Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona New Mexico, and Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 521-A

Prepared in cooperation with the Bureau of Indian Affairs and the Navajo Tribe

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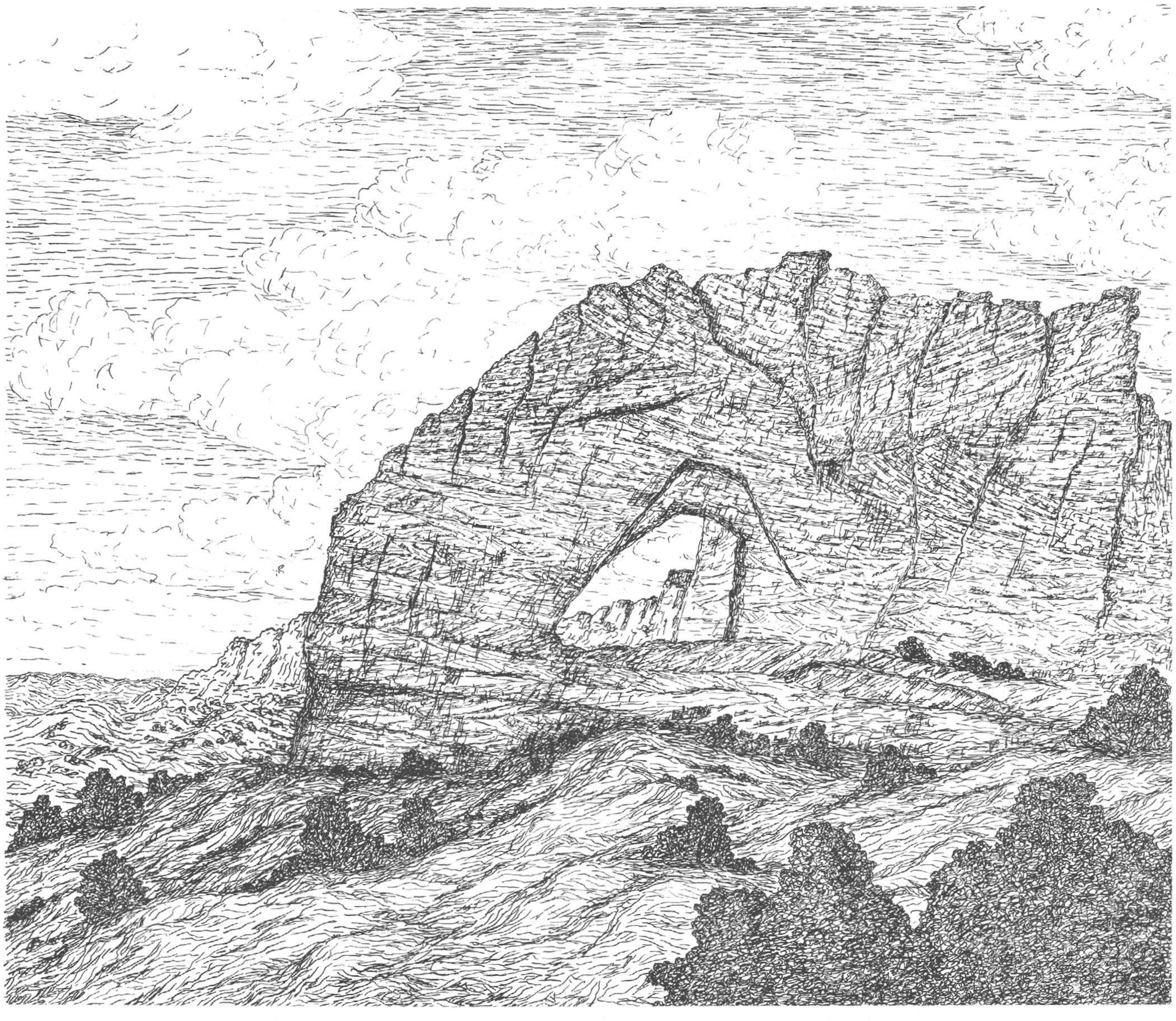

Arch, White Mesa. Sketch by M. E. Cooley.

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By M. E. COOLEY, J. W. HARSHBARGER, J. P. AKERS, *and* W. F. HARDT

With a section on Vegetation
By O. N. HICKS

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By M. E. Cooley, J. W. Harshbarger, J. P. Akers, and W. F. Hardt

ABSTRACT

The Navajo and Hopi Indian Reservations have an area of about 25,000 square miles and are in the south-central part of the Colorado Plateaus physiographic province. The reservations are underlain by sedimentary rocks that range in age from Cambrian to Tertiary, but Permian and younger rocks are exposed in about 95 percent of the area. Igneous and metamorphic basement rocks of Precambrian age underlie the sedimentary rocks at depths ranging from 1,000 to 10,000 feet. Much of the area is mantled by thin alluvial, eolian, and terrace deposits, which mainly are 10 to 50 feet thick.

The Navajo country was a part of the eastern shelf area of the Cordilleran geosyncline during Paleozoic and Early Triassic time and part of the southwestern shelf area of the Rocky Mountain geosyncline in Cretaceous time. The shelf areas were inundated frequently by seas that extended from the central parts of the geosynclines. As a result, complex intertonguing and rapid facies changes are prevalent in the sedimentary rocks and form some of the principal controls on the ground-water hydrology. Regional uplift beginning in Late Cretaceous time destroyed the Rocky Mountain geosyncline and formed the structural basins that influenced sedimentation and erosion throughout Cenozoic time.

The rocks are characterized by the absence of severe deformation. The area has been relatively stable since late Precambrian time and was affected only moderately by the orogeny of Late Cretaceous and early Tertiary time, which produced a variety of folds. Later, in Tertiary and Quaternary time, the area was upwarp and locally faulted.

The reservations are divided into several hydrogeologic subdivisions on the basis of differences in the exposed sedimentary rocks, structure, and physiography. The occurrence of ground water in each subdivision is controlled principally by the geology.

The climate of the Navajo country varies widely, ranging from semiarid below 4,500 feet to relatively humid above 7,500 feet. Precipitation has a strong and fairly uniform relation to altitude and the orographic effects of the physiography. Mean annual temperature is affected by altitude and by the local physiographic position of the weather station. Dunes and other eolian deposits are common and were laid down intermittently throughout Quaternary and part of Tertiary time. The distribution and orientation of the dunes and the direction of crossbeds indicate that the prevailing wind during much of prehistoric time was from the southwest and therefore was similar to the present prevailing wind pattern.

Vegetation is divided into broad zones consisting of grass-shrub at altitudes below 5,500 feet, pinyon-juniper between 5,500 and 7,500 feet, and pine forest above 7,500 feet. In the grass-shrub and pinyon-juniper zones, some of the plant assemblages are controlled by the types of sedimentary rocks exposed.

The Colorado River developed in late Cenozoic time as a superimposed stream on the folded rocks of the Colorado Plateaus. Continuous downcutting by the river and its tributaries resulted in entrenchment of the entire system. Entrenchment was at a maximum during late Pliocene and Pleistocene time and was about 1,800 feet in Glen and San Juan Canyons and as much as 1,000 feet along the Little Colorado River. All runoff from the reservations is to the Colorado River. The Colorado and San Juan Rivers are perennial. All the other streams are ephemeral or intermittent except for short reaches downstream from large springs and where the streambed intersects the water table. Nearly one-sixth of the area drains internally.

The aquifers are composed of beds of sandstone between nearly impermeable layers of siltstone and mudstone. The main aquifers are in the Coconino Sandstone, Navajo Sandstone, and the alluvium; but all other units locally yield some water to wells and springs. The siltstone and mudstone layers act as aquicludes, thus confining the water in the underlying sandstone aquifers under artesian pressure in much of the area. For the most part, the aquifers in the consolidated sedimentary rocks are fine grained and do not transmit water rapidly. Coefficients of permeability are generally less than 10 gpd per sq ft (gallons per day per square foot), and many are less than 3 gpd per sq ft. Yields from wells in these aquifers usually are less than 25 gpm (gallons per minute). Most specific capacities computed from tests of wells range from 0.3 to 5.0 gpm per ft of drawdown.

The basins and uplifts control the movement of ground water in the sedimentary rocks; the other structural features affect the occurrence of ground water only locally. The larger folds divide the reservations into five general areas, which are considered as separate hydrologic basins—Black Mesa, San Juan, Blanding, Henry, and Kaiparowits hydrologic basins.

The main areas of recharge to the ground-water reservoirs are on the highlands—Defiance Plateau, Zuni Mountains, Mogollon Slope, San Francisco Plateau, and Navajo Uplands—along the structural divides between the hydrologic basins. Movement of the ground water in each hydrologic basin is downdip from the highlands and toward the Colorado, Little Colorado, or San Juan Rivers and their larger tributaries rather than toward the centers of the basins. Black Mesa basin is unique in that most water discharges into the Little Colorado River from Blue Spring and nearby springs, which flow at about 220 cubic

feet per second. Natural discharge is from 1,000 springs and numerous seeps. Artificial discharge is from 1,300 drilled wells and 550 dug wells, which are used chiefly for domestic and stock purposes.

The ground water has a wide range in the type and amount of dissolved chemical constituents. Most water having less than 700 ppm (parts per million) of dissolved solids is either calcium or sodium bicarbonate, and water containing more than 700 ppm is sodium sulfate, calcium sulfate, or sodium chloride. The amount of fluoride in the ground water in parts of the Hopi Indian Reservation, the valley of the Little Colorado River, and the San Juan basin is excessive and may be more than 3.0 ppm. The dissolved-solids content of 1,300 water samples analyzed ranges from 90 to more than 25,000 ppm. Water from the flushed aquifers in the Navajo, Wingate, Coconino, and De Chelly Sandstones on the Mogollon Slope, San Francisco Plateau, Navajo Uplands, and Defiance Plateau usually contains less than 1,000 ppm of dissolved solids. Water having the greatest amount of dissolved solids is in deep aquifers in the Black Mesa and San Juan basins.

INTRODUCTION

The Navajo and Hopi Indian Reservations are in the picturesque canyon and mesa country of the south-central part of the Colorado Plateaus. The area is one of physiographic and environmental contrast; the terrane consists of barren alluvial flats and badlands in the main stream valleys, bald-rock plains partly covered by dunes, sharp-crested buttes and ridges, brilliant-hued cliffs, and forested slopes and grassy meadows. Surface water and shallow ground-water supplies are plentiful locally in the highlands but are deficient in other parts of the reservations. Where water shortages are chronic, dependable water supplies have been supplemented by utilizing the deep ground-water reservoirs.

PURPOSE AND SCOPE

Since the early 1940's, an increasing need for dependable water supplies in the reservations has been caused by an expanding Indian population and economy. Concurrent with this expansion, drought has become more severe in the southwestern United States (Thomas, 1963). As a result of the drought, which started about 1925, surface and shallow subsurface water supplies became less dependable, and many sources, previously reliable, dried up altogether. The decreasing rainfall necessitated the finding of new water supplies, particularly ground water.

From 1946 to 1950, the U.S. Geological Survey, at the request of the Bureau of Indian Affairs, made a series of hydrologic investigations to help alleviate the water shortage in several places. In 1950, the Geological Survey in cooperation with the Bureau of Indian Affairs began a comprehensive regional investigation of the geology and ground-water resources of the reservations. A well-development program supported by the Bureau of Indian Affairs and the Navajo Tribe was carried on concurrently with the regional investigation and is being continued by the Navajo Tribe. The principal objectives of these investigations were: (1) to determine the feasibility of developing ground-water supplies for stock, institutional, and industrial uses in particular areas and at several hundred well sites scattered throughout the reservations and in adjoining areas owned by the Navajo Tribe; (2) to inventory the wells and springs; (3) to investigate the geology and ground-water hydrology; and (4) to appraise the potential for future water development.

LOCATION

The Navajo Indian Reservation occupies parts of Apache, Navajo, and Coconino Counties in northeastern Arizona; San Juan and McKinley Counties in northwestern New Mexico; and San Juan County in southeastern Utah (fig. 1). The Hopi Indian Reservation is in the central part of the Navajo Indian Reservation in Arizona. The reservations have an area of about 25,000 square miles, which is about three times the size of New Jersey.

The term "Navajo country" (Gregory, 1917, p. 11) is used broadly to include the Navajo and Hopi Indian Reservations and the area lying principally between the Colorado, San Juan, and Little Colorado Rivers. The term "Hopi country" is an informal designation for the Hopi Indian Reservation. The "checkerboard" area of the Navajo country, so-called because sections are owned by Indians, ranchers, and Federal and State Governments, is along the eastern boundary of the Navajo Indian Reservation in New Mexico and to the south of the reservation in Arizona and New Mexico (fig. 1).

The Navajo country is crossed by only a few main routes of travel. The southern part is traversed by the Atchison, Topeka, and Santa Fe Railway and by U.S. Highway 66, the site of the proposed Interstate Highway 40. The area is crossed north-south by U.S. Highways 89 and 89A, leading from Flagstaff and leaving the area at Navajo Bridge and Glen Canyon Dam near Page, and by U.S. Highway 666 between Gallup and Shiprock. During the 1950's, the Navajo Tribe and the Bureau of Indian Affairs began the construction of a network of all-weather highways that connect the principal localities in the reservations. Page is the only community that has scheduled air service, although there are air terminals near the reservations at Farmington and Gallup, N. Mex., and Winslow and Flagstaff, Ariz. Almost every other community, however, has an airstrip for light planes.

LAND-NET SYSTEM

The reservations are divided by the Bureau of Indian Affairs into 18 administrative districts. Districts 1–5 and 7–18 are in the Navajo Indian Reservation, and district 6 is in the Hopi Indian Reservation.

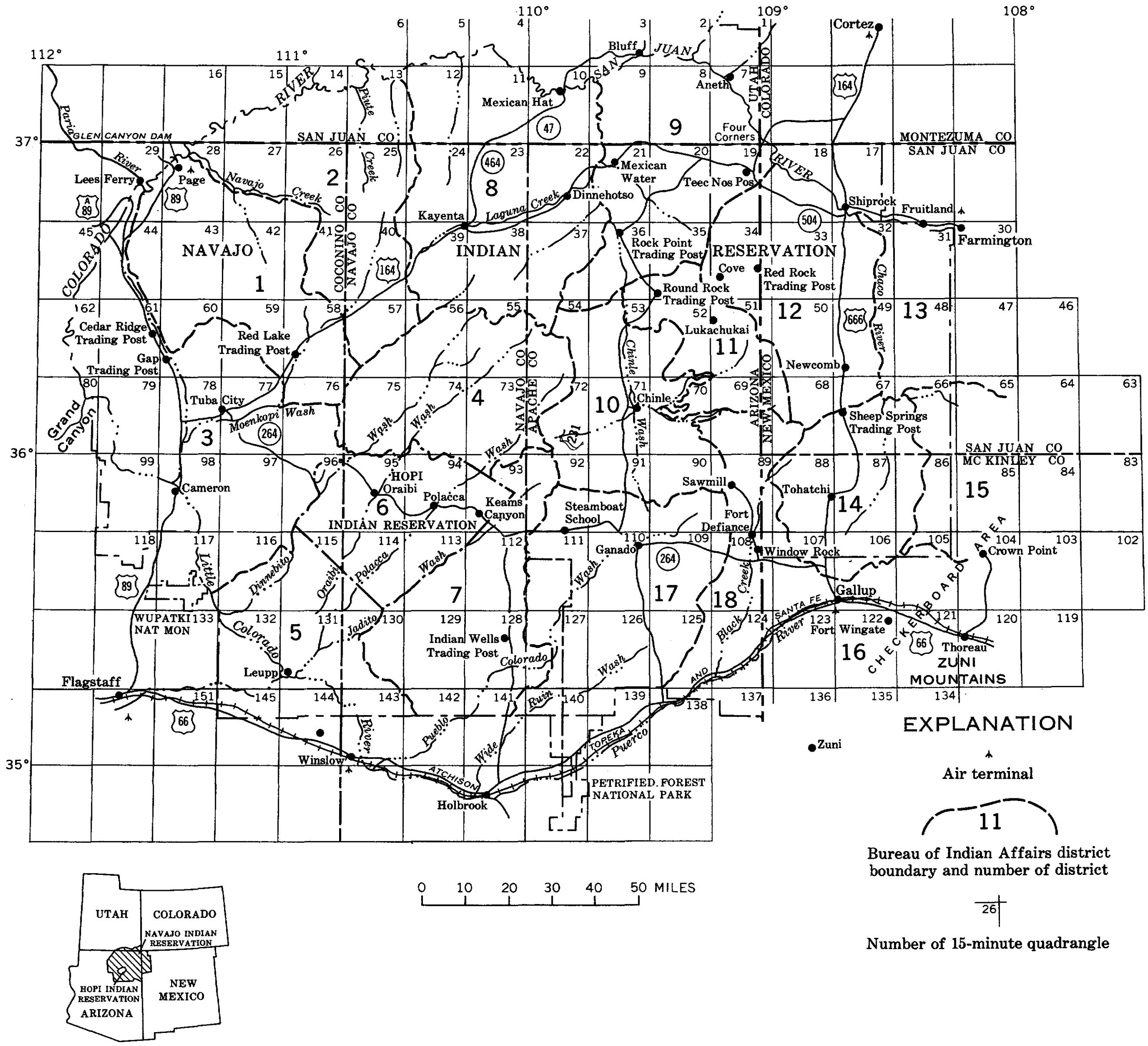

Figure 1.—Location map of the Navajo and Hopi Indian Reservations showing the Bureau of Indian Affairs' administrative districts.

Few detailed maps of the reservations were available at the time of this study, but 15-minute planimetric maps compiled from aerial photographs were available. These maps are numbered arbitrarily from 1 to 151, starting in the upper right corner of the reservations and numbering consecutively from right to left in rows (fig. 1).

TOPOGRAPHIC RELIEF

The major part of the reservations consists of plateaulike features 4,000–7,000 feet above sea level. Rising to altitudes of more than 8,000 feet are Navajo Mountain, Defiance Plateau, the Carrizo, Chuska, and Zuni Mountains, and the northern part of Black Mesa; at altitudes of less than 3,000 feet are the deep canyons of the Colorado River—Grand, Marble, and Glen Canyons—the San Juan Canyon, and the canyon of the Little Colorado River. In general, the valleys of the Little Colorado River, Chinle Wash, and Chaco and San Juan Rivers range from 4,000 to 5,500 feet in altitude. The highest point on the reservations is Navajo Mountain, 10,344 feet, and the lowest is the mouth of the Little Colorado River, about 2,800 feet.

ORGANIZATION OF THE REPORT

This report is the first chapter of U.S. Geological Survey Prof. Paper 521, which will describe the geology

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and hydrology of the sedimentary and volcanic rocks of the reservations. Stratigraphic descriptions of the uppermost Triassic and the Jurassic rocks have been published previously as U.S. Geological Survey Prof. Paper 291 (Harshbarger and others, 1957) and are not included in this report.

The basic geohydrologic data—records of wells and springs; selected chemical analyses; selected drillers' logs, lithologic logs, and stratigraphic sections; and maps showing locations of wells, springs, and stratigraphic sections—are published separately as Arizona State Land Department Water Resources Reports 12–A, 12–B, 12–C, 12–D, and 12–E.

The geologic map at a scale of 1:125,000, or 1 inch equals about 2 miles, will accompany this chapter only. Maps showing the locations of drilled wells, dug wells, and springs are published only with the geohydrologic data in Arizona State Land Department Water Resources Report 12–D. Maps accompanying succeeding chapters that describe the ground-water hydrology of a particular group of aquifers will show the locations of wells and springs discharging only from those aquifers.

FIELDWORK AND COMPILATION OF DATA

Stereoscopic pairs of aerial photographs at a scale of 2 inches to 1 mile were used in plotting all geologic and hydrologic data. Fifteen-minute aerial mosaic maps compiled from these photographs were used as base maps during the investigation and in the compilation of the final maps. The photographs and the aerial mosaic maps were made during the middle 1930's for the Soil Conservation Service of the Department of Agriculture.

Few topographic maps were available during the field investigation. Water developments and cultural features were located on the aerial photographs, and altitudes were obtained by aneroid barometer. Where possible, these altitudes were checked with the topographic maps.

Geologic investigation consisted principally of surface and subsurface geologic mapping, measurement and description of stratigraphic sections, and analysis of sample cuttings from new wells. These methods delineated the aquifers and aided in understanding the intertonguing, facies changes, and other geologic factors that affect the water-bearing characteristics of the rocks.

Stratigraphic sections of rocks ranging in age from Permian to Recent were measured and described. Fieldwork was concentrated principally on Triassic, Jurassic, and Cretaceous rocks in the part of the Navajo country in Arizona. Most lithologic descriptions were made in the field with the aid of a 10-power hand lens. Samples were taken at the time of measurement for analysis of heavy-mineral content, size range of grains, and other lithologic characteristics.

Examination of sample cuttings from water wells was an integral part of the ground-water investigation. Unwashed sample cuttings collected at 10-foot intervals were described by a geologist from binocular microscopic examination. The sample cuttings and drillers' logs of most wells are on file at the Arizona Bureau of Mines depository, Tucson.

Hydrologic fieldwork consisted principally of an inventory and tests of wells and springs. Pressure tests were made of most flowing wells, particularly those in the San Juan basin. Cores of the main water-bearing rocks were analyzed in the hydrologic laboratory of the Geological Survey, Denver, Colo., to determine their permeability, porosity, specific retention, and specific yield. A widespread network of observation wells was maintained for a few years to ascertain possible long-term fluctuations of the water table. In areas of concentrated pumping, water-level measurements in selected wells are continuous.

A field inventory completed in 1956 described 2,338 ground-water supplies consisting of 846 drilled wells, 537 dug wells, and 955 springs. From 1956 through 1961, 402 new wells were drilled, and many new wells have been drilled since 1961. Water levels in nearly all wells and the yields of springs were measured, and more than 1,300 water samples from selected wells and springs were analyzed by the Geological Survey.

Pumping or bailing tests were made of most wells. Most tests were of wells tapping the Navajo Sandstone; the Coconino Sandstone and its lateral equivalents, the De Chelly Sandstone and Glorieta Sandstone; or aquifers in rocks of Cretaceous age. Generally, no observation wells were involved in the tests. All newly drilled wells were tested by bailing or short-term pumping to determine yield and drawdown.

PREVIOUS INVESTIGATIONS

The first description of the Navajo country was by Newberry (1861; 1876), who was with the Ives and Macomb expeditions that studied parts of northwestern New Mexico, northeastern Arizona, and Utah. Marvine and Howell of the Wheeler Survey, as recorded by Howell (1875) and Holmes (1877) of the Hayden Survey, described some geologic features in the Defiance Plateau-Carrizo Mountains area. Early comprehensive reports that included parts of the Navajo country were made by Dutton (1882; 1885) in the Grand Canyon region and southeast of the reservations in New Mexico. Shortly after 1900 the coal deposits in the San Juan basin received considerable attention and were described by Schrader (1906), Shaler (1907), and Gardner (1909).

The basic geologic framework of the Navajo country was outlined by Gregory (1916; 1917), who published the first geologic map and made a hydrologic reconnaissance. Many stratigraphic units that Gregory described originally are accepted as standard.

Other reports that have contributed substantially to the geologic knowledge of the reservations were by Darton (1910), Woodruff (1912), Robinson (1913), Reeside (1924), Miser (1924; 1925), Gregory and Moore (1931), Baker (1936), Williams (1936), Gregory (1938), Sears, Hunt, and Hendricks (1941), Allen and Balk (1954), Kelley (1955), Strobell (1956), O'Sullivan and Beaumont (1957), and Read and Wanek (1961b).

As a result of the present study, 34 papers were published. These are listed in the bibliography and marked with an asterisk.

HISTORY OF THE PROJECT, INCLUDING PERSONNEL

The Bureau of Indian Affairs first requested technical assistance from the Geological Survey concerning ground-water problems on the Navajo Indian Reservation in 1946. H. V. Peterson made several spot investigations in 1946 and 1947. Site investigations were continued by L. C. Halpenny, S. C. Brown, and H. A. Whitcomb in Arizona, and by R. L. Griggs in New Mexico. The regional geologic and hydrologic investigation was begun in 1950 under the general supervision of S. F. Turner, district engineer, Arizona, Ground Water Branch, and under the direct supervision of L. C. Halpenny. Technical assistance in planning during the early phases was given by C. V. Theis, H. E. Thomas (later replaced by H. A. Waite), and S. W. Lohman (later replaced by T. G. McLaughlin), who were district supervisors of New Mexico, Utah, and Colorado, respectively. When L. C. Halpenny succeeded S. F. Turner as district engineer, J. W. Harshbarger became chief of the Navajo Ground Water Project. Most of the information in this report represents the collective efforts of the following personnel, who were employed for all or part of the period 1950–55: J. P. Akers, J. T. Callahan, M. E. Cooley, G. E. Davis, S. E. Galloway, E. L. Gillespie, W. F. Hardt, J. H. Irwin, William Kam, R. L. Jackson, H. G. Page, C. A. Repenning, P. R. Stevens, H. A. Whitcomb, and H. A. Yazhe. Others who were associated with the project are: R. L. Cushman, A. E. Robinson, G. S. Smith, L. K. Thompson, C. T. Pynchon, C. L. Hicks, M. F. Smith, W. A. Beldon, S. H. Congdon, J. F. Lance, H. O. Ash, J. R. Howard, D. K. Greene, and R. A. McCleave.

In 1948, the Organic Fuels Branch of the U.S. Geological Survey, in cooperation with the Bureau of Indian Affairs, began a separate study of the mineral-fuel potential of parts of the Navajo country. This investigation, with emphasis on Cretaceous stratigraphy, covered the eastern part of the Navajo Indian Reservation in northwestern New Mexico and the southwestern part of Black Mesa in Arizona. The fieldwork by E. C. Beaumont, A. E. Burford, P. T. Hayes, R. B. O'Sullivan, and D. L. Zieglar was done under the direction of the following successive supervisors: C. B. Read, L. S. Gardner, C. H. Dane, and G. O. Bachman. The results of this investigation including the geologic mapping and some of the stratigraphic studies are incorporated into this report.

Work on the project continued only intermittently between 1955 and 1960, but in 1960 a renewed effort to complete and publish the reports was begun under the supervision of P. E. Dennis, who succeeded J. W. Harshbarger as district geologist for the Ground Water Branch in Arizona, and under the project leadership of M. E. Cooley, assisted chiefly by J. P. Akers and E. H. McGavock. This work consisted principally of compiling the basic data and illustrations, review and revision of the text, and the updating and integrating of the sections already written with the information obtained since 1955.

ACKNOWLEDGMENTS

The writers are grateful for the assistance, cooperation, and information given by the late J. J. Schwartz, former head of the Bureau of Indian Affairs' water-development program for the Navajo Indians; M. H. Miller, Bureau of Indian Affairs engineer; C. M. Sells, superintendent, Ground Water Development Department of the Navajo Tribe; J. C. Shorty and J. M. Holmes, geologist and hydrologist, respectively, for the Navajo Tribe; Buster Kingsley, Bureau of Indian Affairs supervisor for the Hopi Indians; the Navajo Tribal Council; and other personnel of the Bureau of Indian Affairs and the two tribes.

The collection of hydrologic data was greatly facilitated by the cooperation given by personnel of pumping stations of the El Paso Natural Gas Co., of religious institutions, and of trading posts. Valuable assistance was given by many water-well drillers, most of whom have collected drill cuttings and supplied hydrologic data since 1948. Special thanks are given the Cowley Bros. Drilling Co., St. Johns, Ariz.; the Perry Bros. Drilling Co., Flagstaff, Ariz.; the Myers Drilling Co., Holbrook, Ariz.; and O. C. Robinson, Tucson, Ariz.

In so large an area, it was imperative to confer with other geologists working in the area, and thanks are given L. C. Craig, J. H. Stewart, G. A. Williams, E. D. McKee, J. D. Strobell, Jr., J. B. Reeside, Jr., R. B. O'Sullivan, T. E. Mullens, D. G. Wyant, and V. L. Freeman, all of the Geological Survey, who contributed substantially to these conferences.

Special credit is due S. H. Congdon and H. G. Page, who operated a sedimentological laboratory for the study of the sedimentary rocks of the Navajo and Hopi Indian Reservations and who made and interpreted laboratory analyses.

The authors gratefully acknowledge the substantial help given by Alfonso Wilson and N. C. Matalas of the Geological Survey during the preparation of the sections concerning climate and drainage.

SEDIMENTARY FEATURES

The rock type, color, particle size, rounding, sorting, composition, accessory minerals, and cementation are recorded in all lithologic descriptions of the sedimentary rocks. Grain sizes of detrital rocks are described generally in accordance with the classification presented by Wentworth (1926). In his classification, detrital rocks are listed in order of increasing coarseness as claystone, siltstone, sandstone, granule conglomerate, and pebble conglomerate. These types grade into one another, and modifying terms can be used, such as "sandy siltstone" or "silty sandstone." Additionally, the term "mudstone" is used to designate a rock containing nearly equal proportions of silt and clay. The color designation was determined from the rock-color chart distributed by the National Research Council (Goddard, 1948), and the determination of grain size, roundness, and degree of sorting was made by visual comparison with charts prepared by Payne (1942). Particle size in order of increasing grain size includes clay; silt; very fine grained, fine-grained, medium-grained, coarse-grained, and very coarse grained sand; granule; pebble; cobble; and boulder, according to the Wentworth grade scale (table 1). The grains are classified as well rounded, rounded, subrounded, subangular, or angular. The sorting is indicated as well sorted, fair sorted, and poorly sorted and, in general, is restricted to sandstone. Material is well sorted if more than 90 percent of the grains is in two adjacent particle-size ranges (Payne, 1942), or fair sorted if more than 90 percent of the grains falls into three or four adjacent ranges. Quartz grains are the main constituents of the sediments, and they are described as clear, stained, frosted, or amber. Readily identifiable accessory minerals are pyrite, gypsum, calcite, and mica. Where the accessory minerals are not easily identifiable, their color prevalence and other readily distinguished characteristics are described. The clastic rocks are well, firmly, and weakly cemented, and, where recognizable, the composition of the cement is noted. A noncalcareous, weakly cemented sediment is considered to have an "argillaceous" cement.

TABLE 1.—*Particle-size classification for detrital rocks*

[After Wentworth (1926)]

Size (diameter, in mm)	*Classification*
>256	Boulder.
256–64	Cobble.
64–4	Pebble.
4–2	Granule.
2–1	Very coarse sand.
1–½	Coarse sand.
½–¼	Medium sand.
¼–⅛	Fine sand.
⅛–1/16	Very fine sand.
1/16–1/256	Silt.
< 1/256	Clay.

The description of the bedding and splitting properties in most chapters of this report closely follows the bedding description of McKee and Weir (1953), as modified by Harshbarger, Repenning, and Irwin (1957), with the exception that thinly laminated and laminated bedding may be referred to as very thin bedded (table 2).

TABLE 2.—*Classification of bedding and splitting properties of layered rocks*

[After Harshbarger and others (1957)]

Bedding	Splitting property	Thickness
Very thick	Massive	>120 cm (4 ft).
Thick	Blocky	60–120 cm (2–4 ft).
Thin	Slabby	6–60 cm (2 in–2 ft).
Very thin	Flaggy	1–5 cm (½–2 in).
Laminated	Shaly (mudstone)	2 mm–1 cm.
	Platy (limestone and sandstone).	2 mm–1 cm.
Thinly laminated	Fissile	<2 mm (paper thin).

Crossbedding or cross stratification is divided into three types—simple, planar, and trough—on the basis of the external features of a unit displaying similarly oriented crossbeds, as described by Harshbarger and others (1957, p. 58) as follows:

> The simple type shows no apparent signs of erosion along the bounding surfaces of the individual groups of crossbeds. The planar type is marked by flat surfaces of erosion bounding the group. The trough type is marked by curved surfaces of erosion bounding the group. Festoon crossbedding would be a specialization within the trough type, as its lower boundary is obviously a curved surface of erosion. What often has been referred to as torrential crossbedding ordinarily falls into the planar type. Minor descriptive terms used to modify the three major types are tabular (parallel planar surfaces), wedge (converging planar surfaces), and lenticular (converging curved surfaces).

The crossbeds, as shown in the following tabulation, are classified as to shape, angle of dip, size, and thickness:

Shape	Concave or convex (upward).
Angle of dip:	
High	>20°.
Medium	10°–20°.
Low	<10°.
Size or scale:	
Large	>20 ft.
Medium	1–20 ft.
Small	<1 ft.
Thickness	Same as classification for bedding.

Pseudocrossbedding, formed by a progressive advance of ripples upon each other, is common in silty fine-grained sandstone and siltstone beds. Commonly, the upper part of the ripple mark has been removed and only the lower part is preserved. Well-formed ripple marks are not common within a pseudocrossbedded unit, although they may occur at the top of the unit.

The other features of the sedimentary rocks relate to weathering and topographic expression, such as slopes, ledges, cliffs, and the size of blocks and particles produced by weathering. For the most part, the terms are self-explanatory. Platy weathering generally is associated with very thin bedded units and flaggy weathering with thin- to thick-bedded sediments, especially those consisting of alternating sandstone and siltstone layers. Hoodoo weathering pertains to rounded, irregular, or pillarlike forms, which often have been described as "rock babies."

GEOLOGY AND OCCURRENCE OF GROUND WATER

Practically all the ground water in the reservations occurs in sedimentary rocks that overlie relatively impermeable granitic and metamorphic basement rocks. The water-bearing sedimentary rocks consist of sandstone, conglomerate, and limestone. Those that do not bear water consist of mudstone, siltstone, and silty sandstone. The thickness, lithology, and water-bearing characteristics of the sedimentary rocks are summarized in table 3.

Most of the rocks of the Navajo country contain some water, but only a few formations yield water readily to wells. The major water-yielding units are the Navajo and Coconino Sandstones, which form multiple-aquifer systems with the adjacent strata, and the alluvium, which receives considerable water as discharge from the sedimentary rocks. Minor water-yielding units, in ascending stratigraphic order, are the Shinarump Member of the Chinle Formation, Lukachukai Member of the Wingate Sandstone, Entrada Sandstone, Cow Springs Sandstone, Morrison Formation, Dakota Sandstone, Toreva Formation, Gallup Sandstone, Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone, Chuska Sandstone, and volcanic rocks. Other units that yield water in adjoining regions but only small amounts on the reservations are the Supai Formation, Sonsela Sandstone Bed of the Chinle Formation, Ojo Alamo Sandstone, and the Bidahochi Formation.

TABLE 3.—*Water-bearing characteristics of sedimentary rocks in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah*

[Data are through 1956]

System	Series	Group	Stratigraphic unit	Lithology and thickness (feet)	Water-bearing characteristics		
					General hydrology	Depth of wells (feet)	Depth to water (feet)
				Navajo country			
Quaternary	Pleistocene and Recent		Alluvium and terrace deposits.	Chiefly sand, silt, and gravel, 200.	Alluvium: yields generally small amounts of water to wells along the Little Colorado River, San Juan River, and larger tributaries; <225. Terrace deposits: yield a small amount of water to a few springs.	50->300	10->200
			Dune deposits	Chiefly sand; <100.	Yield small amounts of water to a few springs.		
	Pleistocene		Landslide and talus	Large slump blocks and slide rubble.	Yield small amounts of water in the Hopi country and in the Chuska Mountains.		
Tertiary	Pliocene		Bidahochi Formation	Upper and lower members: siltstone, sandy siltstone, and sandstone; <800. Middle volcanic member: tuff and basalt flows.	Yields small amounts of water to a few wells in central Navajo and Apache Counties; small springs issue from tuff in the Hopi Buttes.	<700	100-600
	Pliocene (?)		Chuska Sandstone	Chiefly sandstone; 1,000.	Yields water to springs in the Chuska Mountains; it is the source of water in the perennial reaches of Tsaile, Wheatfields, and Whiskey Creeks; no wells penetrate the formation.		
	Paleocene		Nacimiento Formation	Alternating shaly units 200-400 feet thick with sandstone beds 50-100 feet thick; >1,000.	Not water bearing within the Navajo Indian Reservation.		

TABLE 3.—*Water-bearing characteristics of sedimentary rocks in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah*—Continued

System	Series	Group	Stratigraphic unit	Lithology and thickness (feet)	Water-bearing characteristics: General hydrology	Depth of wells (feet)	Depth to water (feet)
			San Juan basin				
Cretaceous	Upper		Ojo Alamo Sandstone	Chiefly sandstone and conglomerate; 50–200.	Yields water to a few springs.		
			Kirtland Shale	Chiefly mudstone, siltstone, and silty sandstone; 700.	Yields water to a few wells in the Farmington Sandstone Member; shaly parts not water bearing.	1,000	
			Fruitland Formation	Chiefly mudstone, siltstone, coal, and silty sandstone; 700.	Usually not water bearing.		
			Pictured Cliffs Sandstone	Chiefly sandstone; 100–400.	Yields water to wells and to a few springs northeast of the Chaco River.		
			Lewis Shale	Chiefly claystone to siltstone; 0–400.	Usually not water bearing; forms confining bed between the Pictured Cliffs and Cliff House Sandstones.		
		Mesaverde	Cliff House Sandstone	Sandstone; 200–800.	Yields water to wells and to a few springs near the Chaco River.		
			Menefee Formation	Alternating siltstone, coal, and sandstone beds; 1,100–2,200.	Sandstone beds throughout the formation yield small amounts of water to wells in the southern San Juan basin.	<1,500	Flow–200
			Point Lookout Sandstone, including the Hosta Tongue	Chiefly sandstone; 0–300.	Yields water to wells in the southern San Juan basin.	<1,500	Flow
			Crevasse Canyon Formation	Alternating siltstone, coal, and sandstone beds; 700–900.	Yields water to a few wells in the Gallup area; Dalton Sandstone Member is the chief water-bearing unit.	<1,000	<500
			Gallup Sandstone	Chiefly sandstone; 0–300.	Yields water along southwestern flank of the San Juan basin.	<1,000	200–500
			Black Mesa basin				
Cretaceous	Upper	Mesaverde	Yale Point Sandstone	Chiefly sandstone; 100–300.	Yields water to a few springs in northern Black Mesa.		
			Wepo Formation	Alternating siltstone, coal, and sandstone beds; 300–800.	Sandstone beds yield small amounts of water to a few wells and springs in central Black Mesa.	<600	<400
			Toreva Formation	Upper and lower members are composed of sandstone; middle member is composed of silty sandstone, siltstone, and coal; 200–400.	Sandstone units yield small amounts of water to wells in southern and central Black Mesa; base of formation is a prominent spring zone in the Hopi country.	<800	<400
			Navajo country				
Cretaceous	Upper		Mancos Shale	Chiefly claystone to siltstone; 500–1,800.	Usually not water bearing.		
	Lower(?) and Upper		Dakota Sandstone[1]	Sandstone, siltstone, and coal; 100.	Unit is the chief aquifer of the D multiple-aquifer system[2]; yields small amounts of water to wells in the southern part of Black Mesa basin; some of the wells flow.	200–1,000	Flow–500
	Lower		Burro Canyon Formation	Siltstone and mudstone; <300.	Usually not water bearing.		
Jurassic	Upper		Morrison Formation	Alternating sandstone and siltstone beds; 200–600.	Sandstone units yield small amounts of water to wells in northern Apache and Navajo Counties.[2]	200–700	150–600
			Cow Springs Sandstone	Intertonguing sandstones; 100–300.	Yields small amounts of water in Chinle Valley area and in the southern and eastern parts of Black Mesa basin.[2]	200–500	100–400
		San Rafael	Bluff Sandstone				
			Summerville Formation	Siltstone and some sandstone; 100–200.	Usually not water bearing; sandy facies yields some water to springs in the Chuska Mountains.		
			Todilto Limestone	Limestone and sandstone; 0–75.	Usually not water bearing.		
			Entrada Sandstone	Sandstone and some siltstone; 50–350.	Yields water to a few springs in the northern part of the Navajo Indian Reservation; yields small amounts to wells in the Chinle Valley area and in the southern part of Black Mesa basin.	200–600	150–500
	Middle		Carmel Formation	Siltstone and some sandstone; 0–300.	Yields water to a few small springs in northeastern Coconino County; forms upper confining bed of the N multiple-aquifer system.		

See footnotes at end of table.

TABLE 3.—*Water-bearing characteristics of sedimentary rocks in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah*—Continued

System	Series	Group	Stratigraphic unit	Lithology and thickness (feet)	Water-bearing characteristics: General hydrology	Depth of wells (feet)	Depth to water (feet)
Navajo country—Continued							
Jurassic and Triassic(?)		Glen Canyon	Navajo Sandstone	Sandstone; 0–1,800; thickens northwestward.	Unit is the chief aquifer of the N multiple-aquifer system [3]; yields small to medium amounts of water principally in the northern part of the Navajo Indian Reservation; base of formation is conspicuous spring zone.	100–1, 500	50–1, 400
Triassic(?)	Upper	Glen Canyon	Kayenta Formation	Chiefly a sandstone in the northern part of the Navajo Indian Reservation; chiefly a siltstone in southwestern part of the reservation; 0–700.	Yields water to a few springs; tongues of the Navajo Sandstone in the upper part of the formation yield small amounts of water to wells near Tuba City [3]; a few of these wells flow.	<200	Flow–50
Triassic(?)	Upper	Glen Canyon	Moenave Formation	Silty sandstone and sandy siltstone; 0–500.	Not water bearing.		
Triassic	Upper	Glen Canyon	Wingate Sandstone	Lukachukai Member is a sandstone; 0–300. Rock Point Member is a siltstone and silty sandstone; 0–900.	Yields small and moderate amounts of water to springs and wells in northern Apache and Navajo Counties.[3] Yields some water to springs; unit generally does not yield sufficient water for drilled wells.	300–800	100–700
Triassic	Upper		Chinle Formation (excluding Shinarump Member)	Alternating shaly units 200–400 feet thick with sandstone beds 50–100 feet thick; formation 850–1,500 feet thick.	Shaly units are not water bearing; sandstone beds yield small amounts of water to springs and wells on the Defiance Plateau; Sonsela Sandstone Bed and sandstone beds in the Monitor Butte Member are water yielding in the Defiance uplift and the Zuni Mountains.		
Triassic	Upper		Shinarump Member of the Chinle Formation	Sandstone and some conglomerate and mudstone; 0–200.	Locally, yields small amounts of water to wells and springs throughout northeastern Arizona; it is connected hydrologically with the Coconino (De Chelly) Sandstone of Permian age in the Defiance uplift area.[4]	100–2, 500	Flow–800
Triassic	Middle(?) / Lower		Moenkopi Formation	Siltstone and some sandstone; 0–400.	Yields a small amount of water to a few wells.	100–300	30–200
Grand Canyon area							
Permian	Lower	Aubrey	Kaibab Limestone	Limestone and some limy sandstone; 0–300.	Yields small amounts of water to a few wells near Leupp.[4]	100–300	100–250
Permian	Lower	Aubrey	Toroweap Formation	Chiefly sandstone; 0–100.	Usually not water bearing in the Navajo country.		
Permian	Lower	Aubrey	Coconino Sandstone	Sandstone; 50–700.	Unit is the chief aquifer of the C multiple-aquifer system;[4] yields small to large amounts of water to wells in southwestern part of Navajo country.	100–1, 500	Flow–1, 000
Permian	Lower	Aubrey	Hermit Shale	Chiefly sandy siltstone; 200.	Not water bearing.		
Permian / Pennsylvanian	Lower	Aubrey	Supai Formation	Chiefly siltstone and sandstone; 400–1, 700.	Uppermost sandstone beds of formation interconnect hydrologically with the Coconino Sandstone.[4]	150–>2, 000	100–2, 000
Mississippian			Redwall Limestone	Limestone; 0–500.	Yields large amounts of water to Blue Spring in canyon of the Little Colorado River.		
Cambrian	Middle	Tonto	Muav Limestone	Limestone; 0–300.	Yields small amounts of water to a few springs in Marble and Grand Canyons; most of the water moves into the formation from the Redwall Limestone.		
Cambrian	Middle / Lower	Tonto	Bright Angel Shale	Shale; 0–600.	Not water bearing.		
Cambrian	Lower	Tonto	Tapeats Sandstone	Sandstone and some conglomerate; partly quartzitic; 0–250.	Yields small amounts of water to springs in Grand Canyon.		

See footnotes at end of table.

TABLE 3.—*Water-bearing characteristics of sedimentary rocks in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah*—Continued

System	Series	Group	Stratigraphic unit	Lithology and thickness (feet)	Water-bearing characteristics: General hydrology	Depth of wells (feet)	Depth to water (feet)
			Monument Valley area				
Permian			Cutler Formation	De Chelly and Cedar Mesa Sandstone Members are composed chiefly of sandstone; Organ Rock and Halgaito Tongues are composed chiefly of sandy siltstone; 1,800.	Sandstone members yield small amount sof water to a few wells and springs.[4]	<700	<400
Pennsylvanian			Rico Formation	Alternating sandstone, siltstone, and limestone beds, 300–600.	Usually not water bearing.		
Pennsylvanian			Hermosa Formation	Alternating limestone, siltstone, and sandstone beds; 1,000–1,300.	Few springs issue from unit in upper San Juan Canyon.		
			Defiance Plateau area				
Permian			De Chelly Sandstone	Upper member is composed chiefly of sandstone; Lower member is composed of sandstone and silty sandstone; 300–800.	Upper member yields water to wells; combines hydraulically with Shinarump Member of the Chinle Formation.	<700	<500
Pennsylvanian			Supai Formation	Chiefly silty sandstone; 400–1,300.	Yields water to a few springs.		
			Zuni Mountains				
Permian			San Andres Limestone	Chiefly limestone and siltstone; 0–100.	Usually not water bearing.[4]		
Permian			Glorieta Sandstone	Chiefly sandstone; 300.	Yields small amounts of water to wells.[4]	300–1, 500	<1, 000
Permian			Yeso Formation	Chiefly sandstone.	Usually not water bearing.		
Permian			Abo Formation	Chiefly sandstone.	Usually not water bearing.		

[1] The Dakota Sandstone is Late Cretaceous in age where the Burro Canyon Formation is differentiated.

[2] The D multiple-aquifer system is in the Dakota Sandstone and locally the Cow Springs Sandstone and the Westwater Canyon Sandstone Member of the Morrison Formation.

[3] The N multiple-aquifer system is in the Navajo Sandstone which intertongues with the Kayenta Formation in the western part of the reservations, the sandy facies of the Kayenta Formation in the north-central part of the reservations, and the Lukachukai Member of the Wingate Sandstone.

[4] The C multiple-aquifer system is in the De Chelly Sandstone and Shinarump Member of the Chinle Formation on the Defiance Plateau, the De Chelly Sandstone Member of the Cutler Formation in Monument Valley, the Glorieta Sandstone and San Andres Limestone in New Mexico, and the Coconino Sandstone, Kaibab Limestone, and upper part of the Supai Formation in parts of the Mogollon Slope and Grand Canyon areas.

BASEMENT ROCKS

The rocks of the basement complex in the Navajo country are of Precambrian age and are generally 2,000–7,000 feet below the land surface. They are exposed within the confines of the reservations in only three small areas on the Defiance Plateau (pl. 1). Other exposures of basement rocks near the reservations are in the Grand Canyon and Zuni Mountains.

The basement complex in the Grand Canyon is divided informally into the older and younger Precambrian rocks. The older Precambrian rocks consist chiefly of gneiss and different amounts of schist, granite, aplite, and igneous rocks of mafic composition. Many of the metamorphic rocks in the Grand Canyon are assigned to the Vishnu Schist (Noble, 1914, p. 32–36). The Vishnu Schist, based on meager deep-well data, apparently is not distributed extensively to the east in the Navajo country.

The Grand Canyon Series of younger Precambrian age overlies the Vishnu Schist unconformably, is nearly 12,000 feet thick, and consists of sandstone, shale, and limestone. The younger Precambrian rocks are weakly metamorphosed and were involved in large-scale normal faulting before Early Cambrian time. The Grand Canyon Series may have been deposited over much of the western Navajo country and, if deposited, was removed by erosion during late Precambrian and early Paleozoic time.

Basement rocks presumably of Precambrian age are exposed on the Defiance Plateau in two small canyons near Hunters Point and in Bonito Canyon (pl. 1). The exposures near Hunters Point consist of granite, quartzite, schist, silicified limestone, greenstone, and a low-grade phyllite (J. P. Akers and P. R. Stevens, written commun., 1955; Lance, 1958, p. 69–70). These rocks underlie the Supai Formation unconformably, but because the outcrops are small and isolated, their stratigraphic relations are not apparent. The quartzite exposed in Bonito Canyon is highly fractured, contains pebbles of quartzite and phyllite, and displays some crossbedding.

Although the basement rocks are fractured and may yield some water locally, these rocks as a whole form the basal confining layer to the hydrologic systems in the overlying sedimentary rocks. Small amounts of water issue from seeps and small springs in fractured and weathered parts of the Vishnu Schist in the Grand Canyon (Metzger, 1961, p. 114, 124), and water moving along fractures in the quartzite of Bonito Canyon may discharge into the alluvium along Bonito Creek west of Fort Defiance.

SEDIMENTARY ROCKS

The outcropping sedimentary rocks in the reservations range in age from Early Cambrian to late Tertiary. Rocks of Permian and younger age are exposed in about 95 percent of the area. The aggregate thickness of the sedimentary rocks ranges from 1,100 feet on the Defiance Plateau to more than 10,000 feet in the San Juan basin. The sedimentary rocks are overlain by thin, discontinuous mantles of weakly consolidated dune sand, alluvium, terrace deposits, and landslide rubble.

The sedimentary rocks consist, in order of decreasing abundance, of mudstone, siltstone, sandstone, silty sandstone, limestone, conglomerate, coal, and gypsum. Mudstone and siltstone units are distributed throughout the geologic column and are of marine, fluvial, and lacustrine origin. The sandstone and most of the silty sandstone units are composed of very fine to medium-grained sand and represent fluvial, eolian, and near-shore marine environments. Some of the sandstone units of fluvial origin contain lenses of conglomerate or zones of pebbly material. Limestone is relatively uncommon in the area, but it was deposited in marine and lacustrine environments. Dolomite was rarely deposited and, where found, is usually with limestone. Small deposits of gypsum, as beds, nodules, or selenite plates, may occur in much of the stratigraphic section. Impure coaly sediments deposited along the margins of marine seas are common throughout the Cretaceous rocks. Relatively pure coal beds, some of which have been mined intermittently for several decades, occur in only a few formations.

REGIONAL CONTROLS OF SEDIMENTATION

Sedimentation was influenced by two major geosynclines. The Cordilleran geosyncline to the west of the Navajo country lasted throughout all the Paleozoic Era and part of Triassic time (fig. 2). The Rocky Mountain geosyncline to the north and northeast was present during Cretaceous time. Regional upwarping and orogeny at the end of the Mesozoic Era destroyed the Rocky Mountain geosyncline and formed basins, which were centers of deposition during much of Cenozoic time.

During Paleozoic time, the Navajo country was part of a rather stable shelf region, which extended eastward from the Cordilleran geosyncline. Regional structural warping caused repeated advance and withdrawal of the sea across the shelf, where, in general, deposits are thinner than those to the west in the Cordilleran geosyncline (McKee, 1951, p. 488). During the late Paleozoic and for part of Triassic time, several highlands were elevated and were a source for much of the sediment deposited in the Navajo country. The Uncompahgre Highlands were elevated to the northeast (Burbank, 1933, p. 641–652) and contributed much material to the late Paleozoic and Triassic rocks. The Mogollon Highlands were formed in Early Triassic time (Cooley, 1957) and were a source for much of the Mesozoic deposition (Harshbarger and others, 1957, p. 44).

During Late Triassic and Early Jurassic time, major regional structural changes occurred in the southwestern Unted States. The area occupied by the Cordilleran geosyncline was elevated, and a new structural trough,

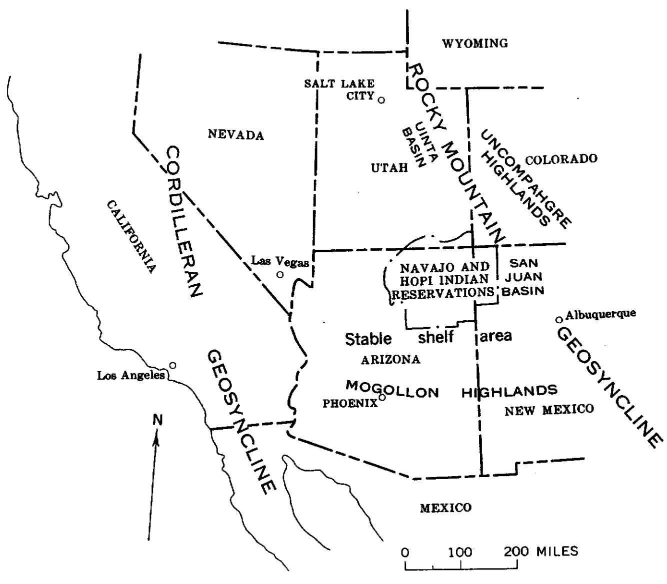

FIGURE 2.—Regional structural features that influenced sedimentation in the Navajo and Hopi Indian Reservations.

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the Rocky Mountain geosyncline, was formed eventually during Cretaceous time in central North America (fig. 2). The area of the Uncompahgre Highlands northeast of the Navajo country was generally low, and the Mogollon Highlands to the south continued to furnish sediment to formations deposited in the Navajo country and surrounding areas. As a result, Jurassic and Cretaceous sediments are coarse nearer the Mogollon Highlands but thicken and are finer grained northeastward across the Navajo country.

Near the end of Mesozoic time another disturbance, sometimes called the Laramide orogeny, which lasted from Late Cretaceous to early Tertiary time, caused the final withdrawal of marine waters and the formation of structural basins of the Colorado Plateaus and nearby regions. The thickest accumulations of Tertiary sediments were in the San Juan and Uinta basins. Most of these sediments were removed largely by late Cenozoic erosion. Regional upwarping in late Tertiary time resulted in the outlining of the Colorado Plateaus and nearby mountains and the development of the Colorado River system.

PALEOZOIC ROCKS

The basal Paleozoic rocks, Early and Middle Cambrian in age, are, in ascending order, the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone (table 3). These units record the earliest marine invasion of the Navajo country from the Cordilleran geosyncline during Paleozoic time. Disconformity above these rocks are remnants of the Devonian Temple Butte Limestone, which are "sandwiched" locally between the Muav Limestone and the Redwall Limestone of Mississippian age. The Redwall is more than 500 feet thick in the Grand Canyon and is the thickest limestone unit in the Navajo country. These older Paleozoic rocks are exposed near the Colorado River and are in the subsurface in all but the southeastern part of the reservations (McKee, 1951, pl. 1). Rocks of Ordovician and Silurian age are missing, and it is doubtful that any were deposited. Because the older Paleozoic rocks are buried to depths of more than 1,500 feet, they are not utilized as aquifers. A few springs issue from these rocks in canyons of the Colorado and Little Colorado Rivers. Blue Spring, the largest spring in northern Arizona, discharges from the Redwall Limestone in the canyon of the Little Colorado River.

Younger Paleozoic rocks of Pennsylvanian and Permian age rest unconformably on the Redwall Limestone and older rocks throughout the southern part of the Colorado Plateaus (pl. 1; table 3). In the Navajo country they range in thickness from 1,000 to nearly 3,000 feet. The formations of Pennsylvanian age—the Hermosa and Rico Formations in the north and the Naco Formation and the lower part of the Supai Formation in the south—represent various combinations of continental and marine depositional environments and consist of shale, limestone, and sandstone.

Rocks of Pennsylvanian age grade upward and intertongue with a red-bed sequence, chiefly of Permian age, that is of continental, near-shore, and shallow-water marine origin. This sequence includes the upper parts of the Supai, Cutler, and Yeso Formations. Giant wedges and lenticular masses of eolian crossbedded sandstone are intercalated within the red beds. The principal eolian rocks are the Coconino Sandstone and parts of the Glorieta and De Chelly Sandstones.

The youngest Permian rocks record the last Paleozoic marine transgression in the Navajo country. The San Andres Limestone was deposited in the southeastern part of the Navajo country and the Kaibab Limestone and Toroweap Formation in the western part. Facies changes in the Kaibab and Toroweap are thought by McKee (1938) to be indicative of multiple transgressions and regressions of the seas.

The Coconino Sandstone and its lateral equivalents, the De Chelly and Glorieta Sandstones, are the chief Paleozoic water-bearing units in the southern part of the Colorado Plateaus. These units are interconnected hydraulically and, with the upper part of the Supai Formation, Kaibab Limestone, and Shinarump Member of the Chinle Formation in the Defiance Plateau, form the C multiple-aquifer system. The hydrologic characteristics of the system seem to be controlled regionally by lithologic characteristics and bedding (fig. 3) and locally by fractures and joints.

MOENKOPI AND CHINLE FORMATIONS

The Moenkopi and Chinle Formations in the Navajo country unconformably overlie the Permian rocks and are a mudstone and siltstone sequence that erodes into spectacular multicolored badlands and "painted deserts" in many parts of the Colorado Plateaus. These rocks are 1,100–1,600 feet thick and form the upper confining layer of the C multiple-aquifer system. The Moenkopi Formation was deposited during the last eastward transgression of the sea from the Cordilleran geosyncline. After a period of widespread erosion, the Chinle Formation was deposited by streams originating in the Mogollon and Uncompahgre Highlands. The sediments of both formations are slightly coarser in the southeastern part of the Navajo country, where several thin persistent beds of sandstone and conglomerate yield small amounts of water to wells.

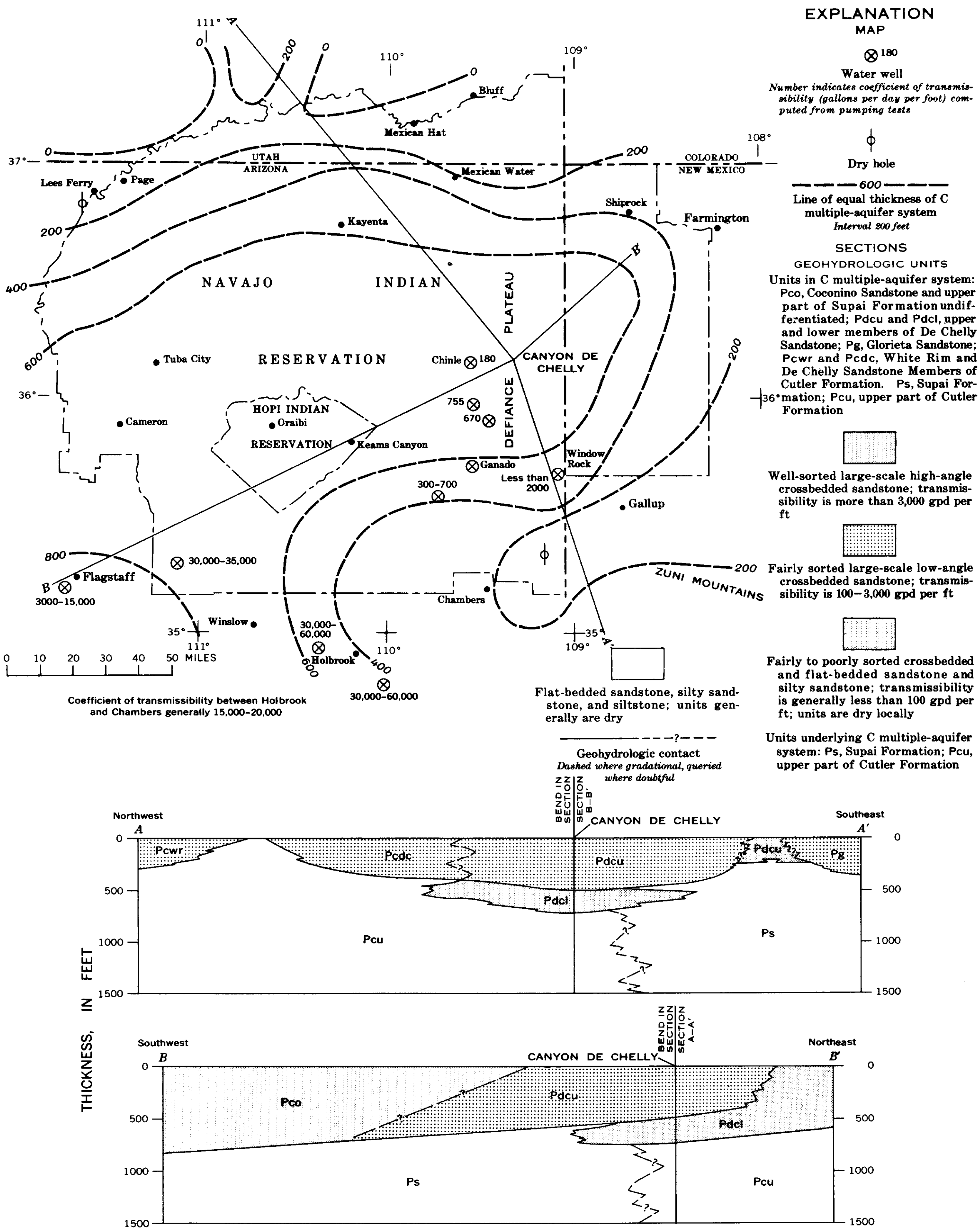

FIGURE 3.—Generalized thickness map and sections of the C multiple-aquifer system, showing variation in the regional hydrologic characteristics.

GLEN CANYON GROUP OF TRIASSIC AND JURASSIC AGE

The Glen Canyon Group, a sequence of orange-red and grayish-red sandstone and siltstone beds, includes, in ascending order, the Wingate Sandstone, Moenave Formation, Kayenta Formation, and Navajo Sandstone. The basal Rock Point Member of the Wingate generally is conformable with the topmost members of the underlying Chinle Formation, but the other units of the group seem everywhere to be disconformable with the Chinle (Harshbarger and others, 1957, p. 5–7). The Glen Canyon Group decreases in thickness from 2,300 feet near the Colorado River to less than 200 feet in the Zuni Mountains, and no unit of the group is present in all parts of the reservations. The Wingate Sandstone wedges out in the northwestern part, and the other formations wedge out to the southeast (pl. 1).

The Navajo Sandstone and the Lukachukai Member of the Wingate Sandstone are even-grained sandstone units displaying large-scale crossbeds, and both probably were deposited by wind. In contrast, the other units of the Glen Canyon Group are composed of siltstone and silty sandstone deposited by streams that flowed from highlands generally east of the reservations. Intertonguing is conspicuous between all the units of the group.

The sandstone aquifers of the Glen Canyon Group are utilized extensively in the northern and western parts of the reservations. The yields are dependable, although generally small, and the water is of good chemical quality. The Navajo Sandstone is the chief aquifer. In the north-central part of the reservations the Navajo combines hydraulically with the sandy facies of the Kayenta Formation and with the Lukachukai Member of the Wingate Sandstone to form the N multiple-aquifer system. In the western part of the reservations the silty facies of the Kayenta acts as a confining bed and separates the ground water in the Navajo Sandstone from that in the Lukachukai Member of the Wingate.

UPPER JURASSIC ROCKS

Upper Jurassic rocks consist of sandstone, silty sandstone, and siltstone units that are divided into the San Rafael Group, Morrison Formation, and Cow Springs Sandstone. These rocks thin southward from 1,500 feet near the San Juan River to about 300 feet in the southwestern part of the reservations.

The San Rafael Group was deposited seaward and landward of the Late Jurassic shoreline, which advanced into the Navajo country from the north. At its maximum transgression, as indicated by the distribution of the Todilto Limestone, an arm of the Late Jurassic sea extended into northeastern New Mexico. The Morrison Formation was deposited by streams during the withdrawal of this sea from the southern part of the Colorado Plateaus. The Cow Springs Sandstone and its lateral correlative, the Bluff Sandstone, were deposited by the wind in the southwestern and northeastern parts of the reservations, respectively. These sandstone units intertongue with most formations of the San Rafael Group and with the Morrison Formation.

Water in the Upper Jurassic rocks occurs chiefly in the sandstone units of eolian and fluvial origin. These units are the Entrada, Cow Springs, and Bluff Sandstones, and sandstone beds in the Morrison Formation. The other units of the Upper Jurassic rocks do not yield water to wells and generally are the confining beds between the aquifers. The Cow Springs Sandstone, Morrison sandstone, and overlying Dakota Sandstone are connected hydraulically at their contact and form the D multiple-aquifer system (fig. 4). Large-scale intertonguing between the Cow Springs Sandstone and the Morrison Formation (fig. 4) greatly enhances the probability of obtaining sufficient yields from deep wells in these formations in many parts of the reservations.

CRETACEOUS ROCKS

Rocks of Cretaceous age crop out on Black Mesa and in the San Juan basin (pl. 1; table 3). Cretaceous rocks are about 1,500 feet thick on Black Mesa and more than 5,000 feet thick in the San Juan basin. Rocks of Late Cretaceous age make up the bulk of the Cretaceous rocks. Early Cretaceous deposition is represented only by the Burro Canyon Formation in the Four Corners area, and elsewhere by the Dakota Sandstone of Early and Late Cretaceous age.

The Dakota Sandstone was laid down along the edge of a transgressive sea, which was the last major marine inundation of the area. This sea reached its maximum extent during the deposition of the lower part of the Mancos Shale. From that time onward, the Cretaceous sea, with intermittent fluctuation, gradually receded. Deposition within and adjacent to seaways resulted in complex intertonguing between the Mancos Shale and the continental and near-shore deposits of the Mesaverde Group. Sandstone was deposited along the advancing and retreating shorelines; mudstone and siltstone were deposited in the marine waters; and sandstone, siltstone, and carbonaceous material, including some coal, were deposited shoreward of the coastal areas (fig. 5).

The youngest strata of Cretaceous age are exposed only in the northern part of the San Juan basin and were deposited during the final withdrawal of the sea. The Cliff House Sandstone, the youngest formation of the Mesaverde Group, intertongues with the Mancos Shale below and the Lewis Shale above. The Lewis

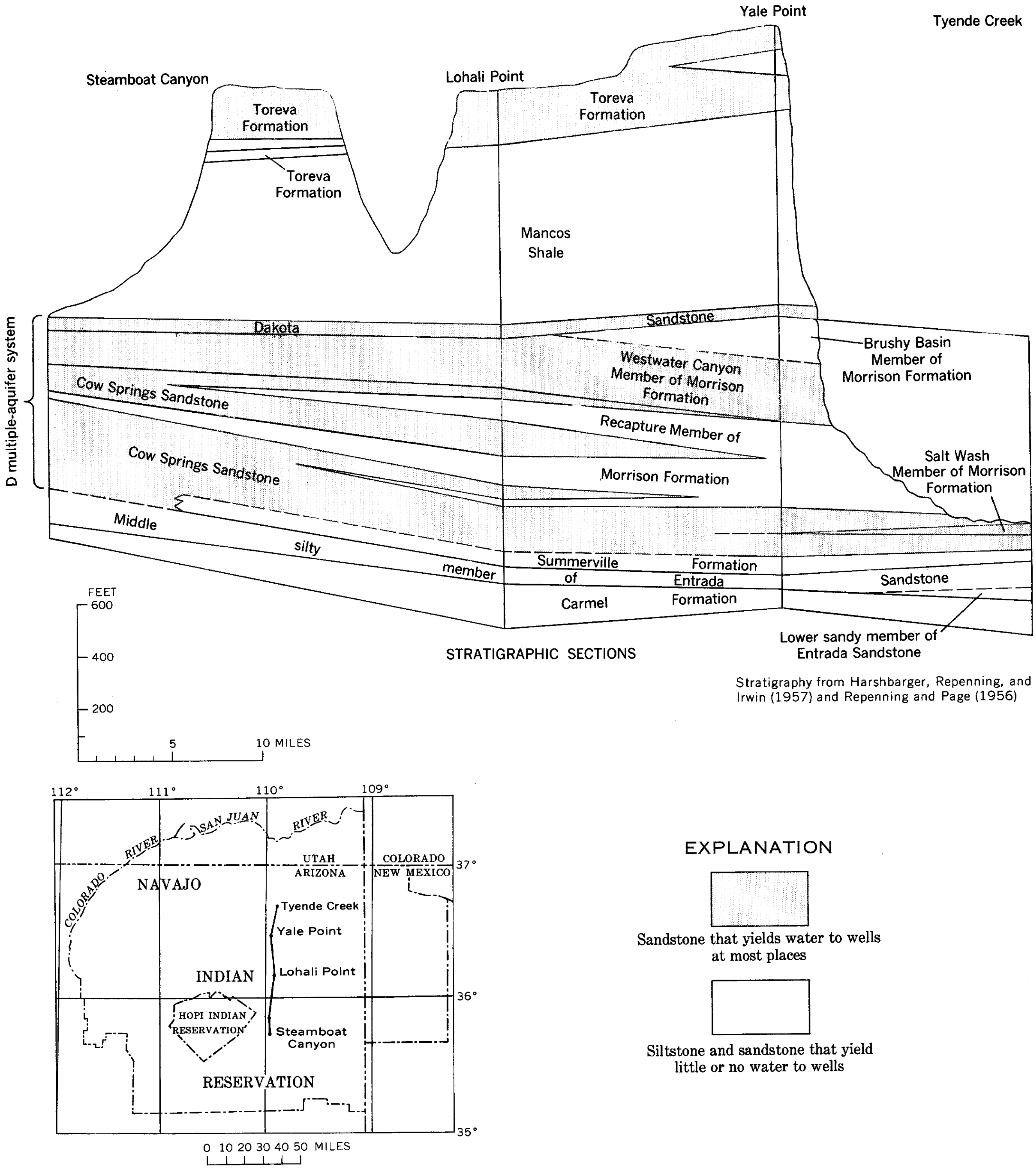

FIGURE 4.—Stratigraphic section showing occurrence of ground water in the Cretaceous and Jurassic rocks.

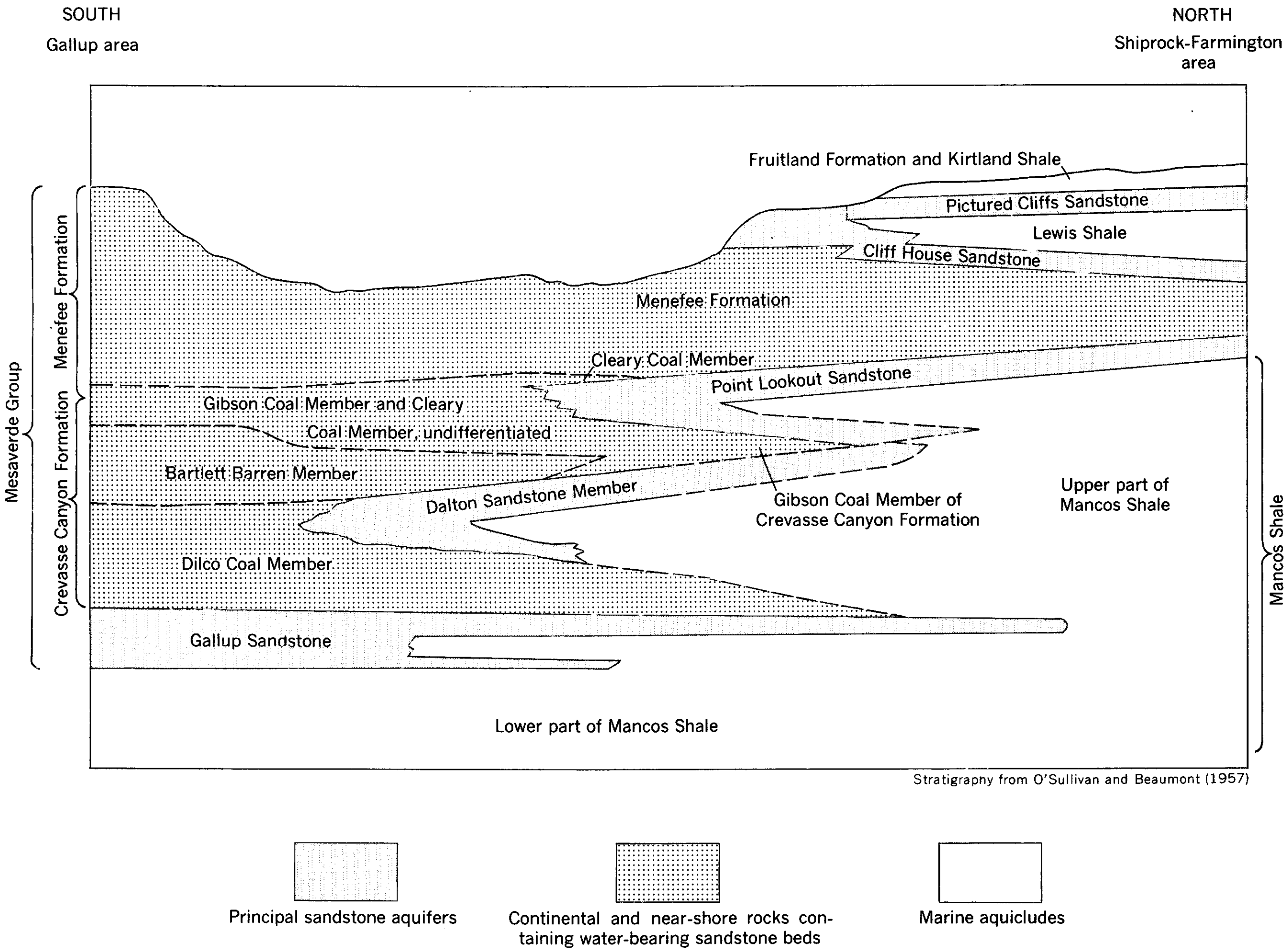

FIGURE 5.—Generalized section of the western San Juan basin, showing the intertonguing of the Upper Cretaceous rocks and their water-bearing characteristics.

Shale is between the Cliff House and Pictured Cliffs Sandstones north of the Chaco River. Southwestward thinning and wedging out of the Lewis Shale causes a coalescing of the Cliff House and Pictured Cliffs Sandstones near the Chaco River. Post-Pictured Cliffs Cretaceous deposition is represented by the coal-bearing Fruitland Formation, the Kirtland Shale, and the conglomeratic Ojo Alamo Sandstone. The Ojo Alamo Sandstone unconformably overlies the Kirtland Shale and grades upward into the Nacimiento Formation of early Tertiary age.

Ground water in the Cretaceous rocks is withdrawn principally from the Dakota Sandstone, Toreva Formation in Black Mesa basin, numerous sandstone units of the Mesaverde Group—Gallup Sandstone, Dalton Sandstone Member, and other sandstone beds in the Crevasse Canyon Formation, sandstone beds in the Menefee Formation, and Cliff House Sandstone (fig. 5)—in San Juan basin, Pictured Cliffs Sandstone, and Ojo Alamo Sandstone.

The Dakota Sandstone combines hydraulically with the Cow Springs Sandstone and Westwater Canyon Sandstone Member of the Morrison Formation and is the chief unit of the D multiple-aquifer system. This aquifer system is well developed in the Black Mesa basin and in the southwestern part of the San Juan basin. The Mancos Shale is a thick aquiclude that separates the ground water in the Dakota Sandstone from that in the sandstone aquifers of the Mesaverde Group (figs. 4, 5). All the water-bearing units of the Mesaverde Group intertongue with the silty units of the group and with the Mancos and Lewis Shales. This intertonguing controls the occurrence and yield and restricts regional movement of the ground water. North and east of the Chaco River the Lewis Shale separates the water of the Cliff House Sandstone—the uppermost unit of the Mesaverde Group—and the water of the Pictured Cliffs Sandstone. South of the river the Lewis wedges out, and the Cliff House and Pictured Cliffs Sandstones join to form a single water-bearing stratum that has been tapped by numerous wells. Only a few springs issue from the Ojo Alamo Sandstone on Mount Cisco Mesa, and a few wells withdraw a small amount of water from the unit east of the reservations.

TERTIARY ROCKS

Erosion after regional uplift was the dominant geologic process during Tertiary time; however, sedimentary rocks of Tertiary age are present in three areas of the reservations (pl. 1). The Nacimiento Formation of Paleocene age crops out in the San Juan basin, the Chuska Sandstone of Pliocene(?) age forms the thick capping layer on the Chuska and Lukachukai Mountains, and the Bidahochi Formation of Pliocene age is exposed in the valley of the Little Colorado River. The Chuska Sandstone and the Bidahochi Formation overlie prominent erosion surfaces, which bevel the pre-Tertiary rocks. The Nacimiento Formation was deposited during the late part of the structural episode that formed the San Juan and other basins of the Colorado Plateaus. The Chuska Sandstone contains beds of eolian and fluvial origin and presumably is a remnant of a widespread deposit. A remnant of a deposit similar in lithology to the Chuska Sandstone in the Chuska-Lukachukai Mountains is present beneath lavas at the Mount Powell Lookout near Thoreau, N. Mex. It was laid down after the formation of the basins and other fold structures and before the development of the Colorado River system in late Tertiary time. The Bidahochi Formation was laid down as basin fill in the ancestral valley of the Little Colorado River.

The Tertiary formations, because of their small areal extent, yield only a limited amount of water. One of the main spring horizons in the Navajo country (Gregory, 1916, p. 138, fig. 14), however, is along the lower contact of the Chuska Sandstone. The Bidahochi Formation contains little water within the reservations, but southward it yields considerable water to wells. The Nacimiento Formation bears virtually no water.

QUATERNARY DEPOSITS

Unconsolidated sediments, mainly of Quaternary age, in order of hydrologic importance are the alluvial, terrace, landslide, and eolian deposits (pl. 2); the Quaternary deposits mostly are less than 30 feet thick but are as much as 225 feet thick in a few places. They form a discontinuous, rather permeable mantle over large parts of the reservations. The alluvium is the chief source of water in dug wells; it is also the source of water in springs and drilled wells in several parts of the reservations, especially where water discharges from the bedrock aquifers into the alluvium (pl. 2). Depth to water in wells drilled in the alluvium is shallow—the depth ranges from a few feet to about 100 feet below the land surface. Few wells or springs are developed in the other Quaternary deposits.

VOLCANIC ROCKS

The eruptive rocks are composed of basalt, monchiquite, or minette, and they occur in flows, dikes, breccia pipes, diatremes, cinder cones, and tuff deposits in widely separated volcanic fields. Ground water is yielded from material filling the diatremes in the Hopi Buttes and the Defiance Plateau (Callahan and others, 1959; Akers, McClymonds, and Harshbarger, 1962), and discharges as springs from flows and tuff beds.

The volcanic rocks are divided by composition into three provinces; the monchiquite and minette provinces (Shoemaker, 1956) cover most of the southwestern and northeastern parts of the reservations, respectively, and the basalt province, a part of the San Francisco volcanic field, is along the southwestern border (pl. 2). There are about 200 volcanic vents in the Hopi Buttes in an area of 1,400 square miles. Another 100 vents are in small scattered groups in other parts of the Navajo country. Impure travertine deposits at springs are associated with the volcanic rocks in the Hopi Buttes (pl. 1), and many of the diatremes show evidence of past spring activity. The upper parts of some diatremes are filled with bedded tuff and limestone and some thinly laminated claystone and siltstone (Shoemaker, 1956, p. 179–185).

The volcanic rocks are late Cenozoic in age, as indicated by relations of the volcanic rocks to erosional stages in the Colorado River system and to Tertiary formations. Dikes and sills intruded the Chuska Sandstone of Pliocene(?) age, and flows, where preserved, filled valleys as deep as 300 feet in the Chuska. The volcanic rocks of the Hopi Buttes volcanic field were assigned by Repenning and Irwin (1954, p. 1823) to the volcanic member of the Bidahochi Formation, which occurs between the upper and lower sedimentary members of the Bidahochi of Pliocene age. All the volcanic rocks of the monchiquite and minette provinces were emplaced during the early stages of entrenchment of the Colorado River system in late Tertiary time. (See "Entrenchment of the Colorado River System," p. A34.) Basalt of the San Francisco volcanic field caps terraces that are in the valley of the Little Colorado River and ranges in age from late Pliocene to early Recent (Cooley, 1963).

STRUCTURE

The reservations are in the south-central part of the Colorado Plateaus province, which is characterized by the absence of the severe deformation that took place nearly everywhere along the plateaus boundary. This province has been relatively stable since late Precambrian time and was only moderately affected by the orogeny of Late Cretaceous and early Tertiary time. Within the Navajo country this orogeny produced an assortment of folds—basins, uplifts, monoclines, anticlines, and synclines (p. l. 1; fig. 6). In late Tertiary and Quaternary time, the area was upwarped and locally faulted.

The larger folds are termed "basins," "uplifts," and "upwarps," and follow generally the definitions of Eardley (1951, p. 5). The Kaibab, Defiance, and Zuni domes are uplifts, and the Monument dome, being larger than the uplifts, is an upwarp. Echo and Circle Cliffs domes have been referred to both as anticlines and small uplifts. The basins are somewhat arbitrarily defined, and they include only the deeper parts of downwarped areas (Kelley, 1955, p. 23).

The smaller folds are monoclines, anticlines, and synclines. The most conspicuous of these are the monoclines, which may be associated either with the basins and uplifts or with smaller folds.

LARGER FOLDS

The Colorado Plateaus is a huge saucer-shaped epirogenic platform that is bordered by complex structures in the mountainous regions of Colorado, Utah, Arizona, and New Mexico. The continuity of the platform is interrupted by a series of downwarped and upwarped regions that trend roughly northwestward between the San Juan Mountains and the mountains of central Arizona. The Colorado Plateaus contains two broad regionally downwarped areas or troughs separated by an uparched region (fig. 7). This uparched region is accentuated by the Zuni, Defiance, Monument, and Circle Cliffs domes (fig. 6). One trough extends across the western part of the Navajo country and is made up of the Kaiparowits and Black Mesa basins and the St. Johns sag; the southern part of this trough was referred to as the

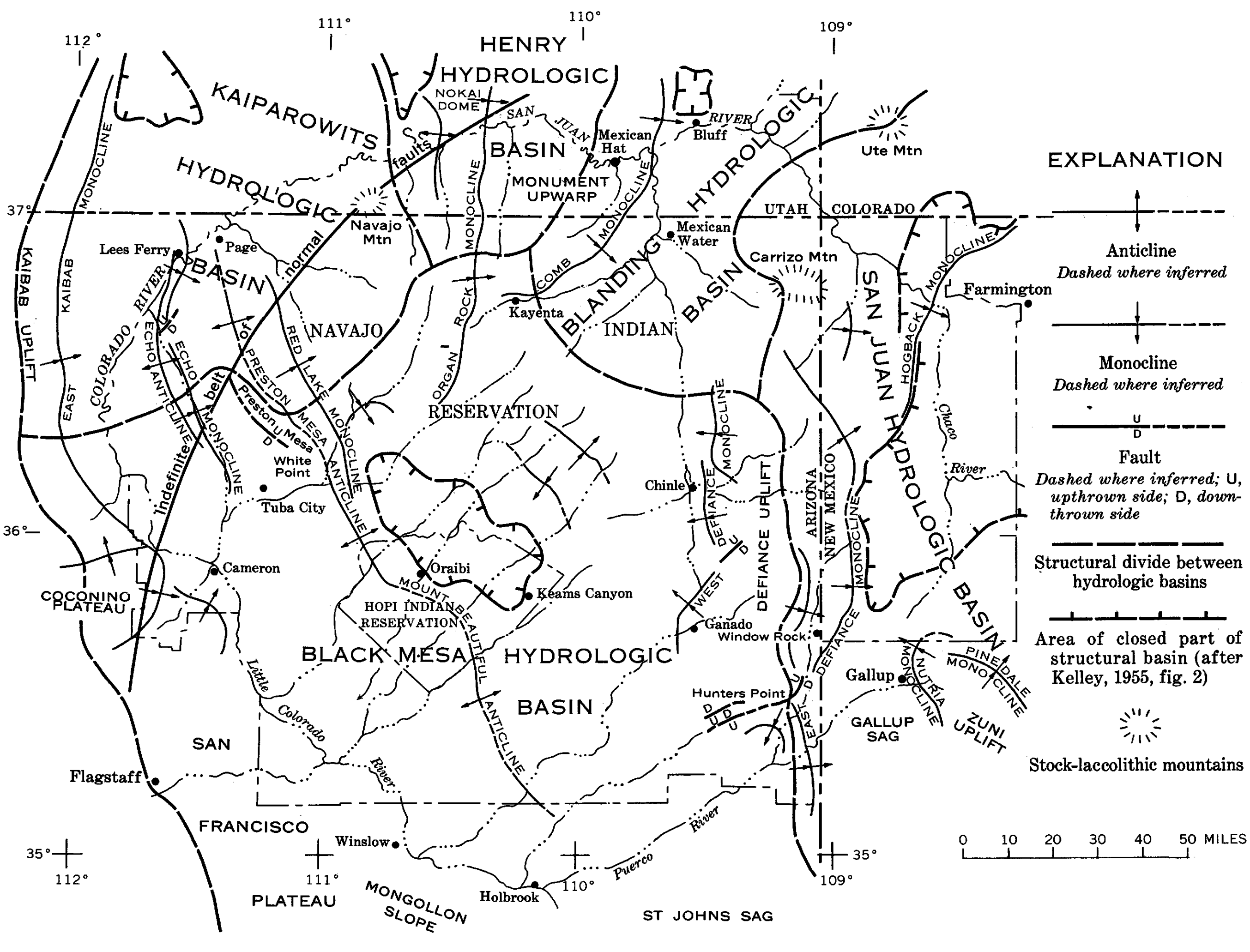

FIGURE 6.—Hydrologic basins and chief structural features that influence the occurrence of ground water.

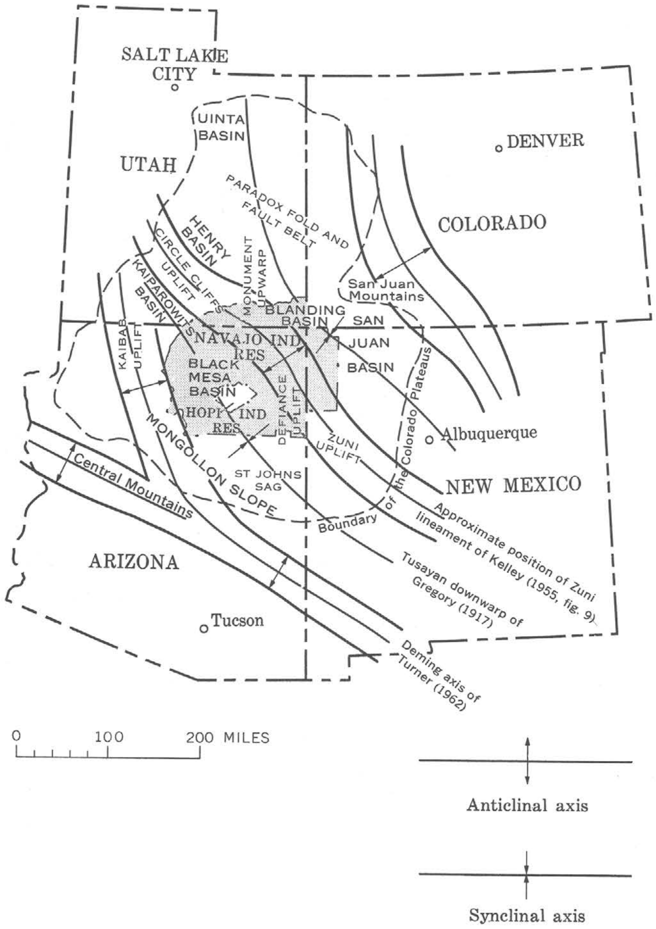

FIGURE 7.—Large-scale folds in parts of Arizona, New Mexico, Utah, and Colorado.

Tusayan downwarp by Gregory (1917, p. 112). The other trough includes only the northeastern part of the Navajo country and comprises the San Juan, Blanding, and Uinta basins.

The domes, uplifts, and upwarps are asymmetrical, and the steeper limb is on the east or northeast side. Most domes are well defined and are bounded in places by monoclines. The basins are not well defined, and their flanks merge gradually into the surrounding structures. The relief of the domes and between the domes and basins differs considerably. The relief between Black Mesa basin and the Defiance and Kaibab domes is 5,000 and 6,000 feet, respectively, but that between the Defiance dome and San Juan basin is about 12,000 feet.

The larger folds control the movement of water in the sedimentary rocks and divide the Navajo country into five general areas, which contain separate hydrologic systems. These areas are termed hydrologic basins and are named for the structural basin in the lowest part of each. Therefore, the Navajo country occupies parts of the Black Mesa, San Juan, Blanding, Henry, and Kaiparowits hydrologic basins (fig. 6).

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SMALLER FOLDS

Smaller folds—anticlines, synclines, and monoclines—are common except along the margin of the Mogollon Slope near the Little Colorado River. The more prominent monoclines commonly form the boundaries of uplifts, platforms, and benches. The anticlines and synclines are imposed upon and extend across all the larger folds.

Monoclinal flexures interrupt other folds and, therefore, are the most conspicuous structural feature of the Colorado Plateaus. Dips along monoclines are usually less than 15°, but locally they are more, and in a few places the beds are overturned slightly. The East Kaibab, East Defiance, and some of the other monoclines have a sinuous trace for more than 125 miles, and many bifurcate into several parts or segments. The displacement along monoclines generally ranges from 400 to 1,500 feet, and, in places, faults are associated with the folds.

The anticlines and synclines generally trend northwest to north and are usually inconspicuous because they seldom have dips steeper than 3°. In the western part of the reservations some of these folds are more than 100 miles long; the longest, Preston Mesa-Mount Beautiful anticline, can be traced for 150 miles in the Kaiparowits and Black Mesa basins. (pl. 1). Small domes and saddles form irregularities along the crests of the anticlines. The most prominent of these features is Nokai dome, which has been breached by the San Juan River.

Monoclines exert a strong influence on the movement and occurrence of water in the sedimentary rocks. Figure 8 illustrates typical examples of the relation of monoclines to ground water in the Navajo country. These relations are: (1) Water-table conditions may prevail on the upthrown and downthrown sides of the monocline (fig. 8*A*); (2) the upthrown side is above the water table and the aquifer is dry (fig. 8*B*); (3) a change from water-table to artesian conditions takes place along a monocline (fig. 8*A*, *C*); and (4) artesian conditions may prevail on both sides of a monocline (fig. 8*A*). In aquifers, principally along the East and West Defiance monoclines, where conditions change from water table to artesian, recharge may be rejected by the aquifer (fig. 8*C*).

Anticlines and synclines do not affect the occurrence of ground water as much as the monoclines. Wells can be drilled along the crests and flanks of anticlines if the structural relief does not exceed the saturated thickness of the water-yielding unit or if artesian conditions prevail across the anticline. In places, however, the formations may be dry on the crests of some anticlines.

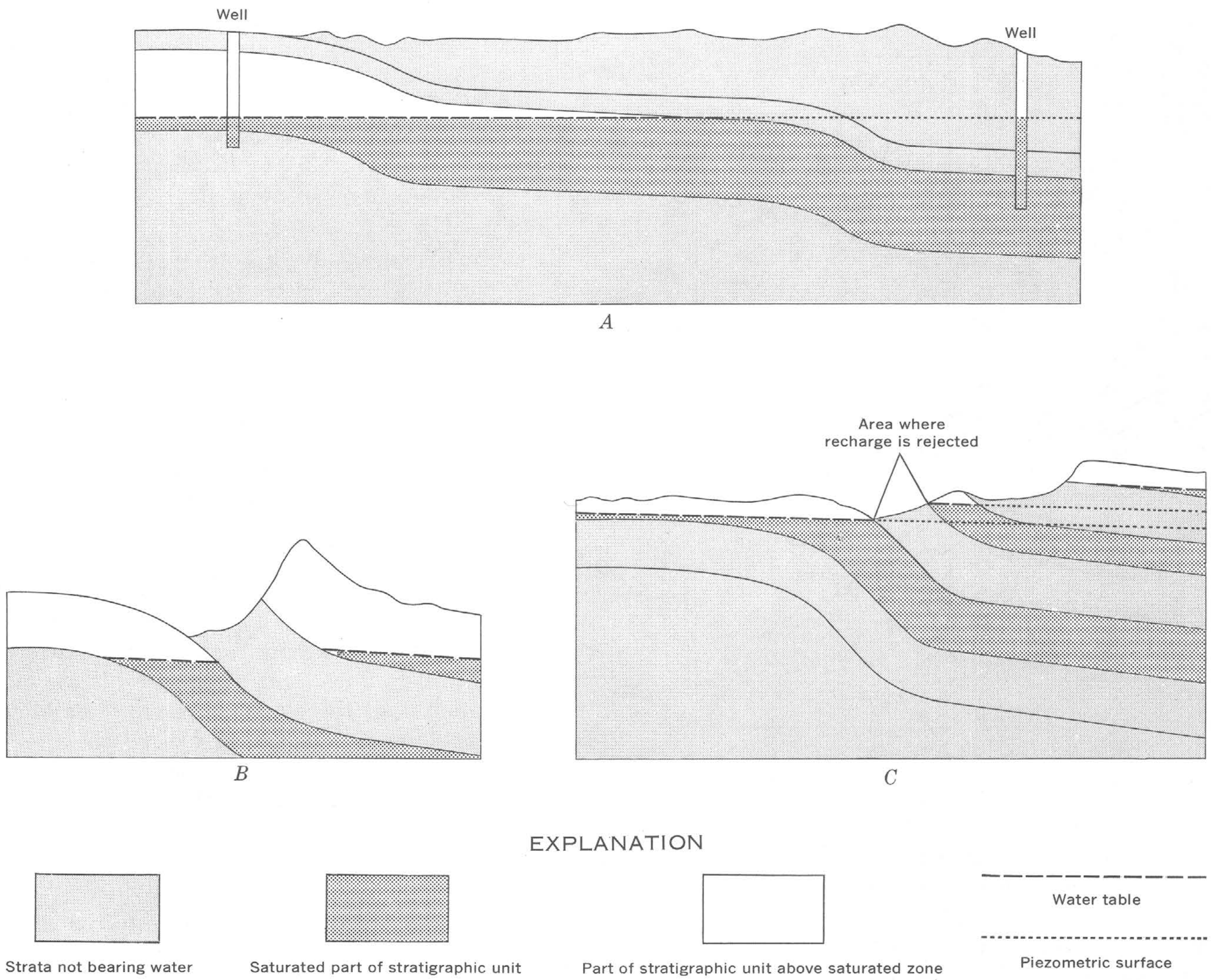

FIGURE 8.—Occurrence of ground water along monoclines.

FAULTS

Faults are uncommon except in a small area on the Defiance Plateau and in the western part of the reservations (pl. 1). Joints, however, are prevalent, and they have increased the permeability of some of the rocks. In most places, faults have displacements of 50–150 feet, but strata are offset more than 500 feet by the fault at Hunters Point and the one between Preston Mesa and White Point (pl. 1). Most are vertical normal faults, trend between east and north, and intersect axes of the folds at acute angles.

Faults in the western and northwestern parts of the Navajo country are in a poorly defined belt 20–40 miles wide (pl. 1; fig. 6). The belt extends northeastward from the San Francisco and Coconino Plateaus and merges with the structures of the Paradox fault and fold belt in the northern part of the Monument upwarp (M. E. Cooley, written commun.). Few faults are related to the arching of the laccolithic Navajo Mountain, but many near Cameron and on the San Francisco Plateau are related to the emplacement of the volcanic rocks.

Faults in the Navajo country are too isolated and displacements are too small to exert much control on ground water. A few springs and seeps discharge along some of the faults on the Defiance Plateau and near the Colorado and San Juan Rivers. One small graben in the southern part of the Defiance Plateau (pl. 1) traps ground water; it has been developed to supply water for the community at Pine Springs.

PHYSIOGRAPHY

The Navajo country has been subjected to vigorous cycles, which consist of periods of downcutting alternating with periods of planation and deposition. As a result, streams have carved a complex maze of plateaus, rock benches, and mesas, which tower above extensive plains and canyons.

The Colorado Plateaus province is separated into physiographic sections on the basis of the distribution of canyons, rock benches, mesas, and plains. The whole province has similar rocks and geologic structural features and contains one master stream, the Colorado River. Each physiographic section, therefore, relates to the distance from the river and to the types of stream patterns developed. Thus, the area adjacent to the Colorado River and its main tributaries is eroded into canyon lands. In a poorly defined belt around the canyon lands, rock benches form a series of prominent cliffs and broad platforms. Beyond the belt of cliffs and platforms, plateaus and plains of erosion are the dominant landforms.

Fenneman (1931, p. 275–325) divided the Colorado Plateaus province into the Grand Canyon section, High Plateaus of Utah, rock "terraces" of southern Utah, Uinta Basin section, Canyon Lands of Utah, Navajo section, and Datil section (pl. 3). The Navajo country is in an intermediate physiographic area between the canyons of the Colorado and San Juan Rivers and the plains and low mesas of the Datil section. The terms "Navajo country" (Gregory, 1917) and "Navajo section" (Fenneman, 1931) are synonymous and refer to the Navajo and Hopi Indian Reservations and a narrow strip of land between the southern boundary of the reservations and the Little Colorado and Puerco Rivers. The Navajo country, a geographic division, does not coincide with the natural physiographic subdivisions of the Colorado Plateaus province, but it comprises combinations of landforms that are common to the surrounding subdivisions. Thus, it includes, in part, the Grand Canyon section along the western border, the Canyon Lands of Utah along the northern border, and the Datil section along the southeastern border.

RELATION OF THE LANDFORMS TO THE SEDIMENTARY ROCKS

The landforms of the Navajo country are characterized and affected by the alternating resistant and weak rock strata. Resistant beds form ledges, cliffs, mesas, and rock benches that are separated by slopes, valleys, and badlands carved in the weak shaly beds. The main cliff-forming strata are the Coconino, De Chelly, Wingate, and Navajo Sandstones, the Kaibab Limestone, and the sandstone units of the Upper Cretaceous rocks. All the wide valleys and many extensive slopes are excavated principally in the Mancos Shale and the Chinle, Fruitland, Kirtland, and Bidahochi Formations (pl. 3).

Three types of canyons are common—the vertical walled, box, and V-shaped. If a canyon has been eroded entirely in resistant rocks, nearly vertical walls are typical; canyons of this type are formed in the Navajo and De Chelly Sandstones. If a canyon is rimmed in a resistant bed having a gentle dip and the canyon floor is cut in soft sediments, a box or modified box is carved; the box is the common canyon type of the Navajo country (Gregory, 1917, p. 132). If a canyon is cut into moderately resistant rocks, a V-shape with steeply inclined walls will form; the canyon of the San Juan River cut in the Paleozoic rocks near Mexican Hat is a good example.

Stripped surfaces (stripped or structural plains) occur on resistant rocks that are exposed areally on plateaus, mesas, rock benches, and dip slopes of hogbacks and cuestas (pl. 3). These surfaces are eroded most commonly on top of the Navajo Sandstone, De Chelly Sandstone, Kaibab Limestone, and Shinarump Member of the Chinle Formation. Many stripped surfaces "contour" the folds of various structural features, such as the Defiance Plateau, the East Kaibab monocline, and the Organ Rock anticline.

RELATION OF THE LANDFORMS TO GEOLOGIC STRUCTURE

The types, shapes, and geographic positions of the large landforms are controlled by the uplifts and basins, which influence the regional attitude of the rocks. Relatively gentle stripped plateaulike features are on the summits of the Defiance and Kaibab uplifts and parts of the Monument upwarp (pl. 3). Along monoclines, common on the flanks of uplifts, hogbacks are formed and are inclined toward the basins. In the basins, where dips are gentle, cuestas and rock benches are the chief physiographic forms. In many areas the alinement of hogbacks, cuestas, and rock benches forms rough concentric rings around the uplifts and the centers of the basins.

Wide valleys occupy an intermediate structural position between the uplifts and the centers of the basins. Thus, the valley of Chinle Wash was carved between the Defiance Plateau and Black Mesa, and the Chaco River valley is between the Defiance Plateau and Zuni Mountains and the center of the San Juan basin (pl. 3). In the same way the Little Colorado River valley is between Black Mesa and the highlands formed by the Coconino Plateau, San Francisco Plateau, and the Mogollon Slope.

HYDROGEOLOGIC SUBDIVISIONS OF THE NAVAJO COUNTRY

The close relation between geology and ground-water hydrology makes it possible to divide the Navajo country into areas that contain similar geologic or physiographic and hydrologic characteristics. These hydrogeologic subdivisions are based, in order of importance of criteria, on the distribution of the outcropping sedimentary rocks, the large folds, and the drainage patterns of the Colorado River and its principal tributaries.

This close relation of geology and occurrence of ground water is illustrated on maps showing the distribution of artesian and water-table areas (fig. 9), depths of water levels in wells (fig. 10), and depths of wells (fig. 11). Water-table conditions prevail in the rocks that crop out in the uplands—principally the Navajo Uplands, Defiance Plateau, Chuska Mountains, and Black Mesa—although the aquifers that are deeply buried in Black Mesa are strongly artesian. Artesian conditions are best developed in the broad valleys of the Little Colorado River, Chinle Wash, Chaco River, and San Juan River, which are generally on the flanks of the basins, although flowing wells are mainly in parts of the San Juan and Blanding basins. In the same way, areas having similar depths to water and depths of wells roughly outline the physiographic and structural features of the Navajo country.

The Navajo country includes the following hydrogeologic subdivisions: eastern Grand Canyon, Painted Desert, Navajo Uplands, Black Mesa, Monument Valley, Chinle Valley, Defiance Plateau, Chuska Mountains, Carrizo Mountains, western San Juan basin, and Zuni Mountains (pl. 3).

EASTERN GRAND CANYON

The eastern Grand Canyon subdivision is along the Colorado River in the western part of the Navajo country (pl. 3). The East Kaibab monocline is the dominating structural feature, and branches of this monocline bound parts of the Kaibab and Coconino Plateaus, Marble Platform, and other broad rock benches. All these landforms are outlined by a widespread stripped surface cut on top of the Kaibab Limestone. Marble Canyon of the Colorado River and the canyon of the Little Colorado River separate Marble Platform from the other parts of the subdivision; these canyons at their confluence have a depth of 3,200 feet.

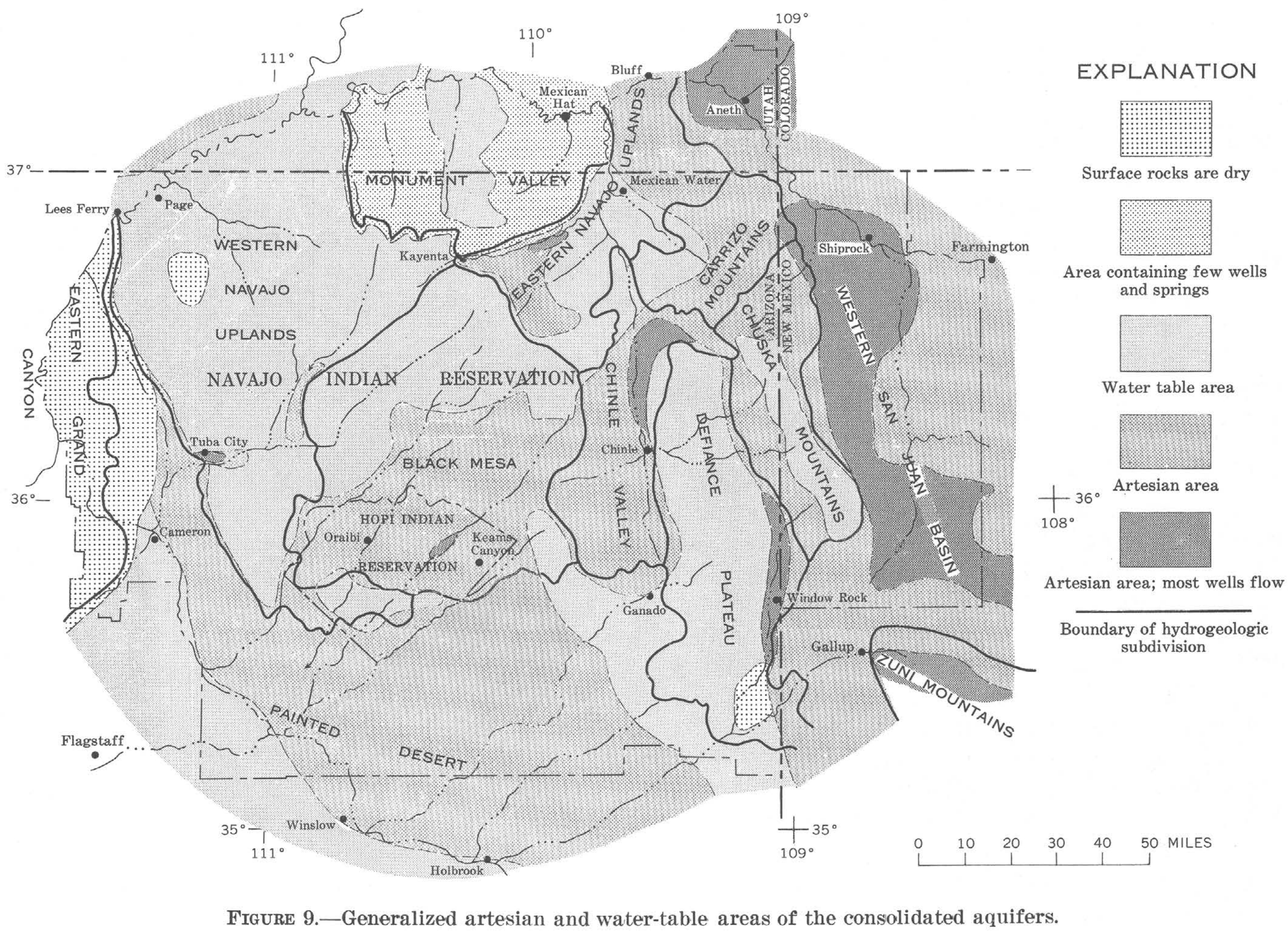

FIGURE 9.—Generalized artesian and water-table areas of the consolidated aquifers.

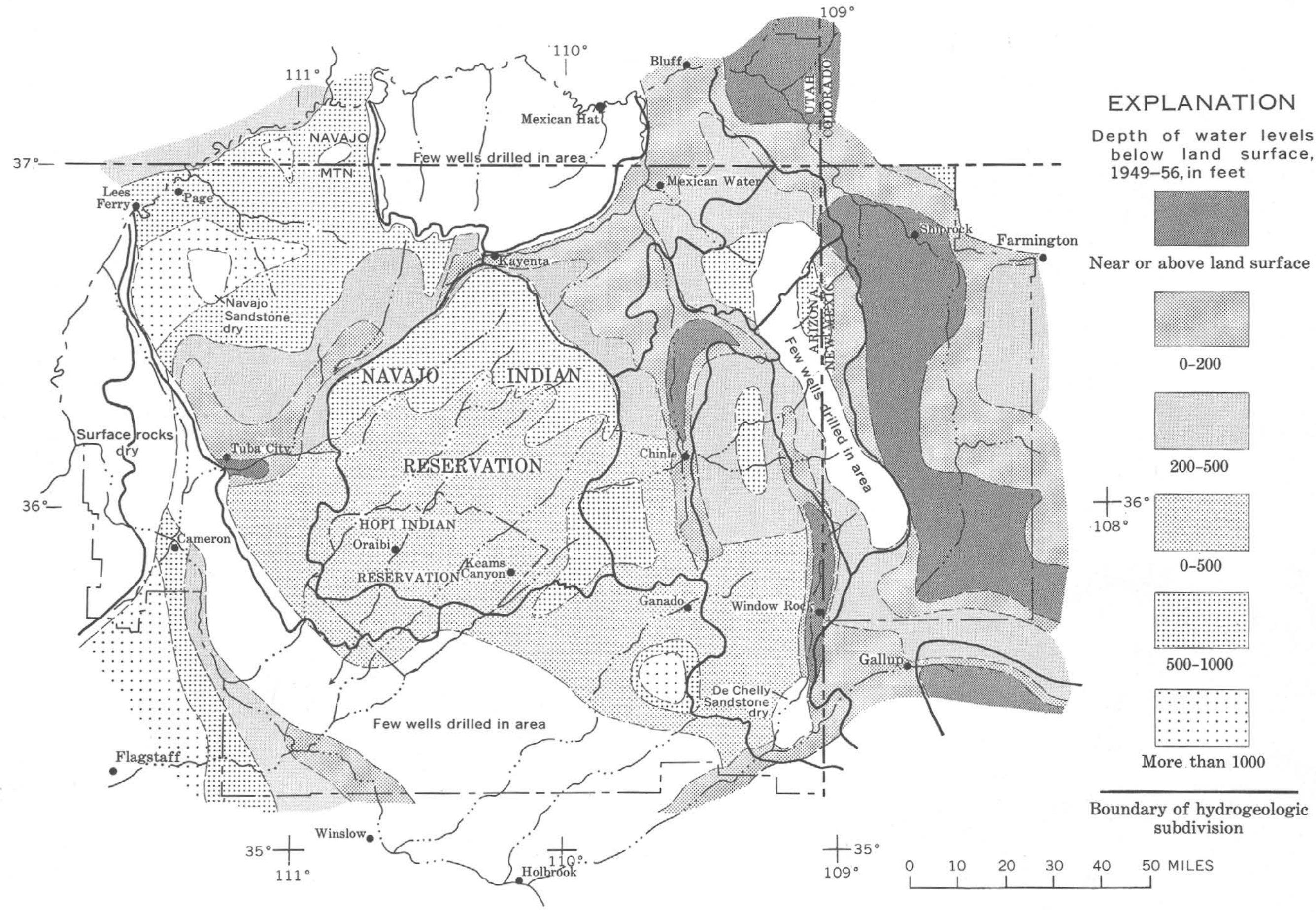

FIGURE 10.—Generalized depth of water levels in wells in the consolidated aquifers.

The deep canyons and fractures, caused by monoclinal folding and faulting, control the occurrence of the ground water in the eastern Grand Canyon subdivision. As a result, the Coconino Sandstone, the principal aquifer, is dry in much of the subdivision. The Redwall Limestone, however, more than 2,000 feet below the land surface, is water bearing; it discharges through Blue Spring and other springs in the bottom of the canyon of the Little Colorado River.

PAINTED DESERT

The Painted Desert subdivision is in the broad southern flank of Black Mesa basin. It is characterized by brilliant-hued badlands carved from the Moenkopi, Chinle, Moenave, and Kayenta Formations. The Little Colorado River drains the subdivision except along the northern part of Echo Cliffs. In the eastern part of the subdivision, Pueblo Colorado Wash, Puerco River, and other streams occupy alluviated valleys between bluffs composed of the Bidahochi Formation. Between these streams, the Bidahochi has been eroded into broad, rolling, slightly dissected tablelands. This rather subdued topography contrasts sharply with the angular cuestas and rock terraces in the western part of the subdivision. There the Little Colorado River flows on a wide alluvial flood plain between dip slopes cut on the Kaibab Limestone and the Moenkopi Formation on the southwest and a sharp cuesta eroded from the Owl Rock Member of the Chinle Formation on the northeast (pl. 3). In the center of the Painted Desert subdivision, a heterogeneous array of volcanic buttes, necks, lava flows, and diatremes comprising the Hopi Buttes towers above the badland slopes carved from the brightly colored Triassic rocks.

The Painted Desert subdivision is underlain principally by Triassic rocks that do not yield water to wells, and ground-water supplies generally are insufficient or of poor chemical quality for stock and domestic use. Locally, some water is obtained from the alluvium along the larger washes, from tuff beds in the volcanic rocks of the Hopi Buttes, from sandstone beds of the Chinle Formation, and from the Wingate and Dakota Sand-

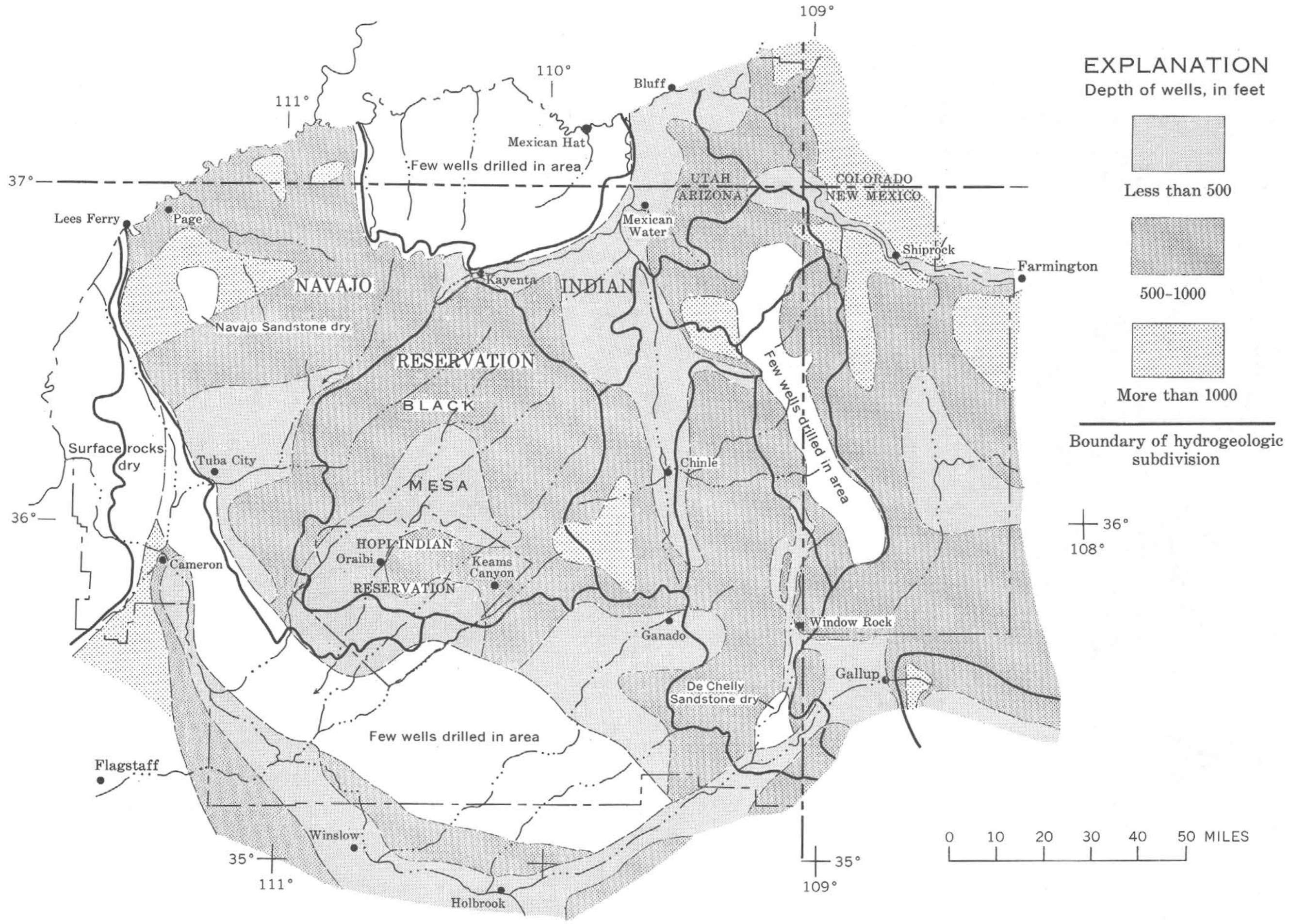

Figure 11.—Generalized range of well depths by area in all aquifers, as of 1956.

stones. The Coconino Sandstone is near the surface and is tapped by wells south of the Little Colorado River. Some water is obtained from the De Chelly Sandstone along the western margin of the Defiance Plateau. North of the Little Colorado River and west of the Defiance Plateau, however, the Coconino Sandstone is buried deeply, and its water generally is highly mineralized.

NAVAJO UPLANDS

The Navajo Uplands is principally an area of dunes and stripped plains that forms an embossed surface on the Navajo Sandstone between the brinks of canyons and at the bases of mesas. It is the largest hydrogeologic subdivision, occupying parts of Black Mesa, Kaiparowits, and Blanding basins, and the divides between these basins. In the western part the dune-covered plains are interrupted locally by Preston and White Mesas, Wildcat Peak, and other prominent buttes and mesas. The northern part has been intricately dissected by the Colorado River and its tributaries into a spectacular system that consists of Glen, Navajo, and other canyons. Navajo Mountain rises above the floor of Rainbow Plateau and dominates the surrounding canyon lands. The eastern part of the subdivision is drained by Chinle Wash and occupies a lowland bounded by Black Mesa, Comb Ridge, and the Carrizo Mountains. The relief of the eastern part is much less and more uniform than that of the western part, and only a few buttes and mesas interrupt the stripped plains cut on the Navajo Sandstone.

The Navajo Sandstone is the chief aquifer, and it is utilized extensively throughout the subdivision. The dependable and relatively large quantities of water in the subsurface contrast with the windswept desertlike surface. Water in the Navajo usually is unconfined because the great thickness and widespread exposures minimize most effects of the geologic structure. Natural discharge of ground water from the reservoir maintains perennial reaches of streams in the canyons near the Colorado River and along Chinle and Moenkopi Washes.

BLACK MESA

Black Mesa is a large moderately dissected highland that occupies the structural center of Black Mesa basin. It is delimited by high outfacing sandstone cliffs of the Toreva Formation and the Yale Point Sandstone—except in the southeastern part, where the Bidahochi Formation overlies the Cretaceous rocks (pls. 1, 3). The southern part of Black Mesa, in the Hopi country, has been dissected by Dennebito, Oraibi, and Polacca Washes into box canyons and gently dipping rock platforms—called First, Second, and Third Mesas. The summit of Black Mesa slopes gently to the southwest, and this slope partly conceals the regional attitudes of the rocks by truncating indiscriminately tilted rocks along small folds. The Wepo Formation crops out in most of the summit area, and it has been eroded into a series of parallel ridges and narrow valleys by the principal washes.

Most of the ground-water supplies developed in Black Mesa are from the Toreva and Wepo Formations. The depth of erosion along Polacca and the other principal washes controls ground-water movement and the total supply of water that can be obtained from these formations. The aquifers below the Toreva are not affected by the topography of Black Mesa, however, and ground-water movement in them is unrestricted. The water in these aquifers is under high artesian pressure. A few wells in the southern part of Black Mesa tap these aquifers—the aquifers in the Dakota, Cow Springs, and Navajo Sandstones. Other water supplies are obtained locally from the alluvium near Polacca and from landslide debris along the sides of mesas in the Hopi country.

MONUMENT VALLEY

The Monument Valley subdivision is bounded on the east by the serrated Comb Ridge and on the west by the palisadelike cliffs bordering the western Navajo Uplands (pls. 1, 3). The San Juan River and tributary streams have carved the sandstone units (Navajo Sandstone, Wingate Sandstone, Shinarump Member of the Chinle Formation, and De Chelly and Cedar Mesa Sandstone Members of the Cutler Formation) into accentuated steep-cliffed buttes and small mesas.

The area generally referred to as Monument Valley is in the southeastern part of the subdivision (pl. 3). The area has been formed on the gentle curvature of a broad anticline, and when viewed from Hoskinnini Mesa to the west, it is a panorama of monumentlike buttes projecting sharply above intermittent dune-covered plains. The buttes consist of a resistant Shinarump cap rock overlying steep irregular slopes of the Moenkopi Formation and vertical cliffs of the De Chelly Sandstone Member of the Cutler Formation.

The San Juan River is entrenched in a deep canyon downstream from Comb Ridge. It has cut into sedimentary rocks steeply tilted by the Comb monocline and other folds near Mexican Hat and into nearly flat-lying strata in the reach downstream from Monitor Butte (pl. 3). The spectacular feature of San Juan Canyon is the "goosenecks," a series of tightly curved meanders, which have been incised 1,500 feet into the Rico and Hermosa Formations. Downstream from Monitor Butte, the San Juan River and its tributary streams have superbly carved the Segi Mesas country (Gregory, 1916, p. 47–48), which includes Piute, No Mans, and Skeleton Mesas. These mesas are as much as 2,000 feet above the floors of the subjacent canyons and are rimmed by cliffs formed from formations of the Glen Canyon Group.

The Monument Valley subdivision is one of the driest and least favorable areas for ground-water supplies in the Navajo country because of the relative impermeability of the sedimentary rocks and because extreme dissection has drained some of the former water-yielding units. Ground water is obtained locally from wells in the Cedar Mesa Sandstone Member of the Cutler Formation and in the alluvium. In the Segi Mesas area a white alkali band along the base of the Wingate Sandstone indicates intermittent seepage, and numerous small springs issue from joints and faults along the edges of the mesas.

CHINLE VALLEY

The Chinle Valley subdivision, underlain by easily eroded Triassic sediments, is similar to the Painted Desert subdivision. It is a lowland between the scarred sandstone slopes on the Defiance Plateau and the imposing eastern escarpment of Black Mesa (pls. 1, 3). Subparallel cuestas of the Wingate Sandstone and the Owl Rock Member of the Chinle Formation and strike valleys cut in less resistant strata form low irregularities. Chinle Wash and its tributaries drain the Chinle Valley and flow on flood-plain deposits, which are more than 200 feet thick locally. Beautiful Valley, displaying varicolored badlands carved from the Chinle Formation, and Snake Flats, a platform of gentle slopes underlain by bedrock and alluvium, occupy the southern part of the subdivision (pl. 3). The northern part of Chinle Valley has considerable relief and contains several conspicuous buttes.

Water is at shallow depth in the alluvium along Chinle Wash and at considerable depth in the De Chelly Sandstone and Shinarump Member of the Chinle Formation in the C multiple-aquifer system. The regional dip is generally westward and northwestward, and the top of the De Chelly Sandstone is more than 1,000 feet below the land surface in the western and northern parts of the subdivision. The water in deep wells that penetrate the unit is under strong artesian pressure, and a few wells flow in a small crescent-shaped are near Round Rock Trading Post (fig. 9).

DEFIANCE PLATEAU

The Defiance Plateau subdivision, a large oval upland, is outlined by dip slopes, hogbacks, and cuestas of the De Chelly Sandstone and sandstone beds in the Chinle Formation (pl. 3). Several isolated volcanic necks—the most prominent being Fluted Rock, the highest point in the subdivision—and the large diatreme in Buell Park interrupt the gentle curvature of the plateau summit. Contrasting with other parts of the reservations, the summit area is covered largely by a thin soil that aids ground-water recharge.

Tributaries to the Puerco River and Chinle Wash have carved several deep canyons; the most spectacular of these are Canyon de Chelly and the canyon of Black Creek (pl. 3). Canyon de Chelly is a straight-walled gorge about 1,000 feet deep cut almost entirely from the De Chelly Sandstone. Within the gorge are blocky steplike benches, monolithic spires, sharp narrow alcoves weathered along fractures, and rounded knobs formed in part by erosion along crossbedding planes. Black Creek crosses the Defiance Plateau in a narrow V-shaped canyon 600 feet deep a short distance upstream from its confluence with the Puerco River.

The De Chelly Sandstone is the principal water-bearing unit in the subdivision, and highest yields are obtained where it is combined hydraulically with the Shinarump Member of the Chinle Formation. In the Bonito Canyon-Buell Park area (pl. 3), large springs issue from the base of the De Chelly and from joints in the Supai Formation. Owing to the high topographic position of the subdivision, the water table is as deep as 700 feet (fig. 10), but, except for a few areas partly drained by canyons, it is continuous throughout the subdivision.

CHUSKA MOUNTAINS

The Chuska Mountains consist of a long narrow mesa formed of the thick horizontally bedded Chuska Sandstone, which rests unconformably on folded rocks of the East Defiance monocline (pls. 1, 3). The Lukachukai Mountains is the name usually applied to the part of the Chuska Mountains subdivision lying between Lukachukai and Cove. The summit area of the mountains is at an altitude of 9,000 feet and displays a topography of rolling timbered hills and grassy meadows dotted by numerous small clear lakes. The western and northern escarpments of the Chuska Mountains consist of steep slopes of Chuska Sandstone terminating along vertical-walled cliffs carved from the resistant beds of the Summerville Formation and the Entrada and Wingate Sandstones. The eastern escarpment is a series of giant "scallops" resulting from slumps and landslides caused by slippage along the east-dipping bedding planes of the underlying shaly rocks of Late Cretaceous age. The Sonsela Buttes, remnants of Chuska Sandstone capped by basalt, were isolated from the main western Chuska escarpment by erosion.

Todilto Park and Red Rock Valley are part of the subdivision. Todilto Park is a small grass-carpeted valley containing perennial streams and lying between columned cliffs of the Entrada Sandstone and Summerville Formation along the western escarpment of the Chuska Mountains. In contrast, Red Rock Valley is an irregular nearly barren lowland formed on red beds of Triassic and Jurassic age between the Chuska and Carrizo Mountains.

The Chuska Mountains subdivision is the best watered subdivision in the Navajo country. Considerable spring discharge from the base of the Chuska Sandstone maintains the perennial reaches of many creeks that drain the area, and only a few deep wells have been drilled to supplement these water supplies.

CARRIZO MOUNTAINS

The Carrizo Mountains project above lowlands of the western San Juan basin and the lower part of Chinle Wash (pl. 3). They consist of a dioritic central mass and projecting laccolithic sills, which were intruded into the surrounding sedimentary rocks. All these rocks have been eroded irregularly into narrow ridges, sharp V-shaped canyons, hogbacks, and buttressed and recessed cliffs. A narrow skeletonlike ridge formed from Triassic and Jurassic rocks connects the Carrrizo Mountains with the Chuska (Lukachukai) Mountains. Wells have not been drilled in the mountains because numerous springs furnish dependable supplies of water.

WESTERN SAN JUAN BASIN

The western San Juan basin subdivision is underlain predominantly by Upper Cretaceous strata, which dip east and north from the Defiance Plateau and Zuni Mountains. In general, the western San Juan basin is characterized by expanses of open country bounded by narrow hogback and cuesta ridges. Smaller areas in the subdivision that contain similar features are the Gallup sag, Mesa de los Lobos, Aneth area, and the lowlands drained chiefly by the Chaco River.

The Gallup sag is a broad area of low ridges and alluviated valleys between the Defiance Plateau and the Zuni Mountains. Mesa de los Lobos is a dissected upland displaying strike valleys and hogback ridges to the northeast of the Zuni Mountains. The areas of the Gallup sag and Mesa de los Lobos form giant steps at altitudes of 6,500 and 7,500 feet, respectively.

Aneth, in the northwestern part of the subdivision (pl. 3), is in an area containing low mesas, narrow alluviated valleys, and box canyons. The canyons are well-defined features north of the San Juan River and are rimmed by the Dakota Sandstone. White Mesa, capped also by the Dakota Sandstone, is the only conspicuous landmark south of the San Juan River.

The remainder of the subdivision is drained by the Chaco River and consists of four physiographic areas informally called the "Chuska Valley," the "Chaco Plateau," the "Mount Cisco Mesa," and the "erosional plains" near Shiprock (pl. 3). The Chuska Valley, named by Gregory (1916, p. 24–26), is a gently sloping area between the Chuska Mountains and the Chaco River. It consists of alluvial plains, dissected terraces, and rock-cut slopes interrupted at intervals by low cuestas. The Chaco Plateau is south of the Chaco River, and, in comparison with the Chuska Mountains and Mesa de los Lobos, its relief seems to be subdued and its profile nearly unbroken. Near Stoney Buttes, however, its topography is rugged and comprises a series of rocky ridges eroded from the Pictured Cliffs and Cliff House Sandstones, which coalesce here to form a thick sequence of resistant beds. Mount Cisco Mesa, between the San Juan and Chaco Rivers, is a broad gently westward-sloping highland whose summit and slopes truncate rocks of Late Cretaceous and Paleocene ages. The erosional plains near Shiprock, N. Mex., are cut on the Mancos Shale and are bordered by high rock benches and hogbacks carved from sandstone units of the Mesaverde Group. Shiprock Peak and other volcanic spires tower above the general level of the plains.

Water in the sedimentary rocks of the subdivision is under artesian conditions nearly everywhere, and deeply buried aquifers are tapped by many flowing wells. Nearly all the Cretaceous sandstone units yield some water, and a few wells tap the underlying Morrison Formation of Jurassic age. The chemical quality of the ground water differs greatly—the dissolved-solids content increases from southwest to northeast across the subdivision. The ground water may contain more than 10,000 ppm of dissolved solids in the Mount Cisco Mesa area.

ZUNI MOUNTAINS

The Zuni Mountains border the southeastern part of the Navajo country and result from structural movements which uparched the strata that now form concentric bands around the core of pink granite exposed in the center of the mountains. The northeast flank of the mountains is characterized by strike valleys and cuestas eroded from beds of Permian to Jurassic age. The largest valley, formed on the Chinle Formation and traversed by U.S. Highway 66, extends from Fort Wingate to beyond Thoreau. Artesian wells in this valley tap sandstone beds in the Chinle Formation, the Glorieta Sandstone, and the San Andres Limestone.

REGIONAL HYDROGEOLOGY

The climate, drainage, and ground water in the Navajo country are controlled, in part, by the regional geologic setting of the Colorado Plateaus province and more specifically by the landforms and structural features within the Navajo country. The high border region of the Colorado Plateaus and the adjoining mountains influence the climate in the interior of the Colorado Plateaus and, thus, the quantity of precipitation available to the underground reservoir, to runoff, and to the vegetation.

CLIMATE

The Navajo country is characterized by a wide range of climate—from semiarid below 4,500 feet to relatively humid above 7,500 feet. In general, the differences in climate are controlled by orographic barriers surrounding the Colorado Plateaus at altitudes of more than 7,000 feet and by the local relief in the Navajo country and nearby parts of the Colorado Plateaus. Because the main moisture-bearing air masses are from the south and southeast, especially during the summer, most of the Navajo country is within a giant rain shadow on the leeward (northeast) side of the southern rim of the Colorado Plateaus and the nearby mountains in New Mexico and Arizona. To a lesser extent, the Navajo country is influenced orographically by highlands around other parts of the Colorado Plateaus, which interrupt and deflect the movement of other moisture-bearing air masses.

PRECIPITATION

The mean annual precipitation on the reservations ranges from less than 6 inches in the canyon lands near the Colorado River to more than 20 inches on the Chuska, Carrizo, and Zuni Mountains. Overall precipitation averages 8–12 inches annually. In some years parts of the low-altitude areas receive less than 3 inches. Pertinent climatic data are summarized in table 4.

Precipitation has a strong and fairly uniform relation to altitude and orographic effects. Thus, the Navajo country and the adjoining regions of the Colorado Plateaus can be separated into three broad climatic divisions. These are designated informally as divisions A, B, and C (pl. 4). The reservations are wholly in divisions A and B, which receive less mean annual precipitation per unit of altitude than the surrounding division C.

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TABLE 4.—*Climatic data for stations in the Navajo and Hopi Indian Reservations and adjoining regions*

[U.S. Weather Bureau, 1911-57; Sellers, 1960a]

Station	Length of record (years)	Altitude (feet)	Mean annual precipitation (inches)	Mean annual snowfall (inches)	Mean annual temperature (°F)
Arizona					
Betatakin	1939-53	7,200	11.72	51.5	49.8
Chinle	1909-57	6,090	9.16	11.0	51.6
Ganado	1929-53	6,350	11.48	28.9	48.7
Grand Canyon	1904-57	6,965	15.81	61.6	48.7
Holbrook	1893-1957	5,069	8.64	9.9	54.8
Jeddito	1931-53	6,700	9.38	38.5	51.6
Kayenta	1916-57	5,675	8.36	17.3	53.0
Lees Ferry	1917-57	3,141	5.95	3.1	62.2
Leupp	1914-53 [1]	4,700	6.37	5.4	54.0
Lukachukai	1914-19, 1938-53	6,400	12.70	----------	----------
Petrified Forest National Park	1931-57	5,460	9.00	9.9	54.6
Tuba City	1898-1957	4,936	6.72	8.9	55.0
Window Rock	1898-1957	6,750	12.61	30.6	47.6
Winslow	1898-1957	4,880	8.05	10.5	55.0
Wupatki	1939-53	4,908	7.75	5.9	57.3
New Mexico					
Chaco Canyon National Monument	1933-53 [2]	6,125	8.53	18.4	50.7
Crownpoint	1915-57 [3]	6,978	10.24	26.1	51.2
Farmington CAA Airport	1942-53	5,494	7.96	----------	51.6
Fort Wingate	1939-52	7,000	12.41	32.0	49.7
Shiprock 1 E	1928-53 [4]	4,974	7.35	9.1	53.3
Tohatchi	1927-53	6,800	10.22	22.4	52.0
Utah					
Bluff	1911-57 [5]	4,315	7.49	9.9	55.5
Mexican Hat	1931-52	4,250	----------	----------	57.5
Colorado					
Cortez	1931-57 [6]	6,177	13.27	39.0	48.8
Mesa Verde National Park	1922-46, 1953-57	6,960	18.42	----------	50.6

[1] Snowfall and temperature 1914-26, 1934-53.
[2] Snowfall 1933-57.
[3] Snowfall 1915-52; temperature 1931-52.
[4] Snowfall 1928-52; temperature 1928-54.
[5] Snowfall 1911-52.
[6] Snowfall 1931-52.

Division A is leeward of the main orographic barriers, where rain-shadow effects are most pronounced. Division C is along the crest of the barriers, where mean annual precipitation varies widely. Division B is intermediate between the two.

The mean annual precipitation measured at the weather stations in either climatic division A or B was plotted against the altitude of the station, and the data fall into a distinct group (fig. 12). By using the relation between the precipitation and altitude in each division as shown by the scatter diagram (fig. 12), an isohyetal map of the mean annual precipitation (pl. 4) was prepared. Other isohyetal maps, showing the average October to April, average May to September, and average annual precipitation, were prepared by Hiatt (1953, figs. 11.7, 11.9, and 11.10; University of Arizona, 1965a, 1965b) utilizing graphical and mathematical relations between precipitation and the effects of topography and altitude. On all these maps, distribution and amount of precipitation apparently are influenced by Black Mesa, Defiance Plateau, Chuska Mountains, and the open valleys of the Little Colorado and Chaco Rivers and Chinle Wash. Precipitation may change abruptly along the boundaries of the highlands, as indicated by a comparison of records at Lukachukai and Kayenta and indirectly by changes in vegetation; buttes, small mesas, and narrow canyons—although they have 500–1,000 feet of relief—affect the precipitation pattern only slightly.

The mean annual snowfall is related to temperature and more distantly to physiography and altitude, although wind, exposure, and other factors cause considerable variation in snow accumulation. Annual snowfall varies widely, ranging from almost zero below 3,500 feet to more than 100 inches above 9,000 feet. The overall mean annual snowfall ranges from 10 to 40 inches (pl. 4).

The annual precipitation graph of the Navajo country usually has two prominent peaks, either for July or August and between December and February (Hiatt, 1953, p. 186). Summer precipitation ranges from 50 to 65 percent of the annual total (McDonald, 1956, fig. 7). In some years, greatest precipitation may occur either in March or April or in October or November; the fact that these peaks tend to be more pronounced at stations in the northern part of the reservations suggests this area is influenced intermittently by climatic patterns of the western Rocky Mountains (Thornthwaite, 1948, fig. 4). The two driest months, May and June, generally receive less than 10 percent of the annual precipitation.

Summer precipitation is sporadic and usually occurs during high-energy convectional and frontal-convectional storms. These storms are distributed randomly in the areas having low relief but are concentrated on and along highlands at altitudes above 7,000 feet. The relation of altitude and precipitation is closer in the summer than it is in the winter (Hiatt, 1953, p. 197). Storms are mostly less than 10 miles in diameter, and each probably consists of several cells 1–3 miles in diameter, where rainfall is concentrated more heavily. Because precipitation usually is relatively intense, some local runoff and flash flooding result. Rainfall-intensity data have been obtained only for a few months in the Polacca Wash area; the maximum observed rate for a 30-minute period was 1.26 inches per hour (Thornthwaite and others, 1942, p. 52).

Winter precipitation results chiefly from frontal activity and generally is distributed evenly. Intensity generally is low and probably contributes substantially to ground-water recharge. Statistical analyses of rainfall data from selected stations in Arizona and western New Mexico indicate that precipitation varies more from year to year in the winter than it does in the sum-

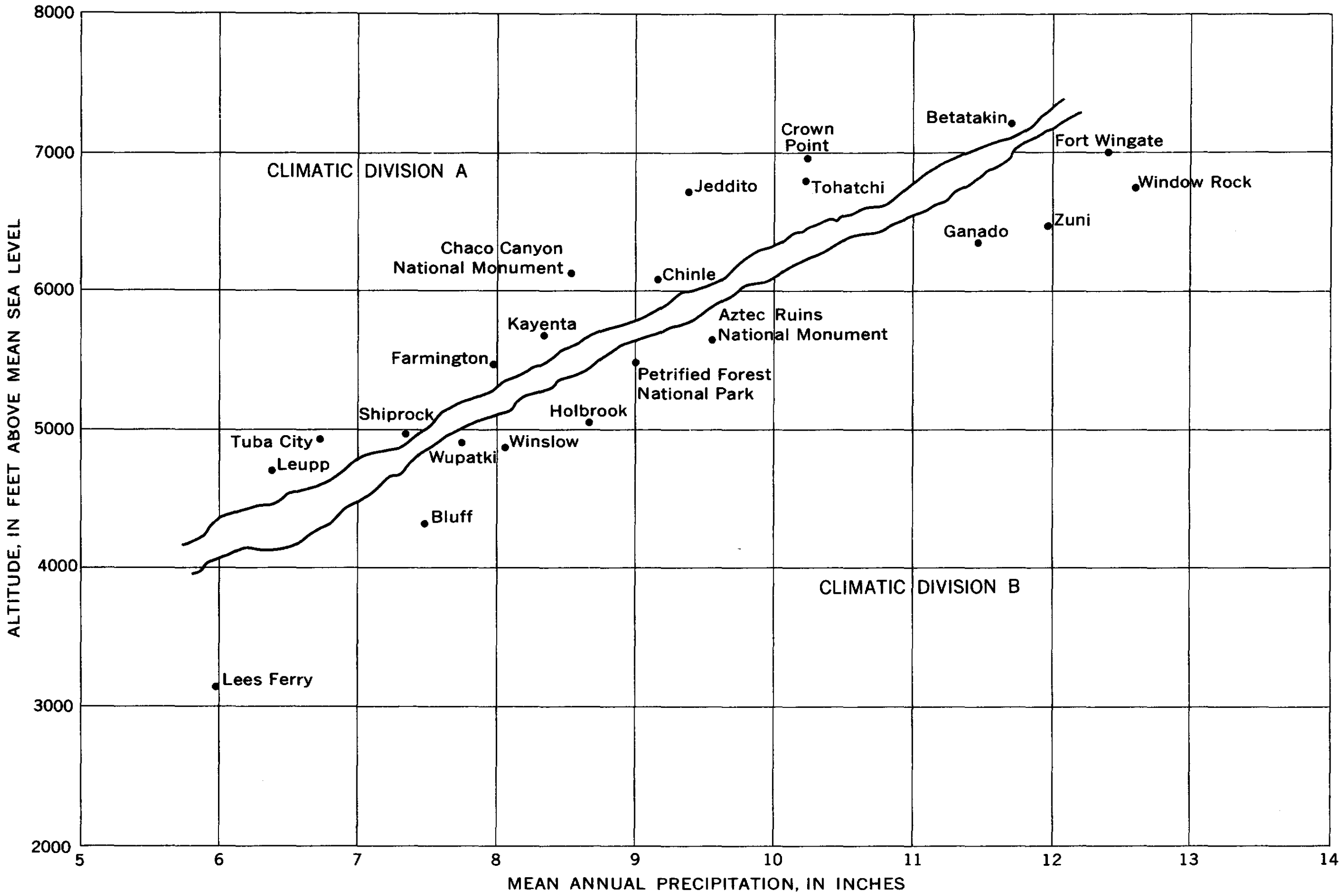

FIGURE 12.—Scatter diagram of altitude and mean annual precipitation in the Navajo and Hopi Indian Reservations and adjoining regions.

mer (Sellers, 1960b, p. 92). Much of the precipitation in the spring and fall is similar to that in the winter, a slow drizzle.

The amount of winter and spring precipitation affects the spring runoff in the intermittent reaches of streams and the amount of soil moisture available for vegetation. In most years, this precipitation causes alluvial soils and dunes to be moist throughout May and part of June, the driest months of the year. In dry years, moisture is negligible at altitudes below 5,000 feet, even in April, and the shifting cover is moved easily by the wind. Potholes in sandstone collect seepage along joints or bedding planes and often contain water during late spring after moderate winter precipitation, although many that contain water in April are dry by June.

TEMPERATURE

Temperatures higher than 100°F are common during the summer below 7,000 feet, and below-zero weather can be expected in all parts of the reservations at times but rarely below 3,500 feet. Altitude affects the length of the growing season, but the average growing season in most of the reservations (altitudes 4,000–7,000 ft) usually is 125–190 days.

Mean annual temperature seems to be a function of altitude. Temperature data for all stations in Arizona plotted on arithmetic graph paper fall along a line that is only slightly curved (Smith, 1956, fig. 2). The weather stations on topographic highs, where cool air drains from the station, have warmer temperatures per unit of altitude than the stations in valleys (fig. 13). For example, the mean annual temperature at Betatakin, on the edge of a high mesa that rims Laguna Canyon, is only 2° less than that at Chinle, although the difference in altitude is about 2,100 feet. An isothermal map of the mean annual temperature (pl. 4) was compiled from the altitude-temperature relation shown in figure 13. The mean annual temperature in most places in the reservations is 48°–54°F.

PRESENT AND PAST WIND DIRECTIONS

There are few weather stations in the Colorado Plateaus that measure wind velocity, and only two record wind direction. Strong winds are common in the

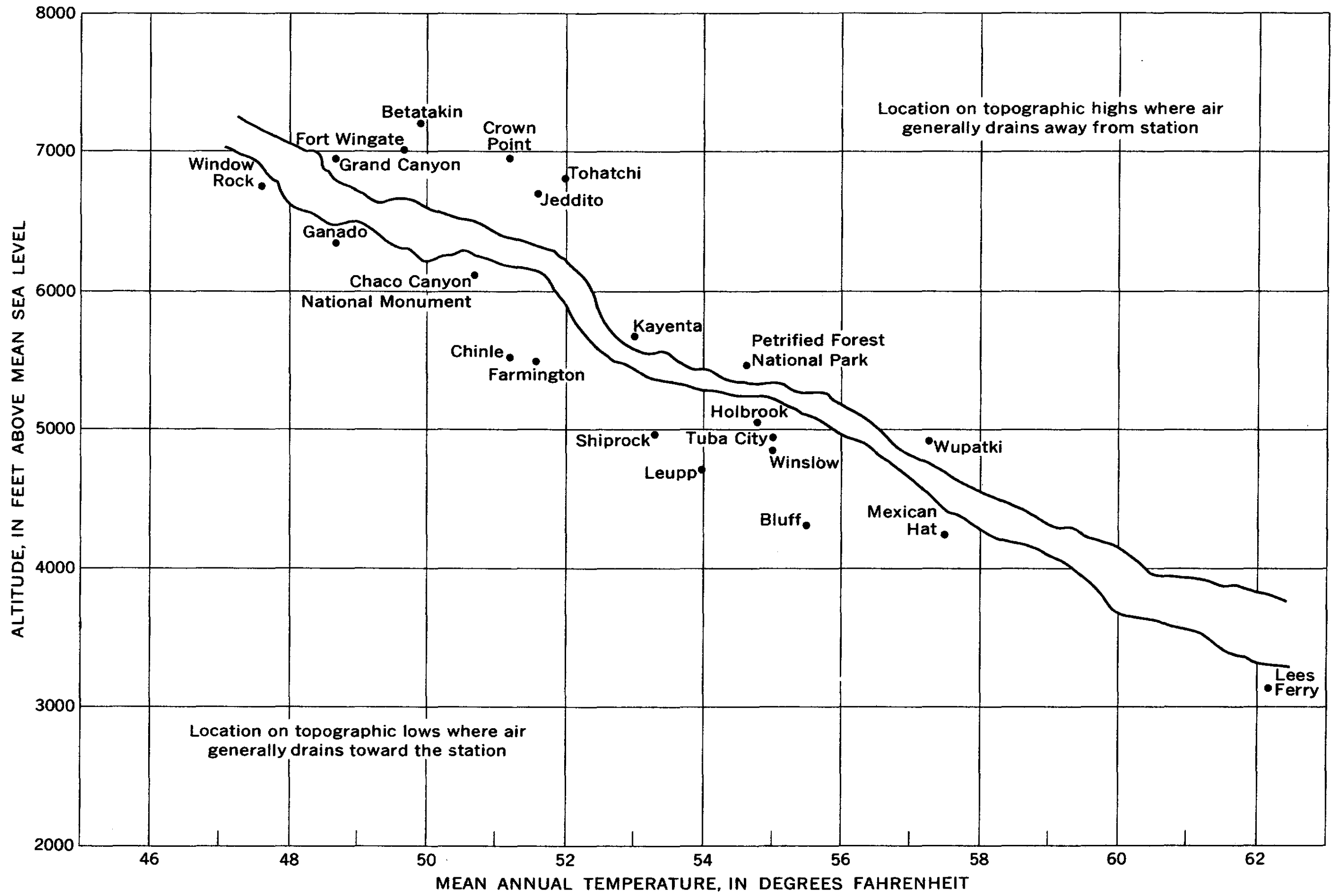

Figure 13.—Scatter diagram of altitude and mean annual temperature in the Navajo and Hopi Indian Reservations and adjoining regions.

southern part of the plateaus. The prevailing winds are southwesterly, although southeasterly and west-southwesterly winds are common; other wind directions are relatively uncommon. Average wind speeds for hourly periods range from 4.8 to 15.3 mph (miles per hour), but a maximum speed of 68 mph has been recorded at Winslow (Sellers, 1960a, table 3a). High-velocity winds causing sandstorms often stop traffic along U.S. Highway 66 between Holbrook and Winslow and elsewhere in many parts of the Navajo country.

The distribution and orientation of dunes and the directions of crossbeds in other eolian deposits indicate regional wind patterns during Quaternary and Tertiary time. Longitudinal dunes of late Pleistocene and Recent ages are alined to the northeast, except in the Mount Cisco Mesa, where they are alined east-northeastward (fig. 14). Other dunes composed of cinders derived from eruptions of late Pleistocene age in the San Francisco volcanic field were formed on the northeast (leeward) slopes of lava flows and low mesas. Barchan dunes having their convex (windward) side to the southwest and other modern dunes are active in several parts of the reservations. Other older dunes overlie terrace deposits of late Pliocene-early Pleistocene age. These dunes, chiefly of the longitudinal type, have been eroded considerably and are distinguishable from the younger well-formed longitudinal dunes also in this area. Both the older and younger longitudinal dunes trend northeastward. To the south of the reservations, a sandstone unit near the base of the upper member of the Bidahochi Formation of Pliocene age displays high-angle, large-scale, sweeping, northward-dipping crossbeds. This unit was considered by Akers (1964, p. 45) to have been deposited by wind. A similar sandstone unit at the base of the Bidahochi Formation is exposed along Wide Ruins Wash south of Ganado (fig. 14). The oldest Tertiary deposit containing beds of eolian origin is the Chuska Sandstone of Pliocene(?) age. Study of crossbedding in this unit indicates that the wind direction was from the southwest (Wright, 1956, fig. 2). Thus, the wind movement in the Navajo country in the past, at least during times of eolian deposition, was from the southwest and generally similar to the present wind pattern.

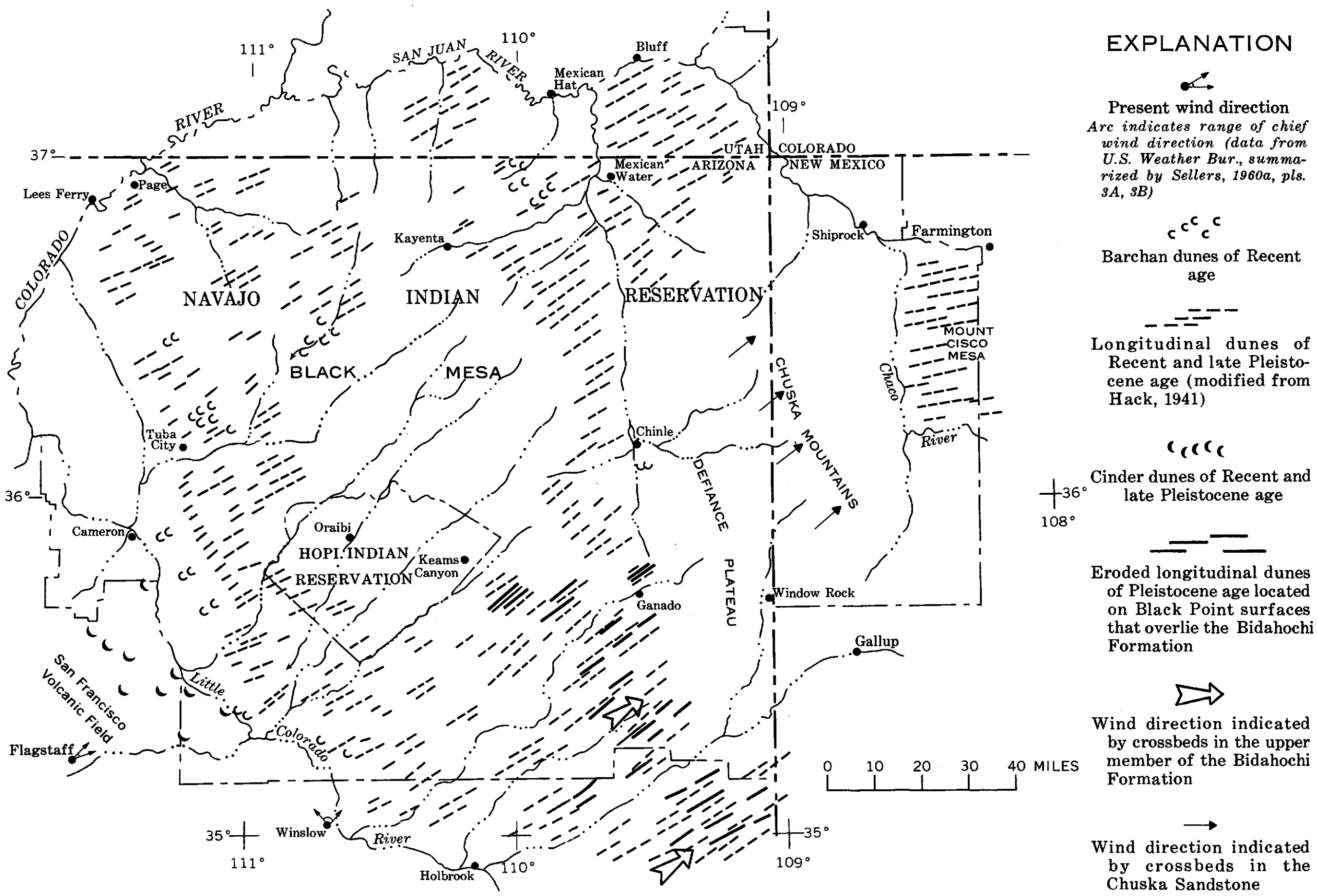

Figure 14.—Map showing past and present prevailing wind directions.

VEGETATION

By O. N. Hicks[1]

Vegetation is divided informally into three rather broad zones—grass-shrub, pinyon-juniper, and pine forest (pl. 4). The grass-shrub is below 5,500 feet and consists of sparse grassland-browse types of vegetation. The pinyon-juniper ranges in altitude from 5,500 to 7,500 feet and is dominated by woodland-browse species. Good rangelands and much of the area under cultivation are in this zone. The pine forest is above 7,500 feet and produces timber, range grasses, and shrubs.

GENERAL DESCRIPTION

The grass-shrub zone includes extensive badlands and wind-scoured plains and is the poorest range in the reservations. The climate leads to sparse cover: rainfall is generally less than 8 inches annually and is sporadic during the growing season, and maximum daily summer temperatures are more than 100°F. Potential evapotranspiration is therefore much greater than the total annual precipitation. Sheet and gully erosion resulting from rapid runoff from high-intensity storms inhibits formation of deep soil. Erosion dissects areas underlain by soft shaly rocks and bares areas underlain by hard sandstone and limestone. The formation of active dunes, blowouts, and accompanying wind erosion hinders the formation of soil and the growth of vegetation.

The vegetation depending only on direct precipitation on the wind-scoured plains and mesas of the grass-shrub zone consists of isolated stands of grass and sparse growth of shrubs—principally greasewood (*Sarcobatus vermiculatus*) and sagebrush (*Artemisia* sp.). Occasionally a dwarf juniper (*Juniperus* sp.) or pinyon (*Pinus edulis*) may interrupt the barrenness of the landscape. The best stands of grass grow in areas underlain by alluvial and terrace deposits laid down by Chinle Wash and the Chaco, Little Colorado, and San Juan Rivers and their larger tributaries. The poorest grass-

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land is in areas underlain by the Chinle and Moenkopi Formations, the Mancos Shale, and the Menefee Formation.

Dense thickets of brush and trees grow around springs and seeps, in areas underlain by a shallow water table, and along channels of ephemeral streams. The principal trees are cottonwood (*Populus* sp.), tamarisk (*Tamarix* sp.), willow (*Salix* sp.), and hackberry (*Celtis reticulata*). Trees are common in places along the Colorado and San Juan Rivers and along the perennial reaches of their tributaries. In the canyons in the northern part of the Navajo country, seepage along the base of permeable strata is indicated by a band of white alkali and by discontinuous lines of juniper, pinyon, and other shrubs.

The pinyon-juniper zone is utilized more by the Indians than any other zone (pl. 4). It is marked by contrasts of gently rolling topography, steep hillsides, rocky ridges, and deep canyons. The vegetation is chiefly pinyon and juniper mixed with grass and browse types. Range areas of sagebrush are on mesa tops, swales, and alluviated valleys; browse species—mountain-mahogany (*Cercocarpus* sp.), bitterbrush (*Purshia tridentata*), cliffrose (*Cowania mexicana*), and others—mantle hillsides and broad ridges. The pinyon-juniper zone generally has good grass cover in areas where the soil is underlain by sandstone, a moderate cover where underlain by limestone, and a poor cover where underlain by mudstone and siltstone.

The pine-forest zone is characterized by pine (*Pinus ponderosa*) forests above 7,500 feet (pl. 4), where dependable precipitation is more than 15 inches annually. This zone includes the commercial timber stands on the Defiance Plateau and Chuska Mountains. The common trees besides ponderosa pine are Douglas-fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmanni*), aspen (*Populus tremuloides*), and oak (*Quercus* sp.). Some *bristlecone pine* (*Pinus aristata*) grows on the summit of Navajo Mountain. Relatively well-watered meadows are carpeted by bluegrass (*Poa* sp.), rushes (*Juncus* sp.), and sedges (*Carex* sp.), and drier sites on low ridges and hillsides are mantled by mountain-muhly (*Muhlenbergia montana*). Grassy meadows of brome (*Bromus* sp.) and fescue (*Festuca* sp.) surround small lakes on the summit of the Chuska Mountains and adjoin the many small streams draining the Defiance Plateau. The sedimentary rock units do not effect a strong control on the formation of soil in the pine forests, and, therefore, there is little relation between the outcropping sedimentary rocks and the vegetation. The kind and amount of vegetation are controlled by exposure, precipitation, slope, and the availability of soil moisture.

RELATION OF VEGETATION TO THE OUTCROPPING SEDIMENTARY ROCKS

The density and association of species of the vegetation are related to the outcropping sedimentary rocks throughout the reservations. These relations are influenced locally by topography, soil, and climate, especially precipitation, and are most pronounced in areas lower than 7,500 feet.

Kaibab Limestone.—The Kaibab Limestone crops out in the valley of the Little Colorado River, principally between 5,000 and 6,500 feet; the outcrop area receives 5–10 inches of precipitation annually (pl. 4). Soil on the Kaibab is meager and bare limestone is exposed over large areas. Despite the lack of soil and generally low rainfall, the Kaibab outcrop is one of the better grazing areas in the Navajo country. The major grasses are black grama (*Bouteloua eriopoda*), blue grama (*Bouteloua gracilis*), galleta (*Hilaria jamesii*) alkali sacaton (*Sporobolus airoides*), and three-awn (*Aristida* sp.), and, characteristically, the plant association includes such browse species as shadscale (*Atriplex confertifolia*) and chamiso (*Atriplex canescens*), rabbitbrush (*Chrysothamnus* sp.), and yucca (*Yucca* sp.)

Moenkopi Formation.—The Moenkopi Formation consists of silty sandstone and siltstone beds and is eroded easily into bare ledgy slopes. It produces more barren range than any other formation in the Navajo country. In the valley of the Little Colorado River, the poor range on the Moenkopi contrasts markedly with the relatively good range on the adjoining Kaibab Limestone. The Moenkopi is exposed in areas near the Little Colorado River and in Monument Valley, where rainfall is low and temperature is high (pl. 4). Vegetation is maintained only in small depressions and on some gentle slopes where soil has accumulated and formed favorable areas for retention of soil moisture derived principally from runoff. Shadscale is the most abundant plant, and only two others, sacaton and galleta, grow in any quantity.

Chinle Formation.— The Chinle Formation is widely exposed between 3,000 and 8,000 feet. The depth and development of soil at different altitudes and on the many members of the Chinle differ considerably from place to place. In the Defiance Plateau area above 7,000 feet a soil usually is present on the Chinle, but thin or no soil overlies it below 5,500 feet in the valley of the Little Colorado River and in Monument and Chinle Valleys. In much of these areas, the Chinle Formation commonly is eroded into badlands, which are devoid of vegetation. In many areas where a mantle of eolian and alluvial material overlies the Chinle Formation the range is good.

Several members of the Chinle Formation influence the type of soil and the distribution of plant species.

Good loamy soil dominated by blue grama and galleta occurs in places on mesas and cuestas capped by the Owl Rock Member. On much of the Defiance Plateau shadscale and blue grama are common on loamy soil that overlies the Shinarump and Monitor Butte Members. Soils having high alkalinity and salinity commonly form on the Petrified Forest Member and contain stands of alkali-sacaton (*Sporobolus airoides*).

Wingate Sandstone.— The Wingate Sandstone crops out from about 5,500 to 6,000 feet in Chinle Valley and the valley of the Little Colorado River (pl. 1). It is covered extensively by fine sandy loamy soil developed from blown-sand and alluvial deposits, which were derived principally from the Wingate and other nearby outcropping sedimentary units. Mormon tea (*Ephedra* sp.), the clumps of which give these areas a distinctive appearance, is characteristic of the soil. Grasses dominate, however, and include Indian rice grass (*Oryzopsis hymenoides*), dropseeds (*Sporobolus* sp.), spiny-muhly (*Muhlenbergia pungens*), galleta, and commonly blue grama.

Post-Wingate Sandstone units of Triassic and Jurassic age.—The vegetation growing on prominent sandstone units of Triassic and Jurassic age consists of similar species associations. The sandstone units cover much of the northern part of the reservations and include the Kayenta Formation, Navajo Sandstone, Entrada Sandstone, Cow Springs Sandstone, and sandstone units of the Carmel, Summerville, and Morrison Formations. Between 6,500 and 7,000 feet, pinyon and juniper predominate, blue grama is the main grass, and Mormon tea is the principal browse species. The characteristic vegetation consists of Mormon tea, Indian rice grass, dropseeds (*Sporobolus* sp.)—sand, mesa, and spike—spiny-muhly, and three-awn. Locally, parts of the area that have poor soil contain almost pure stands of black-brush (*Coleogyne ramosissima*). All the sandstone units are overlain by considerable deposits of windblown sand and dunes that have been stabilized by vegetation, and only locally are extensive blowouts and active dunes common.

Shaly rocks of Cretaceous age.—Shaly rocks of Cretaceous age—chiefly the Mancos Shale, the Menefee Formation, and the fine-grained parts of the Crevasse Canyon and Wepo Formations—crop out widely. Where these rocks are exposed between 4,500 and 6,500 feet and receive an annual precipitation generally less than 10 inches, they support sparse vegetation. Large expanses in the San Juan basin have been eroded extensively and have almost no soil or vegetal cover. The best examples on the reservations are the erosional plains cut on the Mancos Shale near Shiprock (pl. 3). The vegetal cover on the shaly rocks in the San Juan basin is poor on slopes carved from these rocks but may be good on low ridges underlain by sandstone beds intercalated in the shaly formations and by coarse terrace deposits or in the swales, which are underlain largely by alluvium. In the swales where runoff is ponded or spread out on the flood plain and evaporated, alkilinity becomes severe and saltgrass (*Distichlis stricta*) may dominate. In general, vegetation grows on the shaly rocks of Cretaceous age in the San Juan basin; it includes chamiso (*Atriplex canescens*), shadscale, sacaton, galleta, Indian rice grass, three-awn, western wheatgrass (*Agropyron smithii*), and saltgrass. The vegetation on the shaly rocks on Black Mesa includes, in addition to the above-named species, a considerable amount of juniper, pinyon, sagebrush, and blue grama.

Sandstone units of Cretaceous age.—Sandstone units of Cretaceous age include the Dakota Sandstone, Gallup Sandstone, Toreva Formation, Point Lookout Sandstone, Cliff House Sandstone, Pictured Cliffs Sandstone, and sandstone beds in the Crevasse Canyon, Menefee, and Wepo Formations (pl. 1). These rocks have characteristic plant associations that are different from those growing on the shaly rocks of Cretaceous age. Pinyon and juniper generally do not grow below 6,500 feet, but grass and browse are dense—chamiso, galleta, blue grama, and three-awn in association with yucca, rabbit-brush (*Chrysothamnus pulchellus*), snake-weed (*Gutierrezia Sarothrae*), and side-oats grama (*Bouteloua curtipendula*). Above 6,500 feet these rocks crop out in the pinyon-juniper zone and generally form good rangeland.

Cinders.—Range country on volcanic cinders of Pleistocene age in the southwestern part of the reservations has characteristics not found on other geologic units (pl. 1). The cinders are extremely permeable and absorb nearly all the precipitation—much of which is utilized by the vegetation—and runoff and erosion are negligible. Growing on the cinder-covered areas are pure stands of black grama and considerably more grass than in other areas in the same altitude and precipitation zone. In association with black grama are chamiso, sacaton, galleta, rabbit-brush (*Chrysothamnus* sp.), little blue-stem (*Andropogon scoparius*), needle and thread (*Stipa* sp.), and three-awn.

Surficial deposits.—Surficial deposits, consisting mainly of eolian, alluvial, and terrace deposits, mantle extensive areas (pls. 2, 3). These deposits generally are more permeable than the underlying sedimentary rocks, and they hold a larger percentage of the annual precipitation. As a result, the areas underlain by surficial deposits are relatively favorable for maintaining growth, principally of grass and browse, and form much of the better rangeland in areas lower than 6,000 feet in the valley of the Little Colorado River, in Chinle Valley, San Juan basin, and elsewhere. Grass grows extensively on the alluvial and eolian deposits that cover the gentle slopes of Mount Cisco Mesa and overlie the shaly Kirtland and Fruitland Formations, which without this cover would sustain little vegetation (pl. 3). Surficial deposits containing relatively heavy vegetation are also on much of the outcrops of the Chinle, Moenave, and Carmel Formations and on the Wingate and Navajo Sandstones in other parts of the reservations.

DRAINAGE PATTERNS

All runoff in the reservations is to the Colorado River, the master stream of the Colorado Plateaus. Most of the reservations are drained by two principal tributary streams, the San Juan and the Little Colorado Rivers. The Colorado and San Juan Rivers are perennial, but all other streams are either ephemeral or intermittent.

ENTRENCHMENT OF THE COLORADO RIVER SYSTEM

Continuous adjustment, modification, and entrenchment throughout late Cenozoic time of the drainage systems of the Colorado Plateaus resulted in the development of the Colorado River system. Early studies in the southern part of the Colorado Plateaus by Dutton (1882), Davis (1901), Robinson (1907, 1910), and Gregory (1947) led them to postulate the general erosional development and the entrenchment of the Colorado River system from a widespread erosion surface formed in middle and late Tertiary time. The period of erosion represented by this surface has been named the "Great Denudation" by Dutton (1882) or the "Plateau Cycle" by Davis (1901). The succeeding period, during which the Colorado River system was entrenched in canyons and valleys, was called the "Canyon Cycle." Recent geomorphic studies in the Navajo country and surrounding parts of the Colorado Plateaus summarized in this report (p. A36) have substantiated generally the hypotheses presented by these early investigators.

The erosional development stage of the Colorado River system is subdivided into four general cycles (table 5): the Valencia cycle, of probable Miocene age, named from the Valencia surface (Cooley and Akers, 1961a, p. 244); the Hopi Buttes-Zuni cycle, undifferentiated, of Pliocene age, named from the Hopi Buttes surface (Gregory, 1917, p. 121–122) and the Zuni surface (McCann, 1938, p. 260–278); the Black Point cycle, of late Pliocene and early Pleistocene age, named from the Black Point surface (Gregory, 1917, p. 120); and the Wupatki cycle, of middle and late Pleistocene age, named from the Wupatki surface (Childs, 1948, p. 379–381). An older surface, the Tsaile surface of middle Tertiary age (Cooley, 1958, p. 147–148), underlies the Chuska Sandstone. Crossbed and imbrication study shows that the streams on this surface that deposited the fluvial part of the Chuska Sandstone were not related to the present physiography and to the development of the Colorado River system. The late Tertiary and the Quaternary erosion cycles of the Navajo country are shown on plate 3.

The streams that flowed on the Valencia surface began the Colorado River system. The Valencia surface is usually higher than 7,500 feet and predates the cutting of the Grand Canyon. It is preserved below basalt caprocks on Red Butte on the Coconino Plateau, perhaps below some of the lava flows in the Chuska Mountains, and in several places south of the reservations. The summits on Black Mesa and the Kaiparowits Plateau probably represent dissected segments of the Valencia surface.

Accelerated downcutting during the early part of the Hopi Buttes-Zuni cycle entrenched the ancestral Colorado and Little Colorado River systems 1,000–1,500 feet below the level of the Valencia surface. The amount of downcutting was determined from the contouring of the Hopi Buttes and Zuni surfaces near the Little Colorado River (Cooley and Akers, 1961a, fig. 237.3) and by reconstruction of the old valley profiles preserved in other parts of the Navajo country. The ancestral Colorado River during the Hopi Buttes-Zuni cycle flowed in an open valley south of Navajo Mountain, and its confluence with the ancestral Little Colorado River probably was in the western part of the Navajo country (pl. 2). The fluvial and lacustrine Bidahochi Formation was deposited on the Hopi Buttes and Zuni surfaces in the ancestral valley of the Little Colorado River.

Vigorous downcutting caused by uplift of the Colorado Plateaus during late Cenozoic time ended the Hopi Buttes-Zuni cycle, and, during the following Black Point and Wupatki cycles, the present Colorado River drainage system was outlined and entrenched (pl. 3). Excavation of the major valleys of the Navajo country and Glen, San Juan, and Navajo Canyons and Canyon de Chelly probably began during the Black Point cycle (table 5). Regional downcutting continued intermittently throughout the Wupatki cycle and is recorded by the several levels of terraces preserved along the large streams.

The deposits capping terraces of the Wupatki cycle along the Colorado, Little Colorado, and San Juan Rivers and the lower reaches of their tributaries are contemporaneous with the alluvial deposits of Pleistocene age laid down in the upper reaches of streams in

TABLE 5.—*Late Cenozoic erosional and depositional events in the Navajo and Hopi Indian Reservations*

Age			Cycle	Erosional and depositional events	Height of terraces above river level (feet): Confluence of the Colorado and San Juan Rivers	Height of terraces above river level (feet): Little Colorado River in the Cameron-Winslow area	Approximate age of cutting of principal canyons
Quaternary	Pleistocene	Middle and late	Wupatki	Downcutting and terracing.	Five terraces at 30–50, 50–100, 100–200, 200–300, and 400–500.	Five terraces at 30, 50, 75–100, 150–200, and 200–300.	
Quaternary	Pleistocene	Early	Black Point	Downcutting and terracing.	Two prominent terraces at 800–1,200 and 1,400–1,800.	Two prominent terraces at 400–500 and 600–800.	Canyon de Chelly
Tertiary	Pliocene	Late					Glen Canyon; San Juan Canyon
Tertiary	Pliocene	Middle	Hopi Buttes-Zuni	Formation of Zuni surface and deposition of the upper member of the Bidahochi Formation in valley of the Little Colorado River.	About 2,500.	1,000–1,500.	Marble Canyon
Tertiary	Pliocene	Early		Formation of Hopi Buttes surface and deposition of the lower member of the Bidahochi Formation and equivalents.			
			Valencia	Few deposits(?)	About 4,000.	2,000–2,500.	Eastern Grand Canyon
Tertiary	Miocene						

the Navajo country and with glacial-outwash deposits in some of the nearby mountainous areas. Terrace deposits along the Little Colorado River are contiguous with alluvium referred to as the Jeddito Formation by Hack (1942, p. 48–50), along Jeddito, Polacca, and Oraibi Washes, and with the Gamerco Formation (Leopold and Snyder, 1951, p. 6–9) in the Gallup area. Similarly, the alluvium in the upper part of Chinle Wash and the Chaco River drainages is a lateral equivalent of the terrace deposits along the San Juan River.

Deposits of the three lowest terraces in the Shiprock-Farmington area, 30–200 feet above the San Juan River, are continuous upstream along the Animas River to Durango, Colo. The highest of these deposits merges with the outwash sediments of the Durango glaciation. The deposits of the two remaining terraces are correlative with the younger outwash sediments of the Wisconsin glaciation of Atwood and Mather (1932). Field mapping and lithologic studies (Cooley, 1962a, p. 102–113) indicate that the deposits of the three lowermost Wupatki surfaces along the Little Colorado River downstream from Grand Falls are lateral equivalents of the outwash of the three glaciations on San Francisco Mountain described by Sharp (1942). The relations of the terrace deposits in the Navajo country to the outwash in the San Juan Mountains and San Francisco Mountain suggest that deposition occurred during the glaciations when the streams were overloaded and that the intervening periods of downcutting and formation of the terraces are correlative with the drier interglaciations.

Maximum entrenchment during the Black Point and Wupatki cycles in the Colorado River system occurred in Marble and Grand Canyons—as much as 2,500 feet. Upstream from the Grand Canyon, the depth of cutting decreased progressively and was 1,800 feet at the confluence of the Colorado and San Juan Rivers, about 1,000 feet along the Little Colorado River between Cameron and Winslow, and generally less than 600 feet in the upper reaches of Chinle Wash, the Chaco River, and the south-flowing tributaries of the Little Colorado River.

STRUCTURAL ADJUSTMENT OF THE COLORADO RIVER SYSTEM

As the Colorado River system developed in late Cenozoic time, it was generally superimposed on the folded rocks of the Colorado Plateaus. Superposed drainage is indicated especially by the overall east-west trend of the San Juan River across the upturned rocks on Monument upwarp (Baker, 1936, p. 80) and by the southwest trends of tributaries of the Little Colorado River, which are affected only slightly by the gentle folds of Black Mesa basin. The general superimposition of the Colorado River system on the tilted sedimentary rocks virtually was completed during the Valencia cycle or before Pliocene time.

Continuous downcutting by the Colorado River and its tributaries resulted in a general entrenchment of the entire river system and the adjustment of the streams to geologic structure. Most of the structural adjustment took place during the late part of the Hopi Buttes-Zuni cycle and later.

The amount of structural adjustment by streams of the Colorado River system in the Navajo country differs according to depth of downcutting, average annual river discharge, and type of geologic structure. The discharge, stream-order number, and a summary of the amount of structural adjustment of streams are given in table 6. The Colorado River, as would be expected, is the least adjusted stream to geologic structure, as it is only slightly affected by the larger folds. The Little Colorado and San Juan Rivers are partly adjusted to the larger folds and also to some of the anticlines and synclines. The tributary streams to these rivers are more strongly adjusted to geologic structure in the Colorado and San Juan drainage areas, where downcutting was more severe, than are the streams in the area drained by the Little Colorado River.

TABLE 6.—*Relation of streamflow to geomorphology in the Navajo and Hopi Indian Reservations*

[From U.S. Geological Survey water-supply papers, issued annually. Stream-order number obtained by method outlined by Horton (1932) and modified by Strahler (1952); pl. 2 used as base drainage map]

Stream	Annual streamflow (acre-feet)	Stream-order number	Structural adjustment
Colorado River	[1] 12,300,000	7	General trend slightly adjusted to basins and uplifts; present channel slightly deflected by few anticlines and synclines.
San Juan River	[2] 2,014,000	6	General trend partly adjusted to basins and uplifts; present channel moderately to slightly deflected by most anticlines and synclines.
Little Colorado River.	[3] 147,000	6	General trend adjusted to basins and uplifts; present channel slightly deflected by anticlines and synclines.
South-flowing tributaries of Little Colorado River.	50,000–5,000	5, 4, 3	General trend strongly to slightly adjusted to basins and uplifts; present channel slightly adjusted to anticlines and synclines.
Tributaries of Colorado and San Juan Rivers.	50,000–5,000	5, 4, 3	General trend strongly adjusted to basins and uplifts; present channel moderately adjusted to anticlines and synclines.
South-flowing tributaries of Little Colorado River.	<5,000	2, 1	Strongly to slightly adjusted to all structural features.
Tributaries of Colorado and San Juan Rivers.	<5,000	2, 1	Strongly to moderately adjusted to all structural features.

[1] Grand Canyon, Ariz., 1923–60.
[2] Bluff, Utah, 1914–60.
[3] Grand Falls, Ariz., 1925–51 and 1953–59.

INTERIOR DRAINAGE

Areas drained internally total 4,200 sq mi and consist of two general types—permanent and intermittent (pl. 2). Permanent interior drainage prevails where no streams flow outward—about 2,200 sq mi. Intermittent interior drainage prevails where through-flowing drainage is effected only during heavy streamflow.

Permanent interior drainage is found principally in the Navajo Uplands, on the slopes of Mount Cisco Mesa, and along Talahogan Wash—a small stream between Jeddito and Polacca Washes. The largest single area of interior drainage encompasses 960 sq mi between Tuba City and the southern part of the Kaibito Plateau. There, the Navajo Sandstone, overlain by wind-scoured and dune-covered plains, absorbs a considerable part of the meager runoff of the ephemeral streams that originate on Preston Mesa, Wildcat Peak, Mormon Ridges, and other highlands. Conditions are similar on Moenkopi Plateau and near Mexican Water. Another large area of permanent interior drainage contains two main streams, Shonto and Begashibito Washes. Shonto Wash heads near Betatakin above 7,000 feet and empties into a small lake near the old Cow Springs Trading Post (pl. 2). Dunes drifting across the valley floor caused the lake to form and separated the Shonto Wash drainage from the trunk Moenkopi Wash. Gregory (1916, p. 44) reported that reaches of this wash and the nearby Begashibito Wash are separated by drifts of sand.

The areas of intermittent internal drainage, about 2,000 sq mi, prevail in all parts of the Navajo country except west of Echo Cliffs (pl. 2). Parts of drainages are isolated by temporary alluvial-fan and dune barriers. Many small ephemeral lakes, as typified by Red Lake at Tonalea Trading Post along Moenkopi Wash and Tolani Lake in the Oraibi Wash drainage, are formed in depressions on the plains immediately upstream from an alluvial barrier. During heavy runoff these lakes are filled, and for a short time there is through drainage. In years of little runoff, the depressions contain playas and alluviated flats devoid of vegetation.

STREAMFLOW RECORDS AND RUNOFF CHARACTERISTICS

Much runoff is ephemeral and intermittent and is in response to irregular precipitation. Downstream from large springs and in reaches where the streambed intersects the water table, streams are locally perennial. Streamflow data are shown on plate 2.

A map by Busby (1966), which modifies a map by Langbein and others (1949) showing relations of runoff to precipitation, indicates that the average annual runoff originating within the reservations is about 450,000 acre-ft. Much of this water, however, evaporates, percolates into permeable sediments underlying the stream channels, and is diverted for irrigation. Streamflow, as indicated by measurements near the mouths of Moenkopi Wash and the Puerco River, is about 50 percent of that calculated from the runoff map prepared by Busby; about 50 percent of the runoff, therefore, must be lost in transmission. If these streams are representative, the total transmission losses each year from streams originating in the reservations are 200,000–250,000 acre-ft, and the remaining flow that leaves the reservations and reaches the Colorado and San Juan Rivers is less than 250,000 acre-ft per yr and may be less than 200,000 acre-ft.

Annual streamflow from the reservations is small when compared to the average annual discharge of 12,310,000 acre-ft (1923–60) of the Colorado River at Grand Canyon. Of this amount, 2,014,000 acre-ft per yr is discharged by the San Juan River at Bluff, Utah (1914–60) and 147,000 acre-ft per yr by the Little Colorado River at Grand Falls (1925–51; 1953–59). The flow of the Colorado, San Juan, and Little Colorado Rivers that crosses or borders the reservations is derived principally from the high border regions of the Colorado Plateaus and is not incorporated directly into the hydrologic systems of the reservations.

Streamflow of the Colorado and San Juan Rivers usually peaks during May and June as the result of snowmelt in the high mountains; monthly discharge may be as high as 133,000 cfs (cubic feet per second) (Lees Ferry, Ariz., June 1921) and 21,520 cfs (Bluff, Utah, May 1941), respectively, for these streams. Streamflow of the Little Colorado River is highest during March and April and August and September—about 85 percent of the normal flow for the year occurs during these months.

Runoff of the streams tributary to the Colorado, Little Colorado, and San Juan Rivers tends to be sporadic, even in perennial reaches, and is controlled largely by four factors: (1) interception, (2) transmission losses, (3) noncontribution by internal drainages, and (4) effect of convectional and frontal storm systems. The unconsolidated surficial deposits intercept and absorb much of the precipitation and the accompanying overland and channel flow (pl. 2). Much of the water thus intercepted is retained near the surface and is evaporated and transpired. Most streams are influent, and their channels are underlain by relatively permeable rocks; therefore, their transmission losses are high. The areas of internal drainage reduce the total runoff substantially, although these areas are generally favorable for ground-water recharge (pl. 2). As a result, almost no water runs off from large areas in the Navajo Uplands, and the runoff in other areas may decrease locally. Most of the runoff below 7,000 feet results from convectional storms; that from low-intensity frontal storms is small and usually is absorbed by the surficial deposits and permeable bedrock units or is evaporated.

PERENNIAL FLOW

Perennial flow, with the exception of that of the Colorado and San Juan Rivers, is maintained by ground-water discharge. Perennial streams are restricted mainly to the Navajo-Glen Canyon area, the lower part of Chinle Wash, the Chuska Mountains-Defiance Plateau area, and short reaches along the Little Colorado River and Moenkopi, Dinnebito, Oraibi, and Pueblo Colorado Washes.

The lower reaches of several canyons in the Navajo Uplands between Navajo Mountain and Navajo Canyon and in the lower part of the Chinle Wash drainage intersect the regional water table; they contain flowing streams or pools of water and thus contrast sharply with the bald rocks and dunes in the adjoining uplands. This water is mainly from the Navajo and Wingate Sandstones. Even though only a few springs are visible at the stream level, flows in the canyons are increased downstream by seepage at the base of the sandstone canyon walls. Many small canyons tributary to Glen Canyon have stepped profiles and hanging valleys. Some contain a narrow inner gorge near their mouths. A large spring or several smaller springs usually discharge at the head of the inner gorge, and downstream from this point the flow is continuous.

The total base flow between Navajo Canyon and Navajo Mountain, on the basis of miscellaneous measurements and estimates chiefly during June to August 1958, was about 6 cfs, nearly two-thirds of which is contributed by Navajo Creek. This figure is highly conservative; sand and silt deposited at the mouths of tributaries by the Colorado River during the previous spring had not been flushed out, and a substantial part of the discharge to the Colorado River from its tributaries passed through these deposits as underflow.

The Chuska Mountains and Defiance Plateau areas contain more permanent surface water than the other parts of the Navajo country. The Chuska Sandstone, De Chelly Sandstone, and other water-bearing units—generally at altitudes 7,000–9,000 feet—are in advantageous physiographic positions to control and maintain perennial streams by the discharge of ground water. Many lakes are on top of the Chuska Mountains, which is also the top of the Chuska Sandstone; these lakes aid in the recharge to the Chuska (pl. 1). Some of the lakes may be perennial, but others that contained water in 1952 were dry or nearly dry when visited in 1956. In 1966, a few of these lakes were revisited, and they were only slightly smaller in size than they were in 1952.

Tsaile, Wheatfields, Whiskey, and Coyote Creeks form a major stream system that drains much of the western escarpment of the Chuska Mountains. The discharge from these streams funnels through Canyon de Chelly and eventually joins Chinle Wash. Tsaile Creek is perennial from the western escarpment of the Chuska Mountains almost to the confluence of Canyon del Muerto and Canyon de Chelly. The flow of the other creeks dissipates before entering the main drainage in Canyon de Chelly by seepage into channel floors, by evapotranspiration, and by diversion for irrigation of cornfields by the Navajo Indians. The stream in Canyon de Chelly is perennial in short reaches just upstream from Spider Rock, and that in Canyon del Muerto is perennial where the canyon floors are on the relatively impermeable Supai Formation; these flows are maintained in part from discharge from the regional groundwater reservoir in the De Chelly Sandstone. Downstream from the Supai outcrops, this flow percolates into sandy alluvium.

Short-term records of the streamflow along the western escarpment of the Chuska Mountains indicate that the discharge varies annually and seasonally from about 4 to 60 cfs (Harshbarger and Repenning, 1954, table 1). During the growing season, diurnal variations of the flow are caused by variations in transpiration by riparian vegetation. Although the magnitude of the variations has not been measured, observation of Whiskey and Coyote Creeks shows that the terminal points of flow may vary more than a mile between morning and late afternoon.

Many small tributaries of Black Creek are perennial near the Chuska Mountains and along the east side of the Defiance Plateau. The principal ones are Tohdildonih and Buell Washes and Bonito Creek. Tohdildonih Wash, draining Todilto Park, is fed by springs in the Chuska Mountains, and its water is diverted into Red Lake. Underflow from Tohdildonih Wash supplements the ground water in alluvium in what probably was its former channel south of the Tohdildonih Wash Dam (Akers, McClymonds, and Harshbarger, 1962, p. 3). Buell Wash, flowing 50–75 gpm, is intermittent through most of Buell Park but is perennial for a short distance downstream from a spring near the lower end of the park. Bonito Creek, draining Bonito Canyon west of Fort Defiance, receives water from the De Chelly Sandstone and the Supai Formation. The shallow alluvium beneath the creek furnishes a dependable supply of water to the community of Fort Defiance.

Along the eastern escarpment of the Chuska Mountains, Sanastee Wash and a few other small washes near Toadlena are perennial for short distances in their uppermost reaches. However, little of this flow reaches the Chuska Valley area of the western San Juan basin. This perennial flow and that of numerous springs are maintained by ground-water discharge along the base of the Chuska Sandstone.

RECENT FLUCTUATIONS OF THE STREAM REGIMEN

Changes in the stream regimen during the last 4,000 years are indicated by alternating periods of erosion and deposition in all canyons and valleys of the Navajo country, although the number, magnitude, and duration of the events differ from drainage to drainage and along reaches of the same drainage. These differences are indicated by the distribution of terraces and local areas of alluviation along the present main drainageways (fig. 15). The alluvial-erosional sequence is best represented along Moenkopi, Oraibi, Polacca, and Jeddito Washes, and parts of the Puerco River and Laguna and Navajo Creeks. All these drainageways are elongated and contain a few large tributaries that join the main stem at right angles and at a significant change in gradient. The sequence is poorly represented along Chinle Wash and the lower reaches of the Chaco River, where many tributaries have a relatively sharp change of gradient before joining the main stem at nearly right angles (fig. 15).

The flood-plain alluvium deposited in many valleys shows differences in lithologic characteristics that reflect slightly different depositional environments. The alluvium deposited between about 2,000 B.C. and A.D. 900–1200 is the bulk of the late Recent alluvium; it partly fills valleys excavated during late Pleistocene and early Recent time (Hack, 1942; Leopold and Snyder, 1951; Cooley, 1962b). This alluvium consists principally of crossbedded sand and gravel beds that alternate with beds of silt and sandy silt. The deposition was from fast- and slow-moving water that was concentrated partly in channels. The upper part of some of the alluvium contains beds of sand that apparently were deposited by wind. Overlying these beds is alluvium consisting of thin-bedded mud and silt layers that contain considerable carbonaceous material. In places this alluvium is separated from the other alluvial deposits by an unconformity, which is the result of erosion and arroyo cutting that probably occurred about A.D. 1100–1300. The fine-grained sediments apparently

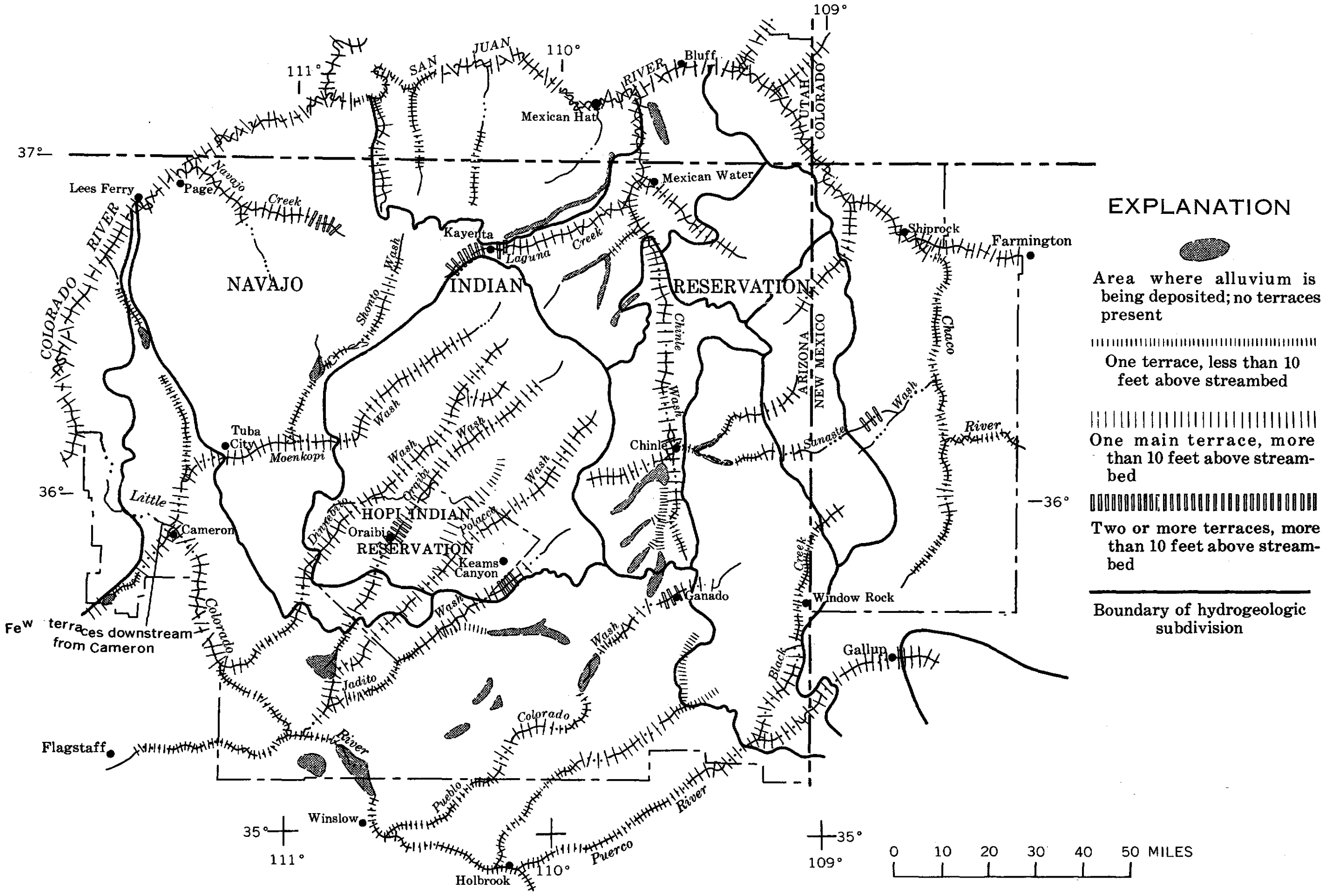

Figure 15.—Alluvial terraces of Recent age.

were laid down by sluggish streams or in small ponds and swampy areas from A.D. 1300 to about A.D. 1850. Alluvial flood plains that extended uninterrupted across the valley floors are shown on topographic maps surveyed before 1885 (Gregory, 1917, p. 130–131).

The events associated with the present episode of arroyo cutting, beginning as early as 1850, abruptly terminated deposition of the fine-grained sediments and drained the swampy areas. The earliest event was the deposition of a thin mantle of sand and gravel. This was followed by the main cutting of the present arroyos, which was especially pronounced in the Navajo country between 1880 and 1890 (Gregory, 1917, p. 130–131). Locally, deposits were laid down within the confines of the arroyo, partly burying cottonwood trees. These events were accompanied by active dune formation, and considerable windblown material overlies and is interbedded with the fluvial material. Most arroyos have been widened continually since the main cutting, and during the 1960's some were aggrading (Cooley, 1962b, p. 50; R. F. Hadley, U.S. Geol. Survey, oral commun., 1962).

Other fluctuations in the stream regimen during historical time include (1) changes in the length of perennial reaches of streams after most streams were entrenched in arroyos and (2) the general decline of streamflow. The perennial reaches of Moenkopi Wash, Canyon de Chelly, and other streams during 1909–13 (Gregory, 1916, pl. 2) were considerably longer than they were during 1950–60 (fig. 16). Arroyo trenching below the water table, however, may have extended perennial reaches of several streams, especially along Laguna Creek. Before the arroyo cutting of 1884 (Gregory, 1917, p. 130), as shown on the old Marsh Pass, Ariz., topographic quadrangle map surveyed in 1883, Laguna Creek was not perennial downstream from Marsh Pass. The flow of this stream now usually is continuous nearly to Kayenta and for about a 3-mile reach upstream from its confluence with Chinle Wash.

A fluctuating stream regimen during the 20th century is indicated by a continuous decline in streamflow, shown by the records at gaging stations in areas contiguous to the Navajo country. If the records of the Colorado River at Lees Ferry may be taken as represent-

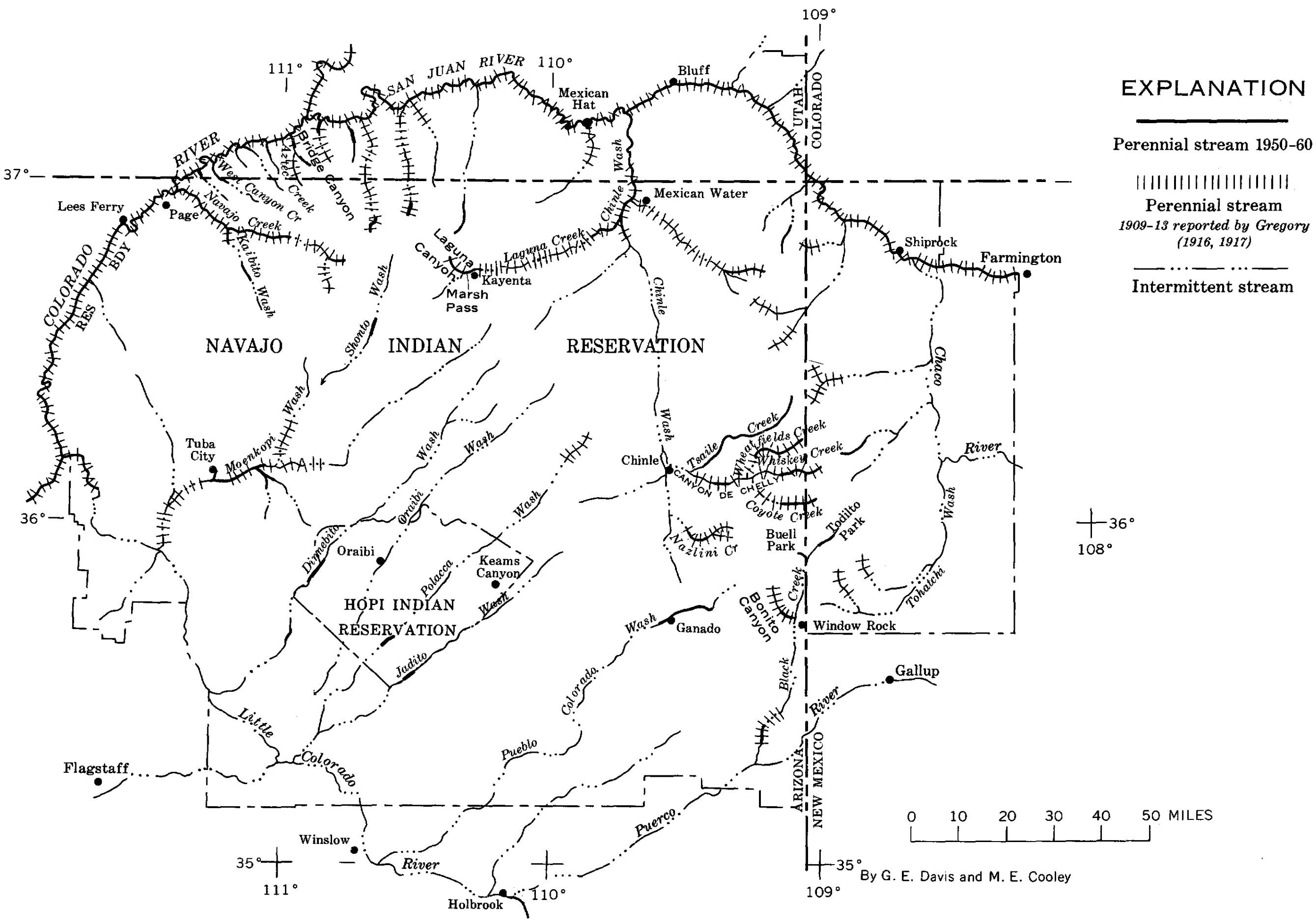

FIGURE 16.—Map showing perennial streams during 1909–13 and 1950–60.

ative of what occurred on the reservations, yearly runoff from 1930–55 was above the 1897–1955 median of the reconstructed virgin runoff only 8 years, whereas it was below the median 18 years (Alfonso Wilson, U.S. Geol. Survey, written commun., 1960).

GROUND-WATER HYDROLOGY

The ground-water hydrology of the Navajo country is controlled by five large hydrologic basins—Black Mesa, San Juan, Blanding, Henry, and Kaiparowits basins (pl. 5). Locally, ground water is exchanged between some of the basins. Part of the water in southwestern San Juan basin moves across a low structural divide into Black Mesa basin, and, similarly, some water from Black Mesa basin overflows into Blanding basin. The area of each basin, in square miles, within the boundaries of the reservations are: Black Mesa, 12,200; San Juan, 6,200; Blanding, 3,100; Kaiparowits, 2,900; and Henry, 1,100.

The main areas of recharge to the ground-water reservoirs are on the highlands along the divides between the basins. Movement of ground water in each hydrologic basin is downdip from the highlands and toward the Colorado, Little Colorado, and San Juan Rivers and their larger tributaries rather than toward the centers of the structural basins. Natural discharge of ground water is to these streams and to about 1,000 springs and numerous seeps. Artificial discharge is to about 1,400 (1961) drilled wells and 550 dug wells utilized chiefly for domestic and stock water.

RECHARGE

Recharge to aquifers in the Navajo country is directly from precipitation and from ephemeral streams or indirectly from interformational leakage. Direct recharge to the aquifers in the consolidated sedimentary rocks is controlled principally by the permeability of the rocks, the structural and physiographic expression, the amount of fracturing, and the altitude of the water-bearing strata; by the presence or absence of surficial deposits; and by the duration, type, and amount of precipitation. The mantles of surficial deposits are recharged by direct precipitation, by influent streams, and by discharge from the consolidated aquifers. Recharge from interformational leakage is common, especially between the water-bearing units adjoining the N, C, and D multiple-aquifer systems (which are mainly in the Navajo, Coconino, and Dakota Sandstones), the aquifers in Cretaceous rocks of the San Juan basin, and the sedimentary rocks and the alluvium (table 3).

The chief areas of ground-water recharge are the Navajo Uplands, Defiance Plateau, and Chuska and Carrizo Mountains. However, much of the ground water in Black Mesa and San Juan basins is from recharge in upland regions bordering the reservations to the south, including the Zuni Mountains, the Mogollon Slope, and the San Francisco Plateau. The areas mentioned above probably together contribute more than 90 percent of the recharge to aquifers in the reservations, and, except for the Navajo Uplands, the recharge areas are chiefly above 6,500 feet and receive more than 14 inches of precipitation annually (pl. 4). Exposures of the sedimentary rocks, volcanic rocks, and surficial deposits that generally favor recharge cover more than 60 percent of the reservations (pls. 2, 5).

Water enters most aquifers through fractures and along bedding planes. Relatively little water infiltrates the unfractured parts of the sandstone aquifers in the outcrop areas because of their low permeability and the generally high rate of evaporation. Faults and large joints in sandstone and limestone have been widened by solution and form excellent channels for recharge. The fractures intercept a substantial part of the precipitation and runoff in the Navajo Uplands, Monument Valley, Defiance Plateau, and eastern Grand Canyon subdivisions. Interception of surface flow by fractures is illustrated by a large joint that crosses Aztec Creek near its junction with Bridge Canyon. This joint diverted most of the flow of Aztec Creek when it was flowing about 115 gpm. Downstream from the fracture the creek was flowing about 15 gpm. The large joint recrossed Aztec Creek a short distance downstream and the water that had been intercepted reentered the creek from springs issuing from along the fractures. Large fractures are usually conspicuous along monoclines and on the more tightly folded anticlines. Other fractures especially effective for recharge are in the shattered zones formed by laccolithic domes in the Carrizo Mountains and on Navajo Mountain.

Aquifers are recharged seasonally from precipitation in the highlands principally in the winter and spring. Maximum discharge of springs and a rise of water levels in a few wells that were measured occur generally in the spring; discharge and water levels then decline during the summer. Summer precipitation is chiefly quick downpours, and, even though it is beneficial to agriculture and grazing, it probably contributes little ground-water recharge.

Single storms and rainy periods lasting a few days furnish some ground-water recharge. During a storm, water may be seen percolating downward along fractures exposed in overhanging ledges. The percolation is fairly rapid, and the water may travel more than 10 feet in 10–15 minutes. As a result of recharge from several rainstorms from October 14 to 18, 1960, water levels in four test holes drilled in the alluvium ¼–½ mile from Pueblo Colorado Wash near Greasewood Trading Post rose an average of nearly half a foot (N. E. McClymonds, U.S. Geol. Survey, written commun. 1960).

REGIONAL GROUND-WATER MOVEMENT

Regional movement of water in aquifers of the Black Mesa basin is to the Little Colorado River, and that in the San Juan, Blanding, Henry, and Kaiparowits basins is to the Colorado and San Juan Rivers (pl. 5). The Colorado and San Juan Rivers are the chief hydrologic connecting links between these basins, and all water in the upper Colorado River system passes through the Grand Canyon before leaving the Colorado Plateaus.

BLACK MESA BASIN

Black Mesa basin, occupying roughly half the reservation, is the principal hydrologic basin. Regional movement of ground water is restricted to the C, D, and N multiple-aquifer systems. In general, water-table conditions prevail on the flanks of the basin, and artesian conditions prevail in the central part.

The C multiple-aquifer system, mainly in the Coconino and De Chelly Sandstones, receives recharge from the Defiance Plateau and from regions south of the reservations that include the Mogollon Slope, San Francisco Plateau, and the Zuni Mountains. Some ground water moves westward and basinward from the Defiance Plateau, but most moves northward from the Mogollon Slope and northeastward from the San Francisco Plateau. The ground water moving northward converges with that moving westward in the southern part of the Navajo country and forms a flow system that is oriented generally west-northwestward along the broad southwestern flank of Black Mesa basin (pl. 5). Movement of ground water in the C multiple-aquifer system in the central part of the Black Mesa basin is hindered by a combination of low aquifer permeability and a large concentration of highly saline water, which is more resistant to movement than fresh water (fig. 17).

All natural ground-water discharge from the C multiple-aquifer system in Black Mesa is to the Little Colorado River system and to Chinle Wash. In part of the basin, the aquifer is saturated and rejects recharge to the Little Colorado River near Holbrook and to the

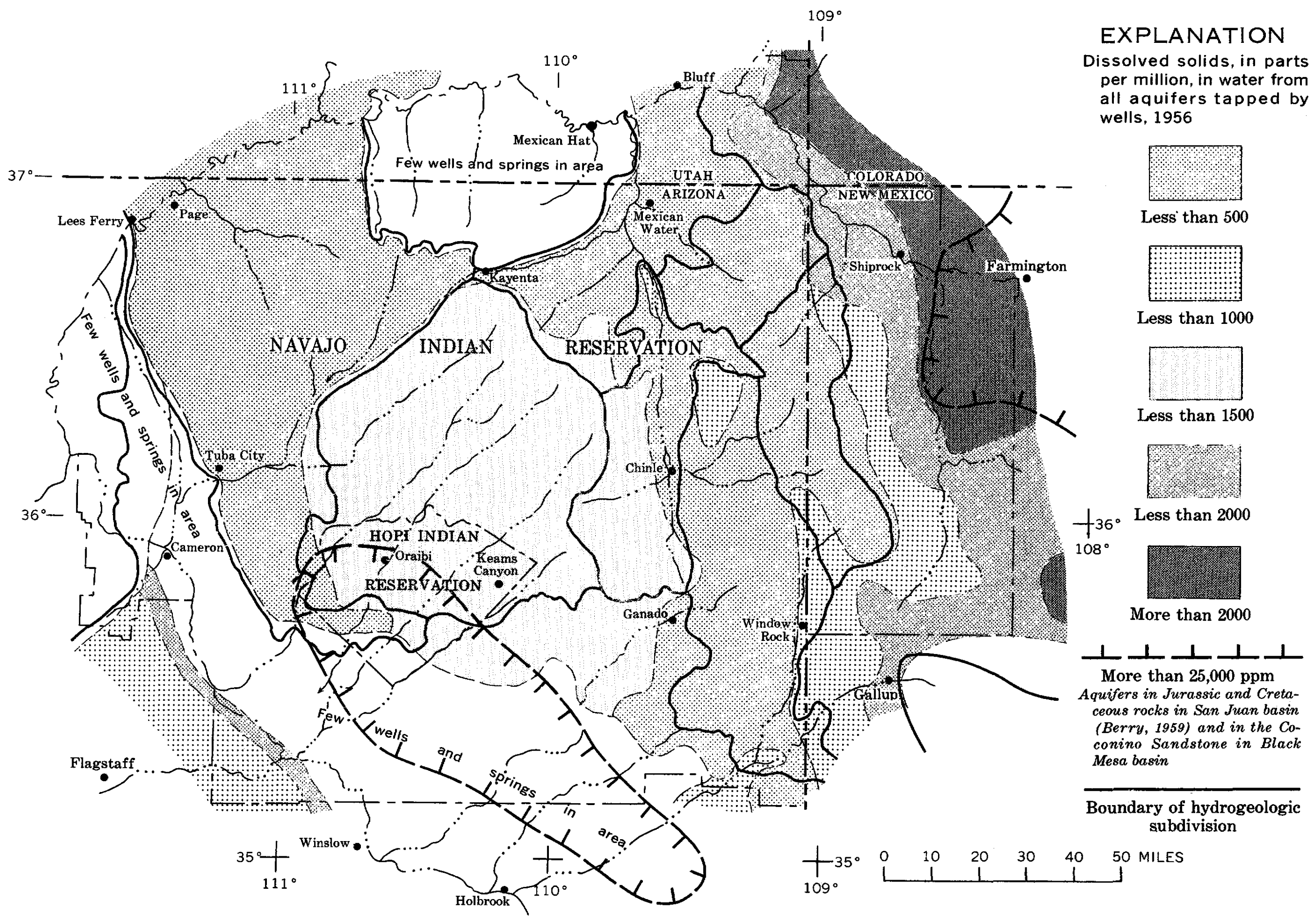

Figure 17.—Distribution of dissolved solids in ground water.

Puerco River, Chinle Wash, and other streams draining the Defiance Plateau. Discharge of the C multiple-aquifer system west of Cameron is not directly to the Little Colorado River, but, because of intense fracturing, it moves downward through the Supai Formation into the Redwall Limestone and eventually reaches the Little Colorado River at Blue Spring.

The N multiple-aquifer system, mainly in the Navajo Sandstone in Black Mesa basin, is recharged principally between Monument upwarp and Echo Cliffs. Water-level contours indicate that recharge from the south is negligible, owing to the deep burial of the aquifer and to its thinning and wedging out southeastward. Water in the N multiple-aquifer system in Black Mesa basin, therefore, moves southward from the recharge area and thence makes a broad arc northeastward toward Chinle Wash or southwestward toward Moenkopi Wash (pl. 5). The main discharge area is along Moenkopi Wash near Tuba City and into the alluvium along Dinnebito and Oraibi Washes. Some of the water in the aquifer system that originates in Black Mesa basin moves out of the basin into Blanding basin and is discharged into Chinle Wash.

Aquifers in Triassic and Jurassic rocks (table 3) and in the Dakota Sandstone of Cretaceous age exposed as narrow bands which roughly outline the general circular shape of Black Mesa (pl. 5) are minor and consist of several thin isolated semiconnected sandstone water-bearing units that are separated by thick sequences of mudstone and siltstone. Ground water in these aquifers moves basinward and toward the points of discharge along streams, although much of the movement is restricted by anticlines and by tonguing-out of the sandstone units. Water moves for a considerable distance in the D multiple-aquifer system in the southern Black Mesa area (pl. 5). Discharge from the aquifers in Triassic and Jurassic rocks and from the Dakota Sandstone is to the flood-plain alluvium along tributaries to the Little Colorado River and Chinle Wash.

The sandstone aquifers of the Upper Cretaceous Mesaverde Group (table 3) capping Black Mesa at altitudes of 6,000–8,000 feet in the central part of the structural basin are recharged only from direct precipitation and infiltration from small streams. Shallow canyons cut by tributaries of the Little Colorado River and small folds localize the movement and occurrence of ground water and control the distribution of artesian areas. The aquifers of the Mesaverde Group are separated from the underlying aquifers by the Mancos Shale, which is 500–700 feet thick in the Black Mesa basin.

Black Mesa basin is unique in that nearly all ground water in the basin is discharged at Blue Spring and several springs near the confluence of the Little Colorado and Colorado Rivers. The yield of the springs measured intermittently near the mouth of the Little Colorado River averages 223 cfs or about 161,000 acre-ft per yr, which represents the total discharge into the Colorado River from Black Mesa basin, an area of about 28,000 sq mi. Perhaps 95 percent or more of this water is from the C multiple-aquifer system because a substantial part of the water discharging from the other aquifers in the basin is evaporated or is used for irrigation, principally near Tuba City.

SAN JUAN BASIN

In contrast to Black Mesa basin, rocks of Late Cretaceous age cover most of western San Juan basin except on the flanks of the Zuni Mountains and Defiance Plateau (pls. 1, 5). The aquifers in Triassic and Jurassic rocks are restricted to a narrow belt of outcrops that outlines the shape of the basin. Permian and older rocks occupy the central parts of the Zuni Mountains and Defiance Plateau.

The aquifers in pre-Cretaceous rocks (table 3) are recharged along narrow exposures on the flanks of the basin where beds are tilted 3°–30°. The exposures are higher than 6,500 feet and are covered by vegetation and soil, which make the area generally favorable for recharge.

Regional movement of ground water in the aquifers in pre-Cretaceous rocks is restricted by low permeability, facies changes, and wedging-out downdip of the aquifers (fig. 5). Therefore, much of the ground water moves subparallel to the sides of the basin. The discharge is to many small streams along the basin flanks and to the San Juan River. Water in the aquifers in pre-Cretaceous rocks in the southwestern part of the basin (Gallup sag) discharges to the alluvium along the Puerco River or moves across the low structural divide into Black Mesa basin (pl. 5).

Aquifers of the Upper Cretaceous rocks in San Juan basin are usually under high artesian pressure and are at various places within a stratigraphic interval of more than 5,000 feet (table 3). Ground-water movement in the units of the lower part of the sequence, including the Gallup and Point Lookout Sandstones and the water-yielding beds of the Crevasse Canyon Formation, is similar to that in the aquifers in Triassic and Jurassic rocks. Water in aquifers in the remainder of the Cretaceous sequence moves toward the San Juan and Chaco Rivers (pl. 5). Because aquifers of the Menefee Formation are thin, lenticular, and tongue-out to the northeast, movement of water toward the center of the basin is inhibited. The Cliff House and Pictured Cliffs Sandstones are exposed in broad areas and are continuous in the subsurface in the central part of the basin. These sandstone units are recharged chiefly from precipitation in their areas of outcrop, and movement of ground water is generally northwestward to the Chaco and San Juan Rivers (pl. 5).

The aquifers in Cretaceous rocks are probably interconnected, although imperfectly, into a multiple hydraulic system in most of western San Juan basin. The development of this system apparently aids movement of water between the aquifers in different parts of the basin and helps to direct the ground-water discharge to the reaches of the Chaco and the San Juan Rivers in the northwestern part of the basin. Some interaquifer movement apparently is downward and is indicated by lows on the piezometric surfaces of the various aquifer systems in the central region of the basin near Farmington (Berry, 1959).

BLANDING BASIN

Recharge to the Blanding basin is from the Carrizo Mountains, the northern part of the Defiance Plateau, the eastern flank of the Monument upwarp along Comb Ridge, and the Ute Mountains in southwestern Colorado. All ground water moves generally northward toward and eventually reaches the San Juan River (pl. 5). This discharge includes the overflow from the San Juan basin and a small amount from Black Mesa basin. Some water issues from the Navajo and Wingate Sandstones to Chinle Wash downstream from Rock Point Trading Post, Laguna Creek, and the lower part of Walker Creek.

HENRY BASIN

Regional ground-water movement in the small part of the Henry basin within the Navajo country is limited to the Navajo and Wingate Sandstones, the Shinarump Member of the Chinle Formation, and the Cedar Mesa Sandstone Member of the Cutler Formation. Recharge to these units is on the summits of mesas and on the broad, gently sloping rock platforms; the ground water is intercepted by deep canyons and is diverted by synclines and anticlines (pl. 1). A small amount of water, therefore, discharges directly to the San Juan

River and to its larger tributaries. Ground-water movement north of the San Juan River is downdip toward the center of the Henry basin and to the Colorado River.

KAIPAROWITS BASIN

All movement of ground water in the Kaiparowits basin is toward the Colorado and San Juan Rivers (pl. 5). The Navajo Sandstone is the chief aquifer and is recharged nearly everywhere within the basin. South of the Colorado River in the Navajo Indian Reservation, ground water in the Navajo is generally unconfined, but the water north of the river near the center of the basin is confined. In the southern part of the Kaiparowits basin, the Navajo Sandstone is the only aquifer that adjoins the streambed between the mouth of Forbidding Canyon and Lees Ferry (pl. 1) and discharges directly to the Colorado River.

In the eastern part of the basin, the Navajo Mountain dome and nearby deep canyons modify the general northwestward ground-water movement toward the Colorado River. Movement from Navajo Mountain is radial in all directions except to the northeast, where the domal structure joins the Beaver Creek and Rainbow anticlines. Ground water in the Navajo and Wingate Sandstones discharges along the rim of Piute Canyon and into the bottoms of Forbidding and Navajo Canyons. In this area the N multiple-aquifer system is well developed, and much of the water that is recharged to the Navajo Sandstone percolates downward through the Kayenta Formation and into the Wingate Sandstone. This interformational movement is aided by strong jointing and fracturing and by zones of shattered rock on Navajo Mountain.

Rocks of Jurassic age contribute very little water to the Colorado River in the Kaiparowits basin because they crop out high on the mesas, buttes, and escarpments. Ground-water movement is localized, and there are a few springs on Navajo Mountain, on the downdip sides of mesas, and in a few places elsewhere in the basin.

DISCHARGE

The main areas of natural ground-water discharge in the Navajo country adjoin the Colorado, San Juan, Chaco, and Little Colorado Rivers, Moenkopi and Chinle Washes, and Navajo Creek (pl. 5). This water becomes part of the streamflow. The total amount of ground water discharged into the Colorado River system is unknown, although 223 cfs has been measured near the mouth of the Little Colorado River, and more than 8 cfs is estimated to be maintaining the flow in the perennial reaches of tributaries flowing into the Colorado River in Glen Canyon and into the San Juan River. In addition, the combined total flow of the perennial reaches of streams in the interior of the reservations was partly measured and is estimated to be about 10 cfs. Most of this flow percolates into the sandy alluvium or is evaporated.

Few springs in the reservations yield more than 10 gpm, and this water is evaporated near the points of discharge. Several springs at Hotevila in the Hopi country furnish enough water to irrigate small terraces built on the nearby rocky cliffs. The total discharge of the springs, excluding that of Blue Spring, is not more than 20 cfs. The main areas of spring discharge are in the canyons adjacent to Glen Canyon, near Tuba City, near Mexican Water, on the Defiance Plateau, and in the Chuska and Carrizo Mountains.

Most springs on the reservations are gravity springs, where the water table intersects the land surface. The common types are contact, fracture, depression, tubular, and seepage. Few of the springs are artesian and no thermal springs were inventoried. Generally the water of an artesian spring flows through an opening in the confining beds overlying the aquifer. These springs are principally in the area of artesian flow along the west side of the San Juan basin (fig. 9), although gravity springs are more common throughout this area.

Contact springs occur principally along the lower contacts of the Navajo Sandstone, Shinarump Member of the Chinle Formation, Lukachukai Member of the Wingate Sandstone, Dakota Sandstone, Chuska Sandstone, volcanic member of the Bidahochi Formation, and the sandstone units of the Mesaverde Group. Numerous springs also discharge along the contact between the alluvium and impermeable consolidated rock units.

Fracture springs flow from joints, faults, and bedding planes. These are the most common types in the Navajo, Wingate, and other thick sandstone units. Large bedding planes, concave upward in the Navajo Sandstone and the Shinarump Member of the Chinle Formation, concentrate downward-percolating ground water, which is discharged usually as small perched springs or seeps, in places hundreds of feet above the regional water table—in some places high on the side of a cliff. Weathering of the Navajo Sandstone in the immediate area of a spring issuing along joints and bedding planes has produced many of the prominent numerous alcoves in the canyon country near the Colorado River.

Tubular springs are rare; these include only Blue Spring and a few associated springs that flow from limestone within the canyon of the Little Colorado River. In the past, however, tubular openings of diatremes in the Hopi Buttes and on the Defiance Plateau also were the orifices of large extinct springs (pl. 1).

Deposition of travertine in the diatremes undoubtedly resulted from spring discharge.

The amount of water discharged from wells cannot be estimated accurately because most wells are equipped with windmills, which pump for short periods of time. In 1956, about 1,000 stock wells were equipped with either a windmill or small pump capable of yielding 3–5 gpm. If these wells pump only 4 hours per day, pumpage is about 1 mgd (million gallons per day) or 1,000 acre-ft per yr. Even if all the wells pumped continually, the discharge would be only about 6,000 acre-ft per yr. Repeated measurements of the water levels in selected wells have shown in general that water levels have not declined. Heavy pumping near Window Rock, however, has caused a permanent lowering of water levels. Continued expansion of Tuba City, Kayenta, Rough Rock, Shiprock, Ganado, Chinle, Pinon, and the Hopi villages may cause overdraft of the aquifers locally.

HYDRAULIC PROPERTIES OF THE AQUIFERS

The main aquifers consist of sandstone having low permeabilities, generally less than 10 gpd per sq ft, and unconsolidated sand and gravel. Sand and gravel form the water-yielding part of the alluvium and generally have a higher permeability than the sandstone aquifers. Alluvial aquifers on the reservations, however, are areally small and relatively thin. Most of the sandstone aquifers are 100–300 feet thick and are traceable on the surface and in the subsurface for many tens of miles. The Navajo Sandstone and the Coconino Sandstone and its lateral equivalent, the De Chelly Sandstone, are more than 500 feet thick over large areas. They have the highest coefficients of transmissibility and are the principal aquifers. The water-bearing beds are separated by thick, relatively impervious layers of sandy siltstone, siltstone, and mudstone. The fine-grained character of all the aquifers precludes rapid movement of water and large yields to wells.

The hydraulic properties of the aquifers were determined or computed from field tests—pumping, bailing, and pressure tests—of wells and from laboratory tests of drill cores and samples from outcrops. Drill cores were analyzed for porosity, specific retention, specific yield, and coefficient of permeability. Samples were analyzed for percentage of soluble material, medium diameter of grains, and coefficient of sorting.

The test data are given in table 7. For convenience in comparing the hydraulic properties, only data from wells completed in a single aquifer are listed. Table 7, therefore, summarizes about four-fifths of the test data available from roughly two-fifths of the wells present in the reservations as of 1956.

An important hydraulic property of an aquifer is its capacity to transmit water. This property commonly is expressed in terms of the coefficients of permeability and transmissibility. The "coefficient of permeability," as defined by Meinzer (in Stearns, 1928), is the rate of flow of water in gallons per day at a temperature of 60°F through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot. Generally, determinations of permeability and transmissibility from pumping tests are made under field conditions where water temperatures are different. Results of a pumping test usually are expressed in terms of transmissibility instead of permeability. The "coefficient of transmissibility" is the rate of flow of water in gallons per day through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent—transmissibility is equal to permeability multiplied by the saturated thickness of the aquifer.

The principal hydraulic data measured and computed from the tests include the yield or rate of flow, drawdown, specific capacity, and the coefficients of permeability, transmissibility, and storage. Coefficients of permeability and transmissibility were determined from 30 pumping tests made in widely scattered parts of the Navajo country, principally from wells completed in the Coconino, De Chelly, and Navajo Sandstones and the alluvium. The coefficient of storage could be determined only for a few places because of the absence of nearby observations wells. The specific capacity was computed from about 450 bailing tests and 30 pressure tests.

The amount of water drained or yielded from storage in an aquifer is expressed as the "coefficient of storage." It is defined as the volume of water in cubic feet released from or taken into storage in a vertical column of the aquifer 1 foot square and the height of the saturated part of the aquifer, when the hydraulic pressure on the column is reduced 1 foot. For water-table aquifers, the coefficients of storage approximates the specific yield of the dewatered material. Computations of storage coefficient from short-term pumping tests of the fine-grained aquifers in the Navajo country may not be reliable because water in these aquifers drains slowly, and the computed coefficients of storage for the water-table aquifers would approach those of artesian aquifers (table 7) and would be too low.

Hydraulic characteristics such as porosity, specific retention, specific yield, and coefficient of permeability were determined for 46 core samples from eight stratigraphic units. "Porosity" is the ratio, expressed as percentage, of the volume of the interstices in a rock to the total volume of the rock and is the sum of the specific yield and specific retention. The "specific

TABLE 7.—*Range of the hydraulic properties of aquifers in the Navajo and Hopi Indian Reservations*

[Well data as of 1956]

Geologic source	Sedimentary laboratory analyses: Samples	Solubles (percent): Range	Solubles (percent): Weighted average	Median diameter (mm): Range	Median diameter (mm): Weighted average	Coefficient of sorting: Range	Coefficient of sorting: Weighted average	Hydrologic laboratory tests: Number of cores	Porosity (percent)	Specific retention (percent)	Specific yield (percent)	Coefficient of permeability (gpd per sq ft)	Pumping tests: Number of tests	Coefficient of transmissibility (gpd per ft)	Coefficient of storage	Specific capacity (gpm per ft of drawdown)	Yield (gpm)	Bailing tests: Number of tests	Specific capacity (gpm per ft): Range	Specific capacity (gpm per ft): Average	Yield (gpm): Range	Yield (gpm): Average	Pressure tests: Number of tests	Specific capacity (gpm per ft)	Flow (gpm)	Remarks
Alluvium	0	----	----	----	----	----	----	----	----	----	----	----	12	325–63,800	5×10−4–0.25	0.80–68.86	10–241	48	0.12–75	----	5–275	45	----	----	----	Specific capacity usually is 0.5–3.0 gpm per ft.
Bidahochi Formation	14	1.0–82.1	----	Clay–0.18	----	2.81–1.09	----	----	----	----	----	----	1	60	----	.12	4	6	.04–26.9	----	12–250	----	----	----	----	Upper and lower members.
Chuska Sandstone	12	.7–17.7	5.3	.11–.35	0.20	1.80–1.12	1.43	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	
Pictured Cliffs Sandstone.	0	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	3	.02–.07	----	8–12	----	----	----	----	
Cliff House Sandstone.	0	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	3	.05–.12	----	5–40	----	1	0.04	0.7	
Menefee Formation	0	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	27	.03–1.38	0.34	6–90	26	6	.11–.41	1.5–11	
Point Lookout Sandstone.	4	----	8.2	----	.19	----	1.23	----	----	----	----	----	----	----	----	----	----	6	.07–1.12	----	7–53	----	2	.42–1.87	11–15	
Yale Point Sandstone.	5	.7–1.5	.9	.16–.27	.21	1.36–1.14	1.23	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	
Crevasse Canyon Formation.	0	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	7	.03–.64	.20	2–45	19	2	1.02–1.7	6–15	
Wepo Formation	6	1.0–2.9	1.3	.21–.35	.27	1.63–1.23	1.44	2	1–2	1.2	0	0.0009–.02	----	----	----	----	----	1	.37	----	15	----	----	----	----	
Gallup Sandstone	2	----	.6	----	.21	----	1.36	2	23	7	16–17	.4–2	9	----	----	.03–4.78	13–264	20	.02–4.84	.55	4–150	38	2	.04–.28	7–11	Specific capacity average does not include highest figure.
Toreva Formation	0	----	----	----	----	----	----	4	29–34	4–7	22–30	0–534	1	18	----	.12	15	27	.05–1.20	.32	4–60	18	----	----	----	Upper and lower members.
Dakota Sandstone	29	0–10.0	1.5	.10–1.38	.24	5.88–1.12	1.24	4	23–28	4.10	17–19	0.7–25	----	----	----	----	----	20	.02–.40	.13	3–36	16	2	.16–.06	3–8	
Morrison Formation:																										
Westwater Canyon Member.	23	0–21.7	3.7	.13–.58	.26	3.76–1.14	1.56	2	20–21	10	10–11	.1–15														
Recapture Member.	24	0–81.8	7.4	Silt–.28	.15	1.85–1.12	1.32	----	----	----	----	----	5	677	----	0.45–0.92	13–350	10	.02–2.20	.43	6–19	11	1	0–44	15	Coefficient of transmissibility computed from one test.
Salt Wash Member.	1	----	27.6	----	.17	----	1.20	----	----	----	----	----														
Cow Springs Sandstone.	31	.02–33.8	6.9	.11–.23	.17	1.47–1.01	1.21	4	19–25	10–20	4–10	.4–2	2	20.7	----	.07–.16	9–16	3	.07–.27	----	8–40	----	----	----	----	Coefficient of transmissibility computed from one test.

Bluff Sandstone	3	1.4-9.8	5.3	.09-.13	.12	1.34-1.20	1.27	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
Summerville Formation.	8	.7-19.8	4.6	.09-.16	.14	1.28-1.13	1.20	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
Entrada Sandstone and Entrada Sandstone and Carmel Formation undifferentiated.	36	.9-18.5	6.5	.07-.41	.13	1.11-1.89	1.27	4	25-31	8-10	14-26	1-65	...	...	...	...	...	6	.02-3.50	...	5-35	...	...	...	...	
Carmel Formation	6	.2-33.7	17.0	.06-.18	.14	1.23-1.12	1.18	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	Sandstone units only.
Navajo Sandstone	16	0-2.3	.5	.13-.31	.18	1.45-1.03	1.18	24	25-35	3-8	18-29	3-494	4	450-3,800	.005	.74-3.24	30-150	74	.4-7.0	.85	5-170	23	...	...	...	Coefficient of transmissibility computed from three tests; coefficient of storage computed from one test; reported yields of 1,100 gpm north of Colorado River near Page.
Kayenta Formation	7	.3-16	5.0	.04-1.47	.11	1.23-1.08	1.16	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
Moenave Formation	13	.1-16	...	.04-.30	...	1.65-1.19	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	Both members.
Wingate Sandstone:																										
Lukachukai Member.	21	.4-20.2	6.2	.06-.25	.21	1.66-1.06	1.23	...	...	...	...	...	...	...	...	...	...	5	.02-.70	...	7-8	...	...	...	...	
Rock Point Member.	21	5.2-31.9	...	.04-.33	...	1.66-1.06	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	
Chinle Formation:																										
Sandstone units	0	...	...	...	...	...	...	...	...	...	...	...	2	150	...	.25-1.1	50-100	12	.03-.50	.12	8-50	14	...	...	...	Coefficient of transmissibility computed from one test.
Shinarump Member.	6	.4-1.8	...	.16-1.35	...	1.76-1.16	...	...	...	...	...	...	1	2,000	...	1.35	50	7	.02-3.33	...	1-60	...	...	...	...	
Shinarump Member of the Chinle Formation and De Chelly Sandstone.	0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	25	.03-2.93	.67	8-135	39	...	...	...	
De Chelly Sandstone.	6	0-3.5	.9	.17-.27	.22	1.28-1.13	1.19	6	13.6-27.2	...	...	4.2-40	5	310-755	...	.21-1.21	25-150	36	.01-3.0	.66	3-200	23	...	...	...	Coefficients of transmissibility and specific capacity computed from three pumping tests.
Glorieta Sandstone	0	...	...	...	...	...	...	2	15.5-15.8	...	...	.2-.9	1	6,600-15,800	...	...	228	4	.05-.23	...	5-34	...	1	.03	2	
Coconino Sandstone	0	...	...	...	...	...	...	1	27.6	...	...	42	1	35,000	1.5×10^{-4}-7.4×10^{-3}	13.3	200	1	.31	...	15	...	...	...	...	
Supai Formation (sandstone).	4	.9-2.5	1.8	[1].11-.15	[1].13	...	...	...	...	...	...	...	...	...	...	...	...	4	.01-.92	...	1-24	...	...	...	...	Defiance Plateau area.
Cedar Mesa Sandstone Member of Cutler Formation.	0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	2	.16-.26	...	18-23	...	...	...	...	

[1] Modal diameter (mm).

yield" may be defined as the ratio, expressed as percentage, of the volume of water drained by gravity from a saturated rock to the volume of the rock. The remaining fraction of water held in the minute pore spaces of the rock by molecular attraction against the pull of gravity is termed "specific retention," which is the ratio, expressed in percentage, of the volume of water retained to the volume of the rock.

PUMPING, BAILING, AND PRESSURE-TEST DATA

Test data indicate that the productivity of all the water-bearing units is low and that few wells yield more than 250 gpm. Well yields in much of the reservations are less than 20 gpm and in some areas less than 5 gpm. Most of the wells supply water for stock and are equipped with windmills, which pump 1–5 gpm from depths as great as 1,100 feet. Most municipal and institional wells yield 5–100 gpm. The few industrial wells generally yield less than 200 gpm. Because of the low productivity of the aquifers, few wells are used for irrigation. However, a well in the flood-plain alluvium along Chinle Wash is reported to have been pumped at more than 500 gpm.

Flowing wells are common only in the San Juan basin (fig. 9). Most flow 15 gpm or less; the highest reported is 1,000 gpm from a wildcat oil-test well near Tohatchi. The driller reported this large flow from a depth between 2,000 and 2,400 feet, the stratigraphic interval occupied by the Morrison Formation and the Cow Springs Sandstone.

The specific capacity is used generally to make a comparison of productivity between wells and, thus, between different aquifers. It is especially useful where only short-duration bailing or pumping tests are available and test data are inadequate to compute the coefficient of transmissibility. "Specific capacity" is defined as the yield, in gallons per minute, divided by the drawdown, in feet. It is related directly to the coefficient of transmissibility of the aquifer. The specific capacity of a well, however, is not an exact measure of the hydrologic characteristics of an aquifer because specific capacity does not take into account differences in the depth of aquifer penetrated, fracturing and lithologic variation of the aquifer, type of well construction, duration and rate of pumping, and well efficiency.

Computed specific capacities generally range from 0.3 to 5 gpm per ft of drawdown, although most are less than 1 gpm. Some wells in the Coconino Sandstone, Bidahochi Formation, and the alluvium have specific capacities greater than 15 gpm per ft of drawdown (table 7). Other wells completed in the Supai Formation, Glorieta Sandstone, Lukachukai Member of the Wingate Sandstone, Cow Springs Sandstone, Dakota Sandstone, Wepo Formation, Crevasse Canyon Formation, Cliff House Sandstone, and Pictured Cliffs Sandstone generally have specific capacities of less than 1 gpm per ft of drawdown.

The coefficients of transmissibility computed for the aquifers in sandstone of the Navajo country, excepting those in the Coconino Sandstone, are low, fairly consistent, and with few exceptions, are less than 1,200 gpd per ft. Most coefficients of transmissibility of the sandstone aquifers in about 80 percent of the reservations—roughly, that area northeast of the Little Colorado River—range from 500 to 1,000 gpd per ft. In contrast, coefficients of transmissibility in the Coconino Sandstone range from 15,000 to 35,000 gpd per ft in the southwestern part of the reservations and in the valley of the Little Colorado River south of the reservations.

Coefficients of permeability of the consolidated sedimentary rocks, computed from pumping-test data, are extremely low. Some are less than 1 gpd per sq ft. Most range from 1 to 3 gpd per sq ft, and those of only part of the Navajo and Coconino Sandstones in the western part of the reservations are more than 5 gpd per sq ft (pl. 5). The coefficients of permeability of the Coconino Sandstone are as much as 70 gpd per sq ft in a well south of the reservations—the highest permeability of any rock unit in the southern part of the Colorado Plateaus.

Coefficients of transmissibility and permeability of the sand and gravel deposits in the flood-plain alluvium along the main washes are the highest in the Navajo country and reflect the diverse lithology of those deposits. Locally, coefficients of transmissibility may be more than 60,000 gpd per ft. Coefficients of 1,500–5,000 gpd per ft are common in many areas, but those less than 300 gpd per ft are rather uncommon. Coefficients of permeability for the water-yielding beds in the alluvium may exceed 100 gpd per sq ft. The most permeable alluvium, on the basis of well-test data and on subsurface information obtained from well logs, is along reaches of Chinle Wash, Black Creek, Pueblo Colorado Wash, Puerco River, and the Little Colorado River.

DRILL-CORE TEST DATA

Cores were taken from sandstone beds in 11 water-bearing units in widely spaced parts of the reservations, but only the Navajo Sandstone was cored extensively (table 7). At each locality two cores were taken, one parallel and one perpendicular to the bedding. All the cores were taken from exposures except one taken from a chunk brought up by a bailer from a fractured zone in the Coconino Sandstone south of the reservations at Joseph City, Ariz.

The laboratory analyses indicate wide differences in the hydraulic properties of the cores (table 7). Results of analyses of 24 cores from the Navajo Sandstone indicate that the porosity ranges from 25 to 35 percent and the coefficient of permeability from 3 to 494 gpd per sq ft. Results of analyses of 31 cores from the other units indicate that the porosity ranges from 1 to 34 percent, specific retention from 1.2 to 20 percent, specific yield from 0 to 30 percent, and coefficient of permeability from 0.0009 to 534 gpd per sq ft.

Laboratory determinations of 52 cores from 26 sites of all the aquifers except those in the Coconino Sandstone show wide differences in the coefficients of permeability, as indicated by the following groupings:

Aquifer	Number of cores having indicated coefficient of permeability (gpd per sq ft)				
	<10	10–20	21–50	51–100	>100
All aquifers	20	9	13	7	3
Aquifer in Navajo Sandstone	2	3	10	6	3
Aquifers other than in Navajo Sandstone	18	6	3	1	0

Four cores taken from limestone beds in the Owl Rock and Monitor Butte Members of the Chinle Formation indicated coefficients of permeability ranging from 0.00001 to 0.0005 gpd per sq ft.

Permeability of cores drilled parallel to the bedding differs from that of those drilled perpendicular to the bedding. The coefficients of permeability of parallel cores were higher in 18 sites and were lower in 8 sites than those of the perpendicular cores. The deviation between the permeabilities of the parallel and perpendicular cores in all the sites is 11 gpd per sq ft; the average deviation for the 12 sites cored in the Navajo Sandstone is 15 gpd per sq ft, and that for the remaining sites in the other stratigraphic units is 8 gpd per sq ft. At 9 of the 26 sites the permeability of one core was more than 4 times greater than the permeability of the other core.

As part of a study of the transmissive character of the principal sandstone units of the Colorado Plateaus as related to the distribution of uranium deposits, coefficients of permeability were determined of 340 samples from 42 localities in the Navajo country (Jobin, 1962, table 31). Mean coefficients of permeability range from 1 to 104 gpd per sq ft. Mean coefficients for 28 localities are less than 10 gpd per sq ft and those for 38 localities are less than 20 gpd per sq ft. The mean exceeded 100 gpd per sq ft in only one locality. The distribution of the means of the coefficients of permeability and their respective stratigraphic units are shown on plate 5.

The coefficients of permeability of cores collected from exposures of the aquifers and the ones reported by Jobin (1962, table 31) are, in general, considerably higher than those computed from pumping tests (pl. 5 and table 7) because of increased permeability from weathering and leaching.

Nearly all the cores, except those of the Navajo Sandstone, were taken in canyons or from vertical ledges and small cliffs. Most sample sites in the canyons were along the margins of the alluvial flood plain and in rocks that were exposed to weathering during the Wupatki cycle of erosion of late Pleistocene time (fig. 18). The samples were cored from ledges and cliffs in places where slope retreat was fairly rapid and where the rocks were weathered only for a relatively short time. The cores of the Navajo Sandstone were taken from outcrops that were exposed during the Black Point cycle of late Pliocene to early Pleistocene age. The rocks of these outcrops were weathered 10–50 times longer that those of most other core sites. Leaching by downward-moving water derived directly from precipitation accompanied the weathering and removed much of the soluble material from the part of the Navajo Sandstone just underlying the surface. The leaching and weathering for so long a time probably account for the high coefficients of permeability determined from the cores in the Navajo Sandstone. Probably leaching was negligible at most sites in the canyons because these sites are near points of ground-water discharge. In fact, some soluble material may have been deposited adjacent to many sites.

SEDIMENTARY LABORATORY-TEST DATA

Laboratory analyses of grain size, coefficient of sorting, and percentage of soluble material aid in determining the hydraulic character of an aquifer. In most sandstone units that yield water to wells in the Navajo country, the median diameter of the grains is 0.12–0.25 mm, or in the range of Wentworth's (1926) fine-grain size classification (tables 1, 7). The diameter of most grains is 0.06–0.35 mm, or in the range of very fine to medium-grained. Only a few water-bearing units—the alluvium, Bidahochi Formation, Dakota Sandstone, and parts of the Morrison, Kayenta, and Chinle Formations—contain grains coarser than medium.

The arrangement of the grains in a sandstone is usually reflected by the coefficient of sorting. Generally, the better the sorting the higher the percentage of pore space. In unconsolidated deposits, porosity is related directly to sorting and grain size, but in consolidated rocks, cementing material fills part of the pore space and decreases the porosity. The sorting in most of the water-bearing units is classified as good to fair (see "Sedimentary Features", p. A6), and the coefficients of sorting range from 1.13 in the De Chelly Sandstone to 1.56 in parts of the Morrison Formation (table 7).

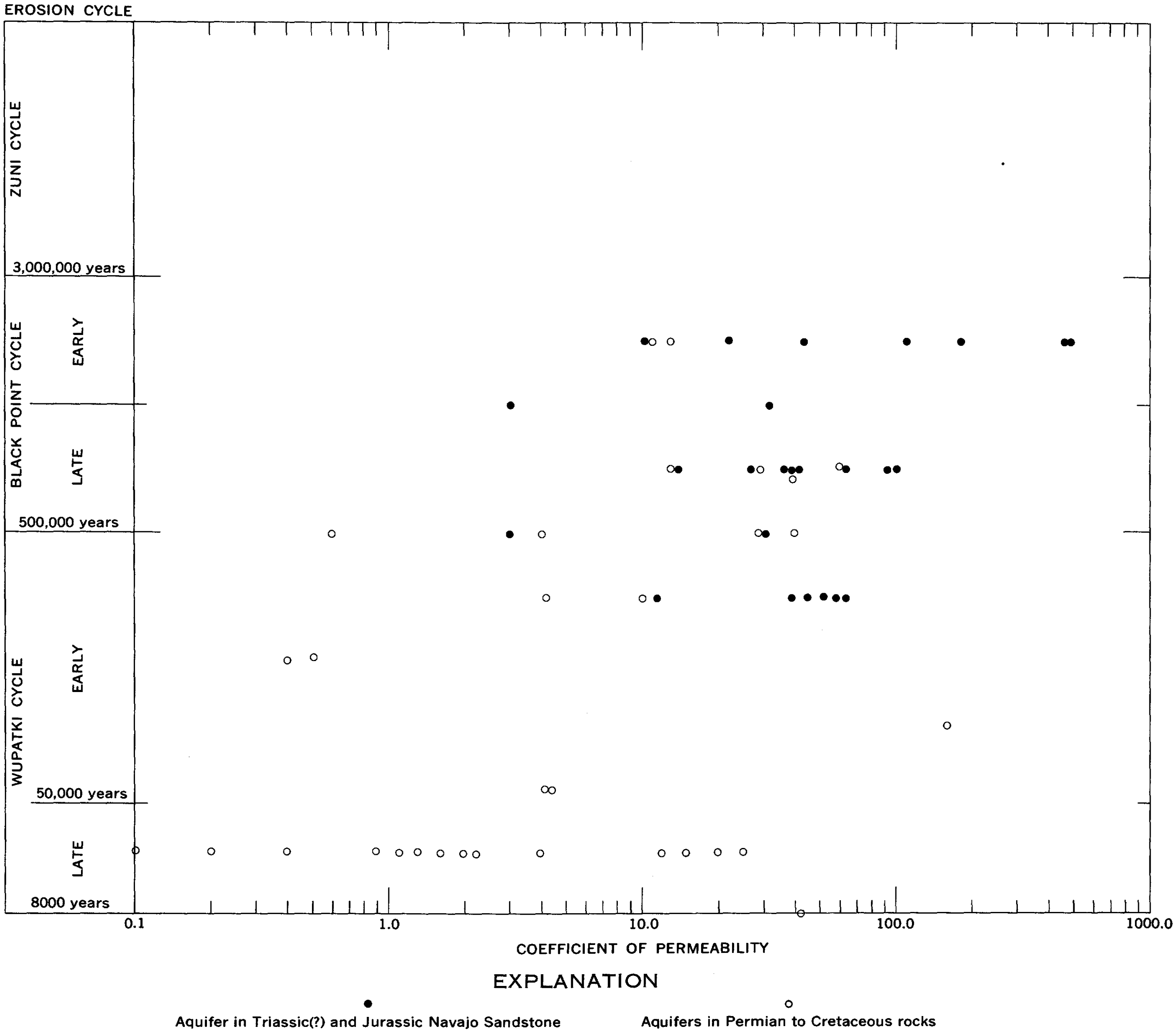

FIGURE 18.—Relation of the coefficient of permeability, determined from core samples, to the amount of time that the rocks have been exposed to weathering.

The soluble material, expressed as percentage, is material dissolved by a solution of dilute hydrochloric acid. The soluble mineral in most of the sandstone aquifers is chiefly calcium carbonate, part of the cementing material. Silica and other relatively insoluble substances are commonly bonding agents. Secondary growth of quartz was observed on quartz grains in sandstone sampled in nearly all parts of the reservations. Grains composed of limestone, dolomite, and other soluble material generally occur in insignificant quantities in the sandstone beds. The soluble material constitutes a large part of many rock units, such as impure limestone beds, calcareous siltstone, and sandstone beds, which are tightly cemented and are essentially aquicludes. Beds commonly containing more than 10 percent of soluble material occur in the Bidahochi Formation, Chuska Sandstone, Dakota Sandstone, Morrison Formation, Cow Springs Sandstone, Summerville Formation, Entrada Sandstone, Carmel Formation, Kayenta Formation, Moenave Formation, and Wingate Sandstone.

The effects of grain size and degree of sorting on the ground-water hydrology of sandstone aquifers in the Navajo country may be masked by soluble material and the amount of fracturing. In most places, the presence or absence of soluble material apparently affects permeability more than fracturing. Leaching of rocks near the surface removes some of the soluble material and thus increases permeability. Rocks in the subsurface have a lower permeability as indicated by pumping tests, however, and probably are unaffected by weathering and are little affected by leaching.

CONCLUSIONS

Several geologic factors influence the permeability and transmissibility of the bedrock sandstone aquifers of the Navajo country. The grain size, generally in the very fine to medium range, causes a slow rate of water movement through the rocks. Cementation, both by the generally insoluble siliceous materials and the more soluble carbonate materials, decreases permeability and transmissibility. Fractures increase overall permeability and transmissibility. Effects of both fractures and cement are noted in the variability of the hydraulic properties computed from pumping tests, but only the effects of cementation are noted in the hydraulic properties determined from drill cores.

Regional geologic factors that directly influence transmissibility and more indirectly permeability are the broad lateral lithologic changes, trends in thickness, intertonguing, and wedging out of aquifers. In most sandstone units, where silt- and clay-size particles increase, permeability and transmissibility decrease. This relation is especially apparent in the Wingate, Navajo, and Cow Springs Sandstones (Jobin, 1962, p. 35–36, 42, 52).

The hydraulic properties computed from the tests are relatively uniform and indicate only slight differences in the aquifers, except for the Coconino Sandstone and the alluvium. In general, the coefficient of permeability is less than 10 gpd per sq ft, the coefficient of transmissibility is less than 1,000 gpd per ft, and the specific capacity is less than 1.0 gpd per ft of drawdown. Contrasting with that of other bedrock aquifers, the coefficient of transmissibility of the Coconino Sandstone in the southwestern part of the reservations and nearby areas is more than 30,000 gpd per ft. The Coconino Sandstone is the principal aquifer in northeastern Arizona, but unfortunately in most of the reservations it contains water too highly mineralized for use or it has been drained by deep canyons carved by the Colorado and Little Colorado Rivers. The Navajo Sandstone yields moderate amounts of water to wells in nearly half of the reservations, but where it has a thick saturated zone this sandstone yields large quantities of water to wells even though its permeability is generally low.

The alluvium generally has much higher coefficients of permeability and transmissibility than the consolidated aquifers, except for the Coconino Sandstone. The alluvium has not been developed as much as the other aquifers, and its water-bearing potential is not fully known; however, its hydraulic properties differ considerably in the Navajo country. The alluvium probably will yield more than 500 gpm to wells in parts of Black Creek and Chinle and Pueblo Colorado Washes.

CHEMICAL QUALITY OF THE GROUND WATER

Chemical analyses of more than 1,300 samples of ground water from the reservations indicate that the water is slightly to highly mineralized, usually hard to very hard, and chiefly of a bicarbonate type. Representative analyses are given by Kister and Hatchett (1963). The general characteristics of the chemical quality of the water are indicated in table 8, which gives the ranges of the chemical constituents of the main aquifers, and by maps, which show the distribution of dissolved solids (fig. 17), fluoride (fig. 19), and hardness (fig. 20).

The dissolved-solids content of the ground water generally ranges from 100 to 47,000 ppm. Dissolved solids usually are less than 500 ppm in water from aquifers in the Navajo Uplands and Defiance Plateau-Chuska Mountains areas (fig. 17). In contrast, concentrations of 2,000 to more than 10,000 ppm are common in water from aquifers in Cretaceous rocks at shallow depths in the San Juan basin and in aquifers in Permian, Triassic, and Jurassic rocks in the Black Mesa basin area north of the Little Colorado River. High dissolved-solids contents were reported from deep water wells and gas-test wells penetrating the Coconino Sandstone in the southern part of the Navajo country. Ground water containing considerably more than 25,000 ppm dissolved solids occurs in oil and gas wells penetrating aquifers in Mesozoic rocks deeply buried in the center of the San Juan basin (Berry, 1959).

The principal chemical constituents of the ground water are calcium and sodium, and bicarbonate, sulfate, and chloride ions. Combinations of these ions form four general chemical types of ground water—calcium bicarbonate, sodium bicarbonate, sodium sulfate, and sodium chloride. Most ground water having less than 700 ppm dissolved solids is either calcium bicarbonate or sodium bicarbonate, and that containing more than 700 ppm is sodium sulfate, calcium sulfate, or sodium chloride. Gradations between these types are common, and much of the highly mineralized water is a bicarbonate sulfate type.

The minor chemical constituents are fluoride, nitrate, magnesium, silica, and iron (table 8). The concentrations of these ions differ considerably in different aqui-

TABLE 8.—*Range of the chemical constituents of ground water in the Navajo and Hopi Indian Reservations*

[Analyses in parts per million, except as indicated]

Geologic source	Number of analyses	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (parts per million)	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate
Alluvium	301	4.1-63	4 -2,870	1.1-2,040	5.5-12,000	34-1,000	0- 79	2.5-8,890	2-27,500	0 -11	0 -439	143-47,100	18-15,500	0-15,500
Bidahochi Formation	18	3.2-28	2 - 80	.9- 16	8.7- 366	127- 292	0- 39	6.4- 492	5- 157	0 - 2.8	.1- 15	132- 1,070	8- 244	0- 53
Chuska Sandstone	13	20 -61	23 - 71	4.8- 11	3.4- 23	48- 278	0- 5	2.7- 24	3- 12	.1- .4	.1- 11	138- 299	43- 222	0- 9
Cliff House Sandstone	6	10 -19	5.8- 276	1.7- 91	141 - 6,140	276-1,140	0- 14	363 -8,230	7- 4,210	0 - 8	.1- 2.5	1,190- 3,120	22- 1,600	0- 1,150
Menefee Formation	60	5.1-21	1 - 168	.7- 34	37- 2,620	93-1,890	0-106	6.2-3,930	3- 956	0 -12	0- 19	129- 7,780	5- 534	0- 350
Point Lookout Sandstone	16	3.9-33	1.2- 684	.5- 267	28- 833	167- 572	0- 45	14 -3,410	3- 113	.2- 3.4	.1- 8.6	249- 5,080	0- 2,800	0- 2,630
Crevasse Canyon Formation	9	7.5-19	3- 64	.9- 231	.9- 661	122-1,030	0- 9	38-2,980	4- 94	0- 1.9	0- 9.2	268- 3,120	11- 3,100	0- 3,000
Gallup Sandstone	33	10 -38	1.0- 456	.5- 268	16- 710	85- 763	0- 28	17-2,850	4- 482	0- 4.8	0- 13	285- 4,140	4- 2,240	0- 2,120
Toreva Formation	71	7.1-26	2.8- 298	1.2- 96	5.8- 228	79- 479	0- 16	12-1,200	3- 100	.1- 1.8	.1-154	130- 1,890	12- 1,140	0- 940
Dakota Sandstone	33	6.5-42	1.5- 330	.9- 103	5.8- 1,430	130-1,550	0- 39	7.8-3,540	6- 500	.1-10	.2- 10	165- 5,560	9- 1,080	0- 1,210
Morrison Formation	50	6.2-28	5.2- 373	1.7- 188	9.2- 695	81-1,200	0- 73	11-1,980	3- 374	.1- 4.0	0-200	168- 2,960	20- 1,700	0- 1,520
Cow Springs Sandstone	11	7.4-18	7.5- 221	2.2- 106	24- 949	208- 898	0- 18	17-2,380	12- 118	.2- 5.1	.1- 18	264- 3,760	20- 988	0- 572
Entrada Sandstone	10	9.1-27	2.5- 262	1.2- 64	15- 543	83- 539	0- 16	5.8-1,930	5- 2,230	.2- 1.2	.3- 33	196- 2,870	11- 916	0- 848
Navajo Sandstone	140	6.7-29	.8- 135	.4- 64	1.2- 295	57-2,300	0- 45	3.7- 625	1- 171	0 - 2.4	0- 80	90- 1,030	6- 598	0- 512
Lukachukai Member of Wingate Sandstone	25	9.3-29	2- 67	1.3- 21	6.2- 308	99- 470	0-247	7.6- 250	3- 121	.1- 1.2	.1- 18	122- 869	10- 254	0- 42
Sonsela Sandstone Bed of Petrified Forest Member of Chinle Formation	8	8.7-45	1.2- 98	.5- 34	76- 621	244- 740	0- 33	23- 864	19- 61	.2- 1.3	.3- 3	353- 1,810	5- 384	0- 174
Shinarump Member of Chinle Formation	23	3.9-28	.8- 304	2.9- 587	6.2- 871	135- 648	0- 0	16-4,110	5- 375	.2- 1.6	.2- 9.8	171- 6,410	14- 3,170	0- 2,820
Other units of Chinle Formation	44	5.6-36	3.6- 141	.7- 40	1.2- 1,420	114-1,150	0-462	17-1,570	7- 4,650	.1- 5.9	.3-129	238- 3,810	8- 640	0- 290
Coconino Sandstone	15	10 -14	67 - 924	40 - 166	23- 5,960	148- 299	0- 0	219-1,350	22-10,100	.2- .6	.2- 5.6	555-30,000	334- 2,990	166- 392
De Chelly Sandstone	49	7.6-20	18 - 457	7.4- 147	5.5- 190	117- 532	0- 6	9.5-1,560	3- 122	0 - 2	0 - 17	126- 2,270	90- 1,740	0- 1,640
Glorieta Sandstone	6	8.2-13	116 - 264	15 - 87	9.2- 1,330	184- 265	0- 0	245 - 637	5- 1,980	.1- .8	0 - 1.7	568- 4,330	458- 779	242- 576

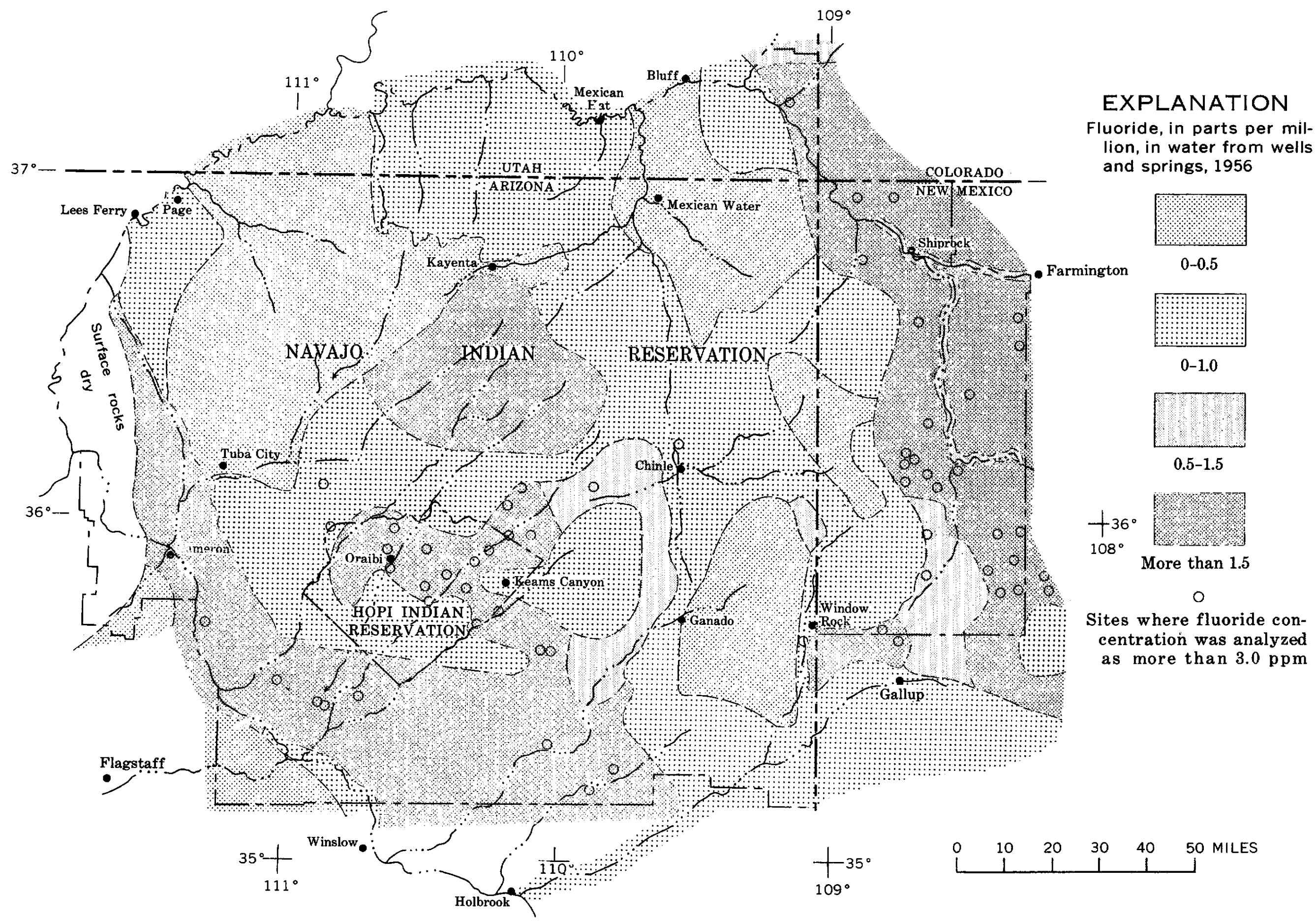

FIGURE 19.—Distribution of fluoride in ground water.

fers, but, except for fluoride and nitrate, are tolerable for most uses on the reservations.

RANGE AND DISTRIBUTION OF THE CHEMICAL CONSTITUENTS

Bicarbonate is by far the most common anion in the ground water of the Navajo country (table 8). It is abundant in water from all the aquifers, but is not as objectionable as the other ions. The bicarbonate usually ranges from 50 to 300 ppm.

Sulfate and chloride are the chief objectionable constituents of the ground water. Concentrations of sulfate are commonly more than 200 ppm and may be as high as 4,000 ppm (table 8). Aquifers in the Entrada Sandstone, Coconino Sandstone, and Upper Cretaceous rocks of the San Juan basin may have a large amount of sulfate. High concentrations of chloride are generally not as widespread as those of sulfate, even though water from the Coconino Sandstone in the Hopi Buttes area and from the alluvium in several scattered places contains more than 10,000 ppm chloride.

The concentration of calcium, including magnesium, and sodium in the ground water usually is less than 300 ppm each. Calcium is the dominant cation where ground-water recharge is considerable. Thus, the ratio of sodium to calcium is low on the Defiance Plateau, Chuska Mountains and Zuni Mountains, and Navajo Uplands, but it increases progressively downdip from the recharge areas. In much of Black Mesa and San Juan basins, sodium and calcium are in more equal proportions; in places sodium may exceed calcium.

The nitrate content of water from springs and drilled wells generally is low, but that from dug wells generally is high. Water from dug wells may contain more than 45 ppm, the upper limit recommended by the U.S. Public Health Service (1962). Much of this nitrate probably was introduced through open or partly open wells. Alluvial water, because of included decaying vegetable matter, tends to be highest in nitrate. Nitrate in water from the consolidated sedimentary rocks is low, usually less than 5 ppm and rarely more than 20 ppm.

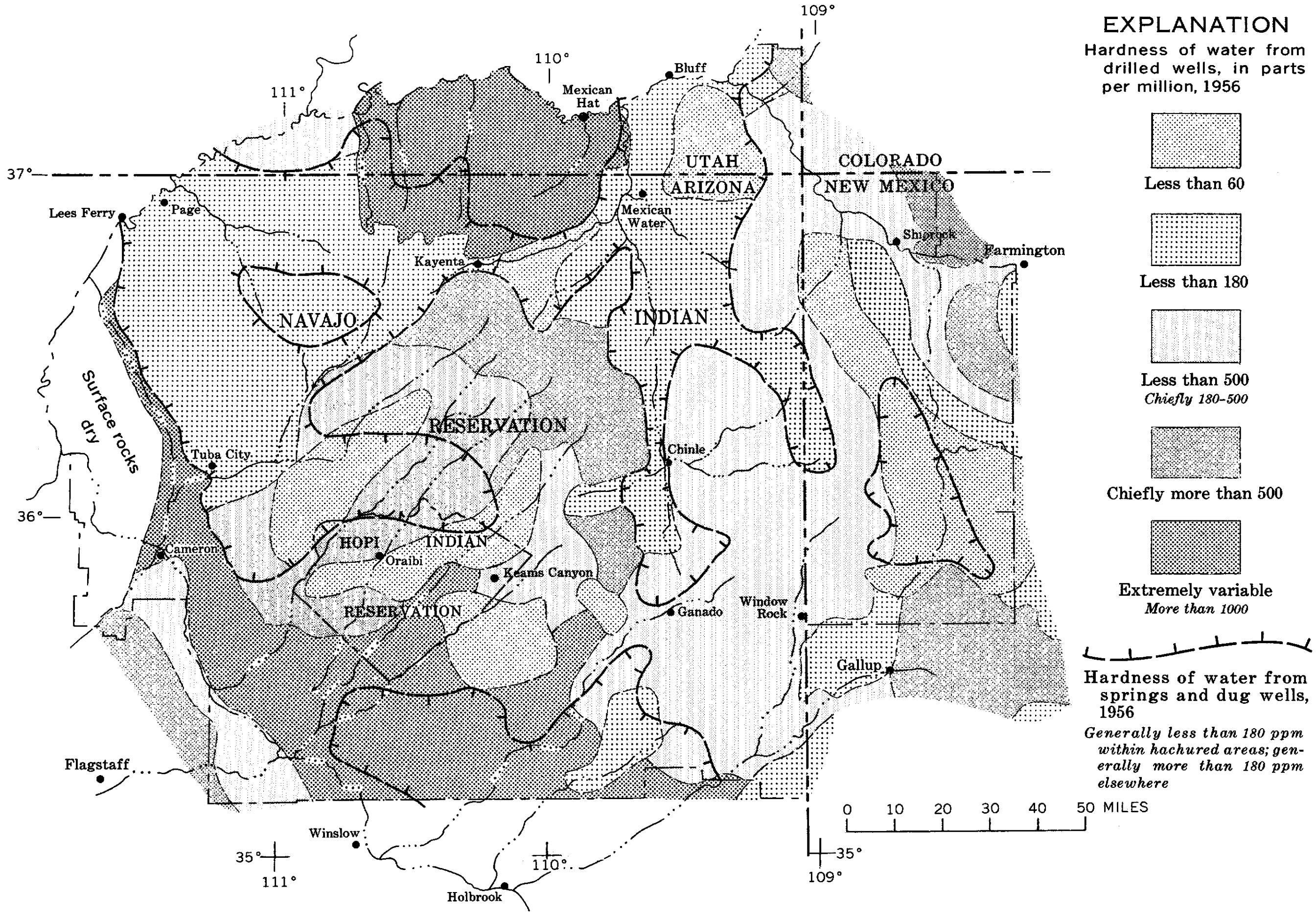

Figure 20.—Distribution of hardness as calcium carbonate of ground water.

Water in aquifers of the Black Mesa and San Juan basins is high in fluoride; elsewhere the fluoride content usually is less than 1.5 ppm. Water from the Dakota Sandstone and the Upper Jurassic rocks used by some of the Hopi villages and that in the adjoining region of Black Mesa basin has a fluoride content of as much as 6 ppm (fig. 19). Other high concentrations of fluoride in Black Mesa basin occur locally in water in the Wepo and Chinle Formations and in the alluvium. Nearly all the water in the aquifers in Cretaceous rocks in the San Juan basin contains objectionable amounts of fluoride. Water in the Menefee Formation in the southern part of the basin commonly has 5–10 ppm of fluoride, the highest average concentration in the Navajo country.

HARDNESS OF WATER

Hardness, the soap-consuming property of water, is caused chiefly by calcium and magnesium and, in some water, by small quantities of strontium and barium. The hardness is reported in parts per million as calcium carbonate. Grains per gallon also is used in reporting hardness. One grain per gallon is equal to 17.12 ppm. The following classification of the hardness of water is used by the Geological Survey:

Descriptive term	*Parts per million*
Soft	0–60
Moderately hard	61–120
Hard	121–180
Very hard	180+

According to this classification, little ground water in the Navajo country is soft, and most is hard or very hard. Hardness ranges from 2 to 15,500 ppm. The distribution of the hardness is shown on figure 20, and it seems to be controlled more by local hydrogeologic conditions than by regional conditions that influence the other characteristics of chemical quality. Generally, hardness is less in water discharging from springs and from shallow dug wells than it is in that from deep wells (fig. 20).

PRINCIPAL CONTROLS OF THE QUALITY OF WATER

The lithologic characteristics of the aquifer and those of adjacent rocks exert a major control on the dissolved-solids content and chemical constituents of ground water. The soluble material is less in the well-sorted "clean" sandstone of eolian origin, represented by the Navajo, Wingate, and De Chelly Sandstones, than it is in other aquifers. The soluble minerals in shaly units above or below an aquifer may affect the chemical quality of its water. An excellent example is the solution of salt beds in the Supai Formation, probably the chief source of the exceptionally high dissolved-solids content of water in the overlying Coconino Sandstone in much of Black Mesa basin (Akers, 1964, p. 80–81).

Another principal control of chemical quality of ground water is the distance the water has traveled from the recharge area. Nearly all chemical analyses of ground water from recharge areas indicate less than 1,000 ppm dissolved solids, and many indicate less than 300 ppm. Dissolved solids increase noticeably downdip toward the centers of hydrologic basins (fig. 17). Dissolved solids downdip also may increase in part because of restricted circulation in the centers of the basins—regional ground-water movement tends to be around the periphery of the basins (pl. 5).

Interaquifer leakage, active in nearly all parts of the reservations, seems to influence the chemical quality of ground water. Flushing, with accompanying interformational movement in the recharge areas, keeps the chemical quality rather uniform and the dissolved-solids content low. High artesian pressures in the hydrologic basins aid interaquifer movement of water, and the chemical quality tends to be fairly consistent, even though thick shaly rocks, such as the Mancos Shale, retard mixing of water.

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[As a result of the present study of the Navajo and Hopi Indian Reservations, 34 papers have been published; these are marked with an asterisk]

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