes from streams, lakes, and reservoirs on the north flank of Grand Mesa, and is of excellent quality for domestic use after a minimum of treatment.

According to Richard J. Mandeville (Western Engineers, Grand Junction, consultants to the Conservancy District, oral communication, Feb. 1964), the main pipeline connects with a turnout in the tailrace of the Lower Molina Power Plant, near Molina, Colo., follows Plateau Creek and the Colorado River to Palisade, traverses the southwestern side of the Grand Valley by way of Orchard Mesa, and extends as far west as Mack. Cross and connecting lines extend to all parts of the valley, including all of Orchard Mesa and the Redlands. Most residents, several towns, and many industrial plants have already signed contracts, and it is expected that, eventually, virtually all rural and town residents will be connected to the system. Construction began in September 1963, was 25 percent completed in February 1964, and is scheduled for completion in October 1964.

Completion of the water system of the Ute Conservancy District should greatly reduce the draft on the artesian wells in the Grand Junction area by eliminating all or most water hauling and distribution of artesian water to nearby homes by pipeline. If the draft on the wells is reduced to just the needs of the individual owners, the declining artesian head should be arrested, and in time the head may gradually recover. Because of the small rate of recharge, however, the complete recovery in head will take considerable time. Thus, the completion of the planned water system will be of great benefit to the artesian systems in the Grand Junction area.

MEASURED GEOLOGIC SECTIONS

The three measured sections given below are quoted from Craig's open-file report (1959).

Black Ridge section, in and north of sec. 18, T. 11 S., R. 102 W.

[Measured by C. N. Holmes, July 1949]

	Thickness (feet)
Dakota Sandstone (incomplete):	
100. Sandstone, grayish yellow, medium- to medium-fine-grained, friable, iron-stained; coarse quartz grains along crossbedding	17. 8
99. Covered	43. 2
98. Carbonaceous shale, black	3. 0
97. Covered	2. 6
96. Carbonaceous shale, black	7. 4
95. Sandstone, conglomeratic, dusky yellow, medium-grained sandstone matrix; pebbles are mainly light colored sandstone and limestone	12. 2
Total Dakota measured	86. 2
Burro Canyon Formation:	
94. Covered	150±
Total Burro Canyon (approximated)	150±
Morrison Formation:	
Brushy Basin Member:	
93. Covered	65±
92. Mudstone, dark reddish brown	9. 2
91. Mudstone, grayish red	10. 8
90. Mudstone, light-gray, somewhat bentonitic	12. 4
89. Silty shale, dark-reddish brown	20. 2
88. Limestone, medium-gray, dense	. 2
87. Mudstone, silty, pale red, clay binding	30. 8
86. Sandstone, light-gray, fine-grained	. 8
85. Mudstone, dark-reddish brown	21. 6
84. Bentonitic clay, white	6. 7
83. Sandstone, light-gray, very fine-grained; concretionary, rounded weathering	. 7
82. Mudstone, dark-reddish brown	10. 4
81. Clay shale, light gray	10. 8
80. Mudstone, dark-reddish brown, silt and fine sand with clay binding	17. 4
79. Sandstone, pale-red, weathering brown, fine-grained; hard, siliceous; lenticular; concretionary weathering	. 9
78. Clay shale, grayish red	6. 7
77. Limestone, medium-gray, weathering brown, very hard, dense	. 6
76. Clay shale, light gray, frothy	14. 8
75. Mudstone, dark-reddish brown	6. 5
74. Sandstone, grayish green, very fine-grained; hard, siliceous	1. 0
73. Mudstone, olive-gray	2. 6
72. Siltstone, light-gray, thin-bedded	1. 2
71. Mudstone, brownish gray, clay binding; fine sand grains	2. 2
70. Sandstone, grayish green, very fine-grained; hard	1. 3
69. Clay shale, grayish brown	6. 5
68. Sandstone, light-gray, fine-grained; contains fine black accessory minerals; hard, siliceous	. 8
67. Clay shale, brownish gray, fissile; light-gray weathering slope	9. 0
66. Mudstone, dark-reddish brown; very fine quartz grains and silt with clay binding	12. 5

Black Ridge section, in and north of sec. 18, T. 11 S., R. 102 W.—Continued

	Thickness (feet)
Morrison Formation—Continued	
Brushy Basin Member—Continued	
65. Sandstone, light-gray, weathering brown, fine-grained, hard	0. 9
64. Mudstone, dark-reddish brown	5. 1
63. Sandstone, very light-gray, weathering dark-yellowish brown, fine-grained; fine black accessory minerals, red chert; hard, siliceous	4. 5
62. Mudstone, very dusky red, some white mottling; contains rounded fine quartz grains, white clay specks	9. 5
Total Brushy Basin (thickness rounded)	304
Salt Wash Member:	
61. Sandstone, yellowish gray, fine-grained; fine black accessory grains	1. 3
60. Covered	1. 2
59. Sandstone, yellowish gray, fine-grained; black accessory grains; some iron stain	1. 4
58. Mudstone, dark-reddish brown	4. 4
57. Sandstone, yellowish gray, medium-fine-grained; contains red and white chert and black accessory minerals; friable; lenticular	9. 2
56. Covered	8. 4
55. Sandstone, yellowish gray, fine-grained; contains red and white chert grains; lenticular	14. 4
54. Mudstone, pale-yellowish brown grading to dark-reddish brown along strike	6. 9
53. Sandstone, grayish yellow, fine- to medium-grained; lentils of fine angular white chert; very friable; channeling, crossbedding; some iron stain; wormy weathering	34. 0
52. Covered	4. 7
51. Sandstone, pinkish gray, fine- to medium-fine-grained; contains fine black accessory grains	3. 9
50. Mudstone, dark-reddish brown	5. 0
49. Sandstone, yellowish gray, medium-grained; composed of subrounded clear quartz, scattered yellow, red, and white chert grains; friable; channeling, lenticular	15. 4
48. Siltstone, dark-reddish brown	6. 4
47. Sandstone, yellowish gray, fine-grained; light iron stain; contains red and white chert grains; friable; lenticular, channeling	25. 5
46. Mudstone, light-grayish green	2. 0
45. Mudstone, dark-reddish brown	3. 9
44. Sandstone, yellowish gray, fine-grained; contains fine red and white chert grains and black accessory grains; channeling	3. 6
43. Covered	4. 6
42. Sandstone, light-gray, fine-grained; contains scattered red and black accessory minerals, some angular white chert; crossbedded, channeled, lenticular; wormy weathering, jointed N. 15° E	10. 8
41. Mudstone, light-grayish green, very silty	2. 4
40. Mudstone, dark-reddish brown	18. 0
39. Siltstone, very light-gray, rubbly slope	2. 1
38. Mudstone to siltstone, grayish red	15. 8

Black Ridge section, in and north of sec. 18, T. 11 S., R. 102 W.—Continued

	Thickness (feet)
Morrison Formation—Continued	
Salt Wash Member—Continued	
37. Sandstone, very light-gray, fine-grained, hard, siliceous	.4
36. Mudstone, olive-gray	5.2
35. Limestone, medium light-gray, dense	.5
34. Mudstone, dark-reddish brown	1.2
33. Sandstone, very light gray, fine-grained; contains black accessory grains, uniform, hard	1.3
32. Siltstone, light-brownish gray	6.2
31. Mudstone to siltstone with scattered fine sand grains, dark-reddish brown; contains rounded amber fine quartz grains	6.7
30. Sandstone, yellowish gray, medium-fine-grained; lenticular, channeled, jointed N. 10° E	10.6
29. Siltstone, light brown, iron-stained	2.0
28. Limestone, medium light gray, dense; fossiliferous (gastropods)	.9
27. Covered	14.9
26. Sandstone, yellowish-brown, fine-grained, iron-stained; some crossbedding	3.5
25. Covered	10.2
24. Sandstone, dark-yellowish brown, weathering dark-brown, medium-fine- to coarse-grained, coarse black accessory grains, white chert and quartz grains	6.5
23. Covered	20.1
Total Salt Wash (thickness rounded)	296
Total Morrison (thickness rounded)	600
Summerville Formation:	
22. Sandstone, yellowish brown, fine-grained, iron-stained; even-bedded, jointed blocky weathering	3.9
21. Sandstone, yellowish brown, fine-grained, stringers of medium-fine quartz grains and coarse black accessory grains, even horizontal bedding; jointed blocky weathering; "salt and pepper" sand	5.0
20. Silty shale, light-grayish green	.5
19. Sandstone, yellowish brown, fine-grained, fine black accessory grains, limonitic stains; even-bedded	2.6
18. Mudstone, mainly silt size, dark-reddish brown, irregular layers of irregularly shaped concretions of limestone, shale, and limy sandstone from 2 to 16 in. in diameter; top 2 ft is greenish gray mudstone	8.2
17. Shale, silty, dark-greenish gray	5.4
16. Mudstone, dark-reddish brown, partly covered; thin sandstone interbeds	13.3
15. Shale, medium dark gray, very fissile	.5
14. Mudstone, dark-reddish brown, contains scattered sand grains	2.4
13. Sandstone, reddish brown, medium-fine-grained; white banding	1.1
12. Silty shale, dark-reddish brown, fissile; mica flecks	.8
11. Sandstone, white, fine-grained, contains red chert and black accessory grains	5.3
10. Mudstone, dark-reddish brown, contains scattered medium quartz grains	3.9
Total Summerville (thickness rounded)	53
Entrada Sandstone:	
Moab Member:	
9. Sandstone, pinkish gray, very fine-grained; contains scattered well-rounded medium-fine quartz grains; black accessory grains; uniform, ledge-forming with very thin shale partings	6.0
Slick Rock Member:	
8. Sandstone, pinkish gray to moderate-reddish orange, fine-grained; contains scattered well-rounded medium quartz grains and black accessory grains; calcareous cement; forms vertical cliff	155
Total Entrada (thickness rounded)	161
Kayenta Formation:	
7. Sandstone, pale-red, banded, fine-grained; contains abundant mica and white and black accessoryminerals; calcareous cement	2.0
6. Sandstone, yellowish orange, medium-fine-grained; contains white chert, black accessory grains	31.9
5. Sandstone, yellowish gray, fine-grained, subangular; black accessory minerals; calcareous cement; several lenses of dark red siltstone	22.0
4. Sandstone, reddish brown, medium-fine-grained; thin-bedded; contains abundant mica along bedding; highly crossbedded	23.6
3. Sandstone, grayish red-purple to grayish orange, medium-fine-grained; contains subangular black accessory grains and white chert; highly cross-bedded, occasional silty shale partings; flaggy weathering	47.5
Total Kayenta (thickness rounded)	127
Wingate Sandstone (incomplete):	
2. Sandstone, yellowish gray, weathering reddish orange, fine-grained, subangular; contains scattered black accessory grains, uniform; cliff-forming	100
1. Base not exposed.	
Total Wingate measured (thickness rounded)	100

Ladder Canyon section, measured on east side of Ladder Canyon from vicinity of old mica mine to prominent knob east of Jacobs Ladder road; secs. 19, 30, and 31, T. 12 S., R. 100 W.

[Measured by C. N. Holmes and L. C. Craig, Apr. 1948]

	Thickness (feet)
Burro Canyon Formation (incomplete):	
85. Sandstone, light-brown, fine-grained; calcareous cement; limonite specks; forms resistant ledge	3.7
84. Shale, silty, chocolate red	5.2
83. Siltstone, red stained; well-fractured	.4
82. Shale, white on fresh outcrop, weathering brown; well-fractured	5.3
81. Shale, grayish green, slightly silty	25.0
80. Clay shale, grayish white, silty; forms frothy slope	15.2
79. Sandstone, buff outcrop; powdery calcareous cement; finely crossbedded; limonite flecks; 0.2 ft clay and shale seam under 2 ft sandstone ledge at top	15.3

Ladder Canyon section, measured on east side of Ladder Canyon from vicinity of old mica mine to prominent knob east of Jacobs Ladder road; secs. 19, 30, and 31, T. 12 S., R. 100 W.—Con.

	Thickness (feet)
Burror Canyon Formation (incomplete)—Continued	
78. Conglomerate, weathering yellowish brown, pebbles as much as 1 in. in diameter of gray chert, well-rounded to very angular quartz, green and red chert; clay and shale particles	1.7
77. Clay, bentonitic, yellowish brown stain	5.0
76. Shale, silty, dark-maroon, red, and gray; forms rubbly slope	5.4
75. Conglomerate, weathering yellowish brown; contains clay and shale particles as large as ¼ in. in diameter, red and green chert; crossbedded; sandstone matrix composed of medium-sized quartz grains; forms lenticular ledge	3.0
Total Burro Canyon measured (thickness rounded)	85
Morrison Formation:	
Brushy Basin Member:	
74. Shale, bentonitic, clayey, slightly silty; lower 110 ft is gray-green to brown, upper part is similar but with a few beds of thin red nonbentonitic silty shale; contains several 6 in. beds of brown-weathering fine-grained sandstone and several thin lenses of light-gray, brown-weathering calcilutite with disseminated quartz grains. Shale is predominantly frothy weathering; contains 1 ft of limy shale at top	171
73. Sandstone, green, weathering brown, fine-grained	1.8
72. Shale, bentonitic, clayey, grayish green; silty in places	30.0
71. Sandstone, white, fine- to very coarse-grained; contains abundant red and amber accessory minerals. Top and bottom 6 in. are well cemented, brown-weathering and resistant, remainder is poorly cemented. Unit is crossbedded; massive	17.2
70. Shale, grayish green, silty; 2 ft red shale at top marks top of lower red part of Morrison. Unit is frothy weathering	16.5
69. Shale, silty, dark-red; contains disseminated quartz grains; tight cementing on fresh surface; thin lenses of fine- to medium-fine-grained sandstone along strike; scattered white chert grains	17.7
68. Shale, sandy and silty, dark-red; contains very fine red-stained quartz grains; 2 ft bed of fine-grain-sized sandstone at top	14.1
67. Sandstone, light-brown, fine-grained; tight cementing	4.5
66. Shale, sandy; red; contains thin lenses of green fine-grain-sized sandstone. Shale contains abundant medium-sized quartz grains	3.0
65. Sandstone, weathering white to brown, grades from fine-grained at base to medium-coarse-grained near top; composed of angular to subangular clear quartz with red and yellow and common green accessory minerals; poorly sorted; poorly cemented, friable; crossbedded	39.2

Ladder Canyon section, measured on east side of Ladder Canyon from vicinity of old mica mine to prominent knob east of Jacobs Ladder road; secs. 19, 30, and 31, T. 12 S., R. 100 W.—Con.

	Thickness (feet)
Morrison Formation—Continued	
Brushy Basin Member—Continued	
64. Shale, silty and sandy, reddish maroon; contains 2 in. lenticular limestone and both red and white thin fine-grained sandstone beds	10.6
63. Sandstone, reddish brown, very fine to fine-grained; weathering brown and wormy	4.2
62. Shale, red to reddish brown and grayish green, silty to sandy; contains lenses of very fine-grained white sandstone. Note: Within ½ mile east of section the base of the Brushy Basin is marked by a conspicuous ledge of conglomerate containing red and green chert granules. Stratigraphically this ledge may correspond to unit 63 above, but lenticularity of beds prevents exact correlation. Base of Brushy Basin arbitrarily placed at top of top Salt Wash-like sandstone ledge on line of section	12.2
Total Brushy Basin (thickness rounded)	342
Salt Wash Member:	
61. Sandstone, white to pale-brown, fine- to medium-grained; poor sorting; composed of subangular to rounded clear quartz and minor red chert; scattered clay pellets; poorly cemented	13.4
60. Siltstone, dark-red and green banded; in part shaly and paper weathering; even-bedded	1.6
59. Shale and sandstone, brown, fine- to medium-grained, poorly sorted; composed of subangular to rounded quartz, poorly cemented; thin gray shale partings; even-bedded, beds as much as 1 ft thick	5.5
58. Sandstone, white to pale brown, medium- to coarse-grained at bottom to fine-grained at top; composed of clear quartz with minor pink and amber accessory minerals; fairly well sorted; poorly cemented; crossbedded; limonite stains, channeling wedges	27.8
57. Shale, slightly silty, dark-brown to gray, fissile	.5
56. Sandstone, white to pale-brown, fine- to medium-fine-grained, fair degree of sorting; composed of well-rounded to sub-angular clear quartz; crossbedded	10.8
55. Sandstone, pale-brown, medium-fine-grained, very poorly sorted; composed of subangular to well-rounded clear quartz and minor pink, amber, and red accessory minerals; clay pebbles weather out leaving holes in the sandstone; conglomerate of claystone and limestone pebbles at bottom	2.4
54. Shale, poorly exposed, silty, grayish green green, forms slope	21.0
53. Covered	21.0

Ladder Canyon section, measured on east side of Ladder Canyon from vicinity of old mica mine to prominent knob east of Jacobs Ladder road; secs. 19, 30, and 31, T. 12 S., R. 100 W.—Con.

	Thickness (feet)
Morrison Formation—Continued	
Salt Wash Member—Continued	
52. Sandstone, medium-fine-grained, subangular, well-cemented; finely laminated	2. 0
51. Covered. Shale (?), gray-green, and sandstone, light-brown	31. 0
50. Limestone, gray-brown (dove), fine-grained	. 9
49. Shale, gray, green, and maroon, clay, silty; 6 in. of light-brown medium-grained sandstone near top	3. 9
48. Sandstone, pale-brown, fine- to very fine-grained; composed of clear quartz and colored accessory minerals	1. 0
47. Shale, gray-green and red, silty; forms rubbly slope	12. 8
46. Sandstone, white to light-brown, fine-grained; composed of angular to subangular clear quartz with pink, amber and gray accessory minerals; little cementing material; crossbedded; ledge forming	2. 8
45. Shale, sandy, grayish green in upper half, grayish green to maroon in lower half, rubbly; contains gray carbonaceous clay band near top and thin irregular brownish weathering limestone near bottom	12. 0
44. Limestone, gray-brown (dove-colored), aphanitic, slabby; contains 6 in. gray-green shaly parting in upper half	2. 8
43. Shale, silty to sandy, gray	5. 4
42. Sandstone, light-brown, fine- to medium-grained, evenly laminated	1. 8
41. Shale, silty to sandy, dark-grayish green; rubbly weathering; forms slope	6. 8
40. Limestone, medium-gray, aphanitic, slabby; contains sparse disseminated quartz grains. Unit contains bone fragment, ostracod and gastropod fragments, and algae(?) in upper part. Note: The Salt Wash-Summerville contact is difficult to place in this section. The lowest thick channeling sandstone of typical Salt Wash aspect is unit 56 and is well above the projected base of the Morrison. This fresh-water limestone (unit 40) is the lowest prominent limestone in the section and the base of Salt Wash is arbitrarily placed at the base of the unit. The mixed-grained sandstone, unit 47, and the carnelian-chert encrustations in unit 31 are characteristic of the Summerville Formation of western-most Colorado	1. 4
Total Salt Wash (thickness rounded)	189
Total Morrison (thickness rounded)	531
Summerville Formation:	
39. Shale, very sandy to silty, grayish green, poorly sorted, rubbly weathering, slope-forming	5. 2
38. Sandstone, light-brown, fine- to medium-fine-grained; unit is gently lenticular and appears as less resistant continuation of underlying unit. A few cuspate ripple marks and some crossbedding noted	5. 4
Summerville Formation—Continued	
37. Sandstone, light-brown, fine-grained, poorly sorted; composed dominantly of clear quartz but contains scattered very coarse rounded grains of quartz, and gray and black chert; finely ripple-marked; parallel-bedded; contains a few thin reddish partings in middle of unit	3. 4
36. Shale, brownish-gray to greenish-gray, rubbly weathering; contains numerous medium-sized rounded clear quartz grains in bottom few feet	10. 2
35. Clay, light-green, possibly bentonitic	. 2
34. Shale, silty, grayish-green, rubbly weathering, contains thin lenses of concretionary limestone	. 7
33. Clay, light-green, possibly bentonitic	. 3
32. Shale, silty, grayish-green, rubbly weathering, contains thin lenses of concretionary limestone	1. 5
31. Limestone, grayish-green, arenaceous, blebs and patches of finely botryoidal carnelian chert encrusting top of unit	. 4
30. Shale, silty, grayish-green, rubbly weathering; contains thin lenses of concretionary limestone	1. 6
29. Clay, slightly silty, light-green, possibly bentonitic	. 4
28. Shale, silty, grayish-green, rubbly weathering; contains sparse disseminated fine-grained clear quartz grains and a few pink and amber grains	1. 8
27. Shale, sandy, dark-red; contains disseminated subangular to rounded fine- to medium-grained amber-stained quartz. Contains a few beds that weather to red-brown concretionary limy fragments	7. 0
26. Sandstone, light-green, fine- to very fine-grained; composed of clear well-rounded quartz and sparse red accessory mineral grains; clusters of several grains form larger tightly cemented balls	. 4
25. Shale, dark-red, arenaceous; contains fine- to medium-grained scattered amber-stained quartz grains; a few beds that weather to red-brown concretionary fragments; 0.2 ft dark maroon clay shale at top	8. 5
24. Shale, sandy, bright-green with red stringers and mottlings; contains amber-colored grains in limonite-stained rock, grains are silt- to medium-sized; poorly sorted; concretionary beds with dark-gray hard limestone centers	2. 1
23. Sandstone, white, purple, and red mottled; composed of very well-rounded quartz grains; calcareous cement	. 2
22. Sandstone, yellow-brown to dark-brown, very limonitic; composed of amber-stained well rounded quartz; platy to shaly weathering	. 2
Total Summerville (thickness rounded)	50

Ladder Canyon section, measured on east side of Ladder Canyon from vicinity of old mica mine to prominent knob east of Jacobs Ladder road; secs. 19, 30, and 31, T. 12 S., R. 100 W.—Con.

	Thickness (feet)
Entrada Sandstone:	
21. Sandstone, very fine-grained; composed of uniform well-sorted clean quartz grains; forms traceable unit of Entrada. Top contact is gradational	12.0
20. Sandstone, whitish yellow to buff, fine- to medium-grained; ledges peel back along horizontal bedding planes; beds 1–3 ft thick; little or no cementing material; contains scattered medium-coarse rounded quartz grains	39.0
19. Sandstone, white-buff, fine- to medium-grained; composed of rounded to angular quartz. Lower 10 ft of this interval is crossbedded; the upper 12 ft is parallel bedded with beds 1–2 ft thick	22.0
18. Sandstone, orange red, medium-fine-grained; composed of rounded to angular quartz grains; horizontal bedding; unit forms the main ledge of the formation	46.0
17. Sandstone, grayish white to orange, medium-fine-grained; grains well-rounded to angular, smaller grains more angular, and large grains perfectly rounded and most abundant in the lower 20 ft of the bed. Basal contact is a sharp slightly irregular bedding plane marking the base of occurrence of the large well-rounded grains. One bed of the Kayenta wedges out beneath contact. Kayenta weathers to form prominent bench	20.0
Total Entrada (thickness rounded)	139
Upper 73 feet of Entrada probably is Moab Member; lower 66 feet, Slick Rock Member	
Kayenta Formation:	
16. Sandstone, white, weathering pink, fine- to medium-grained; composed of angular to subangular clear quartz; even slabby-weathering beds	8.0
15. Sandstone, white to buff, fine- to medium-grained; composed of angular to subangular clear quartz, fairly well sorted; friable to tightly cemented	8.0
Total Kayenta	16
Wingate Sandstone:	
14. Sandstone, white to yellow on weathered surface, fine-grained, fairly well sorted; composed of angular to perfectly rounded quartz grains; friable; crossbedded	20.0
13. Sandstone, orange to white, medium- to fine-grained; forms massive cliff	237.0
12. Sandstone, orange-red, fine- to medium-fine-grained	31.0
11. Sandstone, orange-buff, very fine-grained; contains scattered medium-grained perfectly rounded grains	31.4
10. Sandstone, white, medium-fine-grained; contains scattered coarse grains, poorly sorted; hard, dense; calcareous cement; a similar thin layer is present in Unaweep Canyon section. Basal contact is sharp; change in color from brick-red Chinle to white and pale-brown sandstone of Wingate, slight change in grain size from silt-sized Chinle to very fine- to fine-grained sandstone of Wingate	0.6
Total Wingate (thickness rounded)	320
Chinle Formation:	
9. Siltstone, brick-red; concretionary weathering, concretions are rounded and unstratified, boulders of siltstone are 2 ft in diameter	17.9
8. Siltstone, shaly, brick-red; forms small ledge; laminated	6.2
7. Siltstone, lowest 3 in. contains clay galls; 20 ft of well-fractured shaly rubbly slope-forming siltstone in middle part; top 4 ft is concretionary weathering, concretions are 1 ft to 1 mm in diameter, small concretions have conglomerate-like appearance. Concretions are siltstone throughout	24.0
6. Siltstone, brick-red, mottled white in places; highly fractured; channel cut and fill suggests stream deposition	13.8
5. Siltstone, brick-red, arenaceous; 2-in. conglomerate, maximum size pebbles, 1 in	5.9
4. Siltstone, brick-red, arenaceous; faint laminations; contains clay galls	1.0
3. Siltstone, red; part of the interval covered with siltstone talus	15.2
2. Covered; granitic soil, talus and siltstone. Contact with igneous and metamorphics covered with several feet of weathered granite and talus; contact forms a bench 15–20 ft wide in stream canyon	11.0
Total Chinle (thickness rounded)	95
Precambrian complex:	
1. Gneiss and schist, pegmatites; granitic rocks are intrusive in older metamorphics. Mica mine located nearby in canyon.	

East Unaweep Canyon section, sec. 1–3, T. 14 S., R. 100 W.

[Measured by C. N. Holmes, May 1948]

	Thickness (feet)
Burro Canyon Formation (incomplete):	
116. Top of exposure, not top of formation.	
115. Sandstone, yellow-brown to buff, medium- to medium-coarse-grained; quartz grains well-rounded, friable, crossbedded; small pockets of chert and quartz pebbles 3 in. in diameter; good sorting and rounding are striking feature for the extreme lenticular nature of bed; cut and fill channels	63.5
114. Conglomerate; light-brown; contains both angular and well-rounded fragments of black and white chert and quartz; lenticular unit, small lentils of conglomerate pinch out along strike within 25 ft	2.0

East Unaweep Canyon section, sec. 1–3, T. 11 S., R. 100 W.—Continued

	Thickness (feet)
Burro Canyon Formation (incomplete)—Continued	
113. Sandstone, light-brown, medium-grained; composed of well-sorted and rounded quartz grains; friable, porous, permeable	30.7
112. Covered	13.8
111. Conglomerate, yellow-brown, mainly chert and quartz pebbles 3 in. in diameter in sandstone matrix	3.0
Total Burro Canyon measured (thickness rounded)	113
Morrison Formation:	
Brushy Basin Member:	
110. Shale, chocolate-brown, silty, highly fractured	12.0
109. Sandstone, buff, very fine-grained; calcareous cement; jointed	6.0
108. Shale, reddish brown, silty, highly fractured	8.2
107. Sandstone, very fine-grained, hard, dense; forms small ledge	3.0
106. Clay, bentonitic	11.8
105. Clay shale, light-gray and chocolate-brown; forms tan-weathered slope	11.0
104. Clay, silty, and siltstone; light-brown	11.4
103. Clay, light-brown	11.0
102. Clay, silty; partly covered	22.4
101. Sandstone, light-brown, fine- to medium-grained, limonite spotted, friable; lenticular; forms bench on ridge	3.6
100. Covered	3.0
99. Clay, silty, forms white slope	25.0
98. Clay shale, light-gray	8.0
97. Shale, reddish brown, silty, highly fractured	11.0
96. Siltstone, red; shaly fracture	10.0
95. Clay, bentonitic, light-gray to white	1.0
94. Siltstone, red, shaly, highly fractured	5.0
93. Limestone, white, shaly; angular fracture; forms rubbly slope	5.0
92. Siltstone, limy, white	2.0
91. Claystone, light-gray; shaly fracture	10.4
90. Limestone, silty; contains disseminated coarse black chert grains	.6
89. Siltstone, red and white mottled; angular fracture	19.0
88. Siltstone, red and white mottled; contains scattered angular black chert grain	8.4
87. Shale, silty, red; partly covered	21.6
86. Sandstone, purple maroon, very fine-grained, 0.2 ft bed of coarse angular sandstone to fine conglomerate; containing red and yellow chert grains and granules	3.0
85. Shale, dark-red, silty, thin-bedded	16.0
84. Siltstone, red and white mottled; contains limy shale partings, siltstone concretions 6 in. in diameter along bedding plane	4.0
83. Siltstone, purple; forms rubbly slope	3.0
82. Claystone, purple-maroon, highly fractured; forms rubble-covered slope	2.8
81. Shale, silty, light-gray, limy	11.2
80. Shale, limy, white, thin-bedded	5.5
79. Aragonite	.1

East Unaweep Canyon section, sec. 1–3, T. 11 S., R. 100 W.—Continued

	Thickness (feet)
Morrison Formation—Continued	
Brushy Basin Member—Continued	
78. Siltstone, purple-maroon, highly fractured; forms steep rubbly slope	12.4
77. Siltstone, light-brown, shaly; highly fractured	5.0
76. Covered. Contact with Salt Wash Member difficult to determine at this section; the top thick crossbedded sandstone below the bentonitic clay was chosen. However, the lenticular nature of the sandstones of the Salt Wash makes it impossible to trace any one bed more than several hundred feet	4.6
Total Brushy Basin (thickness rounded)	298
Salt Wash Member:	
75. Sandstone, light-brown, fine- to medium-grained, well-rounded; crossbedded, 3-in. lensing conglomerate of angular shale fragments ¼ in. in diameter; unit forms vertical cliff; friable, permeable and porous. Unit may represent basal conglomerate of Brushy Basin in westernmost Colorado and eastern Utah but, in absence of chert pebbles, it is assigned here to the Salt Wash	16.0
74. Shale, red; partly covered	13.0
73. Sandstone, light yellow-brown, medium-fine-grained; subangular; friable; ledge forming	10.0
72. Shale, red, mottled white, limy	10.1
71. Siltstone, chocolate-brown, highly fractured; forms rubbly slope	10.2
70. Sandstone, yellow-brown, medium-fine-grained, fairly well sorted, subangular grains	3.5
69. Shale, red, silty	2.0
68. Sandstone, white, very fine- to medium-grained, well-sorted	6.0
67. Siltstone, red and white mottled; forms rubbly slope	28.0
66. Sandstone, light-brown, medium-fine-grained; speckling of limonite spots; subangular grains	5.6
65. Shale, red, highly fractured	9.7
64. Sandstone, light-brown, fine-grained, calcareous, tightly cemented	7.0
63. Shale, silty; interval partly covered	20.0
62. Sandstone, light-brown, medium-fine-grained limonite spots, tightly cemented; jointed	6.0
61. Covered	6.2
60. Sandstone, white, fine-grained, tightly cemented; thin-bedded	1.5
59. Sandstone, white, medium-fine-grained, friable; limonite stained spots; porous and permeable; crossbedded	15.0
58. Covered	11.2
57. Siltstone, red and white mottled, shaly, thin clay partings	45.0
56. Limestone, light-gray, crystalline, dense, jointed	1.0
55. Shale, light-gray, limy	4.6
54. Sandstone, light-brown, fine-grained, tightly cemented, dense; jointed, thin-bedded	2.4

East Unaweep Canyon section, sec. 1–3, T. 11 S., R. 100 W.—Continued

	Thickness (feet)
Morrison Formation—Continued	
Salt Wash Member—Continued	
53. Shale, light gray-green, silty, well-fractured	8.8
52. Covered	14.2
51. Sandstone, light-brown, medium-grained, friable, limonitic, fairly well sorted, angular to subangular grains; crossbedded	3.0
50. Shale, maroon-red, silty; well-fractured	1.0
49. Siltstone, gray, shaly	7.4
48. Limestone, dove-gray, dense; forms a resistant ledge	0.6
47. Siltstone, gray, shaly	5.0
46. Limestone, dove-gray, dense, ledge-forming	2.0
45. Siltstone, shaly, gray	2.0
44. Limestone, dove-gray, dense; concretions	1.0
Total Salt Wash (thickness rounded)	279
Total Morrison (thickness rounded)	577
Summerville Formation:	
43. Siltstone, gray, shaly	3.8
42. Sandstone, white, uniformly fine-grained; calcareous cement; forms ledge	2.0
41. Siltstone, dark-gray on fresh surface, shaly	4.2
40. Sandstone, white, fine-grained, dense; composed of subangular to angular grains; calcareous cement	1.0
39. Siltstone, dark-gray, shaly; forms light-gray weathered slope; highly fractured	6.4
38. Sandstone, white, fairly well-sorted, consists of subangular grains, contains coarse angular black chert grains; forms very persistent ledge for many miles	2.4
37. Siltstone, red and gray mottled, well-bedded, 0.2-ft limestone bed	3.4
36. Sandstone, white, dense, fine-grained; calcite crystals encrusting surface	1.7
35. Siltstone, dark-brown, shaly, highly fractured	10.1
34. Siltstone, gray, shaly, fractured	2.6
33. Siltstone, dark-brown; dense; gray limestone concretions 3 in. in diameter; highly fractured	2.5
32. Siltstone, gray, shaly, limy, highly fractured	11.0
31. Sandstone, white, well-sorted, subangular to well-rounded, friable; deep-red iron stain in part of sand	8.7
30. Sandstone to siltstone, dark-maroon, very limonitic, disseminated perfectly rounded amber coarse quartz grains	.2
Total Summerville (thickness rounded)	60
Entrada Sandstone:	
Moab Member:	
29. Sandstone, white, red stained; contains perfectly rounded coarse grains; friable, loose sandstone	16.2
28. Sandstone, white, poorly sorted; well-rounded to angular grains	1.0
27. Sandstone, white to slightly pink; contains clean angular to subangular quartz grains, friable; bench forming	22.4
26. Sandstone, pinkish-white, medium- to fine-grained, angular to perfectly rounded quartz grains; horizontal bedding, forms bench weathering back from "slick rim" cliff	5.6
25. Sandstone, orange-red, medium-grained; angular to subangular grains, horizontal bedding	2.1
Total Moab Member	47.3
Slick Rock Member:	
24. Sandstone, orange-red, medium-grained; forms "slick rim"	21.8
23. Sandstone, orange-red, medium- to fine-grained; contains rounded quartz grains	5.6
22. Sandstone, orange-red, medium-grained, fairly well-sorted, crossbedded, friable; 5 ft swing to crossbedding, increasingly crossbedded near top of interval	29.0
21. Sandstone, orange to orange-red, friable; contains coarse perfectly rounded grains of amber-stained quartz grains in medium-fine-grained matrix. Contact between the Wingate Sandstone and Entrada appears gradational in lithology; Kayenta Formation is missing. Wingate is dense, tightly cemented and reddish brown; the Entrada is orange, friable, and has perfectly rounded medium-grain sizes in fine-grained quartz matrix	4.6
Total Slick Rock Member	61.0
Total Entrada (thickness rounded)	108
Wingate Sandstone:	
20. Sandstone, reddish brown; consists of well-sorted medium-sized quartz grains; highly crossbedded	44.9
19. Sandstone, medium-grained, dark limonite spots, well-cemented; reddish-brown and black mottling on weathered surface	4.0
18. Sandstone, medium-grained, well-cemented, horizontally bedded; forms break in slope	104.7
17. Sandstone, salmon-pink, medium-fine-grained, friable; contains some mica flecks, weathers into ½–¼ in. plates, 3-ft tangent swing of crossbedding	50.4
16. Sandstone, reddish brown; uniformly fine-grained sand; crossbedded, tangent swing 20–30 ft	37.2
15. Sandstone, reddish brown, medium-fine-grained, contains scattered coarse quartz grains but sorting good in general; friable; crossbedded, 1-ft swing in foresets	26.0
14. Sandstone, salmon-pink, very fine-grained, poorly sorted, contains scattered coarse well-rounded, amber grains	2.5
13. Sandstone, dense, crystalline calcite cement, hard shale pellets; consists of fine-grained sand with scattered coarse quartz grains. Note: Contact of Chinle Formation with Wingate is sharp and distinct. Dense maroon siltstone of Chinle underlies vertical cliff of salmon-pink Wingate	.5
Total Wingate (thickness rounded)	270

East Unaweep Canyon section, sec. 1–3, T. 11 S., R. 100W.—Con.

	Thickness (feet)
Chinle Formation:	
12. Siltstone, maroon, hard dense; contains scattered mica flecks; gray-white limestone concretions near top	10.0
11. Siltstone and very fine-grained sandstone; concretions as much as 5 ft in diameter; shaly sand and silt; in places contains scattered mica flakes	43.0
10. Siltstone, dull brick-red, dense, hard, very fine-grained; concretionary in places along strike, concretions 3 in. to 3 ft diameter	27.0
9. Conglomerate, mainly siltstone pellets; contains calcite, cement	1.0
8. Siltstone, dull brick-red, thin-bedded, ½–1 in. partings; forms shaly slope	10.2
7. Siltstone, brick-red, some white mottling; few concretions	2.0
6. Siltstone, brick-red; contains a few scattered coarse quartz grains	14.8
5. Conglomerate, red, arkosic; finer pebble size than basal conglomerate; pebbles are mainly siltstone, clay, and some quartz; lenticular	2.8
4. Siltstone, brick-red, shaly, highly fractured; forms shaly slope	5.6
3. Conglomerate, red, arkosic; contains feldspar pebbles and granules of quartz, clay, and shale fragments; conglomerate varies in thickness along strike	1.5
2. Covered; granitic soil	2.1
Total Chinle (thickness rounded)	120
Precambrian complex:	
1. Granite, schist, and gneiss complex; pegmatite dikes. Base of measured section.	

SELECTED DRILLERS' LOGS OF WELLS

Drillers' terms in the following logs have not been modified; "oil shows" reported by drillers are believed to be fictitious; I added geologic formation tops.

Log of well 1 in the SW¼NE¼ sec. 29, T. 1 N., R. 1 W., Ute P.M.

[0–1,200 ft drilled by H. L. Morgan, using cable-tool rig; 1,200–1,639 ft drilled by A. R. Chvilicek, using hydraulic rotary rig]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface soil	40	40
Red and yellow clay	22	62
Gravel and sand	9	71
Mancos Shale:		
Shale	643	714
Dakota Sandstone and Burro Canyon Formation:		
Sandstone (water and gas)	3	717
Broken shale and slate	67	784
Dark gray sandstone (gas)	12	796
Shale and bentonite	31	827
Red and green shale	29	856
Bentonite and shale	64	920
White sandstone	36	956
Morrison and Summerville Formations:		
Gray clay and shale	29	985
Sandy shale	11	996

Log of well 1 in the SW¼NE¼ sec. 29, T. 1 N., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Con.		
Sandy clay	31	1,027
Broken bentonite and shale	73	1,100
Red and green shale	156	1,256
Slate and shale	34	1,290
Gray-green shale	92	1,382
Gray limey sand	28	1,410
Sandy lime shells	35	1,445
Varicolored shale	67	1,512
Red lime	6	1,518
Shale and lime shells	37	1,555
Entrada Sandstone:		
Sandstone, salmon (La Plata)	82	1,637
Variegated shale	2	1,639

Log of well 2 in the NW¼NE¼ sec. 29, T. 1 N., R. 2 W., Ute P.M.

[Drilled by D. S. Isaacs]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Red sandy top soil	20	20
Dakota Sandstone and Burro Canyon Formation:		
Sandy	34	54
Sandy red shale	27	81
Sandstone (water at 82)	2	83
Green shale	12	95
Red shale	28	123
White sandstone	5	128
Morrison and Summerville Formations:		
Red shale	10	138
Green shale	5	143
Hard rock	2	145
Gray shale	15	160
White sandstone	5	165
Gray shale	10	175
Red shale	51	226
Green shale	24	250
Gray shale	25	275
Gray shale and sandstone stringers	15	290
Gray sandstone, very hard	57	347
Red shale	3	350
Hard gray rock	60	410
Sandstone	20	430
Hard rock, quartz stringers	8	438
Gray	42	480
Hard gray rock, quartz stringers	70	550
Gray sandstone, increase in water	30	580
Light gray sandstone, increase in water	30	610
Red rock	20	630
Entrada Sandstone:		
White sand (heavy flow of water; 20 gpm)	19	649
Pink sand (no more increase in water)	35	684

Log of well 3 in the NE¼NE¼ sec. 32, T. 1 N., R. 2 W., Ute P.M

[Drilled by D. S. Isaacs]

	Thickness (feet)	Depth (feet)
Quaternary deposits and Morrison Formation:		
Red top soil	29	29
Morrison and Summerville Formations:		
Gray shale	21	50
Brown sandstone	2	52
White sandstone (some water)	8	60

Log of well 3 in the NE¼NE¼ sec. 32, T. 1 N., R. 2 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Con.		
Very hard brown rock	5	65
Gray sandstone (increase in water)	18	83
Hard rock	7	90
Red sandstone	17	107
Very hard	2	109
Gray sandstone (increase in water)	51	160
Red sandstone	80	240
Hard red rock	25	265
Pink sandstone (increase in water)	10	275
Hard white rock (commenced flowing)	45	320
Entrada Sandstone:		
White sandstone	65	385
Pink sandstone	90	475
Kayenta Formation:		
Brown sandstone (water increasing)	75	550
Wingate Sandstone:		
Dark red sandstone	105	655

Log of well 4 in the SW¼NW¼ sec. 33, T. 1 N., R. 2 W., Ute P.M.

[Drilled by D. S. Isaacs]

	Thickness (feet)	Depth (feet)
Quaternary deposits and Morrison Formation:		
Red top soil	29	29
Morrison and Summerville Formations:		
Gray-green shale	26	55
Gray shale	5	60
Very hard gray rock (some water)	35	95
Dark red shale	3	98
Gray shale, hard stringers	17	115
Gray-white sandstone (some increase in water)	35	150
Gray shale	15	165
Red shale	12	177
Hard brown rock	2	179
Red shale	3	182
Hard red rock	17	199
Entrada Sandstone, Kayenta Formation and Wingate Sandstone:		
White soft sandstone (water increased)	41	240
Pink sandstone	137	377
White sandstone	86	463
Pink sandstone	37	500

Log of well 5 in the NW¼NW¼ sec. 18, T. 1 S., R. 1 E., Ute P.M.

[Drilled by Mesa Drilling Co.]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface	10	10
Gravel (water)	15	25
Quicksand	55	80
Mancos Shale:		
Shale	638	718
Dakota Sandstone and Burro Canyon Formation:		
Gray sand and shells (gas at 730 ft)	62	780
Burro Canyon and Morrison Formations:		
Shale with bentonite	438	1,218
Morrison and Summerville Formations:		
Sand (3 gpm)	18	1,236
Red shale	85	1,321

Log of well 5 in the NW¼NW¼ sec. 18, T. 1 S., R. 1 E., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Con.		
Red sand	1	1,322
Red shale	12	1,334
Gray sand	3	1,337
Red shale	4	1,341
Gray sand	7	1,348
Sandy shale	6	1,354
Red shale	4	1,358
Hard lime shell	3	1,361
Brown and blue shale	17	1,378
Hard lime	4	1,382
Gray shale and lime shells	32	1,414
Lime shell, very hard	5	1,419
Gray shale with lime shells	18	1,437
Gray sand with lime	8	1,445
Gray shale	32	1,477
Hard lime	7	1,484
Lime and sand	16	1,500
Red shale	40	1,540
Entrada Sandstone:		
Water sand (water at 1,540, 1,550, and 1,599 ft)	73	1,613
Red and green shale	2	1,615

Log of well 6 in the NE¼SW¼ sec. 29, T. 1 S., R. 1 E., Ute P.M.

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Quaternary deposits and Mancos Shale:		
Surface sand and mud	64	64
Mancos Shale:		
Shale	356	420
Dakota Sandstone and Burro Canyon Formation:		
Sandstone (salt water)	16	436
Shale, gray, sticky	22	458
Sandstone, hard	5	463
Shale	34	497
Chert, abrasive	18	515
Variegated shale	68	583
White sandstone	67	650
Morrison and Summerville Formations:		
Brown and green shale	130	780
Bentonite	20	800
Gray sandstone	7	807
Bentonite	25	832
Variegated shale	38	870
Gray sandy shale	70	940
Bentonite	25	965
Brown hard shale	30	995
Salt and pepper sands	15	1,010
Sand and lime ribs	125	1,135
Red shale	13	1,148
Green shale with lime ribs	82	1,230
Gray to brown sand and lime	60	1,290
Hard lime and sand	17	1,307
Green bentonite	21	1,328
Entrada and Wingate Sandstones:		
Sandstone	202	1,530
Red sandy shale	30	1,560

Log of well 7 in the SW¼NW¼ sec. 5, T. 1 S., R. 1 W., Ute P.M.

[Drilled by J. D. Pinkerton]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Adobe topsoil	20	20
Gravel	11	31
Mancos Shale:		
Shale	159	190
Sand	5	195
Shale	127	322
Hard lime	3	325
Hard lime and slate	4	329
Soapstone, red shale	6	335
Dakota Sandstone and Burro Canyon Formation:		
Coal	3	338
Coal and slate	6	344
Gray shale	9	353
Coal	2	355
Gray shale	2	357
Coal	3	360
Red and brown shale	8	368
Bentonite	3	371
Red shale	8	379
Sandy lime	7	386
Gray shale	3	389
Red shale	6	395
Gray shale	5	400
Coal	5	405
Sand	9	414
Brown shale	4	418
Chert, very hard	5	423
Gray shale, bentonite	8	431
Green shale	3	434
Green shale with sand	1	435
Gray shale	50	485
Red sandy shale	1	486
Gray shale	3	489
Red shale	19	508
Gas sand	2	510
Pink shale with hard lime	6	516
Green shale	10	526
Gray shale	28	554
Fine sandy gravel (well flowed salty water)	5	559
Sand with fine gravel	6	565
Morrison and Summerville Formations:		
Gray shale	13	578
Red shale	7	585
Gray shale	7	592
Red shale	3	595
Gray shale with bentonite	30	625
Red shale	45	670
Red and gray shale with hard lime	190	860
Gray shale with sandy lime	3	863
White sand	4	867
Gray shale	2	869
Red shale with bentonite	2	871
Blue shale with lime streaks	8	879
White sand	1	880
Gray shale with bentonite	2	882
Red shale	6	888
Hard lime	2	890
Red shale with lime streaks	11	901
Red shale with white sand	5	906

Log of well 7 in the SW¼NW¼ sec. 5, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations:—Cont.		
White sand (water-bearing)	28	934
Red shale	6	940
Gray shale with hard lime	105	1, 045
Gray shale with sandy lime	30	1, 075
Gray shale with hard lime	22	1, 097
Bentonite	11	1, 108
Red shale	17	1, 125
Hard lime	5	1, 130
Entrada Sandstone:		
White sand (well flowed 9 gpm)	45	1, 175
Salmon colored sand (well flowed 12 gpm)	40	1, 215

Log of well 8 in the SW¼SW¼ sec. 7, T. 1 S., R. 1 W., Ute P.M.

[Drilled by D. S. Isaacs]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Sand and gravel	25	25
Dakota Sandstone, and Burro Canyon, Morrison, and Summerville Formations:		
Yellow shale	30	55
Sandstone	3	58
Bentonite	17	75
Yellow sandy shale	10	85
Green shale	20	105
Gray shale	40	145
Red shale	7	152
Green shale	3	155
Bentonite	25	180
Pink shale	7	187
Bentonite	4	191
Hard white lime	2	193
Gray shale	10	203
Gray sticky shale	30	233
Hard brown rock	3	236
Green sticky shale	4	240
Red shale	60	300
Green shale	20	320
Gray shale	32	352
Hard gray rock	6	358
Gray shale	34	392
Red shale	57	449
Gray shale with hard rock stringers	30	479
Hard white rock	5	484
Red shale with sandstone stringers	45	529
Hard gray sandstone	41	570
Gray bentonite shale	51	621
White lime	4	625
Gray shale	68	693
Red shale	2	695
Hard brown rock	14	709
Hard white rock (set 5-inch casing, cemented to 713 ft to shut off cave)	4	713
Hard white rock	7	720
Gray shale and sandstone	38	758
Dark red shale, white sandstone, and shells	15	773
Entrada Sandstone:		
White to pink sandstone (water raised and flowed)	13	786
White to pink sandstone (water increased, flowed 1½ gpm)	20	806
Pink sandstone	47	853

Log of well 9 in the SE¼SW¼ sec. 7, T. 1 S., R. 1 W., Ute P.M.

[Drilled by F. B. Dykes]

	Thickness (feet)	Depth (feet)
Dakota Sandstone and Burro Canyon Formation:		
Rock	16	16
Shale	7	23
Brown sandstone	23	46
Rock	3	49
Brown sandstone	30	79
Morrison and Summerville Formations:		
Hard blue bentonite	17	96
White limestone	9	105
Hard purple shale and cobs	27	132
Red limestone	18	150
Hard blue shale	9	159
Red bentonite	26	185
Gray bentonite	11	196
Blue shale and cobs	36	232
Limestone	5	237
Hard purple shale	9	246
Rock	14	260
Hard blue rock	12	272
Clay	3	275
Dark-blue shale	8	283
Light-blue shale	4	287
Red shale and cobs	3	290
Hard purple rock	11	301
Blue rock	6	307
Purple shale	3	310
Hard purple shale and cobs	21	331
Dark-red shale	37	368
Dark-blue shale	33	401
Gray clay, soft	6	407
Rock	2	409
Light-blue shale	15	424
Dark-blue shale	41	465
Hard red shale	7	472
Rock	4	476
Light-blue shale	5	481
Red shale	5	486
Red tight clay	29	515
Hard red rock	14	529
Blue-gray rock	7	536
Gray shale	31	567
Gray rock	9	576
Tight gray clay	31	607
Gray sandstone	14	621
Sticky clay and cobs, gray	10	631
Dark-blue shale, very tight	21	652
Dark-blue rock, hard	8	660
Brown sandstone	29	689
White limestone	6	695
Light-gray rock	13	708
White limestone	5	713
Hard gray shale	49	762
Red and green clay	23	785
Red rock	20	805
Tight red clay	49	854
Entrada Sandstone:		
Fine gray sand, water-bearing	5	859
Fine brown sand, water-bearing	9	868
Sandy clay, brown	14	882
Soft brown sand, water-bearing	9	891

Log of well 10 in the NW¼SE¼ sec. 10, T. 1 S., R. 1 W., Ute P.M.

[Drilled by J. P. Sloss Drilling Co.]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Wash gravel	29	29
Mancos shale:		
Blue shale	106	135
Gray shale with lime stringers	155	290
Sandy lime	20	310
Blue and gray shale and sandy lime	60	370
Dakota Sandstone and Burro Canyon Formation:		
Water sand (hole full of water)	5	375
Gray shale	5	380
Sandy lime	10	390
Blue shale	25	415
Green shale	25	440
Light green sandy shale	10	450
Hard sand (increase in water)	18	468
Green shale	32	500
Lime shells	15	515
Green, red, and brown shale	35	550
Brown hard sand	15	565
Morrison and Summerville Formations:		
Red, green, and brown shale	145	710
White and brown sand	35	745
Sandy shale	40	785
Green shale	3	788
Brown sand	12	800
Brown shale	15	815
Water sand (flowing 3 gpm)	46	861
Sandy shale	79	940
White sand	3	943
Gray lime and shale, sandy	109	1, 052
Lime shells and shale, gray	48	1, 100
Red shale	15	1, 115
Entrada Sandstone:		
Water sand, pink (flowing 5 gpm)	61	1, 176

Log of well 11 in the NW¼SW¼ sec. 15, T. 1 S., R. 1 W., Ute P.M

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface soil	25	25
Mancos shale:		
Shale (salt water)	55	80
Black sandy shale	10	90
Solid gray shale	30	120
Dakota Sandstone and Burro Canyon Formation:		
Sand rock	20	140
Sandy lime (hard sulphur water)	20	160
Light sandstone	10	170
Dakota sand (well flowed 2 gpm)	21	191
Gray bentonite	9	200
Red shale	18	218
White betonite	5	223
Red shale	10	233
Sandstone	20	253
Red bed	42	295
Sandstone	8	303
Morrison and Summerville Formations:		
Red shale	15	318
Bentonite, red	18	336
Bentonite, white	19	355
Red shale	40	395
Bentonite	99	494

Log of well 11 in the NW¼SW¼ sec. 15, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Continued		
Red shale	60	554
Red shale	6	560
Hard lime	5	565
Red bed	14	579
White sandstone	89	668
Red bed	7	675
Bentonite	50	725
Lime	52	777
Gray shale	18	795
Hard lime	10	805
Green shale	26	831
Red shale	21	852
Entrada Sandstone:		
La Plata sand	126	978

Log of well 12 in the NW¼SE¼ sec. 16, T. 1 S., R. 1 W., Ute P.M.

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Gravel	48	48
Dakota Sandstone and Burro Canyon Formation:		
Sandstone	8	56
Clay	47	103
White sandstone	52	155
Yellow clay	37	192
Sandstone (little water)	64	256
Morrison and Summerville Formations:		
Shale	51	307
Red bed	21	328
Green shale	14	342
Red shale	15	357
Gray shale	37	394
Red and green shale	15	409
Bentonite	84	493
Red shale	7	500
White sandstone	15	515
Red bentonite	23	538
White bentonite	9	547
White sandstone	6	553
Bentonite	41	594
Sandstone	69	663
Bentonite	14	677
Green shale	13	690
Bentonite	35	725
Hard lime	12	737
Red bed	24	761
Lime	56	817
Red bed	9	826
Green shale	15	841
Gray shale	8	849
Lime	2	851
Red shale	3	854
Red sandy shale	9	863
Entrada Sandstone:		
La Plata sandstone	138	1, 001
Kayenta Formation and Wingate Sandstone:		
(Log not available, well deepened)	391	1, 392
Chinle Formation:		
Chinle	5	1, 397

Log of well 16 in the NE¼NE¼ sec. 21, T. 1 S., R. 1 W., Ute P.M.

[0-865 feet, driller not known; 865-1,117 feet, drilled by J. D. Pinkerton]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Boulders	20	20
Dakota Sandstone and Burro Canyon Formation:		
Sandstone	10	30
Shale	20	50
Coal	5	55
Shale	15	70
Sandstone	20	90
Shale	30	120
Sandstone	17	137
Green shale	18	155
Red shale	2	157
Green shale	10	167
Gray shale	5	172
Red shale	9	181
Hard lime	3	184
White sandstone	36	220
Morrison and Summerville Formations:		
Gray shale	4	224
Hard lime	4	228
Various colored shales	195	423
Hard gray sand	3	426
Various colored shales	105	531
Gray sand	7	538
Red shale	15	553
Red shale and shells	30	583
Hard gray sand	10	593
Red shale	7	600
White sand	63	663
Gray sandy shale	130	793
Blue and green shale	12	805
Red shale	20	825
Entrada Sandstone:		
White sand (artesian water at 832 ft)	40	865
Entrada Sandstone, Kayenta Formation, and Wingate Sandstone:		
Sandstone	252	1, 117

Log of well 17 in the SE¼NE¼ sec. 21, T. 1 S., R. 1 W., Ute P.M.

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Boulders	9	9
Dakota Sandstone and Burro Canyon Formation:		
Sand rock	38	47
Shale	31	78
White sand (little water)	6	84
Hard sand	7	91
White water sand (lots of water)	28	119
Morrison Formation:		
Red clay	21	140
Red and blue shale	20	160
Hard clay lime	10	170
Blue shale	40	210
Blue and red mixed shale	55	265
Hard gray slate	9	274
Red and blue structure	23	297
Fine white sand (no increase of water)	13	310
Blue and gray shale	150	460
Heavy red clay	30	490
Mixed blue and gray shale	15	505

Log of well 17 in the SE¼NE¼ sec. 21, T. 1 S., R. 1 W., Ute P. M.—Continued

	Thickness (feet)	Depth (feet)
Morrison Formation—Continued		
White sand (more water in hole, to 10 inches of top)	7	512
Fine red sand	7	519
White sand	5	524
Hard red sand	14	538
White water sand (well flowed)	30	568
Red sandy clay	5	573

Log of well 18 in the SE¼NE¼ sec. 21, T. 1 S., R. 1 W., Ute P.M.

[Drilled by D. S. Isaacs]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Sand, gravel, and boulders	35	35
Dakota Sandstone and Burro Canyon Formation:		
Yellow shale	10	45
Hard rock (water)	12	57
Sandstone stringers	18	75
Morrison Formation:		
Red shale	48	123
Gray shale	10	133
Green shale	27	160
Gray shale	8	168
Hard lime	3	171
Gray shale	117	288
Green shale	31	319
Gray shale with hard lime stringers	94	413
Red shale	57	470
White sandstone	53	523

Log of well 19 in the NE¼SE¼ sec. 21, T. 1 S., R. 1 W., Ute P.M.

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Dakota Sandstone, and Burro Canyon, Morrison, and Summerville Formations:		
Shale	30	30
Dakota sand	26	56
Light-gray shale	29	85
Red shale	5	90
White sand	7	97
Green shale	23	120
Bentonite	20	140
Green and red shale	25	165
Gray shale	8	173
Red and gray shale	12	185
Coarse gravel	6	191
Green shale	9	200
Bentonite	13	213
Red and green shale	8	221
Green shale	18	239
Red shale	16	255
Green shale	6	261
Red shale	8	269
Bentonite	5	274
Red shale	18	292
Green shale	15	307
Red and green shale	8	315
Green shale	9	324
Red and green shale	11	335
Gray shale	17	352
Bentonite	18	370

Log of well 19 in the NE¼SE¼ sec. 21, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Dakota Sandstone, etc—Continued.		
Green shale	12	382
Red shale	75	457
Gray sand	4	461
Red shale	8	469
White sand	11	480
White sand (flowed 3½ gpm)	35	515
Brown sand	29	544
Gray shale	11	555
Brown shale	17	572
Conglomerate shale	3	575
Chert	5	580
Red shale	5	585
Gray shale	2	587
Bentonite	27	614
Gray shale	6	620
Dark gray shale	4	624
Gray shale	2	626
Dark gray sand	7	633
Shale, bentonite	17	650
Chert	8	658
Sandy shale	4	662
Hard sand	7	669
Green shale	3	672
Chert	3	675
Gray sand	5	680
Chert	25	705
Green shale	4	709
Chert	17	726
Green shale	1	727
Red bed	19	746
Entrada Sandstone:		
Sand (at 769 ft flowed 2 gpm)	123	869
Kayenta Formation:		
Chert	5	874
Dark red sand	18	892
Broken sandstone	48	940
Crevice, open (flow increased to 8½ gpm)	3	943
Wingate Sandstone:		
Light pink stone (flow increased to 13 gpm)	53	996

Log of well 20 in the NE¼NW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.

[Drilled by Fred Sturm]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface	3	3
Gravel	21	24
Dakota Sandstone and Burro Canyon Formation:		
Gray shale	5	29
Coal	5	34
Gray shale	5	39
Water sandstone	21	60
Gray sandstone	12	72
Hard lime shells	5	77
Salt(?)	3	80
Coarse gray sandstone and dead oil	5	85
Shale and bentonite	10	95
Bentonite	8	103
Green shale	1	104
Bentonite	26	130
Green shale	1	131
Bentonite	4	135
Blue shale	10	145

Log of well 20 in the NE¼NW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Dakota Sandstone and Burro Canyon Formation—Continued		
Red shale	5	150
Bentonite	8	158
White sandstone	12	170
Morrison and Summerville Formations:		
Varicolored shale	5	175
Red sandy shale	20	195
Varicolored shale	20	215
Blue shale	5	220
Hard lime	5	225
Bentonite	15	240
Varicolored shale	10	250
Bentonite and varicolored shale	40	290
Bentonite	25	315
Varicolored shale	5	320
Bentonite	15	335
Red shale	5	340
Brown shale	10	350
Bentonite	70	420
White sandstone	12	432
Bentonite and shale	33	465
Bentonite	45	510
Sandstone	5	515
Brown shale	5	520
White sandstone	15	535
Brown shale	20	555
White water sandstone (about 10 gpm)	35	590
Red sandstone and shale	20	610
Lime	2	612
Red shale and sandstone	7	619
Hard lime	3	622
Gray shale	3	625
Gray shale and limestone	5	630
Gray shale	5	635
Limestone and shale	5	640
Hard limestone	16	656
Gray shale	7	663
Limestone	5	668
Limestone and shale	12	680
Limestone	5	685
Limestone and shale, blue and gray	55	740
Hard limestone	3	743
Gray shale	8	751
Hard limestone	1	752
Limestone and sandstone	4	756
Hard limestone	5	761
Gray shale	9	770
Green shale	23	793
Limestone	1	794
Green shale	6	800
Red shale	15	815
Entrada Sandstone:		
Water sand, white and salmon-colored	60	875
Brown sand rock	50	925

Log of well 21 in the SW¼NW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.

[Driller not known]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Soil	4	4
Gravel and boulders	48	52

Log of well 21 in the SW¼NW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Dakota Sandstone and Burro Canyon Formation:		
Brown shale	2	54
Cemented gravel	10	64
Bluish-gray shale	26	90
Hard blue lime	2	92
Bluish-gray shale	18	110
Chocolate shale	5	115
Green to gray shale	10	125
Very hard white sandstone	10	135
Dark-gray sandstone	2	137
Hard light-gray sandstone (150 gallons per hour)	11	148
Morrison and Summerville Formations:		
Blue lime	3	151
Chocolate shale	21	172
Blue shale	13	185
Bluish-gray shale	35	220
Light-brown shale	8	228
?	2	230
Red and gray shale	7	237
Blue shale	8	245
Brown shale	2	247
Gray shale	13	260
Dark-chocolate shale	10	270
Light-gray shale	11	281
Hard brown shale	6	287
Bluish-gray shale	23	310
Hard blue lime	2	312
Gray shale	16	328
Sandy gray shale	7	335
Gray bentonite	20	355
Sandy gray shale	5	360
Gray bentonite	28	388
Gray sandstone	12	400
Gray bentonite	28	428
Blue lime	3	431
Gray shale and bentonite	10	441
Gray sandstone	3	444
Gray shale	8	452
Brown shale	8	460
Blue shale	8	468
Red shale	34	502
Gray sandstone	8	510
Red shale	6	516
Soft gray sandstone	15	531
Red shale	1	532
Gray lime, shells, and shale	9	541
Red shale	15	556
Gray sandstone	5	561
Lime, shells, and sandstone	15	576
Gray sandstone	2	578
Red shale	8	586
Hard blue lime	2	588
Hard gray sandstone	4	592
Hard blue lime	4	596
Red shale	18	614
Gray lime	2	616
Red shale	5	621
Blue shale	5	626
Hard blue lime	6	632
Gray shale	2	634

Log of well 21 in the SW¼NW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Con.		
Gray lime	10	644
Lime and shale	11	655
Hard blue lime	2	657
Lime, shells, and shale	39	696
Hard blue lime	3	699
Lime, shells, and shale	15	714
Sandstone, soft and hard layers	34	748
Red shale	4	752
Hard blue lime	6	758
Blue and gray shale	13	771
Very hard shale	30	801
Entrada Sandstone:		
Reddish-brown sandstone	109	910
Light-gray sandstone	5	915
White sandstone	12	927

Log of well 22 in the SE¼NW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.

[Drilled by Mesa Drilling Co.]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Topsoil	12	12
Gravel	13	25
Dakota Sandstone and Burro Canyon Formation:		
Blue shale	5	30
Green shale	30	60
Shale	30	90
Red bed	15	105
Morrison and Summerville Formations:		
Blue shale	5	110
Gray shale and bentonite	40	150
Blue shale	20	170
Bentonite and shale	195	365
White sand and shale	15	380
Bentonite and shale	40	420
Shale	15	435
Gray sandstone	15	450
Bentonite	5	455
Gray sandstone	20	475
Sandy lime	15	490
Sandy shale	10	500
Lime	3	503
Bentonite	2	505
Brown shale	35	540
Brown lime	3	543
Brown shale	9	552
Red shale	10	562
White sand	11	573
Gray shale	2	575
Lime and shale	15	590
Gray shale	25	615
Hard lime	5	620
Gray shale	10	630
Lime	6	636
Shale and lime	24	660
Gray shale	10	670
Shale	5	675
Lime	10	685
Shale	1	686
Lime	3	689
Shale	1	690
Lime	20	710

Log of well 22 in the SE¼NW¼ sec. 22, T. 1 S., R. 1 W. Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Con.		
Green shale	15	725
Red shale	17	742
Entrada Sandstone:		
Water sand	68	810

Log of well 23 in the NW¼SW¼ sec. 22, T. 1 S., R. 1 W., Ute P.M.

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Gravel	7	7
Dakota Sandstone and Burro Canyon Formation:		
Sand rock	33	40
Red bed	50	90
Blue shale	40	130
Sand, white (water)	10	140
Blue shale	22	162
Red sandstone (water, hole full)	8	170
Morrison and Summerville Formations:		
Gray sand and shale	51	221
Dark-green shale	3	224
Red and gray shales	103	327
Bentonite	13	340
Dakota sands and shale	120	460
Red bed, sandy	45	505
Morrison sand (water)	35	540
Red sandstone	20	560
Gray shale	47	607
Blue shale and bentonite	73	680
Hard lime	29	709
Gray shale	5	714
Lime	21	735
Green shale	10	745
Red clay	10	755
Entrada Sandstone:		
Red sand, La Plata	108	863
Yellow clay	6	869

Log of well 25 in the SW¼SW¼ sec. 23, T. 1 S., R. 1 W., Ute P.M.

[Drilled by T. N. Johnson]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface	2	2
Mancos Shale:		
Brown shale	52	54
Dakota Sandstone and Burro Canyon Formation:		
Conglomerate	10	64
Bluish-gray shale	26	90
Hard blue lime	2	92
Bluish-gray shale	18	110
Chocolate	5	115
Greenish-gray	10	125
Hard white sand	10	135
Dark-gray	2	137
Hard gray sand	11	148
Morrison and Summerville Formations:		
Blue shale	3	151
Chocolate shale	21	172
Blue shale	13	185
Bluish-gray shale	35	220
Light-brown shale	8	228

Log of well 25 in the SW¼SW¼ sec. 23, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Continued		
Hard blue lime	2	230
Red and gray shale	7	237
Blue shale	8	245
Brown shale	2	247
Gray shale	13	260
Dark-chocolate shale	10	270
Light-gray shale	11	281
Hard brown shale	6	287
Bluish-gray shale	23	310
Hard blue lime	2	312
Gray shale	16	328
Gray sand and shale	7	335
Gray bentonite	20	355
Gray sand and shale	5	360
Gray bentonite	28	388
Gray sand	12	400
Gray bentonite	28	428
Blue lime	3	431
Gray shale and bentonite	10	441
Gray sand	3	444
Gray shale	8	452
Brown shale	8	460
Blue shale	8	468
Red shale	34	502
Gray sand	8	510
Red shale	6	516
Gray sand	15	531
Red shale	1	532
Gray lime shale	9	541
Red shale	15	556
Gray sand	5	561
Lime and sand	15	576
Gray sand	2	578
Red shale	8	586
Hard blue lime	2	588
Hard gray sand	4	592
Hard blue lime	4	596
Red shale	18	614
Gray lime	2	616
Red shale	5	621
Blue shale	5	626
Hard blue lime	6	632
Gray shale	2	634
Gray lime	10	644
Lime and shale	11	655
Hard blue lime	2	657
Lime and shale	39	696
Hard blue lime	3	699
Lime and shale	15	714
Soft gray sand	34	748
Red shale	4	752
Hard blue lime	6	758
Blue and gray shale	13	771
Blood-red shale	30	801
Entrada Sandstone:		
Red sand (flowed 16 gpm)	54	855

Log of well 26 in the NE¼ SW¼ sec. 24, T. 1 S., R. 1 W., Ute P.M.

[Drilled by Eureka Oil Co.]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Sand and gravel	16	16

Log of well 26 in the NE¼SW¼ sec. 24, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Mancos Shale:		
Shale	61	77
Gray sand	14	91
Black shale and slate	14	105
Brown shale and gypsum	5	110
Brown shale	28	138
Gypsum and bentonite	2	140
Black gypsum and bentonite	15	155
Black shale, some pyrite	5	160
Gray limestone or shale	8	168
Dakota Sandstone:		
Salt and pepper sand (gas)	10	178
Shale and gravel	12	190
Hard sandstone, fine to coarse	15	205
Coarse sand	3	208
Soft shale and brown clay	7	215
Coarse sand	3	218
Coal	5	223
Hard sandstone	4	227
Coal	5	232
Water sand (sulfur water)	20	252
Coal	3	255
Water sand, hard	11	266
Gray sand	4	270
White sand and conglomerate, milky	16	286
Darker and coarser sand	10	296
Burro Canyon Formation:		
Green shale	54	350
Hard white sandstone	4	354
Softer white sandstone	11	365
Hard white sandstone, dark in middle, hard at bottom	15	380
Morrison and Summerville Formations:		
Blue shale	5	385
Blue limey shale, very hard	7	392
Red marl	8	400
Hard sandstone	5	405
Red and brown shale	2	407
Blue and green shale	8	415
Shale with some sand	3	418
Hard sand rock	1	419
Blue shale with sand	4	423
Green shale	15	438
White sand	4	442
White clay or bentonite	13	455
Hard green rock	2	457
Green shale	33	490
Sand	1	491
Gray shale turning to brown	1	492
Shales of different colors	59	551
Red sand	7	558
Brown shale	17	575
Hard white sandstone	5	580
Shales of different colors	75	655
Soft white sandstone	15	670
Red sandstone	3	673
Soft white sandstone, good water, flowing	27	700
Hard shale	170	870
Gray shale	8	878
Shale, gray, blue, green, red, and some sand streaks	122	1,000

Log of wsll 26 in the NE¼SW¼ sec. 24, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Entrada Sandstone, Kayenta Formation, and Wingate Sandstone:		
Red sandstone, good water	5	1,005
Red sandstone, several oil showings	315	1,320
Red sandstone	125	1,445
Red conglomerate, oil shows	105	1,550
Red conglomerate, shale streaks	20	1,570
White sandstone	24	1,594
Very hard white sandstone	66	1,660

Log of well 27 in the SW¼ NW¼ sec. 25, T. 1 S., R. 1 W., Ute P.M.

[Drilled by H. L. Morgan]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface soil	7	7
Soft sand and gravel	28	35
Dakota Sandstone and Burro Canyon Formation:		
Coal and shale	15	50
Black slate and shale	20	70
Sandy shale	10	80
Quicksand and shale	45	125
Bentonite	35	160
Red shale	15	175
White sand	15	190
Blue shale	5	195
Brown sand and shale	25	220
White sand	5	225
Red sand	36	261
Morrison and Summerville Formations:		
Red clay and shale	25	286
Bentonite	79	365
Brown clay	15	380
Bentonite	145	525
Brown sandy clay	100	625
White sandstone	35	660
Red shale	25	685
Gray and green shale	7	692
Bentonite	33	725
White sands	5	730
Lime and sand	95	825
Gray and green shale	5	830
Red shale	15	845
Entrada Sandstone:		
Salmon-colored sandstone (water from 845 ft on down, picked up gradually)	68	913

Log of well 28 in the SW¼NW¼ sec. 25, T. 1 S., R. 1 W., Ute P.M.

[Drilled by C. T. Wilson]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Loam, sand, and gravel	35	35
Mancos(?) Shale:		
Blue shale	35	70
Dakota Sandstone and Burro Canyon Formation:		
Hard blue sandy shale	20	90
White bentonite	70	160
Mixed shale	40	200
White water sand (considerable water)	100	300

Log of well 28 in the SW¼NW¼ sec. 25, T. 1 S., R. 1 W., Ute P.M.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations:		
Pink shale	60	360
Hard blue lime	35	395
White shale	85	480
Hard silica quartz	10	490
White bentonite	50	540
Hard sandy lime	25	565
Gray limestone, fossils	10	575
Soft lime	25	600
Hard red rock	14	614
Extra hard gray sand	52	666
Red sand	4	670
Hard gray lime	36	706
Snow-white chalk	44	750
Red sandy shale	15	765
Blue sandy lime	45	810
Blue lime, fossils	14	824
Hard gray sand	22	846
Water sand (water increased)	9	855
Green shale	7	862
Red rock	18	880
Entrada Sandstone:		
White water sand	5	885
Water sand	35	920
Brown water sand	20	940

Log of well 29 in the NW¼NE¼ sec. 26, T. 1 S., R. 1 W., Ute P.M.

[Drilled by John W. Moore]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Gravel	15	15
Dakota Sandstone and Burro Canyon, Morrison, and Summerville Formations:		
Gray sandy shale	110	125
White sand (water at 135 ft)	30	155
Red and green shale	145	300
Gray sandy shale	50	350
Bentonite	130	480
Red shale	75	555
White sand (small flow of water at 575 ft)	30	585
Red shale	40	625
Gray shale	75	700
Gray shale and lime shells	40	740
Gray shale	30	770
Red shale	30	800
Hard shell	3	803
Entrada Sandstone:		
White sand	67	870

Log of well 30 in the NE¼NW¼ sec. 26, T. 1 S., R. 1 W., Ute P.M.

[Drilled by Billy Doyle]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Rock and gravel	16	16
Dakota Sandstone and Burro Canyon Formation:		
Brown shale	2	18
Coal	2	20
Pipe clay	1	21
Gray shale	52.5	73.5
White sandstone (some water)	8	81.5

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Log of well 30 in the NW¼NE¼ sec. 26, T. 1 S., R. 1 W., Ute P. M.—Continued

	Thickness (feet)	Depth (feet)
Dakota Sandstone and Burro Canyon etc.—Con.		
Gray shale	18.5	100
Blue shale	37	137
Red shale	16	153
Sandstone	10	163
White sandstone (some gas)	11	174
Morrison and Summerville Formations:		
Blue shale	16	190
Red and blue shale	14	204
Blue lime, very hard	4	208
Red shale	2	210
Blue shale	2	212
Red shale	4	216
Hard white limestone	1	217
Red shale	2	219
Blue shale	15	234
Red shale	9	243
Blue shale	15	258
Red shale	5	263
Blue shale	12	275
Blue and green shale	3	278
Red shale	4	282
Blue shale	18	300
Red shale	10	310
Red and blue shale	19	329
Blue lime	10	339
Blue shale	4	343
Red and blue shale	17	360
Red and white sandstone	10	370
Blue shale and lime	17	387
Light-blue shale	43	430
Blue shale	2	432
Brown and gray shale	23	455
Lime and bentonite	44	499
Red rock	12	511
Sandy gray shale	21	532
Hard red rock	17	549
Gray shale and white sandstone	23	572
Red shale	28	600
Gray shale	20	620
White sandstone	14	634
Blue shale	66	700
Red shale	7	707
Sandy green shale	10	717
Gray shale	16	733
Thin streaks of sandstone	14	747
Gray shale	15	762
Blue shale	28	790
Blue lime	6	796
Blue shale	4	800
Red shale	30	830
Entrada Sandstone, Kayenta Formation, and Wingate Sandstone:		
White sandstone	30	860
Yellowish sandstone	190	1,050

Log of well 31 in the NW¼NW¼ sec. 26, T. 1 S., R. 1 W., Ute P. M.

[Driller not known]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Surface	20	20
Rock and gravel	50	70
Dakota Sandstone and Burro Canyon Formation:		
Red shale	45	115
Hard white sandstone (with poor water)	10	125
Morrison and Summerville Formations:		
Red shale	10	135
Blue shale	85	220
Blue shale, lighter color	50	270
Soft white sandstone (with salt water)	10	280
Blue shale	120	400
Red shale	15	415
Blue shale	30	445
Blood-red rock	20	465
Very hard white sandstone	35	500
Red rock	20	520
Hard red and white sandstone	85	605
Whitish shale	15	620
White sand, good water	5	625
Hard white shale	25	650
Hard shale, white and red streak	75	725
Hard blood-red shale	10	735
Entrada Sandstone, Kayenta Formation, and Wingate Sandstone:		
Soft white sandstone (water began to flow at 740 ft)	80	815
Red sandstone	55	870
White sandstone	60	930
Red sandstone	260	1,190
White sandstone	3	1,193
Chinle Formation:		
White material, like lime	4	1,197
Blood-red material	13	1,210
Granite [conglomerate?]	3	1,213

Log of well 33 in the SW¼NW¼ sec. 29, T. 1 S., R. 1 W., Ute P. M.

[Drilled by C. T. Wilson]

	Thickness (feet)	Depth (feet)
Quaternary deposits:		
Sandy loam and gravel	20	20
Wet plastic clay	10	30
Blue-red clay	5	35
Gravel	33	68
Morrison and Summerville Formations:		
Bentonite	4	72
Water sand and pea gravel (water increased)	30	102
Hard sandy lime	16	118
Light shale and bentonite	13	131
Sandy shale	29	160
Porous lime rock, gas in water	30	190
Gray water sand (water increased)	41	231
White and blue shale	19	250
Hard sandy lime	53	303
Red and white shale	27	330
Hard blue lime	108	438
White water sand (water increased)	13	451
Bentonite shale	19	470
Green shale	5	475
Red sandy shale	2	477
Red sandy—wet	13	490
Entrada Sandstone:		
Water sand, water raised	45	535
Water sand, flowing	15	550
Water sand, no increase	25	575

Log of well 35 in the SE¼ SE¼ sec. 30, T. 1 S., R. 1 W., Ute P. M.

[Drilled by H. L. Morgan]

	Thickness (feet)	*Depth (feet)*
Quaternary deposits:		
Granite boulders	44	44
Morrison and Summerville Formations:		
Gray shale	11	55
Hard lime	5	60
Variegated shale	20	80
Gray sandstone	5	85
Variegated shale	30	115
Hard chert or granite(?)	8	123
Hard lime	2	125
Green shale	5	130
Dark-brown shale	20	150
Gray and green shale	15	165
Red shale	23	188
Entrada Sandstone:		
White sandstone	51	239
Orange sandstone	19	258

Log of well 37 in the NE¼ NW¼ sec. 15, T. 11 S., R. 101 W.

[Drilled by D. S. Isaacs]

	Thickness (feet)	*Depth (feet)*
Quaternary deposits:		
Red sandy soil	37	37
Sand and gravel	38	75
Dakota Sandstone and Burro Canyon, Morrison, and Summerville Formations:		
Black shale	43	118
Gray sandstone	12	130
Gray sandstone, water increased	7	137
Coal	3	140
Gray sandstone	17	157
Gray shale	10	167
Gray sandstone	25	192
Gray shale with hard stringers	8	200
Green shale	32	232
Gray sandy shale	20	252
Soft white sandstone	30	282
Gray shale with hard white pebbles	58	340
Red shale	5	345
Hard white rock	2	347
White sandstone, water-bearing	26	373
Gray shale with hard stringers	52	425
Pink shale	35	460
White sandstone	7	467
Pink shale	50	517
Soft white sandstone	58	575
White sandstone	5	580
Hard rock	77	657
Entrada Sandstone, Kayenta Formation, and Wingate Sandstone:		
White sandstone	98	755
White sandstone with thin layers of shale	182	937
Light-pink and red sandstone	93	1, 030

Log of well 43 in the NE¼ SE¼ sec. 22, T. 11 S., R. 101 W.

[Drilled by Forrest B. Dykes and J. D. Pinkerton]

	Thickness (feet)	*Depth (feet)*
Quaternary deposits:		
Sandy red topsoil	7. 5	7. 5
Gray clay and cobbles	7. 5	15

Log of well 43 in the NE¼SE¼ sec. 22, T. 11 S., R. 101 W.—Continued

	Thickness (feet)	*Depth (feet)*
Morrison Formation:		
Rock	2	17
Gray clay and cobbles	11	28
Gray rock	4	32
Rock	8	40
Hard rock	24	64
Limestone	12	76
Hard rock	17	93
Brown sandstone	27	120
Gray sandy limestone	15	135
Hard sandstone	54	189
Hard light-blue shale	38	227
White limestone	14	241
Hard gray rock	45	286
Mudstone	6	292
Light-blue shale	49	341
Red shale	15	356
Red rock	6	362
Shale	19	381
White gravel and sand, soft	2	383
Brown sand and small gravel, soft (began to flow)	10	393

Log of well 44 in the NW¼SE¼ sec. 22, T. 11 S., R. 101 W.

[Drilled by D. S. Isaacs]

	Thickness (feet)	*Depth (feet)*
Quaternary deposits:		
Topsoil, granite boulders	12	12
Morrison and Summerville Formations:		
Soft gray sandstone	8	20
Red shale	30	50
Gray sandstone, increase in water	5	55
Red shale with sandstone stringers	35	90
Limestone	6	96
Gray shale	14	110
Gray shale with hard stringers	10	120
Gray sandstone, increase in water	10	130
Gray shale with limestone stringers	10	140
Bentonite	15	155
Gray shale with hard stringers	34	189
Gray shale	3	192
Hard white rock	8	200
Gray sandy shale	14	214
Gray shale with hard stringers	31	245
Hard lime	4	249
Gray shale with hard stringers	3	252
Green shale with hard pebbles	8	260
Gray shale	4	264
Pink shale	11	275
Hard rock	12	287
Entrada Sandstone:		
White water-bearing sandstone, water raised	43	330
White and pink sandstone, water raised	20	350

Log of well 45 in the NW¼SE¼ sec. 23, T. 11 S., R. 101 W.

[Drilled by Mesa Drilling Co]

	Thickness (feet)	*Depth (feet)*
Quaternary deposits:		
Topsoil	20	20
Morrison and Summerville Formations:		
White shale	100	120
White sand	3	123
Red rock	17	143

Log of well 45 in the NW¼ SE¼ sec. 23, T. 11 S., R. 101 W.—Continued

	Thickness (feet)	Depth (feet)
Morrison and Summerville Formations—Con.		
White shale	10	150
Red rock	55	205
White shale	80	285
Hard sand	105	390
Red rock	35	425
White shale	25	450
Red rock	30	480
Sandy shale	25	505
Red rock	25	530
Hard gray sand	28	558
White water sand, filled to within 75 ft of top	7	565
Red sandstone	30	595
White shale	25	620
Sandy shale	15	635
Red rock	15	650
Entrada Sandstone, Kayenta Formation, and Wingate Sandstone:		
Sand, well began to flow	20	670
Red sand, water-bearing	252	922

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