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PRELIMINARY REPORT OF INVESTIGATIONS OF SPRINGS IN THE MOGOLLON RIM REGION, ARIZONA

By

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With sections on:

Base flow of streams

By

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and

Quality of water

By

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ABSTRACT

The Geological Survey has made a reconnaissance of springs in the Mogollon Rim region in central Arizona. This region is the source of much of the water in the Gila, Salt, and Verde Rivers. The region has not previously been systematically studied with respect to the occurrence of ground water.

The Mogollon Rim is an escarpment that extends about 200 miles in a northwest direction from near Clifton and Morenci in southeastern Arizona and gradually disappears north of Prescott. Lumbering, ranching, and in local areas copper mining are the principal industries. Main lines of drainage extend north on the plateau, north of the rim, and south or southwest below the rim. For convenience in discussion and because of structural differences, the region has been separated into western, central, and eastern divisions.

Pre-Cambrian to Recent rocks crop out. Pre-Cambrian formations and those of Paleozoic age constitute the thickest sections. Recent basalt flows cap the plateau portion, except in the central part of the region. Large areas in valleys below the rim are occupied by lake-bed deposits. The valleys are alined northwest, suggesting the possibility that a structural trough extends almost the full length of the rim southwest of the scarp. In some areas, erosion has caused recession of the escarpment for distances of a few miles to 10 or 15 miles from the major rim faults.

The origin of late deposits of sodium sulfate in the Verde basin has not been adequately explained. As the salts are concentrated near mineralized districts on the southwest side of the basin, a possible genetic relationship between the two should be considered.

Pre-Cambrian granite and basalt of probable Tertiary and Quaternary age are the igneous rocks most widely exposed in the region. Diabase dikes and sills are prominent in some areas; they were intruded probably during Late Cambrian time. A thickness of 2,000 feet of volcanic rocks of probable Cretaceous and Tertiary age is exposed in one area along the rim, but these rocks as yet have not been studied in detail. A hypothetical relationship is advanced to explain the coincidence in estimated volumes of rock erupted in the San Franciscan volcanic field and the volumes displaced by subsidence of the Verde basin.

Fold structures are relatively uncommon in the region and are of small extent except the Holbrook dome northwest of Snowflake. High-angle faults, for the most part normal, are the most prominent structures identified. Faults parallel to the rim have been mapped in several areas. The inferred relations are shown on three diagrammatic sections. These faults are thought to account for the presence of two rims in the eastern division, and perhaps as many as three near Payson.

Major orogeny in the region is believed to have occurred four times, as follows: (1) In the pre-Cambrian; (2) in Miocene(?) time southwest of the Mogollon escarpment; (3) in Pliocene(?) time at least in the Flagstaff area, and; (4) at or near the beginning of Quaternary time. The Laramide structures, prominent elsewhere on the plateau, are reflected only weakly in the rim region, so far as is known.

Studies of perennial base flow of major streams draining southward from the rim indicate a sustained yield of about 175 cfs (cubic feet per second) measured at existing gaging stations. Runoff records and partial seepage runs show a loss of water between the upper reaches of the streams and the storage reservoirs. There is a general tendency for the water to become progressively more highly mineralized with increasing distance from headwater springs.

Natural lakes, ponds, swamps, and cienagas are common in the eastern and western divisions of the rim. They lose considerable water, and some are fully desiccated each summer. They are of little use in their present condition, but might be developed as natural water catches from which recharge could be artificially induced.

Data on both precipitation in the region and runoff from the region are incomplete. If 12 inches is conservatively assumed as mean annual precipitation, then about $6\frac{1}{2}$ million acre-feet of water falls annually on the plateau portion of the rim region. Available data indicate that only about 150,000 acre-feet of spring discharge occurs annually. Thus, of the total that falls as rain and snow, about 98 percent leaves the rim region by evaporation, flood runoff (including the increased ground-water discharge that occurs during and after floods and which may be called seasonal ground-water discharge), and subsurface discharge outside the areas investigated.

Unconfined ground water occurs in rocks of almost every age in the region. Water is obtained from springs and from wells. Rocks of Quaternary age are the most prolific aquifers. Well information is highly incomplete. Water under artesian pressure occurs in rocks of many ages. The Mississippian Redwall limestone is the aquifer supplying the group of springs with largest discharge - 18,500 gallons per minute at Fossil Creek. In the Silver Creek Valley near Shumway, water under artesian pressure is obtained for irrigation from wells penetrating the Coconino sandstone.

Much recharge takes place by direct infiltration of rain and melting snow. The basalt that caps a large part of the eastern and western divisions, and the jointed and channelled Permian Kaibab limestone in the central division both permit rapid downward percolation of water. The permeable nature of the caprocks, and the relatively high precipitation along the rim, provide conditions favorable for inducing additional recharge. Geologic conditions related to recharge in the broken country below the rim were not investigated. The effect upon recharge and runoff of "prescribed burning" of forest litter and undesired growth on the Fort Apache Indian Reservation warrants investigation.

Contact springs are most numerous in basalt-covered areas. Discharges in these areas range from less than a gallon per minute to about 100 gallons per minute, and in a very few cases to as much as 3,000 gallons per minute.

Fluctuations in yield of some of the larger springs have been determined. Extremes are represented by Fossil Creek, where fluctuation was negligible, and by Cold Spring, where the discharge in May 1952 was about 5 times the discharge in December of that year.

Faulting is important in controlling the occurrence of springs. Springs occur at places where the discharge is localized in part by graben structures of varying scales of magnitude and in part by contact of permeable over imper-permeable rocks. In the Payson region, faulting exposes the highly cavernous

Redwall limestone at two or more levels progressively lower with increasing distance from the rim. Spring discharge from higher levels goes underground at outcrops of the Redwall and is believed to reappear downstream as flow from other springs.

Those areas in which artesian-conduit springs occur, such as Fossil Creek and Sycamore Canyon, are considered most promising for development. At Clifton Hot Springs in the Gila River drainage, and at the Salt Banks on Salt River, it might be possible to eliminate the salty water from the river flow. Detailed geologic and hydrologic investigations would be necessary at each place.

The pre-Cambrian quartzites along the Salt River contain springs which yield water containing as much as 37,000 parts per million of dissolved solids, mainly sodium and chloride. Springs from rocks of Paleozoic age in the region yield waters which generally contain less than 500 ppm of dissolved solids, mostly calcium, magnesium, and bicarbonate. Springs in basalt near the rim yield the best waters of the region, some of which contain less than 100 ppm of dissolved solids.

Calcium and bicarbonate are contained in rather large amounts in some of the spring waters of the region. These concentrations result from the action of water charged with carbon dioxide upon carbonates in the rocks. Some of the springs deposit travertine. Most of the water in the region is of good quality for irrigation or domestic uses. Waters that deposit travertine or those which are saline, however, present utilization problems. The salt-spring inflow to the Salt River increases salt-balance problems in irrigated areas farther down stream.

Further investigation of quality of water is needed to aid in identifying and studying aquifers, tracing water movement underground, and determining the importance of salt-spring contamination of surface water.

The origin of the warm, salty waters of the region is uncertain. Field relations suggest that no bedded salt occurs in areas that might reasonably supply water to the springs. A tentative hypothesis is developed, relating the high mineralization to leaching of basement rocks at Salt Banks and on the White River, and to leaching of volcanic rocks at Clifton Hot Springs and perhaps Verde Hot Springs.

The relations between altitude and air temperatures, and altitude and water temperatures, have been shown graphically. Temperatures of springs measured are in general a few degrees Fahrenheit higher than mean air temperatures at equivalent altitudes.

INTRODUCTION

Purpose and Scope of Investigation

Inhabitants of the broad valleys of south-central Arizona have used surface waters of the Gila, Salt, and Verde Rivers since prehistoric times. In the past 50 years the waters of these streams have been increasingly controlled and utilized as a mainstay of agriculture. Until the present investigation no over-all study had been made of the geology and hydrologic conditions in the source areas in which much of the water so utilized originates. These source areas are located in the Mogollon Rim region about 100 miles north of the areas of heaviest utilization.

The present investigation, concerned principally with ground water, was undertaken to determine: (1) The location of springs contributing to flow in the Gila, Salt, and Verde Rivers; (2) fluctuations in discharge of the principal springs; (3) water-bearing properties of rock formations in spring-discharge areas; (4) relation of chemical quality of spring waters to the formations from which they emerge; (5) relation of geologic structures to localization of springs; (6) sources of highly mineralized water detrimental to use for irrigation; and (7) location of areas in which spring flow might be increased by development. As the work progressed, two additional fields for study became apparent: (1) Investigation to determine the possibility of widespread artificial recharge; and (2) investigation to determine the effect on spring flow of extensive "prescribed burning" of timberland on Indian lands. Up to 1952, controlled burning to eliminate forest litter, down timber, underbrush, and stunted trees had been done on about 60,000 acres on the Fort Apache Indian Reservation.

As originally planned in 1950, the investigation was intended to consist of an over-all reconnaissance, followed by detailed study of selected areas. To December 1952, about two-thirds of the reconnaissance had been completed. Because the region is large and the geology is complex some of the descriptive statements contained herein will require revision as further work is done.

Location and Extent of Area

The principal springs contributing to the Gila, Salt, and Verde Rivers issue along the great south-facing escarpment known as the Mogollon Rim (fig. 1). The rim is expressed topographically as a scarp, ranging in height from about 100 feet at its northwest end to a maximum of nearly 2,000 feet in the central division, between Cottonwood and Showlow (fig. 1). At the southeast end, the Mogollon Rim is lost in a complex of volcanic mountains. The Natanes Rim, possibly structurally equivalent, is 200-500 feet high. Structurally, the region is one of complex geology south-southwest of the margin of the Colorado Plateau. Geographically, the region is a zone about 200 miles long, trending generally northwest from near the Arizona-New Mexico State line to an indeterminate point of disappearance north of Prescott. The width of the zone ranges from about 50 miles to more than 75 miles, and the zone includes 10,000 to 15,000 square miles. In this report the term "Mogollon Rim" refers to the scarp alone. The "Mogollon Rim region" and the "rim region" are used interchangeably to refer to a zone extending both north and south of the scarp in which geology and occurrence of ground water were studied during this investigation.

For convenience of discussion the region has been separated into three divisions on the basis of physiographic and geologic differences. Lines separating the three divisions are shown in figure 1. The position of the lines is arbitrary, as the division boundaries are gradational.

Previous Investigations

Little geologic work has been done to date in the Mogollon Rim region, for one reason because ore deposits occur at only a few localities. Many reports include general reference to the region and the Mogollon escarpment is widely known as the southwestern boundary of the Colorado Plateau. General studies have been made by Darton (1910, 1925)1/, Darton and others (1924), and Wilson (1939). Harrell and Eckel (1939) discussed part of the region with reference to ground water. Details of the geology of the Clifton-Morenci copper deposits were described by Lindgren and Boutwell (1905). L. E. Reber, Jr. (1938), discussed geology and ore deposits of the Jerome district. H. H. Robinson (1913) analyzed the San Franciscan volcanic field, near Flagstaff. Structures in Oak Creek were studied by Mears (1950). Detailed studies in an area immediately west of the Verde basin (fig. 3) have been made in recent years by the Geological Survey, but the results of these studies have been reported only in a few abstracts to date (1953).

The stratigraphy of the Rim country is better known than any other phase of its geology. Among those contributing recently to stratigraphic knowledge are: Gutschick (1942, 1952), Huddle and Dobrovolny (1945, 1950), Hughes (1949), Jackson (1951), McKee (1934, 1938, 1951), McNair, (1951), Reiche (1938), and Stoyanow (1936, 1942).

Other references are cited in the bibliography.

Personnel and Acknowledgments

The present investigation was initiated by S. F. Turner, former district engineer, Ground Water Branch, U. S. Geological Survey. The field work has been done under the general direction of A. N. Sayre, Chief, Ground Water Branch, and under the direct supervision, first, of Mr. S. F. Turner, and later of L. C. Halpenny, present district engineer (GW) in Arizona. Mrs. N. D. White, engineer, analyzed the data relating to stream flow and prepared the section on base flow of streams on pages 25-26.

Chemical-quality studies were under the direct supervision of J. D. Hem, former district chemist for Arizona and New Mexico, under the general direction of S. K. Love, Chief, Quality of Water Branch. Mr. Hem prepared the section on quality of water on pages 39-47.

Local officials of the U. S. Forest Service, U. S. Office of Indian Affairs, and U. S. Weather Bureau have provided maps and information, and on occasions have accompanied the author in the field. Their help is acknowledged with much appreciation. Ranchers and farmers have courteously granted access to their lands and permitted measurements to be made of spring discharges.

Prof. J. W. Anthony, University of Arizona, spent many hours making spectrographic analyses of samples of travertine obtained along the rim.

1/ See references at end of report.

GEOGRAPHY

Land Forms and Physiographic History

The cliffs of the Mogollon Rim (fig. 2), the rock-walled canyons, and the outlying buttes and mesas associated with rim topography are the dominant features of the landscape. Owing to the brilliant reds that characterize many beds at the base of the rim, and the contrast with overlying buff sandstones, light-yellow to white sandy limestones, and cap rocks of black basalt, the scenery has become famous as a tourist attraction. Forested slopes at higher altitudes and tumbling mountain streams add to the scenic beauty.

The high plateau country north of the rim consists of flatlands and hills separated by steep-walled canyons. Below the base of the rim are broad valleys, separated by irregular hills and mountains in varying stages of dissection. These valleys are in large measure occupied by lake-bed sediments which erode readily to form a butte-and-canyon topography similar to the margins of the Mogollon Rim, but subdued in scale.

Drainage

Streams flow northward and southward from a drainage divide nearest the crest of the Mogollon escarpment. Most streams trending north follow the dip-slope surface of the plateau. Locally, joint trends are reflected in rectangular patterns of the smaller streams. The principal stream draining the plateau is the Little Colorado River, which flows northwest to join the Colorado River in northern Arizona (pl. 1).

Southwest of the drainage divide the Gila River, which flows nearly due west through central Arizona, is the trunk stream. The Salt River, principal tributary of the Gila, drains the central division of the Mogollon Rim region. The Salt River flows generally southwest from its headwaters to its junction with the Gila River, near Phoenix, and supplies most of the impounded water used for irrigation in the Phoenix area. The White and Black Rivers are the headwater streams, meeting to form the Salt River. South-trending Carrizo Creek, Tonto Creek, and the Verde River are major tributaries of the Salt River.

Climate

The country along and immediately north of the topographic rim has a cold-temperate climate, with moisture sufficient to support what is reportedly the largest stand of yellow pine in the United States. Farther north, where the altitude is less, temperatures are more moderate and precipitation drops markedly. Weather Bureau records summarized in the following table indicate that mean annual temperature and precipitation vary with location and altitude, although not consistently.

Table 1.--Climatological Data (U. S. Weather Bureau, 1951)[1/]

Weather station	Altitude (feet)	Length of record (years)		Mean annual precip. (in.)	Mean annual temp. °F.
		Temp.	Precip.		
Holbrook, 45 mi. north of rim.	5,069	59	61	7.10	55.4
Winslow, 45 mi. north of rim.	4,880	45	44	6.96	55.5
Flagstaff, 15 mi. north of rim.	6,993	60	60	25.79	45.0
Williams, 15 mi. north of rim.	6,750	51	51	23.30	49.9
Alpine, on the rim.	8,000	28	35	19.55	-
McNary, on the rim.	7,305	18	17	29.60	-
Lakeside Ranger Station, on the rim.	7,000	15	23	22.31	-
Pinedale, 6 mi. north of rim.	6,500	34	38	20.45	-
*San Carlos Reservation headquarters	2,532	21	22	17.95	64.8
Whiteriver, 15 mi. south of rim.	5,200	11	11	19.83	55.2
Cibeque, 15 mi. south of rim.	5,300	22	23	24.23	53.9
Payson Ranger Station, 12 mi. south of rim.	4,900	39	49	27.74	-
Montezuma Castle, 20 mi. south of rim.	3,180	13	13	13.81	60.4

* Although San Carlos Reservoir is about 65 miles south of the Mogollon Rim, it is less than 20 miles south of the Natanes Rim, described in section on structure in this report.

1/ Since preparation of this report, the U. S. Weather Bureau has published a detailed study of precipitation in the Mogollon Rim region, see: Hiatt, W. E., The analysis of precipitation data, in Subsurface facilities of water management and patterns of supply - type area studies: The physical and economic foundations of natural resources, Vol. IV, Interior and Insular Affairs Comm., U. S. House of Rep., 1953, p. 186-206.

Temperatures and precipitation south of the rim vary with local conditions of topography. The principal climatological factor related to water supply is movement of moisture-laden air masses from the south and southwest toward the north and northeast. The barrier afforded by the rim causes sufficient elevation of the air masses in many instances to result in cooling, condensation, and precipitation. Thus, the country along the crest of the rim and immediately southwest receives relatively high amounts of moisture annually, both as rain and as snow. The Mogollon Rim serves as a water catch and provides an area favorable for recharge to subsurface reservoirs as well as a source area for runoff. The possibility of inducing additional ground-water recharge will be discussed later in this report.

Development and Industry

Agriculture, lumbering, and recreation are the principal industries of the Mogollon Rim region. Ranching is important both on the plateau and in the lower lying lands. Dry farming is successful in local areas on the plateau, a few miles north of the topographic high. Irrigation with surface water is practiced in the bottom lands of streams above and below the rim. The valleys of the Verde River, Tonto Creek, and Oak Creek, south of the rim, and of the Little Colorado River and Silver Creek north of the rim, contain most of the irrigated lands within the rim region. Limited irrigation with ground water pumped from wells is practiced in the Snowflake-Shumway district and in a few other small areas.

Lumbering is an important industry in the rim region, the cutting being done largely in a zone extending a mile or two south of the topographic rim and 10 to 25 miles north. Three large sawmills and many smaller mills were operated in the region in 1951-52.

The Mogollon Rim region is one of Arizona's outstanding recreation areas, providing hunting, fishing, hiking, boating, and swimming. The colorful cliffs and ruggedly carved topography combine with the green of the high-lying timberlands to make the region famous for its beauty.

Parts of the rim region are easily accessible. Commercial airlines make regularly scheduled stops at Prescott, Globe, Clifton, Flagstaff, and Winslow. Charter plane service, or access by private plane, is available at a number of places. The Santa Fe Railway crosses the northern part of the region (fig. 1), passing through Williams, Flagstaff, Winslow, and Holbrook. Spur lines extend from the main line of the railroad to points closer to the topographic rim. Spur lines enter Prescott, Clifton, San Carlos, and Globe. Two main highways cross the rim--U. S. Highway 60 extending north from Globe through Showlow and U. S. Highway 89 (Alternate) extending from Prescott through Cottonwood and Sedona to Flagstaff. U. S. Highway 89 (fig. 1) roughly marks the western boundary of the rim region. State highways, county and Federal roads, and ranch roads provide access to many parts of the region. Nevertheless, parts of the rim country are so rugged, and in some areas so undeveloped, that many localities can be reached only by horse or on foot, and then not without difficulty.

Minerals

Three of Arizona's best-known mining districts - Jerome, Globe-Miami, and Clifton-Morenci - lie within the general area of the present investigation. Many lesser properties producing various metallic ores lie in the mountain belt peripheral to the Mogollon Rim. It is emphasized, however, that along the scarp no commercial deposits of metallic ores have yet been reported.

One of the largest deposits of sodium sulfate minerals in the world lies about a mile southwest of Camp Verde, in the Verde River basin. This deposit has been worked intermittently for many years and in the early winter of 1952-53 was being reopened after a period of inactivity.

In local areas along the rim, flagstone quarries are being successfully worked. The Coconino sandstone is the principal rock quarried, and slabby sandstone beds in the Supai formation supply the remainder of commercial flagstone obtained. Cinder cones along highways and rail lines on the plateau provide material used for road metal, ballast for the railroads, and aggregate for concrete-cinder building blocks. Coal has been mined from Cretaceous strata on the Fort Apache Reservation, but the operations have been intermittent and not extensive, as the grade of the coal is poor and the seams generally are thin.

Water

Municipal and domestic water supplies in the region are obtained both from surface sources and from springs and wells. Surface reservoirs supply most of the water used in Flagstaff and Williams. The towns of Pinetop, McNary, and Lakeside obtain most of their water from springs. Cottonwood, Winslow, Snowflake, and Showlow obtain their public supplies from wells. The choice is based on availability and convenience.

Use of surface and subsurface supplies of water for irrigation has already been mentioned.

Industrial water is of importance for mining, milling, and smelting of ores and for milling of lumber. Mines at Jerome obtained their principal supplies from springs on Mingus Mountain. The ores were milled and smelted in the Verde River valley at Clarkdale, where artesian wells supplied the water necessary. The smelter and mill were closed in 1950. At Clifton-Morenci, the water for all operations is obtained from surface streams. Lumber mills at Flagstaff use principally surface water. The main source of water for the mills at McNary is the flow from numerous springs, retained in surface reservoirs. The source of water for operation of the sawmill at Overgaard is not known.

GEOLOGY

Stratigraphy

Rocks of Pre-Mesozoic Age

Wilson (1939, p. 1118) reports an aggregate thickness of older pre-Cambrian sedimentary and volcanic rocks of 12,000 to 15,000 feet in the Payson region. Overlying these, in parts of the area he studied, are more than 1,000 feet of younger pre-Cambrian sedimentary rocks - the Apache group. Pre-Cambrian rocks are prominent in the canyon of the Salt River and in the San Carlos Indian Reservation, but in many places in the Rim region they are deeply buried by younger rocks.

The essentials of Paleozoic stratigraphy in the Mogollon Rim region are shown on the correlation chart, plate 2. The principal water-bearing characteristics of the rocks of Paleozoic age in the west, central, and eastern divisions of the Rim are briefly described on the chart and mentioned in the text in relation to occurrence of springs. As the present investigation has contributed only a few well logs and two reconnaissance sections to information already published, the reader is referred to the sources, listed in the bibliography, from which stratigraphic data were obtained.

Strata of Paleozoic age tend to be persistent in thickness throughout the region studied. Several lines of reasoning indicate that most of these strata originally extended far south of their present limits of exposure. McKee (1951, p. 486-487) summarized the evidence as follows: (1) Excepting the Cambrian, strata of Paleozoic age exposed along the rim give no evidence of being marginal facies; (2) Devonian and Mississippian strata thicken toward the southwest; and (3) Permian beds aggregate about 2,000 feet in thickness where exposed along the rim. Evidence regarding former southwestward extensions of strata of post-Paleozoic age includes the following: (1) The presence of 300 feet of the Lower Triassic Moenkopi formation at points along the rim indicates a former extension of these deposits; and (2) along the southern margin of the Colorado Plateau, Pliocene(?) gravels contain pebbles and cobbles composed of rocks ranging from pre-Cambrian to Permian. According to McKee, the only likely direction from which these gravels could have come is from the south. It is concluded, therefore, that the sedimentary rocks at one time extended far south and southwest of their present limits of outcrop; that the region south-southwest of the present topographic rim was formerly much higher than the plateau region; and that, during long-continued erosion of the uplifted area, detritus moved generally north-northeast and was in part deposited as gravels over a wide area along the southern margin of the Colorado Plateau.

Upper Cretaceous Sedimentary Rocks

Darton (1925, p. 150) reported the occurrence of Cretaceous clastic deposits in Apache and Navajo Counties, especially in areas adjacent to the rim. Fossils from these beds were identified by J. B. Reeside, Jr., as being of Late Cretaceous (Carlile) age.

Fossils were collected from two localities during the present study. Dr. Reeside again made the determinations and concluded that the assemblage would "indicate an age about equivalent to that of the Greenhorn limestone of the High Plains," thus perhaps slightly refining the age determination reported in 1925. According to Wilmarth (1938, p. 870), the Greenhorn limestone underlies the Carlile shale and overlies the Graneros shale in the type locality near Pueblo, Colo. These three formations constitute the lower part of the Colorado group of present usage.

Fossils identified from beds exposed in a road cut 3.3 miles south of Showlow along Arizona Highway 173, included the following:

Ostrea soleniscus Meek
Cardium pauperculum Meek
"Mactra" utahensis Meek
Cassiope sp.
Cliona sp.
Inoceramus labiatus Schlotheim var. aviculoides Meek and Hayden
"Cyrena" sp.
"Tellina" sp.
Gyrodes depressa Meek
Volutoderma gracilis (Stanton)
Lamna sp.

A collection obtained near Pinedale, Navajo Country, in sec. 16, T. 10 N., R. 20 E., contained the following forms:

Serpula intrica White
Pteria gastrodes Meek
Ostrea soleniscus Meek
Lucina juvenis Stanton
Cardium pauperculum Meek
"Mactra" arenaria Meek
Pugnellus fusiformis Meek
"Gervillia" propleura Meek
Exogyra columbella Meek
Veniella, n. sp. a globose form
Legumen n. sp.
Corbula kanabensis Stanton

Well-log data and examination of a partial suite of drill cuttings from a well drilled at Pinetop, sec. 4, T. 8 N., R. 23 E., show the presence of 600± feet of bluish-gray shaly rocks (column 12, p. 2) whose stratigraphic position is not known. Overlying these strata are 250-300 feet of tan and reddish sandstones and clays that are considered equivalent to Upper Cretaceous beds exposed nearby, along the rim. The shaly beds are not known to crop out in the area and may represent a tongue of Cretaceous rocks covered elsewhere by a mantle of volcanic rocks.

Tertiary and Quaternary Sedimentary Rocks

Lake beds.--The index map (fig. 3) shows the location and approximate outlines of four lake-bed areas, observed during the present investigation. It is estimated that lake-bed deposits occupy more than 1,000 square miles in the four areas shown. Jenkins (1923, p. 70-71) estimated that, in the Verde basin, lake beds of the Verde formation cover more than 300 square miles and are more than 2,000 feet thick.

San Carlos basin.--An even larger area in the San Carlos Indian Reservation is underlain by Tertiary and Quaternary rocks, mostly of lake-bed origin. Knechtel (1938, p. 197) concluded that these lake beds are equivalent to part of the Gila conglomerate. The aggregate thickness of the lake beds is estimated to be between 700 and 800 feet.

Although time did not permit a thorough study of the lake beds in the San Carlos basin and the full section was not measured, partial sections are shown in figure 4. Section A shows the general composition of what is apparently a near-shore facies. Section B is representative of part of the total sequence, in which tuffaceous material is abundant. Section C is characteristic of a calcareous facies that occurs within a few miles of the agency at San Carlos. In other exposures the limy facies is far thicker, estimated to be 500 feet or more. Toward the top of the thicker exposures, one and sometimes two basalt flows are intercalated and very light-colored tuffaceous beds are common, and basalt commonly caps the entire sequence.

About 20 miles northeast of San Carlos, in the canyon of Blue River (pl. 1), beds believed equivalent to part of the lake-bed series are about 200 feet thick and consist almost exclusively of evaporite limestones. Other evaporite salts may be present in this sequence.

A Pliocene or Pleistocene age for much of the lake-bed section is suggested by the small collections of fossils. Basal sandstones shown in section B (fig. 4) contained bones identified by Jean Hough as parts of the radius and ulna of a large camel, perhaps *Camelops*, a Pleistocene form. Mrs. Hough points out, however, that large camels existed in Pliocene time as well, and identification of the bone fragments was tentative. The beds could, therefore, be of either Pliocene or Pleistocene age.

According to T. C. Yen, fossil snails found at the site of section C (fig. 4) are identifiable as *Physa* sp., and *Physa* cf. P. *anatina* Lea. He considers the forms suggestive of early Pleistocene age.

Other basins.--So far as is known, the lake beds of the Tonto and Payson basins have not been described. As these beds were examined only superficially, it can be noted here only that the beds in the Tonto basin differ markedly from those in the other basins. Their red and green color, and the presence of gypsum in beds and as crystals or anhedral masses disseminated profusely in silt and clay, are the obvious points of difference. Many erosional remnants in the basin, each 50 to 150 feet in height, appear to consist of more than 50 percent gypsum. In appearance and high gypsum content these strata bear a striking resemblance to strata in the Lower Triassic Moenkopi formation near Snowflake. No genetic relationship has been established, however.

In the Payson basin the lake beds include a fairly high proportion of sand and pebbles. Some of the beds are buff to light rusty red in color, but the prevailing tone is light creamy yellow to white, more nearly comparable in appearance to the beds in the Verde and San Carlos basins than to those in the neighboring Tonto basin. A few snails were found in limestones in the lake-bed sequence of the Payson basin, but the forms have not yet been identified.

Origin of sodium sulfate in Verde basin. --Mahard (1949, p. 107) believes that the sodium sulfate deposits near Camp Verde were formed at a time when "Verde Lake or an isolated playa upon the extensive lacustrine plain evaporated until only a rich brine remained."

Bedded sodium sulfate salts - thenardite, mirabilite, and glauberite nearly pure and about 50 feet thick, overlain by saliferous silts and clays another 25 feet thick, are displayed in the quarry near Camp Verde (fig. 5). The quarry operator, John Savage, informed the writer in 1952 that records in his possession show that shafts penetrating 100 feet below ground level at the foot of the quarry encountered mainly sulfate salts. Twenhofel (1939, p. 450-452) cites evidence to show that, as lakes in closed basins dessicate progressively, the more soluble salts (as those of sodium sulfate) tend to concentrate toward the lowest part of the lake basin. In such a fashion, Searles Lake, Calif., has accumulated salts saturated with brine, about 100 feet thick. These salts include about 20 percent sodium sulfate. Clarke (1924, p. 234) describes how sodium and sulfate are concentrated in the Caspian Sea in deep waters at the end of the sea farthest from influx of fresh waters. He states further that mirabilite precipitates from nearly saturated waters as the waters cool. In some places, such as Great Salt Lake, even seasonal cooling causes precipitation of the salts. In warm, dry air, mirabilite loses water and inverts to thenardite. Deposition in a deep-water basin, with continuing influx of salty waters, or in the relict part of a desiccating lake seems to be more in accord with the observed thickness of the deposits than deposition on a playa.

The localization of sodium sulfate salts in the southwestern part of the Verde basin suggests the possibility of operation of local controls during the time of formation. Known areas of igneous and metamorphic rocks and of copper mineralization exist on the west side of the valley, but are absent elsewhere. A genetic relationship may in time be established between geologic conditions resulting from leaching of the Jerome district ores and smaller ore deposits in the Black Hills. The high sodium concentration may be related to decomposition of igneous rocks. The possibility should be considered that former springs discharging water with high concentrations of sodium sulfate contributed to the deposits.

Alinement of lake-bed areas. --A northwest alinement of the four lake-bed areas is apparent on the map (fig. 3). The Verde basin is interpreted in the present report as a graben. The Payson basin is almost certainly a graben. On Table Mountain, near the center of the basin, horizontal strata of the Cambrian Tapeats sandstone occur about 1,000 feet topographically lower than equivalent beds in the Mazatzal Mountains (Wilson, 1939, pl. 10) to the southwest, and on the hills to the northeast of the valley near Payson (pl. 5, this paper). It is possible that the four lake-bed areas mark a generally depressed region southwest of, and parallel to, the Mogollon Rim.

Travertine.--Travertine deposits were observed at ten localities (fig. 3) during the present investigation. Active deposition is continuing at four places: Tonto Natural Bridge; Fossil Creek; Salt Banks on Salt River (fig. 6); and Columbine Terrace, on the White River. The other six terraces are inactive. Several features of the travertine deposits are noteworthy.

Size.--The travertine deposits observed range widely in size. The smallest is at Verde Hot Springs where it clings to volcanic rock above the present spring orifices. The deposit is about 20 feet long and from less than a foot to 5 feet in other dimensions. The deposits at Fossil Creek and on the White River are each about half as large as the famous Mammoth Hot Springs in Yellowstone Park, Wyo. The inactive terrace at Fossil Creek is nearly a mile long and more than half a mile wide (figs. 7 and 10) and extends several hundred feet up the slope of the mountain against which it lies. The terrace terminates in a sheer cliff about 100 feet high facing Fossil Creek. Deposition of travertine in the Fossil Creek spring area is taking place about the orifices of most of the springs, all of which now discharge within a zone extending from creek level to about 10 feet above creek level. The White River terrace (fig. 3) is more than 1½ miles long, about half a mile wide, and 50 feet thick at its river margin.

The Tonto Natural Bridge is a tourist attraction of some note. This travertine terrace spans Pine Creek about 180 feet above creek level. Travertine is being deposited from seeps on the lower 10 or 15 feet of the buttresses which support the span. Deposition istaking place also in a ditch which conducts flow from a spring that issues on the surface of the upstream end of the terrace. Travertine has nearly closed over the top of some parts of the ditch, as well as having formed a solid flume of travertine in the ditch.

Age.--Two periods of travertine deposition relative to late basaltic eruptions along the Mogollon Rim are indicated. The White River terrace rests on basalt that flowed down the canyon of the White River, after that canyon had already been well established. The Corduroy terrace (figs. 3 and 8), on the other hand, is overlain by an oxidized red soil layer less than a foot to about 3 feet thick, which is in turn overlain by basalt. Leaf imprints from the travertine of the Corduroy terrace were examined by R. W. Brown who reports *Salix* sp. (willow) and *Prunus* sp. (cherry or plum) and considers the composition of the flora and appearance of the leaves to indicate "the later half of the Cenozoic." If the basalt capping the Corduroy terrace and the basalt underlying the White River terrace are of comparable age, the deposition of travertine was contemporaneous with the later stages of basaltic activity along the rim. The other travertine terraces examined are not in contact with basalt.

Relation to drainage.--The terraces at Fossil Creek, Natural Bridge, Wailing Cow Ranch, and Corduroy (fig. 8) rest upon 2 to 10 feet of boulders, cobbles, and pebbles which overlie the bedrock and which are cemented by the oldest part of the travertine. These basal conglomerates are integral parts of the terraces and, where terraces are cut by gullies that reach the bedrock, are seen to extend continuously beneath the travertine. The conglomerates thus indicate that travertine deposition progressed upward, and suggest that artesian pressures at one time were adequate to force water to emerge at levels as much as 100 feet above the base of the terrace. At the localities named, the base of the conglomerate is now 5 to at least 150 feet above the stream channel. A parallel condition occurs on the East Verde River (fig. 9), where the travertine was deposited on the granitic walls of the canyon. If a basal conglomerate occurs, it is concealed. Artesian pressures of the magnitude suggested are not currently present in the region.

Occurrence of strontium.--Qualitative spectrographic analyses of 21 travertine samples were made by Prof. J. W. Anthony, University of Arizona. The samples represented, respectively, 3 zones at Tonto Natural Bridge, 6 at the Salt Banks, and a complete section of the Wailing Cow travertine terrace, sampled at 5-foot intervals. The basal 2-foot zone at Wailing Cow Ranch showed only a very faint strontium line. A sample from the far upstream end of the terrace at Tonto Natural Bridge showed calcium only - no other metallic elements. This part of the terrace had presumably been subjected to leaching and weathering for a long period. The remaining 19 samples from the three terraces showed definite strontium lines.

Interestingly enough, a single sample from the gypsum series of lake beds in the Tonto basin, and two random samples of limestone from the lake beds in the Payson basin, also showed the presence of strontium. Seven samples from zones shown in measured section B (fig. 4), in the tuffaceous facies of the lake beds in the San Carlos basin were run. Possible faint strontium lines appeared in two instances. The other five samples were barren of strontium. The common occurrence of strontium in evaporite deposits of the Mogollon Rim region suggests that the element is widespread in the older rocks from which the salts deposited by evaporation must have been leached. A search for strontium-bearing minerals to be used in age determinations might well prove rewarding.

Igneous Activity

Pre-Cambrian and Cambrian(?) intrusive rocks

Pre-Cambrian intrusive rocks in the region near Payson have been mapped and described by Wilson (1939, p. 1127-30), in the Clifton-Morenci area by Lindgren and Boutwell (1905, p. 2-3, 9), and in the Jerome area by Reber (1938, p. 46-50). The general pattern of outcrops of pre-Cambrian intrusive rocks is shown on the geologic map of the State of Arizona (Darton and others, 1924). In the present study, rocks of this category were of interest primarily in that locally they constitute a basement of low permeability and help to control the occurrence of springs. They were not otherwise studied.

Diabase, tentatively assigned to the Cambrian (A. G. Shride, oral communication, 1951), occurs in the Salt River Canyon as dikes, and more commonly as sills that range in thickness from less than an inch to at least 200 feet. In that locality, Shride found the diabase intruding the Troy quartzite (Cambrian) and all older formations, but at no place was diabase found intruding the Devonian Martin formation, which unconformably overlies the Troy quartzite. Shride considers the intrusions to have taken place probably, but not certainly, in Late Cambrian time, as no exposures were found that showed the Martin formation at contact with eroded diabase surfaces. Comparable diabase intrusions occur throughout the southeastern part of the Mogollon Rim region, where rocks of the Apache group and the Troy quartzite are exposed.

The possible relation of the intrusive rocks to the occurrence of springs discharging salty water is discussed on pages 70-74.

No other intrusive rocks were observed in the present investigation except for a few basaltic feeder dikes related to extrusive rocks of Tertiary and Quaternary age in the Oak Creek Canyon area.

Extrusive Rocks

Pre-Cambrian extrusive igneous rocks in the Payson region have been described by Wilson (1939, p. 1120). More than 2,000 feet of agglomerate and tuff are exposed in the valley of Fossil Creek. The State geologic map (Darton and others, 1924) shows a broad belt of volcanic material that trends south-southwest and separates the lake beds in the Verde valley from those in the Payson basin. Map relationships suggest that the volcanic rocks rest on Permian strata north of the Verde-Payson axis, and for the most part on pre-Cambrian metamorphic rocks south of the axis. So far as is known, no study of these volcanic rocks in central Arizona has been made. They are shown on the map as of probably Cretaceous and Tertiary age.

At Fossil Creek about 100 feet of basalt caps the canyon rims on both sides. On the east rim these basalt flows lie undisplaced across a fault zone that brings strata of the Pennsylvanian and Permian Supai formation in nearly vertical contact with 1,200 feet of the agglomerate mentioned above (fig. 10). As considerable erosion must have occurred after the faulting to smooth the fault blocks to a nearly plane surface in this locality prior to eruption of the basalt, it is believed that the basalt is of Quaternary age. Elsewhere in the Mogollon Rim region, basalt flows of Tertiary and Quaternary age are a prominent feature of the geology. On the San Carlos Indian Reservation basalt flows cap hundreds of square miles of plateau and mesa lands. Other flows are intercalated with lake-bed deposits in the San Carlos and Verde basins.

Northward, the margin of the Colorado Plateau is capped with volcanic materials. Although the volcanic complex has not been studied in detail, basaltic flows and cinders appear to constitute the largest part of the cap. A mountainous region consisting largely of volcanic rocks extends from the Clifton-Morenci district northward along the State line to and beyond Springerville.

In areas below the rim, basalt occurs less commonly, although in the Verde basin the Verde formation rests in many places on an erosional topography with steep-walled canyons cut at least 200 feet into basalt (fig. 11A). In the same area basalt flows are found locally interstratified with the Verde formation, and other flows cap strata of the Verde. At a few places in Oak Creek Canyon, strata of the Verde overlie basalt that rests on the Supai formation (fig. 11B). Northeast of the limits of the Verde formation basalt rests on rocks of the Supai formation.

The proximity of the San Franciscan volcanic field on the plateau, to the Verde basin, which is interpreted as a graben (pl. 3C), suggests a possible genetic relationship. It is estimated that the Verde formation covers about 300 square miles. Available data suggest that the pre-Tertiary(?) floor of the Verde graben was depressed as much as half a mile. If it is assumed that about two-thirds of the outcrop area of the Verde formation was deposited in the more deeply down-faulted parts of the graben, and the remaining one-third was deposited on less depressed areas, then about 100 cubic miles of rock must have been displaced at depth by subsidence of the graben floor.

Robinson (1913, p. 38, 49, 52-87) estimates that the volumes of rock extruded during the three stages of eruption in the San Franciscan volcanic field, aggregate about 103½ cubic miles, divided as follows: (1) First Period, basalt, 30 $mi.^3$; (2) Second Period, acidic to intermediate, 53½ $mi.^3$; (3) Third Period, basalt, 20 $mi.^3$.

The correlation, based as it is for the Verde graben on partial data, may be purely fortuitous. On the other hand, further investigation may demonstrate an isostatic relationship between the two. A paper by Escher (1952, p. 752-754) cites world-wide evidence suggesting genetic connections between large grabens and volcanic activity in adjacent regions. Basaltic lavas are generally characteristic of such associations.

Canyon basalts. --The occurrence of basalt flows within the canyons of three southward-draining streams is of interest. The canyon basalts have been observed only in Sycamore Creek, northwest of Cottonwood and in Forestdale Creek and the White River, near Showlow. In each, the flow is several miles long and 200 feet to about 1,000 feet below the canyon rims. The basalt in places has been completely cut through by the stream, and elsewhere rests on sedimentary rocks a few feet to 50 feet or more above the present stream channel.

Structure

Folding

The largest fold known in the Mogollon Rim region, the Holbrook structure, was described by Darton (1925, p. 202-203) who noted that it passed into a monocline at its western end. Approximately 4 miles north-northeast of Snowflake, near the eastern end of the Holbrook structure, Silver Creek has cut a gorge through the Coconino sandstone. Southward, an artesian basin occurs in the valley of Silver Creek. The Coconino sandstone is the aquifer. Incomplete investigation suggested that the Silver Creek valley, upstream from Snowflake, occupies a structural trough. This trough is diagrammatically illustrated on the geologic section (pl. 3 A).

A phenomenon common in the Oak Creek Canyon area is reverse drag of strata adjacent to faults of the Oak Creek fault system (pl. 4). Mears (1950a, 1950b) discusses the occurrence and presents hypotheses to explain its origin. He concludes that, for the Oak Creek Canyon examples, the most satisfactory explanation involves faulting with normal drag and a subsequent reversal of direction of movement along the faults and preservation of drag direction because of lubrication resulting from gouge in the fault zones.

Three areas of folding were observed in the Verde basin. About a mile south of the mouth of Sycamore Canyon, a contact trending N. 70° E. brings basalt and overlying beds of the Verde formation against folded strata of the Supai. The Verde formation warps upward near the contact. The present investigation did not include a study of the contact. Mahard (1949, p. 122-23) disagrees with Jenkins, who cited the locality as a fault. In Mahard's opinion, the basalt and layers of the Verde abut against a hill of folded Supai rocks and higher beds in the Verde formation overlap part of the ancient hill. He explains the warping of strata of the Verde by assuming slump during and prior to final lithification. In the canyon of Wet Beaver Creek, between Camp Verde and Montezuma Castle National Monument, the Verde formation has been warped into gentle alternating anticlinal and synclinal folds with crest-to-crest magnitudes of a few tens of feet, and amplitudes of a few feet to a maximum of about 10 feet. Montezuma's Well is a spring located a few miles up the valley of Wet Beaver Creek from Montezuma Castle. The "well" is interpreted as a collapse depression in limestones of the Verde formation that have locally been domed to form a hill about 100 feet high. According to E. D. McKee (oral communication, 1949) soundings in the pool of water that occupies the "well," and exploration by a diver, showed the bottom to be about 50 feet below water surface, and to be approximately level, with no marked depressions or "bottomless pits." Water from the pool emerges through an opening a few feet wide and about 2 feet high in one flank of the dome.

Faulting

Faulting transverse to rim.--As the investigation progressed, it became evident that marker formations of Paleozoic age occur along the Mogollon Rim at altitudes differing by more than 2,000 feet at points visited. A compilation of occurrences led the writer to the tentative conclusion that the Mogollon Rim can be divided into three sections which are believed to represent major structural blocks. This division into western, central, and eastern sections shown on the index map (fig. 1), is tentative and necessarily somewhat arbitrary. Detailed mapping would be required to determine whether the divisions of the rim occur along rather narrow zones of large-scale faulting transverse to the trend of the rim, or whether the relative elevation or depression of a formation used as a structural marker results instead from accumulated movement along numerous faults of relatively small throw distributed over a broad area.

Evidence of Supai formation.--In the western division the lower part of the Supai formation occurs most commonly at altitudes ranging from about 3,500 to 4,500 feet in the area around Cottonwood and Sedona, and, so far as observed, eastward to Fossil Creek. In the central division, the base of the Supai formation is found most commonly in the range from 4,500 to 6,000 feet, between Payson and Tonto Creek. The eastern half of the central division was almost untouched in the present reconnaissance. In the eastern division, on the Fort Apache Indian Reservation, the base of the Supai formation, so far as observed, lies in the range from about 4,000 to 5,000 feet. Granting that lateral variations in thickness of the formations underlying the Supai formation cause some of the differences in altitude, it is nevertheless the writer's strong impression that in general the western division is structurally lowest; the central division is structurally highest; and the eastern division, north of Salt River, is intermediate in degree of uplift; and these differences are the reflection of movements along fault zones that trend essentially transverse to the Mogollon Rim.

Near the line separating the western and central divisions the escarpment swings south-southeast. Outcrops of the Coconino sandstone, for example, are offset 10 to 20 miles on opposite sides of a rather narrow intervening band of volcanic rocks (Darton and others, 1924). Although the reason for this offset has not been determined, it is thought significant that it extends southward from the trace of the Oak Creek fault, as far as that fault has been mapped.

Further evidence of transverse faulting is found in a study of altitudes at the base of the Martin formation in the Payson region, and is summarized below in table 2. Data have been compiled from locations and descriptions of sections given by Huddle and Dobrovolny (1951, p. 103-104) and from personal observations. The localities are arranged in order from west to east. The rise in altitude of the base of the Martin formation from west to east is considered to be the result of a series of faults transverse to the rim. The decline in altitude from Diamond Point to Tonto Creek is an expression of dip of that structural block.

Table 2. --Altitude of the base of the Devonian Martin formation at points in the Payson region.

Locality	Altitude, base of Martin formation (feet)
1. E. Verde River, west of Pine-Payson road.	4,000±300
2. E. Verde River, ½ mile east of Pine-Payson road.	4,600
3. Wailing Cow Ranch on E. Verde River.	4,600
4. Ellison Creek, at Cold Spring.	5,250± 50
5. Diamond Point, ¼ mile east of fire lookout tower.	5,750± 50
6. Tonto Creek, 1 mile north of Kohl Ranch.	5,400± 50

Faulting parallel to rim. --The geologic map of Arizona (Darton and others, 1924) shows faults parallel to the rim in only a few places as follows: (1) Sycamore Canyon northwest of Cottonwood; (2) the Jerome mining district immediately southwest of Cottonwood; (3) the area between the north end of Mazatzal Mountains and the rim near Pine; and (4) the Sierra Ancha north of Roosevelt Reservoir. It is only in the areas named above that sufficient work, even of reconnaissance nature, had been done by 1924 to identify such structures.

Three traverses are presented as diagrammatic sections (pl. 3 A, B, C). The section drawn to illustrate structures between Payson and Ellison Creek (pl. 5) is based on a complete traverse. The vertical and horizontal scales are the same. The two diagrammatic sections (pl. 3 A, B) from San Carlos northeast across the Natanes and Mogollon Rims, in which the vertical scale is exaggerated, combine information obtained in the present investigation with information shown on the State geologic map. As only reconnaissance topographic maps are available for the Indian reservations, it is difficult to reconcile geology with topography in these areas. It is believed, however, that the general pattern of structures and of outcrops in relation to topography is properly illustrated.

The similarity in pattern of structures in the western division (pl. 3 C), and the eastern division (pl. 3A, B) is especially noteworthy. North-northeast of the topographic rim, at some places (pl. 3C) less than a mile from the scarp and at others 15 to 20 miles from the scarp (pl. 3A), the plateau block is depressed. Northward from the rim, strata dip to progressively lower altitudes. South-southwestward from the rim, a series of normal faults step the strata successively lower to a structural trough. The sequence is interrupted (pl. 3C) by horst blocks in local areas between Munds Mountain and House Mountain. Southwest of the structural trough, the strata are again uplifted. Thus, on the Black Hills (pl. 3C) pre-Cambrian rocks occur at altitudes about 1,000 feet higher than the top of pre-Cambrian rocks as observed along the Mogollon Rim except on the Mazatzal Mountains and on Christopher Mountain. Wilson (1939, p. 1148, 1152) has described those mountains as remnants of an early pre-Cambrian mountain range, overlapped in the Mazatzal Mountains by sediments of Paleozoic age and on Christopher Mountain, by rocks of younger pre-Cambrian age.

In the eastern division, the stratigraphy and fault structures characteristic of the Mogollon Rim extend about 50 miles farther south than in the western and central divisions. The Natanes Rim (pl. 3, fig. 12) is therefore considered to be the structural equivalent of the Mogollon Rim as the latter is developed in the western and central divisions. In part of the eastern division, the Mogollon Rim does not exist as a well-defined escarpment; the Natanes Rim does. The geologic sections (pl. 3, A, B) have been prepared to illustrate the relations expressed above. Although the Apache series, exposed on the Natanes Rim, is far older than rocks at the base of the Mogollon Rim near Oak Creek, rocks of the Apache series are exposed at the base of the Mogollon escarpment in eastern Tonto Basin (Wilson, 1939, p. 1148-1153) in an area near the middle of the central division.

The Payson-Ellison Creek sections (pl. 5A, B, C) were drawn only across the traverse mapped and are not long enough to reveal the regional pattern in the Payson region where two and perhaps three rims occur, probably as the result of repetition of structures and stratigraphy caused by faults paralleling the rim. They serve, however, to illustrate structures characteristic of many places in the Mogollon Rim region.

Age of regional structures in central Arizona.--Wilson (1939, p. 1161-1162) states in his summary that, "long before [upper pre-Cambrian] Apache sedimentation, the [central Arizona] region underwent a profound crustal disturbance, termed the Mazatzal Revolution." The resulting structures included "subparallel folds, thrust faults, and imbricate, steeply dipping reverse faults, generally of northeastward to northward trend." The pre-Cambrian granite that is exposed so widely in the Payson region, for example, represents a batholithic intrusion that, in the Mazatzal Mountains at least, "is definitely of post-Mazatzal--pre-Apache age." And he concludes: "The central Arizona region underwent no great deformation between the Mazatzal Revolution and the Tertiary Basin and Range orogeny."

Fenneman's summary (1931, p. 324-325) of the physiographic history of the Colorado Plateau province includes periods of uplift as follows: (1) General uplift, local swells, and formation of the great monoclines in a period beginning with the close of the Cretaceous; (2) late Eocene or post-Eocene uplift; (3) another undated period of major uplift in Tertiary time; (4) inauguration of the canyon cycle of erosion by "great general uplift" at or following the beginning of Quaternary time.

Threet (1951, p. 1513) briefly described overthrust faulting in a block west of Hurricane Cliffs adjacent to the western margin of the Colorado Plateau, and analogous, therefore, to the area of interest in the present report. Threet's evidence indicates overthrusting in Late Cretaceous time. He considers the overthrusting to be related to Laramide flexures in the Plateau.

In the eastern division of the Mogollon Rim, Upper Cretaceous strata appear to lie with angular unconformity upon the Kaibab limestone. This relationship was illustrated diagrammatically by Darton (1925, fig. 29, p. 202). East of Darton's section the Cretaceous beds are in depositional contact with Coconino sandstone on the southwest, and with the Moenkopi formation on the northeast. These relationships indicate northward or northeastward tilting of the area in post-Moenkopi--pre-Late Cretaceous time.

Widespread deposits of gravel along the Mogollon Rim have been mentioned. In some areas the gravels are at least 200 feet thick. As the gravels are considered to be of Tertiary age, and as they are overlain in places by Tertiary and Quaternary basalt, the deposits provide evidence of very large-scale structural movements in the area south-southwest of the Mogollon Rim in late Tertiary or Quaternary time, or both.

Robinson (1913, p. 36) described faults in the Flagstaff region as post-Pliocene. More recently, Mears (1950-b, p. 1557) speaks of the Oak Creek fault as Pliocene and indicates that gravels on the rim in the Oak Creek region are of Miocene age and are overlain by Pliocene basalt. McKee (1951, p. 498-500) summarizes evidence suggesting that major uplift in the Prescott region, south-southwest of the rim occurred in late Miocene or early Pliocene time.

Reconnaissance investigation of the lake beds in the Payson basin suggests that there is gradation from coarse clastic materials at the southern end toward evaporites and finer-grained clastics at the northern end, indicating a source-area toward the south. However, it is the writer's observation that these beds dip southward at angles of less than one degree to perhaps as mucn as 3°, thus reversing what would be normal depositional slopes. It is probable, therefore, that the region was gently tilted southward after the lake-beds were formed. By analogy with lake beds at San Carlos, dated on fossil evidence as Pliocene(?) to early Pleistocene, the tilting must have occurred since early Pleistocene time.

The records of earthquakes in the Mogollon Rim region have been summarized by Heck (1947, p. 48-62). In the period 1868-1938, there were 25 earthquakes of intensity sufficient to be reported by inhabitants of the region. Of this number, 9 were felt in Flagstaff, Snowflake, Cottonwood, Whiteriver, or the Clifton-Morenci district. Most of them were in the 4 or 5 range on the earthquake-intensity scale. One, however, on September 23, 1910, centered apparently north of Flagstaff, was of intensity 8 to 9. It is concluded, on the basis of earthquake evidence, that the rim region is still one of mild seismic activity, and therefore in all likelihood a region in which fault movement continues to some degree.

Information presented in the paragraphs above is interpreted to indicate that faulting has occurred in the Mogollon Rim region at various times from Wilson's Mazatzal Revolution to, and including, the present. There appear to have been four major periods of orogeny, namely: (1) early Proterozoic; (2) Miocene(?), southwest of the rim; (3) late Tertiary, possibly Pliocene; and (4) at or near the beginning of Quaternary time. Laramide structures, although dominant elsewhere in the Plateau Province, appear to be of relatively minor significance in the history of the Mogollon Rim. The rim is still a region of structural activity, but on a greatly subdued level relative to the four major periods.

Geologic history

Present knowledge permits only a generalized outline of the geologic history of the Mogollon Rim region. Drawn from many sources, the deduced sequence of events is as follows - gaps representing "no information" are readily apparent:

1. Formation of lower pre-Cambrian rocks, including deposition of sedimentary strata and extrusion of dominantly acidic lavas.
2. Mazatzal Revolution (of Wilson) and intrusion of granitic batholith; demonstrated only for west part of central division.
3. Erosion; Mazatzal Mountains and Christopher Mountain remaining above a generally denuded surface.
4. Deposition of upper pre-Cambrian (Apache group) sediments; now exposed only in the region southeast of Christopher Mountain.
5. Deposition of Middle Cambrian Tapeats sandstone west of Christopher Mountain; Troy quartzite east.
6. Intrusion of diabase sills and dikes, apparently only in areas underlain by Apache group.
7. Erosion, perhaps continuous through Middle Devonian time.
8. Deposition of Martin formation and the conformably overlying Redwall limestone.
9. Erosion; collapse breccias and caves in Redwall; continued until late Pennsylvanian time.
10. Deposition, starting with Naco formation and continuing with successively younger Supai formation, Coconino sandstone, and Kaibab limestone; end of Paleozoic era.
11. Lower Triassic Moenkopi formation deposited over most or all of rim region; deposition through Shinarump and Chinle times at least in northern part of eastern division.
12. Uplift and erosion; planation in some places down to strata of the Kaibab.

13. Deposition of Upper Cretaceous strata in eastern division, overlying beveled surface of older rocks.
14. Extrusion and explosive eruption of Cretaceous(?) and Tertiary volcanic rocks in central division; probably in eastern division as well.
15. Laramide Revolution continuing through this time interval caused folding and faulting to the north, within Plateau Province, and faulting including overthrusting along western margin of Plateau.
16. Erosion.
17. "Prescott" orogeny south-southwest of rim region (Miocene?). Deposition of thick rim gravels.
18. Pliocene(?) volcanic activity in San Franciscan volcanic field.
19. Pliocene or post-Pliocene faulting in Flagstaff region at least; trend generally north.
20. Lake beds formed to estimated 2,000-foot thickness in Verde, Payson, Tonto, and San Carlos basins.
21. Renewed faulting along old zones of weakness. Direction of relative movement reversed in some places.
22. Erosion; formation of a few travertine terraces.
23. Pleistocene to Recent extrusion of basalt; explosive eruption of basaltic cinders in Flagstaff region and in eastern division of rim. Extrusion of canyon basalts.
24. Erosion, deposition of large travertine terraces; canyon cutting to at least 50 feet lower than base of canyon basalts and base of some travertines; region remains seismically active. Sunset Crater eruption about 1066 A. D.

WATER RESOURCES

Surface Water

Lakes, ponds, and marshes

Both artificial and natural lakes are present in many localities on the plateau portion of the Mogollon Rim region. Lake Mary, near Flagstaff, and Lyman Reservoir, on the Little Colorado River near St. Johns, are examples of artificial lakes. Lake Mary provides much of Flagstaff's municipal water supply. Water stored in Lyman Reservoir is used for irrigation.

Mormon and Ashurst Lakes, near Flagstaff, are two of the largest and are considered characteristic of all the natural lakes in the region. Mormon Lake is about 4 miles long and 2 miles wide. When full, it is reported to be less than 6 feet deep at the maximum. In periods of successive years of subnormal precipitation it dwindles to a muddy puddle, or dries up entirely (fig. 13c). Ashurst Lake is less than half the size of Mormon Lake and tends to be more permanent, but in large measure it is a shallow, reed-grown pond. Between Showlow and Springerville there are many dozen "cienagas" (swamps or marshes) of varying sizes, many occupied at times by ponds. In the fall of the year, or in periods of deficient rainfall, these ponds become mud-coated areas (fig. 14). Their possible value as recharge areas will be discussed later in this report.

Few natural bodies of standing water occur below the rim. One of the principal ones, a lake near Cottonwood known as Pecks Lake, occupies a crescent-shaped area. It is shallow, muddy, and commonly overgrown with algae. The altitude of its water surface is about that of the water level in the Verde River nearby. It is considered to be an oxbow lake belonging to the present cycle of erosion in the Verde basin. At the downstream end of the Verde Basin, the Verde River passes through a narrow rock gorge. Throughout its course in Verde Basin, the river has for the most part a gradient sufficient to cause rapids and riffles to be commonplace. Inspection of aerial photographs of the reach of Oak Creek between Sedona and the mouth shows the presence of several meander scars cut in rocks of Paleozoic formations exposed. It is estimated that the abandoned Oak Creek meanders are 10 to 25 feet or more above present stream level. From these occurrences it appears that local base levels must have lowered rather abruptly more than once. A study of the drainage history of the Verde River and its tributaries might help to clarify the geologic history of the region.

A Study of Perennial Base Flow in Major South-Flowing Streams in Mogollon Rim Region

By

N. D. White

The present study was made for the purpose of determining the amount of water available on a sustained-yield basis from streams in the Mogollon Rim region. A figure was sought that would represent the base discharge that is unaffected by seasonal climatic fluctuations and relatively unaffected by drought cycles. For practical purposes the median annual minimum discharge of each stream was used, and called the "perennial base flow." The perennial base flow has been computed for five major streams in the region: (1) Salt River near Chrysotile; (2) Oak Creek near Cornville; (3) White River near McNary; (4) Verde River near Camp Verde; and (5) Tonto Creek above Gun Creek near Roosevelt.

Available records of discharge for the five streams selected date generally from 1940. As an indication of the relation between precipitation and runoff, a water year in which the runoff was neither extremely high nor extremely low was selected by inspection for each station, and a table prepared showing the total amount of water falling on the drainage basin of each stream and the mean discharge of the stream by months (table 3). Graphs were also prepared for each year of record from 1940 to 1951, showing daily discharge in cubic feet per second at the gaging station and daily precipitation in inches at a nearby weather station. Figure 13 is the graph for Oak Creek near Cornville. It is apparent from the data in table 3 that only a small percentage of the precipitation falling on the drainage basin reaches the gaging station as discharge. Both the tabular and the graphical forms of the data indicate that rainfall is not always reflected immediately as discharge at the gaging station. There is a lag between the time when precipitation occurs and the time when the discharge at the gaging station responds. The length of the lag is dependent largely upon drainage-basin characteristics, especially the topography and the geology.

Except for the possible influence of drainage-basin characteristics, the discharge of a stream may be expected to reach a minimum in the months of minimum precipitation, unless affected by some other factor such as snowmelt or reduced evapotranspiration. When discharge increased perceptibly at a time when there was no rainfall (fig. 13), it was assumed that the increase was due to one of the other factors.

The median annual minimum discharge for each station was obtained by listing the minimum daily discharge in each year for the period 1940-51, and selecting the median figure, that is, the midpoint, so that the number of years in which the minimum daily discharge was higher equalled the number of years in which the minimum daily discharge was lower. The results are given in table 4. To obtain the total shown in table 4, the discharge for Oak Creek and for White River was subtracted from the total for the five streams, as Oak Creek is a tributary of the Verde River, and White River is a tributary of the Salt River above the gaging stations considered. The total median annual minimum flow is therefore approximately 175 cubic feet per second, or 347 acre-feet per day, or 127,000 acre-feet per year, which is equivalent to about 0.3 inch of runoff per year.

Field Observations

It was not the purpose of the present study to determine the pattern of surface-water flow southward from the rim. However, the discharge of springs below the rim is the source of much of the water moving southward toward the large reservoirs on the Gila, Salt, and Verde Rivers. Furthermore, as the relation between the amount and chemical quality of water discharged by the springs and of waters reaching the reservoirs is close, a few observations relating streamflow and quality of water have been made in the field. The results are presented below.

Tonto Creek.--During a low-flow period in 1952, 10 water samples were collected from Tonto Creek and from springs and streams tributary to the creek. Including the headwater spring, 6 of these samples were collected from Tonto Creek. The chemical analyses of the samples, water temperatures at sampling points, and discharge data at point of collection are shown in table 5.

Examination of the table shows that, because of inflow from springs and tributary streams, diversions for irrigation and the resulting return flow and seepage, and evapotranspiration, there are variations of considerable magnitude in discharge and in chemical quality from place to place. The over-all trend, however, is for the discharge to increase rapidly within the first few miles, then to diminish as water is diverted, evaporated, and transpired. Similarly, the water becomes more highly mineralized as distance from the rim increases.

Oak Creek and Verde River.--Table 6 shows changes in discharge and in quality of water in the Verde River. Table 6 shows similar information for Oak Creek. The coverage is less extensive than for Tonto Creek. In the reaches examined Oak Creek and Verde River gain in flow, and table 6 indicates that at the time the samples were collected about three-fourths of the flow in Verde River a mile below the mouth of Oak Creek was coming from Oak Creek.

Information sought in collecting the samples represented by analyses in table 6 was the extent of change in quality of the water of the Verde River at low flow in the vicinity of Oak Creek. The progressive increase in total mineral concentration is represented approximately by the increase in values for specific conductance. Even though the Verde River receives large volumes of water from Oak Creek, which has the lowest specific conductance of any waters shown in table 6, the Verde River waters show a marked increase in mineralization downstream from the mouth of Oak Creek. The increase is particularly marked in sodium and potassium and in sulfate. Oak Creek water is low in these constituents. It seems likely that inflow of a water high in sodium and sulfate reaches Verde River somewhere in the vicinity of the mouth of Oak Creek. This inflow has not yet been definitely discovered. However, the observed increase in sodium and sulfate is believed to be related to the presenee of evaporites in the Verde formation. The sodium sulfate quarry previously mentioned is located in this general area.

The two samples from Oak Creek for which analyses are included in table 6 indicate no important increase in sulfate concentration between the sampling points. The gain in flow of 25,000 gallons per minute (about 56 cfs) corresponds to measured discharges of springs in the reach between the upper gaging point and the mouth of Oak Creek, totaling about 21,500 gallons per minute, plus about 3,500 gallons per minute derived from seepage and from small unknown springs. Chemical analyses of waters from the major tributary springs represented in table 6 are in general comparable in proportion of the principal constituents to analyses of waters emerging from Permian strata exposed near the headwaters of Oak Creek. It is suggested that the springs represented in table 6B discharge water originating primarily in Permian sedimentary rocks, and only slightly altered in chemical quality by additional constituents derived from the Verde formation.

Gila River. --Changes in chemical quality of waters in the Gila River have been examined in detail and reported by Hem (1950, p. 1-67). A summary statement (p. 67) shows that during the water year 1944, 105,000 tons of dissolved mineral matter was carried by the Gila River past the Calva gage, at the downstream end of the Safford Valley. Of this total, 20,900 tons was acquired by the river between the gage at Solomonsville and the gage at Calva (pl. 1). The increased salt load is attributed (p. 67-68) to leaching of valley fill in the basin, to mineralized artesian waters seeping upward along fault zones or discharged from springs and wells, and to some extent to partial leaching of irrigated lands. Incidentally, Hem states that, in addition to the gain in river load, there are "significant qualtities of soluble salts... accumulating in the soil and shallow ground waters of... the lower part of the valley."

That the waters of the Gila River become increasingly mineralized farther downstream has also been pointed out by Hem (Halpenny and others, 1952, p. 327-331). His summary of the "salt balance" problem in irrigated lands of the Salt River Valley area shows that the quality of Gila River water is affected by addition of highly mineralized water from the Salt River drainage, by use and reuse for irrigation, and by evapotranspiration in areas of nonbeneficial use of water by riparian vegetation.

Summary. --Partial investigations of streams carrying water from Mogollon Rim springs toward points of use suggest the following conclusions: (1) There is a tendency for stream flows to reach a peak in discharge from springs and effluent seepage relatively near headwater sources, then to diminish in perennial base flow downstream; (2) the concentration of dissolved mineral matter in these waters increases progressively downstream; and (3) contributing factors include leaching of salts from irrigated lands.

Ground Water

Source

The source of all ground water discharged in the Mogollon Rim region is precipitation falling as rain or snow. Data were not available when this report was prepared for determining accurately the volume of water falling on the region. Similarly, discharge data are incomplete for runoff, for discharge from springs, and for pumping from wells.

Despite the wide margin of error involved, the following analysis has been made to show the ratio between known spring discharge and average annual precipitation. The plateau portion of the rim region that lies between the crest of the escarpment and U. S. Highway 66 is roughly

200 miles long and 50 miles wide. It is in approximately this area that the springs tabulated for the summary of discharge (table 8) receive recharge. Weather data (table 1) indicate that an assumption of 12 inches of precipitation per year is conservative. Using these figures, 6,400,000 acre-feet of precipitation per year is obtained. Table 7 shows that springs measured in the present investigation discharge a maximum of about 140,000 acre-feet annually. Thus, about 2 percent of the total precipitation falling on the rim region appears as spring flow in the region. It may be that this figure is as much as 50 to 100 percent in error, but it serves to establish the order of magnitude of the ratio of spring discharge to precipitation. It is believed that the figure of 2 percent is, if anything, too large.

Occurrence

Water-table conditions.--At various localities in the rim region, ground water is encountered under water-table conditions in rocks of almost every geologic age. Rocks of the Apache group yield water to Cassadore Spring, on the San Carlos Indian Reservation. The Martin formation is the source of many springs in the central division. Water-table conditions are indicated at Cold Spring on Ellison Creek, and at Henturkey Spring on Tonto Creek. The Redwall limestone is the source rock for Warm Spring on Salt River, and examination of drill cuttings suggests that this formation is the aquifer at the Dehorn well on the San Carlos Indian Reservation. The Supai formation is the source rock for numerous springs in the upper reaches of Oak Creek Canyon and along the rim near Pine. Beds high in the Supai formation supply water to a deep well at Bellemont, west of Flagstaff, and to many wells on Grasshopper Flat, west of Sedona. The Coconino sandstone is the source of some springs in Oak Creek Canyon and on the Mogollon escarpment east of Pine, notably Tonto Spring, the headwater spring of Tonto Creek.

The Moenkopi formation supplies limited amounts of water, generally mineralized with salt and gypsum, to shallow wells in the vicinity of Shumway and Snowflake. Upper Cretaceous rocks near the rim in the general vicinity of Showlow yield water to a few small springs, and supply water to a few wells at Lakeside.

Tertiary and Quaternary rocks are the most important in terms of occurrence of water under water-table conditions. Many dozens -- perhaps hundreds -- of springs issue from basalt north of the rim. Discharges range from less than a gallon per minute to about 3,000 gallons per minute, at the head of Silver Creek southeast of Shumway. Essentially all the 8,000 gallons per minute flowing from springs that drain northward from the rim (table 7) issues from basalt. There are a few large springs in basalt whose waters drain southward.

Unconsolidated alluvium supplies water to wells in many localities. Near Payson are numerous shallow drilled or dug wells in alluvial materials lying in erosion pockets on the granitic bedrock of the area. Yields are not large, but in years of normal precipitation the supply in storage is adequate for domestic needs. In the region between Flagstaff and Williams, unforested "prairies" are underlain by a few feet to as much as 60 feet of alluvium. These beds supply water to domestic wells and to a few springs that occur at the margins of the alluvium where it is in contact with locally impervious basalt. In the Verde basin, especially on the bottom lands of the Verde River, dug wells obtain domestic water supply from alluvium at depths of a few feet to a few tens of feet. The most productive water-table wells in the region are on the San Carlos Reservation, in the flood plain of the San Carlos River. Wells within a few miles of the agency at San Carlos are reported to yield as much as 2,400 gallons per minute. Several are used for irrigation.

Artesian conditions.--Water under artesian pressure is common in the rim region and occurs in rocks ranging from pre-Cambrian to Tertiary or Quaternary. Artesian springs along the rim yield the largest discharge of any group measured. Artesian warm springs dump large volumes of highly mineralized water into the Gila and Salt Rivers, and lesser amounts into the Verde River. In the Silver Creek drainage, from a point south of Shumway to Snowflake, wells encounter water in the Coconino sandstone under artesian pressure. Farther north, outside the area of the present investigation, there is a comparable area of artesian-well development near Holbrook. A few flowing wells and others showing artesian rise yield water from the Verde formation in the Verde basin.

Rocks of the Apache group and diabase intruding the Apache group are exposed at the Salt Banks on Salt River (fig. 15). Warm, salty water issues from a travertine terrace at this locality. All the water samples collected and analyzed indicated concentrations of dissolved solids near the range of sea water. (In the same stratigraphic position, but about 25 miles upstream, the White River Salt Springs emerge about $\frac{1}{4}$ mile from the White River mouth.)

The group of fresh-water springs along Fossil Creek, in a reach about a quarter of a mile long, issue from the Redwall limestone. Their aggregate discharge is about 18,500 gallons per minute, the largest spring flow of any measured along the rim. Their temperature (table 8), and their tendency to build travertine pipes to progressively higher levels above the creekbed indicate artesian pressure.

Springs in and adjacent to the flood plain of Oak Creek south of Oak Creek Canyon (table 6) are considered to discharge water from the Supai formation. Interpretation of their occurrence in relation to faulting in the area (pl. 4), and temperatures a few degrees above mean annual temperature, suggest artesian conditions.

Springs at Columbine Terrace (fig. 16), on the White River, discharge about 7,500 gallons per minute. It is not clear as yet whether they issue under artesian pressure. The source rock is the Fort Apache limestone member of Stoyanow (1936) in the Supai formation.

The Coconino sandstone supplies artesian water to wells in the Snowflake-Shumway area. The structures governing the artesian system in that area and in the Hay Hollow basin, about 15 miles east-northeast of Snowflake, have not been determined in detail.

Volcanic rocks of probable Cretaceous or Tertiary age are exposed near Clifton Hot Springs and rocks of other types and ages occur in the canyon not far away. These springs yield waters ranging from 105° to 130°F (Hem, 1950, p. 32) and contribute large amounts of salt to the San Francisco River. The Verde Hot Springs emerge from volcanic rocks of probable Cretaceous or Tertiary age. The waters range in temperature from 100°F to 105°F.

Interpretation of drillers' logs of wells in the Verde basin indicates that water under artesian pressure is encountered in beds of the Verde formation at various places in the valley. Aquifers occur at several depths, as many as five being reported in one well. The driller reported that artesian pressures increased progressively as deeper aquifers were penetrated. Montezuma Well and Soda Springs, a few miles apart in the valley of Wet Beaver Creek, are thought to be artesian springs, even though the temperature of the water does not suggest deep penetration.

Recharge

Much of the recharge occurring on the plateau portion of the Mogollon Rim region is by direct infiltration of rain and of snowmelt. Additional recharge takes place by seepage from runoff in the few permanent, and many intermittent streams that cross areas of permeable rock.

An outstanding feature of the geology of the recharge areas is the high recharge receptivity of the surface rocks. In most of the plateau portion of the eastern and western divisions the land surface is underlain immediately by basalt, cinders, or the Kaibab limestone. Most of the basalt flows are jointed (fig. 17) and shattered and conduct water downward with great rapidity except where intercalated beds of clay or altered ash provide local layers of relatively low permeability. The occurrence of basalt springs is largely controlled by such low-permeability layers, although locally some basalt flows appear to be tight and thus to impede the downward movement of water. After emergence as spring discharge, the water in many places percolates downward again through fractures in the basalt.

In a few areas in the western division and in many in the eastern division, water falling on the volcanic rocks is temporarily impounded in open, unforested areas, often referred to as parks or prairies. In these areas the land surface generally is underlain immediately by clays which greatly retard downward percolation of water, although the rocks on which the clay layers rest may be highly permeable. Temporary lakes and ponds exist in such localities for parts of most years. The origin of the parks and prairies in the Flagstaff region has been tentatively related (Feth, 1952, p. 107-110) to nearby geologic structures, and to extensive falls of volcanic ash. Parks and prairies are most common in the eastern division.

Cienagas (fig. 14) are numerous, characteristically swampy, and of little value even for grazing.

In the central division the rocks exposed on the plateau are mostly the Kaibab limestone and the Coconino sandstone. Both formations are highly permeable, especially as they are jointed or otherwise broken along the rim (fig. 2). The degree to which fissures in the Kaibab limestone provide opportunity for recharge is suggested by Colton's description (1938, p. 29-32). His paper describes explorations to levels as much as 275 feet below the land surface in solution openings in the Kaibab limestone. Some of the fissures examined extended below the base of the Kaibab into the Coconino sandstone. Solution of limestone along faults of small replacement is cited by Colton as the origin of the fissures.

Conditions relating to recharge south of the rim had not been investigated at the time of writing the present report. Patently, there is some recharge by infiltration of water from both permanent and intermittent streams where they cross areas underlain by pervious but unsaturated rocks. It is probable that interformational leakage, in zones in which water occurs under artesian pressure, constitutes a source of water for some rock units. The importance of such recharge in supplying shallow aquifers in the valleys below the escarpment may be great. A study of all sources of recharge in the Verde basin would be especially worthwhile, as the potential for ground-water storage appears to be large.

Potentialities for artificial recharge.--Possibilities for artificial recharge with resulting increases in ground water moving north and south from the rim, appear to be particularly promising because of the high permeability of the surface rocks throughout the entire plateau portion.

So far as is known, no attempts have been made to induce recharge along the Mogollon Rim by artificial means. Structures to detain spring snowmelt and water from summer rains in areas of jointed and shattered rocks should be considered. Some of the marshy areas offer another possibility worthy of examination, as they are natural water catchment and storage areas. It is thought that piercing of their clay seals would permit downward percolation to the underlying aquifers, at least from some of them. It is believed that a program of artificial recharge would salvage water that cannot now be used beneficially. The geologic relations need to be worked out, however, and a complete program cannot be devised without consideration of the possible effects upon existing surface-water supplies.

The program of "prescribed burning" now in progress on the Fort Apache Indian Reservation is worthy of close examination. Designed to improve the forest, the burning program appears also to have a marked effect on the water crop derived from the burned areas. Older Indians report (H. F. Kallander, oral communication, 1952) that in these areas springs that had been dry for as much as 30 years now flow. Highly useful information could be collected by making discharge measurements in areas that are to be burned a few years in the future, and by continuing the measurements for a few years after burning. Such measurements might reveal a method whereby the yield of an area in both surface runoff and ground-water recharge could be materially increased without damage to the watershed.

Discharge

The present investigation was concerned largely with the occurrence of springs in the Mogollon Rim region and included only a cursory investigation of wells. The aquifers supplying water to wells in the region have been noted under "Occurrence." Data are not available from which to prepare an estimate of the quantity of water discharged by wells in the region.

The discussion of the occurrence of ground water earlier in this paper showed that springs discharge from rocks of many different types and geologic ages. Reconnaissance geologic maps were made of a few areas to determine the relations between structures and the occurrence of springs (pls. 4 and 5; figs. 10, 18, 19, and 20). Table 8 presents the basic data on springs accumulated by the end of 1952. Some of the springs of larger discharge were measured several times in order to determine their fluctuations. The springs of the region are classified as nonartesian or artesian. The nonartesian springs are classified as contact, fault, or conduit; the artesian, as fault or conduit springs.

Nonartesian springs. --Basalt flows are the aquifers supplying most of the contact springs. The Williams Creek Fish Hatchery spring, the spring at the head of Silver Creek, and Concho Springs are among the largest in this category (table 8). Williams Creek is tributary to the White River. The other springs are in the Little Colorado River drainage. In these three places, the water emerges at the contact between an impervious layer and the overlying basalt or intercalated gravel. All three are in the eastern division. Several other basalt springs in this division discharge from about 1 cfs to about 2½ cfs. A few springs issue from volcanic rocks on the slopes of the San Francisco Mountains near Flagstaff; their discharges are reported to be large but they were not measured.

Contact springs emerge from sedimentary rocks of Paleozoic age in many canyons cut back into the rim. Yields range from less than a gallon per minute to about 200 gallons per minute. The controlling contacts in some places are between a permeable sandstone and an underlying relatively impermeable siltstone. In other places the control was not determined. A number of springs in the upper reaches of Oak Creek Canyon emerge along crossbedding planes in sandstones of the Supai formation.

Cassadore Spring, on the San Carlos Reservation, issues from jointed pre-Cambrian quartzite along the contact with an underlying diabase sill. The springs at Tonto Natural Bridge emerge just above the contact between sandstones of Paleozoic age and pre-Cambrian metarhyolite.

In this category are grouped springs localized by faulting which do not show clear evidence of artesian rise. Cold Spring, on Ellison Creek, (pl. 5, map and sec. A-A') emerges near the intersection of two faults. The low temperatures of the water at Cold Spring, 55°F, suggests that the water table is intersected by the faults. The wide fluctuation of discharge of this spring (table 9) indicates relatively small ground-water storage and a nearby recharge area.

Springs in Lower Webber Canyon, near Payson, are shown in figure 20 in relation to faulting in the surrounding area. The fact that this major group of springs discharges within the area of a graben illustrates a regional characteristic that is considered important and discussed in a following section on the relation of faulting to occurrence of springs.

The headwater springs in Oak Creek Canyon are classified as fault springs, as they emerge at the intersection of the water table with the Oak Creek fault and a west-trending cross-fault.

The clearest-cut example of a limestone conduit spring encountered in the present study is that of Columbine Terrace Spring on the White River. This spring issues from the Fort Apache limestone member (of Stoyanow) of the Supai formation. The total discharge of the spring was determined as the difference in flow of the river above and below the terrace area and aggregated about 7,500 gallons per minute. At least two-thirds of the discharge emerges from a single orifice about 1 foot by 3 feet in cross section, as a dome of water several inches high (fig. 16A). From this orifice the water flows about 250 feet across a travertine bench before cascading down the face of the terrace (fig. 16B). As only one discharge measurement was made, the range of fluctuation is not known.

Solution openings are prominent in exposures of the Redwall limestone. Figure 21 illustrates the point in Sycamore Canyon about a mile upstream from Summers Spring. Summers Spring is probably a conduit spring although it issues from soil and rubble and a direct relationship with the Redwall limestone must be inferred. As at Columbine Terrace, the Summers Spring waters emerge as low domes before cascading down a few feet to a channel whence they flow about 200 yards to Sycamore Creek. Three measurements in 1952 (table 9) indicate a relatively constant flow. Perhaps more significant are the measurements of the discharge of Sycamore Creek about 1½ miles downstream from the springs. The discharge was measured by the Surface Water Branch of the Geological Survey at the Packard Ranch on Sycamore Creek in June or July of 1946, 1947, 1950, 1951, and 1952. The range in discharge was from 4,500 to 5,125 gallons per minute. About half the total flow is from Summers Spring; the remainder is from springs and seeps in the Redwall in a reach extending up the canyon about 4½ miles beyond Summers Spring. The constancy of discharge suggests a relatively large storage area and recharge area for the springs in Sycamore Canyon. Faulting in Sycamore Canyon near Summers Spring is shown in figure 18.

Artesian springs.--According to employees of the power company that utilizes the discharge of the springs at Fossil Creek, individual orifices tend to build travertine walls across the openings, thus raising the level of emergence. Occasionally, however, orifices become obstructed and new ones form at lower elevations. Reconnaissance mapping (fig. 10) indicates that a fault with about 1,200 feet of displacement forms a barrier and localizes the points of emergence. The springs issue from solution channels in the Redwall limestone and possibly in the overlying Naco formation. The discharge of this group of springs has been measured four times (table 9) and shows markedly little variation. The uniformity of flow suggests that there is a large storage area on the plateau tributary to the Fossil Creek springs. The relative warmth of the water, about 71°F, indicates penetration to considerable depth before emergence.

The group of springs in the flood plain of Oak Creek (pl. 4) together yield about 22,500 gallons per minute. Their temperatures range from 67° to 71°F, about 10 degrees above the mean annual air temperature (fig. 21). Reconnaissance mapping indicates the presence of a number of faults. These springs are thought to originate in the Supai formation. The reasons for this conclusion are discussed in the section on surface water (p. 28).

The springs at the Salt Banks on the Salt River, the White River, Salt Springs, and those at Clifton discharge warm, salty water under artesian pressure.

Warm Springs, on the San Carlos River about 15 miles northeast of San Carlos, emerge at 85°F from limestones in the Naco formation. A geologic reconnaissance map (fig. 19) shows the prevalence of faulting in the vicinity. It is probable that the fault shown trending northwest, and approximately bisecting the area mapped, acts as a ground-water dam which brings the water to the surface.

Summary of spring discharge.--The aggregate discharge of springs in the rim region is shown in table 7. The table shows that, of the spring flow draining southward, the western and central divisions contribute about five-sixths of the spring flow and the eastern division, one-sixth. The spring flow draining northward is derived predominantly from basalt aquifers in the eastern division. Approximately ten times as much spring flow moves southward from the rim region as flows northward. However, considerable northward-flowing spring discharge occurs outside the Mogollon Rim region as defined in this report. Blue Spring, in the canyon of the Little Colorado River about 13 miles upstream from its mouth, discharges about 200 cfs, an amount equal to about two-thirds the combined discharge of all the south-flowing springs measured in the Mogollon Rim region.

Table 9 shows fluctuations in discharge of those springs measured more than once, either during the present investigation or previously by the Surface Water Branch of the Geological Survey. The wide range of fluctuation in discharge of some of the springs is related to snowmelt. The low ranges of fluctuations in the flow of Fossil Creek springs, Sycamore

Canyon springs, Page Spring, and Bubbling Pond are believed to be related to large volumes of ground-water storage.

Influence of Faulting in Localizing Springs

The influence of faulting in localizing points of discharge from springs is believed to go beyond those cases where faults serve as channels, or as dams to ground-water movement. It is the writer's impression that a significant number of springs along the Mogollon Rim occur in structural lows, although at points of discharge the springs may well be classified as contact or fault-dam springs.

It has been noted that the springs in Lower Webber Canyon (fig. 20) discharge in a graben. Another area where a graben may affect the occurrence of springs is shown on plate 4, an area from Spring Creek to Sedona, on the northeast side of the Verde basin. A structural low is thought to localize the large springs on Oak Creek and Spring Creek. This structure is bounded on the north by a west-trending fault through Grasshopper Flat (Mears, 1950a) and by a fault in the southwestern part of T. 17 N. R. 5 E. It is bounded on the south by two southwest-trending faults, north of Little Park and House Mountain, respectively. Other faults near Big Park may likewise be related to the structural low. The presence of a small graben which controls the occurrence of springs is indicated at Tonto Natural Bridge. Two series of step faults, with displacements of only a few feet to 25 feet and a total displacement of about 50 feet, constitute the graben, which has an axial trend approximately at right angles to Pine Creek Canyon. It is concluded that downfaulted areas are especially favorable to the occurrence of springs.

Another type of relationship between faulting and the occurrence of ground water exists in the Payson region. During most of the year the flow of Upper Webber Canyon, Bray Creek, Chase Creek, and the East Verde River disappears along a line roughly parallel to and about 3 miles south of the Mogollon Rim. This line is believed to coincide with a fault zone that brings the Redwall limestone to or near the surface. The cavernous nature of the Redwall limestone has already been remarked. Within less than a mile downstream the East Verde River again attains perennial flow at Burnt House Springs (pl. 5). South of Burnt House Springs the East Verde River flows for several miles, receiving an increment from Ellison Creek below Cold Spring. At an undetermined point the river again disappears, and final permanent flow is not attained until a short distance above the junction of the East Verde River with Webber Creek (fig. 20). It is thought that the points at which the East Verde River becomes intermittent represent outcrops of the Redwall limestone, twice repeated by faulting.

Potentialities for Development of Springs

One purpose of the present investigation was to delineate areas in which detailed studies could be made looking toward better development of the water resources. The most promising areas are those in which artesian conduit springs occur.

At Fossil Creek the discharge area is located on a bench in the canyon. There are two ways in which the yield might perhaps be increased. Wells could be drilled to intercept the ground water and, by pumping, the head could be lowered with a possible corresponding increase in yield. A quarter of a mile downstream from the springs the stream channel is about 100 feet lower in altitude. If a tunnel were driven upstream from this point to penetrate the cavernous area at the springs, a decrease in back pressure would result and the yield should correspondingly increase. A thorough study of the geology of the recharge areas and of the canyon in which the springs emerge is required before development could be properly planned.

Summers Spring, in Sycamore Canyon, is about 15 feet higher than the bed of the creek. Further examination of the area might reveal conditions favorable for development. Comparable conditions exist at Columbine Terrace. There the discharge could be increased by lowering the outlet and eliminating wastage by evapotranspiration.

The reach on Oak Creek in which Page Springs, Bubbling Pond, and Turtle Pond occur (pl. 4) appears to warrant careful study.

The yields of many smaller springs in the region could be increased by clearing debris from spring orifices. In many places, much of the discharge is lost by seepage. It is estimated, for example, that about half the total discharge of Arsenic Cave spring (table 8) bypasses the collecting box and does not enter the pipe in which water was carried several miles to point of use. The Bureau of Indian Affairs has undertaken a program of development at the spring.

Material improvement in the chemical quality of water reaching the surface reservoirs on the Gila and Salt Rivers would result if highly mineralized water could be diverted at its source. In this connection, careful geologic and engineering studies should be made at Clifton Hot Springs in the Gila drainage, and at the Salt Banks (S. F. Turner, oral communication, 1947), on the Salt River. The concentration of dissolved solids is so high that the loss in volume of water, by diversion of flow from the salt springs, would be far outweighed by the resulting improvement in chemical quality. Approximate contributions of dissolved solids from these springs on which data are available are estimated as follows:

1. Discharge at Clifton Hot Springs averages about $2\frac{1}{2}$ cfs, and mineralization is such that Hem (1950, p. 34-35) estimated that the springs contribute about 50 tons of dissolved solids per day, or 18,000 tons per year, to the San Francisco River.

2. White River Salt Springs, near the junction with the Black River, have a combined flow of about 950 gallons per minute and add about $12\frac{1}{4}$ tons of salt per day, or 4,500 tons per year, to the White River. Additional volumes of salt are discharged into the White River from sources as yet undetermined.

3. The discharge at the Salt Banks has been roughly estimated at 2 cfs, or about 4 acre-feet per day (unpublished data in the files of the Geological Survey). The average of three analyses indicates a total mineral content of about 35 tons per acre-foot, or 140 tons per day. Thus, the Salt Banks are estimated to add about 50,000 tons of dissolved solids to the Salt River each year. Estimates of salt-spring inflows (unpublished data in the files of the Geological Survey) which have been made in the past indicate a total contribution to Salt River greatly in excess of the amount from springs mentioned under 2 or 3 above. Further study of the salt springs present in the Salt River basin is needed.

Quality of Water

By

J. D. Hem

Scope of Chemical-Quality Studies

Samples of water have been collected for chemical analysis from more than 100 springs and a few wells during this investigation. Additional chemical-quality data are available in the files of the Geological Survey for a large number of ground-water and surface-water sources within the Mogollon Rim region. These additional data were collected during earlier investigations by the Geological Survey. These older analyses have been found useful because they provide some information on areas where field work has not yet been done in the present study. A few chemical analyses of interest in the study of the Rim region are contained in published Geological Survey reports which will be referred to when appropriate to this discussion.

Methods of Analysis

The water samples were analyzed by procedures commonly used by the Geological Survey (Collins, 1928, Am. Public Health Assoc., 1946). During parts of the period 1940-44 a laboratory was maintained in Safford, Ariz., where chemical analyses were made for samples collected in the upper Gila basin and in other places in the State. Analyses of samples collected after 1945 were made in the Geological Survey's laboratory in Albuquerque, N. Mex. Most of the analyses made since 1950 were made by J. L. Hatchett, chemist.

Constituents and characteristics determined in the more comprehensive analyses included silica, iron, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, boron, specific conductance, and pH (see analysis (A-5-16)13 in table 10). The dissolved solids, calcium and magnesium hardness, and percentage of sodium were computed from the determined constituents. Less complete analyses were made where sources close together yielded similar waters, or where samples were taken at relatively short intervals to determine if the quality changed with time. In most of the analyses sodium and potassium were calculated together as an equivalent quantity of sodium, from the difference between the sums of the determined anions and cations.

The results of a few of the chemical analyses are given in tables 5, 6, and 10. Only a small number were selected for the purposes of this report, to show in a general way the chemical character of water encountered in the principal aquifers and the constituents of some of the more saline spring waters in the region. Some of these analyses are shown graphically in figure 23. This illustration was prepared by the method of Collins (1923, p. 394). A more complete listing of analyses is planned for a later report on this area when more data will be available.

Relation of Chemical Character of Water to Aquifers

Pre-Cambrian rocks.--Salty water emerges from pre-Cambrian quartzite along the Salt River, notably at the junction of the Black and White Rivers and at the Salt Banks, and at other places not yet investigated along the Salt River and its tributaries. The water from springs at the Salt Banks has a dissolved-solids concentration approximating that of sea water. With the exception of chloride, however, the proportions in which the constituents appear in the spring water are very different from those in sea water.

Sodium and chloride are present greatly in excess of any of the other components of the Salt Banks spring inflow, giving it essentially the character of a solution of common salt. The other components, however, are of interest, because they are present in comparable proportions of other saline springs along the Salt River. Characteristically, the bicarbonate content is high, being equivalent to or considerably in excess of the sulfate. Calcium and magnesium are present in large and nearly equivalent amounts. Boron concentrations are very high in the sources for which this component was determined.

The strata from which these saline springs issue are deeply buried in the area north of the Salt River, but are exposed for tens of miles near the bottom of the Salt River Canyon and in the lower reaches of some of its tributaries. It seems likely, therefore, that the saline waters have a complex history and may derive much of their dissolved matter from rocks other than the ones from which the springs flow. The possible origin of the dissolved matter is discussed in later sections of this report.

The concentration of dissolved mineral matter in waters from the White River Salt Springs, (A-4½-20)35ad, is only about a fourth as great as that in the Salt Banks but the proportion of the constituents present is much the same at both sites.

Saline water is not everywhere typical of the rocks in which the Salt Banks springs occur, as is shown by the analysis for Cassadore Spring in table 11. This spring yields water containing moderate amounts of dissolved solids, mostly calcium, magnesium, and bicarbonate.

Rocks of Paleozoic age. --Ellison Creek, (A-11½-11)30dc in table 10, issues from the Martin formation of Devonian age. Water from this spring is typical of waters from limestone and does not show any other characteristics of importance. Silica is comparatively low, and calcium, magnesium, and bicarbonate make up nearly all the dissolved matter.

Redwall limestone. --Some of the larger springs along the Rim, and Blue Spring which flows into Little Colorado River about 13 miles above its mouth, issue from the Redwall limestone. The springs near the Rim which include Summers, Indian Gardens, and Fossil Creek Springs (see table 10) yield typical limestone waters, containing moderate amounts of dissolved solids, largely calcium, magnesium, and bicarbonate. Some of the spring waters appear to be supersaturated with carbon dioxide and calcium bicarbonate at atmospheric pressure and are actively depositing travertine. Blue Spring and associated springs which emerge for several miles along the Little Colorado River also are depositing travertine. The water of Blue Spring is highly mineralized, containing particularly large amounts of sodium and chloride. The water of Blue Spring is considerably more dilute, however, than the saline waters of somewhat similar composition that issue along Salt River, for example. The sodium and chloride in the water of Blue Spring are undoubtedly derived from sources outside the Redwall limestone.

Supai formation. --Springs issuing from the Supai formation are characterized generally by moderate dissolved-solids concentrations comparable to those of water from springs in the Redwall and Martin formations yielding good-quality water. Waters from the Supai, however, usually are slightly higher in chloride and sodium and have a lower Ca/Mg ratio. No very highly mineralized water has yet been found in the Supai in this area. The water from the large spring at Columbine Terrace which issues from the Fort Apache limestone member (of Stoyanow) of the Supai formation differs in quality from the other waters from the Supai for which analyses are given in tables 6 and 10 (Cottonwood and Page Fish Hatchery Springs). The Columbine Terrace spring water is rather high in sulfate, which suggests that it may have dissolved some gypsum, possibly from within the Supai formation.

Coconino sandstone.--The water sample from Tonto Spring for which an analysis is given in table 10 and other available data indicate that water from the Coconino sandstone along the rim is low in dissolved solids and contains mostly calcium, magnesium, and bicarbonate. It has been previously pointed out by the writer (in Babcock and Snyder, 1947, p. 11-12) that the water in the Coconino sandstone is of good quality near the rim but increases in mineral content as it moves down the dip toward the north. It is believed that this formation has been partly leached of soluble matter near the rim where circulation of ground water has been the most active. Saline water is reported in wells in the Coconino in areas north of the rim (Babcock and Snyder, p. 10), but its origin in these areas is not yet known. The salt water seems to be most prevalent in areas where the Moenkopi formation overlies the Coconino, and as the Moenkopi is known to contain salt some relationship may exist.

Extrusive rocks.--The available analyses of samples of water from basalt indicate that the least mineralized water of the area occurs in these rocks. This water is low in dissolved solids, has a low calcium/magnesium ratio that may approach unity, and is proportionally high in silica. These characteristics are commonly found in water associated with basalt in other areas. The basalt in this area is near or at the land surface and is fissured; therefore, ground water in it circulates rapidly. These factors and the rather insoluble nature of the rock result in water having a low content of dissolved solids.

The water of the Clifton Hot Springs issues from alluvium in an area of volcanic rocks and probably is of deep-seated origin, and may be in part juvenile. This water differs in chemical quality in several important respects from the salt-spring waters issuing along the White and Salt Rivers. The Clifton spring water is essentially a solution of sodium and calcium chloride. Bicarbonate, sulfate, and magnesium all are very low in comparison to the other components and much lower than in the Salt Banks or White River Salt Springs.

The Verde Hot Springs, which issue from volcanic rocks, yield a water of different character from the other salt springs mentioned previously. The Verde Hot Springs water contains more sodium and bicarbonate than anything else, although both sulfate and chloride concentrations are high. This water also contains a considerable amount of boron.

Neither the Clifton nor Verde Hot Springs yields water the quality of which would be considered at all typical for igneous rocks. The increased solvent power of hot water, or the introduction of juvenile water into the system, may be the cause of the high mineralization of the waters.

Sources of Certain Constituents of Dissolved Matter in Ground Waters

Silica.--Pure silica in the form of quartz and chert is one of the least soluble of mineral substances. Most of the silica contained in natural waters is probably derived from the decomposition of more complex silicate minerals. Because such silicate minerals, in addition to quartz, make up a large part of igneous rock but are minor constituents of limestone and most sandstones, the waters highest in silica both on an absolute basis and in proportion to the total mineral content in solution are often those coming from igneous aquifers such as basalt. This relationship is apparent in table 11, although there are some exceptions.

Calcium and magnesium.--Calcium and magnesium, the alkaline-earth metals, are among the most abundant mineral constituents of natural waters. Both are found in igneous rocks. Limestone is made up largely of calcium carbonate but some magnesium carbonate is always present. In dolomite the quantity of magnesium is about equivalent to the calcium. In many sandstones calcium carbonate, probably with some magnesium, is the principal cementing material between the sand grains. Solution of these carbonates is the most common source of the calcium and magnesium in waters from limestone and sandstone.

Calcium carbonate is dissolved readily in water containing carbon dioxide. The dissolution of the mineral may be written as the following chemical equilibrium:

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{++} + 2HCO_3$$

The equilibrium point is usually dependent upon the supply of carbon dioxide available. Whether the carbon dioxide is retained in solution or escapes is in part dependent upon the temperature and pressure. Ordinarily the quantities of calcium carbonate and water available are comparatively large. Calcium is derived also from direct solution of gypsum ($CaSO_4 \cdot 2H_2O$) and other minerals.

Sodium.--Sodium is present in small proportions in some of the silicate minerals in igneous rocks but is not usually in a form that is readily soluble. Localized beds of salt or sodium sulfate exist in some of the rock formations in this part of Arizona but their effect on the ground-water quality is not yet fully known.

Bicarbonate.--The principal anion in the more dilute waters in the area is bicarbonate. It is produced principally by the solution of carbonate in water containing carbon dioxide. Some of the more saline waters in the area have unusually high concentrations of bicarbonate. As pointed out in the preceding discussion of solution of calcium carbonate, the equilibrium can be shifted toward the formation of more bicarbonate when large amounts of carbon dioxide are in solution. Apparently a large supply of carbon dioxide is available to the water circulating at depth in certain of the rock formations in this area. Under the conditions of high pressure existing far below the surface the carbon dioxide dissolves in the water in much greater amounts than under atmospheric pressure, and the resulting solution can carry increased amounts of calcium and bicarbonate.

Several sources of carbon dioxide are possible within the rock formations. Carbon dioxide is given off in soil by the action of plants and the decay of plant materials. These sources are probably not sufficient to account for the high bicarbonate concentrations found in the saline waters of this area. Carbon dioxide is produced also in the biochemical reduction of sulfate. This reaction is of common occurrence deep below the land surface, and, as sulfates probably exist in most of the sedimentary rocks of the area, sulfate reduction may produce enough carbon dioxide to give high bicarbonate concentrations. Another possible source of carbon dioxide, mentioned by Foster (1950, p. 40-41), is the decomposition of organic debris included in the sediments. Owing to the great age of the sediments in the area, this reaction is believed likely to have been completed long ago, and the resulting carbon dioxide removed by percolating water.

Sulfate.--The most probable source of sulfate in ground water of this area is gypsum, which is commonly found in sedimentary rock. Bedded sodium sulfate exists near Camp Verde and is a source of sulfate in ground waters in that vicinity. Oxidation of pyrite and other sulfides may be a source of sulfate in a few localities in the region.

Chloride.--Chloride minerals are present in igneous rock as very minor impurities but are generally soluble so that they can be taken up in circulating water if the rock structure is such that the water can come into contact with the chlorides. Chlorides may be contributed by magmatic or juvenile water, and this source may be a partial cause of the high chloride concentrations observed in some of the springs.

Chemical Character of Water in Relation to Use

Most of the ground water emerging along the south side of the Mogollon Rim would be suitable for irrigation. Most of the water is decidely hard but not sufficiently so that it would interfere greatly with its use for ordinary purposes. Waters depositing travertine and those of high salinity, however, present utilization problems.

The saline springs in the Salt River basin yield some of the most highly mineralized waters in the State. Below the Salt Banks at extreme low river stages, the suitability of the Salt River water for irrigation is questionable because of the high sodium percentage and boron concentrations caused by the inflow from saline springs. The system of large storage reservoirs in which the water of the Salt River is received before its use in the irrigated areas prevents any of the low-flow water from being used directly. In the reservoirs the low flows are diluted with flood inflows and the mixture resulting has been a satisfactory irrigation water. However, as pointed out elsewhere (Halpenny and others, 1952, p. 147-149), the large amounts of salt contributed by the salt springs have to be disposed of eventually in drainage from the irrigated area, and they contribute greatly to the salt-balance problem.

It has been estimated (unpublished data in the files of the U. S. Geological Survey) that 315,000 tons of soluble salt per year is added to the Salt River by spring inflows above Roosevelt Reservoir. This is equivalent to more than 850 tons per day. Obviously the present study has not yet located all the sources of saline inflow, but it has found evidence of saline inflows on White River farther upstream than had previously been reported.

A lesser problem of salt inflow to the upper Gila River system at Clifton Hot Springs has been mentioned earlier in this report and elsewhere (Hem, 1950, p. 34-35). Some comments on the effect of spring inflow on quality of water in the Verde River and Tonto Creek systems are made in the section on surface water in this report.

Deposition of Travertine

A considerable number of springs in the rim region are actively depositing travertine. To deposit calcium carbonate in quantity, a spring water must be supersaturated with respect to calcium bicarbonate when the water issues from the spring opening. The pressure on the water is greatly reduced when it issues from the ground, the lower pressure allows carbon dioxide to escape into the air, and the reaction

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{++} + 2HCO_3^-$$

proceeds to the left. The excess of calcium carbonate is deposited until a new equilibrium with a lower content of calcium and bicarbonate in solution is reached. Several hours may elapse from the time when the water issues from the ground and the time when a new point of equilibrium is reached. Considerable quantities of travertine are deposited at or near the spring openings in the rim region. Spring waters that reach adjacent river channels are diluted with waters of lower mineralization and little or no more deposition takes place. The conditions that favor a high content of calcium bicarbonate and deposition of travertine when pressure is relieved would seem to include high pressure and large supplies of carbon dioxide and calcium carbonate. Such conditions are most likely to exist in deep-seated limestone aquifers.

A water that deposits travertine would require a period of aeration or similar treatment before passing into any system of piping. The deposits that would result if the water were not first allowed to come to equilibrium with air would quickly clog the pipes.

Suggested Lines of Further Investigation

The quality of water of the entire region should be more completely investigated, and samples should be taken from more sources. Several uses for these data are suggested as follows:

1. The chemical quality of water from all aquifers should be more closely determined. These data may aid in identifying the source of the water of springs.
2. The use of analytical results to trace ground-water movement may be capable of a considerable development in this area and would be a helpful supplement to other hydrologic data in studying the water movement.
3. Correlation of quality-of-water and other data for the area near the rim with data gathered farther to the north will help determine which areas may be hydrologically related.
4. Closer study of the salt-spring inflows along the Salt River and tributaries will provide basic data for any possible action program aimed at reducing these inflows to improve salt-balance conditions downstream .
5. Collection of samples at seasonal intervals from certain springs, especially those of large discharge and wide fluctuation, might provide data of value in determining rates of water movement underground, and the volumes of water retained in storage in the aquifers, provided that periodic changes in chemical quality could be correlated with periods of heavy precipitation or of drought, for example. Studies of aquifer characteristics and of geologic controls must be made to correlate with data derived from chemical analyses.

Temperatures of the springs.--The graphs (fig. 22) show the relation between altitude, mean annual air temperature, and temperature of spring water. Only slight differences are apparent between the temperature-altitude gradients of springs discharging less than 25 gallons per minute and those of larger discharge. Spring-water temperatures consistently range a few degrees above mean annual air temperatures at comparable altitudes, a fact that is in accord with Van Orstrand's analysis of more than 3,000 ground-water temperatures as reported by Allen and Day (1935, p. 41, footnote). Van Orstrand found that at depths of 30 to 60 feet ground-water temperatures were generally 2° to 3° F higher than mean annual air temperatures. The constancy of temperatures of most springs in the rim region suggests that waters of the springs examined penetrate at least 50 or 100 feet below land surface in traveling from points of recharge. Lovering and Goode (1951, p. 1461) show that in the Tintic district, Utah, the effects of annual surface-temperature changes were apparent in limestone and quartz latite to depths as great as 20 meters (about 65 feet). However, at 20 meters the change in rock temperature was only 0.2 percent of the seasonal change in surface temperature. Most spring temperatures measured in the Mogollon Rim region diverge only a few degrees from the air-temperature gradient line (fig. 22). In those cases where water temperature is appreciably above the line, penetration to depths sufficient to reflect the influence of the geothermal gradient is assumed to have occurred.

Hypothesis Regarding Origin of Salty Springs

The largest salt-water springs observed in the present study emerge either from volcanic rocks or from pre-Cambrian quartzite injected by diabase. Temperatures of Clifton Hot Springs have been cited as 127° to 160°F, Verde Hot Springs 100° to 105° F, Salt Banks 70° to 78°F, and the White River Salt Springs ranging up to 83°F. The higher temperatures are in the waters issuing from the Clifton and Verde Hot Springs. The possibility that the high temperatures and the relatively high mineralization of waters emerging at those places reflect residual volcanic heat and gases cannot be entirely neglected. The relatively low boron content of Clifton Hot Springs waters accords poorly with the concept that volcanic emanations are a prime source of boron (Allen and Day, 1935, p. 122; Mason, 1952, p. 123), but it does not entirely rule out the possibility. Logan (1951, p. 1505) suggested juvenile water as the source of boron in waters used for irrigation in California basins. The analysis in table 10 for Clifton Hot Springs shows a boron concentration of 0.74 part per million in the water from those springs. In contrast, analyses of water samples from the Salt Banks include two boron determinations of 17 to 26 parts per million, respectively, and a sample from Verde Hot Springs, 7.2 parts.

No volcanic rocks are exposed within many miles of the Salt Banks and the White River Salt Springs (Darton and others, 1924). The temperatures of waters at those springs are also much lower than in those at Clifton and Verde Hot Springs. It therefore becomes necessary to seek an explanation other than volcanism for the abundance of mineral matter in the water, especially of sodium chloride. No bedded salt is known to occur within about 50 miles up-gradient from the salt-spring localities. Verde Hot Springs lie between two lake-bed basins, Payson and Verde. Bedrock barriers intervene in both directions so that it seems unlikely that salts leached from lake beds can be responsible for mineralization of Verde Hot Springs waters.

Deep exploratory wells on the Colorado Plateau in the area between Snowflake and Holbrook have penetrated as much as several hundred feet of salt in the Supai formation. Whether this salt was deposited in local basins or represents beds of wide extent exaggerated in thickness by flowage to form salt domes is not known. In any event, salt has not been reported in any outcrops of the Supai, and no wells penetrating the Supai south of the rim are known to have encountered salt. Therefore, although the Supai formation crops out within 15 or 20 miles of the White River-Salt River springs, it is not now considered to be the source of salt in the spring waters.

There are no known sources to which mineralization of the waters might be directly ascribed. The writer suggests as a tentative hypothesis, therefore, that the dissolved minerals in the waters at all four localities are derived by leaching of the igneous and metamorphic rocks that occur at and near the springs and underlie at depth, large areas tributary to the saline springs, and that some of the dissolved solids may be derived from the partly serpentinized Mescal limestone in the Apache group present in the area. Clarke (1924, p. 15, 20) states that sodium, chloride, and strontium are commonly present in minerals that make up igneous rocks, and indicates (p. 252) that boron may be derived by leaching of boro-silicates, such as tourmaline and dumortierite, which occur in granites and in some gneisses. Rankama and Sahama (1950, p. 486) note the relative abundance of boron in "ultrabasic serpentine rocks." Serpentinized rocks are abundant in the area of the salt banks on the Salt River, although they are absent near Clifton Hot Springs so far as is known. It thus appears possible that the high boron content of waters at the Salt Banks may be derived from leaching of serpentine during slow passage of the waters through the rocks. Wahlstrom (1947, p. 311) states that the average Na_2O content of diabase is 2.8 percent. Kent (1949, p. 235-237) lists the occurrence of numerous warm springs and hot springs in association with dolerite and diabase[2/] dikes in the Union of South Africa. Tables of analyses of waters from thermal springs and boreholes (Kent, 1949, p. 240) indicate that, in South Africa, waters having a relatively high sodium chloride content are most commonly derived from granites, norites, and Archean gneisses. Some of these waters, notably those of the Evangelina and the Buffelshoek Springs in Transvaal, issue from an association of pre-Cambrian granite and gneiss with "diabase" dikes.

Mason (1952, p. 217) states that albite is one of the principal sodium-bearing minerals found in metamorphic rocks. Tyrrell (1929, p. 174-175) suggests that in the decomposition of oligoclase in granite, for example, sodium "goes into solution as carbonate, chloride, etc..." and indicates that comparable processes occur during chemical weathering of all igneous rocks. He further states that rocks of basic composition yield more soluble products than the acidic igneous and metamorphic rocks.

It appears, then, that decomposition of the pre-Cambrian granite underlying the quartzite, and decomposition of the Cambrian(?) diabase injecting the quartzite at the Salt Banks and at the White River Salt Spring, might explain the presence of the constituents in the spring waters, including boron, and the strontium in the travertine at Salt Banks. It remains difficult, however, to account for the high concentration of dissolved mineral increment from hot, highly mineralized waters occurring at great depth in a zone of little circulation, as is suggested by Thomas (H. E. Thomas, personal communication, June 5, 1953).

2/ The British "dolerite" is the equivalent of the American "diabase;" the British "diabase" is the equivalent of the American "altered diabase" (Tyrrell, 1929, p. 120-121).

The fact that at the Salt Banks some seeps and springs emerge at the contact of quartzite over diabase suggests a possibility worthy of consideration. The recharge area is visualized as being a considerable distance from the springs. It is assumed that the water travels slowly, penetrating at least 500 feet and probably much farther below the land surface. It is probable that the water temperatures are higher at depth than at the orifices, because the water is cooled during slow upward movement from points of maximum penetration. Being, then, warm and partly mineralized the water actively leaches minerals in the igneous and metamorphic rocks through which it passes. The sills of diabase may form a lower confining member not directly related to the regional water table if the sills lie in trough-like or synclinal positions. The diabase intrusion may act as a ground-water dam, causing water percolating down an ancient granitic surface beneath sedimentary rocks to rise to the surface as pictured by Kent (1949, fig. 2 B).

The preceding hypothesis might also be applied to the White River Salt Springs.

A comparable series of conditions and processes may explain both the temperature and mineralization of the waters in Clifton and Verde Hot Springs. In these localities, however, retained volcanic heat and gases may be involved.

At all four localities there may be some juvenile water rising along deep fault zones. A combination of two or more of the suggested possibilities, or factors as yet unknown, may ultimately prove to be the source of heat and mineralization.

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Table 3. --Monthly mean discharge at selected stations and related climatological data.

Month.	Total precipitation at weather station (inches)	Monthly precipitation over the area (cfs)	Monthly mean discharge (cfs)	First and last killing frost (Date, and temp. °F)
SALT RIVER NEAR CHRYSOTILE--Drainage area 2,830 square miles, Weather station--McNary				
Oct. 1948	3.38	8,300	120	Oct. 24, 30°
Nov.	.05	120	141	Nov. 5, 22°
Dec.	4.89	12,000	405	
Jan. 1949	4.35	10,700	1,441	
Feb.	2.00	5,200	712	
Mar.	1.88	4,600	2,014	
Apr.	.73	1,900	2,636	
May	.49	1,200	1,150	May 9, 30°
June	1.52	3,900	437	
July	7.49	1,800	464	
Aug.	3.09	7,600	501	
Sept.	2.74	6,900	185	
OAK CREEK NEAR CORNVILLE--Drainage area 357 square miles, Weather station--Flagstaff				
Oct. 1942	1.00	310	26.1	Oct. 14, 27°
Nov.	0.24	77	29.8	
Dec.	1.38	430	36.4	
Jan. 1943	3.26	1,000	48.8	
Feb.	1.24	410	178	
Mar.	1.66	510	393	
Apr.	1.18	370	35.0	
May	0.18	56	17.1	
June	0.15	48	13.7	June 11, 32°
July	1.72	530	14.7	
Aug.	2.45	760	35.5	
Sept.	1.67	530	27.2	
WHITE RIVER NEAR MCNARY--Drainage area 74 square miles, Weather station--McNary				
Oct. 1945	2.06	130	18.5	Sept. 25, first freeze
Nov.	0.07	4.8	16.2	
Dec.	3.72	240	16.1	
Jan. 1946	2.02	130	15.0	
Feb.	1.10	76	15.0	

Table 3. --Monthly mean discharge at selected stations and related climatological data--continued.

Month	Total precipitation at weather station (inches)	Monthly precipitation over the area (cfs)	Monthly mean discharge (cfs)	First and las killing frost (Date, and temp. °F)
WHITE RIVER NEAR MCNARY (Continued)				
Mar.	2.05	130	38.5	
Apr.	2.16	140	67.3	
May	T	T	44.5	
June	T	T	17.4	June 29, 28°
July	3.54	230	15.5	
Aug.	4.80	310	44.2	
Sept.	5.32	350	123	
VERDE RIVER NEAR CAMP VERDE--Drainage area 5,000 square miles, Weather station--Jerome				
Oct. 1942	0.50	2,200	158	
Nov.	0.10	430	179	
Dec.	1.32	5,700	219	Dec. 5, firs freeze
Jan. 1943	2.71	11,800	247	
Feb.	1.27	8,500	570	
Mar.	2.07	9,000	1,468	
Apr.	1.16	5,200	190	Apr. 11, last freeze
May	0.01	42	103	
June	0.06	270	82.0	
July	0.32	1,400	84.2	
Aug.	3.64	15,800	284	
Sept.	1.93	8,700	147	
TONTO CREEK ABOVE GUN CREEK--Drainage area 678 square miles, Weather station--Pinedale				
Oct. 1942	3.90	2,300	16.7	Oct. 15, 32°
Nov.	0.21	120	22.0	
Dec.	2.64	1,600	54.2	
Jan. 1943	1.96	1,200	260	
Feb.	0.64	400	151	
Mar.	1.10	650	469	
Apr.	0.25	170	52.3	
May	0.47	280	19.1	May 20, 26°
June	0.33	200	5.1	June 15, 31°
July	2.73	1,600	1.69	
Aug.	3.43	2,000	34.2	
Sept.	1.95	1,200	15.9	

Table 4.--Median annual minimum discharge at selected stations and total minimum surface flow at five stations.

Stream	Median annual minimum flow (cfs)
Salt River near Chrysotile	100
Oak Creek near Cornville	11 a/
White River near McNary	10 b/
Verde River near Camp Verde	74
Tonto Creek above Gun Creek	.8
TOTAL	175

a/ Tributary of Verde River; not included in total
b/ Tributary of Salt River; not included in total

Table 5. --Comparison of discharge, temperature, and chemical quality of waters in Tonto Creek and tributaries, from headwater spring to 1 mile above mouth.

Spring or Creek no.	Location	Discharge a/ (gallons per minute)	Date of collection	Temperature (°F.)	Parts per million: Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C.)
(A-12-12)																	
33baa	Tonto Creek headwater spring	900 M	10/17/52	48	8.7	26	7.6	0.7	111	3.1	2	0.2	0.3	104	96	2	174
(A-11-12)																	
16bdc	Horton Creek near Tonto	100 E	10/17/52	52	10	40	9.6	.7	144	19	1	.4	.8	152	140	1	263
26d	R-C Spring	1,000 M	5/14/52	48	8.9	43	9.0	2.3	163	13	1	.1	.4	158	144	3	275
(A-10½-12)																	
24aaa	Bear Flat Spring	6 M	10/20/52	62	15	54	13	2.3	227	2.3	3	.2	.0	202	188	3	348
24ad	Tonto Creek at Bear Flat	2,050 M	10/20/52	58	7.8	50	16	.2	213	12	3	.2	.3	194	191	0	351
(A-9-11)																	
18c	Tonto Creek at Gisela Ranches	2,200 E	10/23/52	62	11	48	17	46	211	10	74	.4	.3	311	190	34	571
(A-8-10)																	
13ca	Tonto Creek at 76 Ranch	1,500 Eb/	10/16/52	72	-	-	-	-	205	-	69	-	-	-	-	-	552
13cb	Rye Creek at 76 Ranch	450 E	10/16/52	75	25	70	14	20	288	15	16	.4	.2	303	232	16	500

a/ M, measured; E, estimated.
b/ Diversions of 1,000 to 1,500 gallons per minute.
c/ Below gaging station.

Table 5. --Comparison of discharge, temperature, and chemical quality of waters in Tonto Creek and tributaries--continued.

Spring or Creek no.	Location	Discharge (gallons per minute)	Date of collection	Temperature (°F.)	Parts per million												Percent sodium	Specific conductance (micromhos at 25° C.)
					Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$			
(A-7-10) 10c	Tonto Creek, 14 mi. above mouth	1,000 Ec/	10/16/52	80	16	48	13	27	196	13	40	.4	.3	254	174		25	449
(A-5-11) 8c	Tonto Creek, 1 mi. above mouth	580 M	10/23/52	76	20	64	16	24	208	62	30	.4	.1	318	226		19	520

Table 6. --Comparison of discharge, temperature, and chemical quality of waters in Verde River and Oak Creek, from near head of Verde basin to below mouth of Oak Creek.

Spring or Creek no.	Location	Discharge a/ (gallons per minute)	Date of collection	Temperature (°F.)	Parts per million: Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25° C)
VERDE RIVER																	
(A-17-3) 7c	1 mile upstream from Sycamore Canyon	8,000 E	12/13/52	55	21	49	25	30	316	11	14	0.4	0.9	306	226	23	514
(A-15-4) 21cb	Oak Creek about ¼ mile above mouth	37,000 M	12/14/52	52	16	51	24	13	281	4.9	13	.2	.3	260	226	11	448
(A-14-4) 4	About 1 mile below Oak Creek	50,000 E	12/16/52	46	15	56	31	27	314	45	15	.2	.4	344	267	18	576
(A-13-5) 35	About 18 miles below Oak Creek	50,000 E	12/11/52	48	21	59	35	33	324	66	20	.4	.5	394	291	20	643

a/ M, measured; E, estimated; R, reported.

Table 6. --Comparison of discharge, temperature, and chemical quality of waters in Verde River and Oak Creek--continued.

Spring or Creek no.	Location	Discharge a/ (gallons per minute)	Date of collection	Temperature (°F.)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (Micromhos at 25°C.)
AREA OF MAJOR SPRING INFLOW ALONG OAK CREEK																	
(A-16-4																	
14d	Oak Creek about 14 mi. above mouth	11,800 M	12/15/52	48	15	38	19	5.5	215	3.1	4	.2	.1	191	173	6	327
15da	Bubbling Pond	4,125 M	12/11/51	67	17	56	24	9.2	275	5.1	18	.2	1.1	266	238	8	470
15dd	Turtle Pond	160 M	2/12/52	66	18	48	21	6.2	246	3.9	10	0	0.8	229	206	6	404
16ddd	Head of Spring Creek	125 E	12/11/51	70	13	65	27	14	306	5.6	32	0	1.1	309	273	10	561
23d	Page Fish Hatchery Springs	14,000 R	8/4/49	68	18	42	19	8.7	227	3.7	8	0	.8	212	183	9	364
33b	Sheepshead Canyon Springs	65 M	7/9/52	71	17	70	29	17	341	5.6	31	.2	.8	339	294	11	595
34bb	Frizell Ranch Spring	5 E	7/9/52	66	17	78	32	13	366	6.6	34	0	.2	361	326	8	641

Table 7. --Summary of maximum aggregate discharge of springs visited prior to December 1952.

Relation to Mogollon	Discharge (gallons per minute)	Source rock	Discharge (gallons per minute)
South-flowing springs		Tertiary or Quaternary	
Western division	31,000	Basalt	14,300
Central division	34,000	Verde formation	100
Eastern division	14,000	Permian	
Total	79,000	Kaibab limestone	100
North-flowing springs	8,000	Coconino sandstone	1,200
TOTAL	87,000 a/	Supai formation	33,200
		Carboniferous	
		Naco formation	3,400
		Redwall limestone	24,900
		Devonian and Cambrian	7,600
		Pre-Cambrian	2,100
		Other	100
		TOTAL	87,000

a/ Equivalent to approximately 142,000 acre-feet per year.

Table 8. --Records of springs in or near the Mogollon Rim region.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
WESTERN DIVISION							
(A-16-4)							
15da	Frey Ranch Springs	2-12-52	Alluvium	F	60 M	66	A.
15da	Tree-Root Springs	7-9-52	Supai formation	F	260 M	71	
15da	Bubbling Pond	12-11-51	do.	-	4,125 M	67	A.
15dd	Turtle Pond	2-12-52	do.	F	160 M	66	A.
16ddd	Springs on Spring Creek	2-12-52	Alluvium, Verde formation and basalt	F	2,700 M	67	A.
23d	Page Fish Hatchery Springs	2-13-52	Supai formation (?)	F(?)	8,000-9,000 M	68	A.
33b	Sheepshead Canyon Springs	7-9-52	Verde formation	C	65 M	71	A.
34bb	Frizell Ranch Springs	7-9-52	do.	-	5 E	66	A.
(A-17-3)							
5	--	10-10-51	Redwall limestone	-	15 E	66	
5dbd	Summer's Spring	10-10-51	do.	-	2,700 M	67	A. Discharge measured 12-12-52, 2,250
(A-18-3)							
32a	--	10-10-51	Redwall limestone	C	-	77	Seep; too small to measure.

a/ See figure 24 for explanation of spring numbering system.
b/ F, fault spring; C, contact spring.
c/ M, measured; E, estimated; R, reported.
d/ A, see analysis in tables 5, 6, or 10.

Table 8.--Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/(gallons per minute)	Temperature (° F.)	Remarks d/
(A-18-6)							
5a	--	8-18-49	Supai formation	-	750 E	55	Record by P. W. Hughes
5b	Hummingbird Spring	8-18-49	do.	F	25 E	55	do.
5bc	--	8-18-49	do.	-	50 E	55	do.
7a	--	8-18-49	do.	F	15 E	55	do.
27ccc	Indian Gardens	2-14-52	Supai formation(?)	F	115 M	58	
34bb	Thompson Pasture Springs	2-14-52	do.	F	180 M	57-60	
(A-19-4)							
2ac	Dorsey Spring	8-11-49	Basalt	-	-	-	Reported by P. W. Hughes
(A-19-5)							
9aa	Lockwood Spring	8-5-49	--	-	1 E	50	Reported by D. G. Metzger
13cc	--	8-25-49	Coconino(?) sandstone	-	1 E	52	Reported by P. W. Hughes & J. H. Feth
22ba	--	8-30-49	--	F	-	54	Reported by J. H. Feth & D. G. Metzger
30c	Barney Spring	8-25-49	Coconino sandstone	-	1/8 M	47	Reported by D. G. Metzger
(A-19-6)							
15d (2)	--	8-13-49	Coconino sandstone	C	21 M	52	Do.
15d (3)	#3 in Oak Creek	8-13-49	do.	-	15 E	52	do.
22d	--	8-13-49	do.	-	182 M	54	do.

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-19-6)							
34b	Grassy Meadow Spring	8-17-49	Supai formation	-	1 E	54	Reported by P. W Hughes
34c	Lelani Spring	8-17-49	Supai (?) formation	F	30 E	55	Do.
(A-20-4)							
3bc	Lower Hulls Spring	8-10-49	Basalt	-	-	51	Reported by D. G Metzger & P. W Hughes
9aab	Poison Spring	8-31-49	Basalt	-	20 E	52	
10c	Grey's Spring	7-29-49	Alluvium and basalt	-	-	60	
35a	Babes Hole Spring	7-29-49	Kaibab limestone	F	1 E	50	
35aa	Kelsey Spring	8-10-49	Basalt	-	-	-	Reported by D. G Metzger and P. Hughes
(A-20-6)							
3b	Woody Spring	8-1-49	Basalt and tuff	-		-	Reported by J. F Feth & D. G. Metzger
8ca	Aspen Spring	7-29-49	Basalt	-	-	46	Reported by D. G Metzger
12dc	Landon Spring	7-29-49	--	-	-	-	Do.
(A-21-4)							
32daa	Little L. O. Spring	8-31-49	Alluvium and basalt	-	1 E	52	

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temp-erature (°F.)	Remarks d/
(A-21-5)							
3bcc	Navajo Ord. Depot Spring in "O" Area	8-9-49	Basalt	-	5 E	50	Reported by D. G Metzger and P. W. Hughes
4ba	Navajo Ord. Depot Indian Camp Springs	8-9-49	do.	-	-	-	Do.
10aa(1)	Navajo Ord. Depot Spring #2	8-9-49	Volcanic rocks	-	60 E	48	Do.
10aa(2)	Navajo Ord. Depot Spring #3	8-9-49	do.	-	-	-	Do.
11ab	Navajo Ord. Depot Spring #1	8-9-49	Basalt and Recent gravel	C	100 R	48	
(A-21-6)							
21bc	--	8-18-49	Volcanic rocks	-	3 E	48	Reported by D. G. Metzger
21bd	--	8-18-49	do.	-	1 E	47	Do.
28ca	Fisher Spring	8-18-49	do.	-	1 E	51	Do.
31cc	Patterson Spring	7-29-49	Basaltic soil	-	Dry when visited	-	
EASTERN DIVISION							
(D-1-24)							
16	Tule Spring	3-20-51	--	-	20 E	-	
(D-1-25)							
30	Arsenic Cave Spring	3-20-51	Volcanic agglomerate	-	2 E	71	

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(D-4-30)							
30db	Clifton Hot Springs Group	10-29-40	Volcanic rocks	F	1 E	120	A. Reported by J D. Hem
30db	Do.	8-11-41	Do.	-	2 E	105	Do.
30db	Do.	10-29-40	Do.	-	1 E	100	Do.
(A-4-27)							
20b	Ess ("S") Spring	6-18-52	Basalt	C	200 M	58	A.
(A-4½-20)							
35ad	White River Salt Springs	9-20-51	Cambrian sandstone and Apache group quartzites	F(?)	10 E	83	A. Salty taste
36b	Do.	9-20-51	Do.	C	30 E	-	
36c	--	9-20-51	Devonian (?) limy sandstone	C	875 M	76	
(A-5-24)							
18	--	2-19-52	Supai formation	-	40 M	45	Reported by S. F Turner and J. H Feth
(A-5-29)							
27aa	Gillard Hot Springs	11-18-40	Alluvium	F	100 E	181	Reported by J. D Hem
(A-6-23)							
4c	Columbine Terrace Springs	5-21-52	Supai formation (Fort Apache limestone of Stoyanow)	-	9,000 E	-	A. Discharge measured 6-52, 7,650
17	"OldFarm Springs"	5-20-52	Alluvium	-	-	53	
(A-7-23)							
3	Bull Cienega Spring	5-21-52	Basalt	C	2 E	54	

Table 8. --Records of springs in o[illegible] the Mogollon Rim region--[illegible]nued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-8-22)							
11ccc	Amos Ranch "Big Spring"	6-20-52	Basalt	C	150 E	54	
(A-8-23)							
24cd	Gov't Spring Sump	6-18-46	--	-	75 M	49	Reported by L. C. Halpenny and R. S. Jones
24cd(2)	Gov't Spring	6-18-46	Basalt	-	40 E	-	Do.
24cd(3)	Gov't Spring #4	6-18-46	Do.	-	20 E	-	Do.
24cd(4)	Gov't Spring	6-18-46	Do.	-	20 E	--	Do.
25aa	Gomez Spring	6-18-46	Recent mud	-	200 R	70	Do.
27aa	Upper Bull Cienaga Spring	6-20-52	Basalt	-	100 E	50	
(A-8-24)							
19aa	Haystack #1	6-18-46	Basalt	-	40 E	52	Reported by L. C. Halpenny and R. S. Jones
19ab	Haystack #2	6-18-46	Do.	-	20 M	49	Do.
19cb	Earl Spring #3	6-18-46	Do.	C	20 E	49	Do.
21aa	--	6-20-46	Do.	-	100 E	47	Do.
23d	Boy Spring	12-7-51	Do.	C	5 M	42	Discharge measured 5-20-52, 200 (snowmelt)
27ab	Blue Lake	6-13-52	Do.	-	-	63	--
27ac	--	5-19-52	Do.	-	260 M	51	
27ac	Williams Springs	6-18-46	Do.	-	1,260 R	52	Discharge measured 5-20-52, 2,350.

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-8-25) 3c	Gooseberry Creek Spring	5-22-52	Basalt	C	1,200 M	43	Discharge measured 6-23-52, 715
(A-8-26) 26dc	Sheep Springs	5-22-52	Do.	C	60 M	44	
CENTRAL DIVISION							
(D-2-16) 14	Spring Branch Ranch Creek	5-8-51	Limestone and Basalt	-	2 E	72	
(A-1-15) 26aa	Maurel Spring	4-11-46	Alluvium	-	50 M	64	Reported by L. C. Halpenny
(A-1-20) 12	Cold Spring at Warm Springs	3-2-51	Alluvium	-	2 E	60	
12	Warm Springs	3-13-51	Naco formation	-	3,350-3,400 M	85	Reported by R. L. Cushman and W. H. Wilson
(A-2-19) 10b	--	11-6-51	--	-	-	67	Reported by R. L. Cushman and W. H. Wilson
18	Cassadore Springs	3-13-51	Apache group quartzite	C	35 E	67	A. Do.
(A-3-16) 6	Rock Spring	5-18-52	See "Remarks"	-	5 E	59	A. Issues from are of granite, diabas and alluvium.

Table 8.--Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-5-16) 13	Salt Banks (on Salt River)	12-8-51	Apache group quartzite intruded with diabase	-	-	70-78	A.
(A-5-19) 34	Warm Spring on Salt River	9-21-51	Redwall limestone	F	1,180 M	70	
(A-10½-12) 24aaa	Bear Flat Spring	10-20-52	Volcanic rocks	-	6 M	62	A.
(A-11-6) 3b	Verde Hot Springs	12-10-51	Volcanic rocks	F	10 E	100-106	A. Saline. Resor lodge; bathing, drinking
(A-11-9) 5cd	Natural Bridge	7-26-46	Cambrian sandstone	-	-	63	Reported by K. K Kendall
5dc	--	7-26-46	Do.	-	-	67	
(A-11-10) 4c	Springs in Lower Webber Canyon	10-22-52	Redwall limestone	F	1,300 M	49	
9b1	The Grotto Spring	5-15-52	Martin formation	-	350 M	58	Discharge measu 7-10-52, 10.
9b2	Big Spring	5-15-52	Alluvium	-	175 M	58	A. Disch. measured 7-10-52, 1C
(A-11-11) 13dcc	Wildcat (Arsenic) Spring	10-20-52	Martin formation	-	5 E	60	

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-11-12)							
16bac	Henturkey Spring	10-17-52	Martin formation	-	60 M	51	
20	Indian Gardens	5-17-52	Redwall limestone	-	-	58	A.
26d	R-C Spring	5-14-52	Troy quartzite	-	800 E	48	A.
34dd	Columbine Spring	10-20-52	Pre-Cambrian volcanic rocks	-	5 E	-	
(A-11½-9)							
23	Red Rock Spring	7-22-46	Supai formation	-	3 E	60	Reported by K. K. Kendall
30	Oak Spring	7-25-46	--	-	3 E	66	Do.
(A-11½-11)							
30dc	Cold Spring	5-17-52	Martin formation	F	4,200 M	55	A. Discharge measured 7-11-52, 1,060; 11-11-52, 830
(A-12-7)							
14	Fossil Creek Springs	2-15-52	Redwall limestone	F	18,600 M	70	A.
22	--	7-28-46	--	-	5 E	69	Reported by K. K. Kendall
(A-12-8)							
23	Strawberry Spring	7-24-46	Coconino sandstone	-	1 E	58	Do.
26da	--	7-24-46	Supai (?) formation	-	1 E	60	Do.
35c	Cottonwood Spring	7-18-46	Do.	-	1 E	56	A. Reported by K. K. Kendall
(A-12-9)							
8	Parsnip Spring	7-23-46	Supai (?) formation	-	10 E	52	Reported by K. K. Kendall
30dd1	Dripping Springs	7-19-46	Do.	-	3 E	56	Do.

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-12-10)							
11cb	Washington Park Spring	10-18-52	Coconino sandstone	-	10 E	52	
11cc	McGee Spring	10-18-52	Alluvium	-	2 E	51	A.
14a	East Verde Spring	10-18-52	Coconino sandstone	-	125 E	52	A.
34	"Burned House Springs"	10-18-52	Martin formation	-	100 E	58	
(A-12-12)							
32(1)	Winters No. 1 - Domestic	5-16-52	Coconino sandstone	-	1 E	47	
32(2)	Winters No. 2	5-16-52	Do.	-	2 E	51	
32(3)	Winters No. 3	5-16-52	Kaibab (?) limestone	-	20 M	47	
33baa	Tonto Spring	10-17-52	Coconino sandstone	-	900 M	48	A.
(A-16-8)							
16a	Foster Spring	10-11-51	Basalt	C	-	-	
NORTH FLOWING							
(A-8-23)							
4ab	Pinetop Spring	6-19-46	Basalt	C	350 E	50	Reported by L. C Halpenny and R. S. Jones
4ba	Halleck Spring	6----52	Do.	C	5 E	49	
(A-8-26)							
5c	C. C. Hall Spring	6-23-52	Basalt	-	6 M	43	
5ccb	C. C. Cabin Spring	6-23-52	Do.	-	5 M	43	
(A-9-22)							
36a	Big Spring (near Lakeside)	2-20-52	Basalt	-	1,100 M	53	
36ad	Walnut Spring	6-23-52	Do.	-	225 M	52	

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-9-23)							
18ad	Paige Spring	6-16-52	Basalt	-	300 M	54	A.
23c	Pat Mullen Spring	6-11-52	Cinders	-	- -	-	Seep; water in pools no visible flow.
26db	Whitcomb Spring	6-11-52	Basalt	C(?)	40 E	50	
26dc	Chipmunk Spring	6-11-52	Do.	-	4 M	48	
34cba	Thompson Spring	6-11-52	Do.	-	20 E	49	
(A-9-24)							
21ddd	Danstone Spring	6-13-52	Basalt	C	38 M	48	A.
26bdc	McCormick Spring	6-13-52	Do.	-	1 E	50	
26cc	Los Burros Springs	6-11-52	Do.	-	25 M	46	
28cb	Telephone Spring	6-13-52	Do.	-	2 E	48	
(A-11-18)							
27ab	Trough Springs	11-7-52	Alluvium	-	1 E	54	
(A-11-23)							
19a	Bourdon Ranch Spring	6-25-52	Basalt	C	100 E	59	Weedy and covered with tules.
20d	Silver Spring	2-14-52	Do.	C	2,100 M	60	A. Discharge measured 6-12-52, 3,22
(A-12-21)							
25da	Old Mill Spring	3-12-51	--	F	-	65	
(A-12-22)							
31bd	E. Shumway Spring	3-12-51	--	-	-	63	
33ac	--	12-12-50	Basalt	-	-	-	
(A-12-26)							
19	Concho Springs	12-6-51	--	-	1,100 M	59	

Table 8. --Records of springs in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temperature (°F.)	Remarks d/
(A-13-9)							
14	Clover Spring	11-10-52	Kaibab (?) limestone	-	20 E	46	
21	Little Pivot Rock Spring	7-28-46	Do.	-	-	48	Reported by K. K. Kendall
(A-20-6)							
13cc	Fulton Spring	7-29-49	Basalt	-	8 M	50	Reported by D. G. Metzger
(A-20-7)							
7ad	Black Spring	8-1-49	Do.	-	-	50	Reported by J. H. Feth and D. G. Metzger
(A-21-3)							
23acb	Buck Springs	8-31-49	Do.	F	Dry when visited	-	
(A-22-6)							
13a	Little Leroux Spring	9-30-49	Basalt	-	-	-	Reported by P. W. Hughes
14a	Leroux Spring	9-30-49	Do.	-	25 R	48	Do.
18d	Maxwell Spring	9-30-49	Do.	C	-	-	Do.
18dc	--	9-26-49	Alluvium	-	-	51	Do.
(A-22-7)							
25dd	--	8-27-49	Redwall (?) limestone	C	1 E	-	Reported by field party
(A-22-8)							
19db	Little Elden Spring	10-11-50	Latite, porphyry	-	-	-	Stagnant puddle
31b	--	10----50	Supai formation	F	1 E	-	
(A-31-2)							
13	Indian Gardens	2-21-51	--	-	150-200 R	-	-

Table 8. --Records of spring in or near the Mogollon Rim region--continued.

Spring no. a/	Name	Date first examined	Water-bearing formation	Type of spring b/	Discharge c/ (gallons per minute)	Temp-erature (°F.)	Remarks d/
(A-32-7)							
	Blue Spring	6-14-50	Redwall limestone	-	200 M	69	A. Reported by P. W. Hughes and J. A. Baumgartner
(A-35-5)							
	Vasey Spring	5-17-50	Redwall limestone	-	2,400 M	60	Reported by J. A. Baumgartner, L. C. Halpenny, and P. W. Hughes
(B-33-4)							
	Havasu Springs	6-14-51	Redwall limestone	F	26,700 M	-	Reported by J. A. Baumgartner, D. G. Metzger, and J. L. Hatchett
9	--	5-20-50	Do.	-	200 E	70	Reported by P. W. Hughes and J. A. Baumgartner
10	--	5-20-50	Do.	-	10 E	68	Reported by P. W. Hughes
15	--	5-20-50	Supai formation	-	100 E	67	Do.
26	Headwater Spring (Havasu)	5-21-50	Alluvium	-	20,000 E	66	Do.

Table 9. --Fluctuations in discharge of selected springs in Mogollon Rim region.

Spring no.	Name	Measured discharge in gallons per minute						
		1946	1947	1948	1949	1950	1951	1952
(A-1-20) 12	Warm Springs	-	-	-	-	-	4/11-3, 325a/	2/21-3, 400a/
(A-8-23) 4ab	Pinetop Spring	6/19-350	-	-	-	-	-	2/19- 265
(A-8-24) 23d	Boy Spring	-	-	-	-	-	12/7- 5	5/19- 200
(A-8-25) 3c	Gooseberry Creek Spring	-	-	-	-	-	-	5/22-1, 200
		-	-	-	-	-	-	6/23- 715
(A-9-22) 36a	Big Spring(near Lakeside)	-	-	-	-	-	-	2/20-1, 100
		-	-	-	-	-	-	5/22-1, 030
(A-11-10) 9b1	The Grotto Spring	-	-	-	-	-	-	5/15- 350
		-	-	-	-	-	-	7/10- 10
9b2	Big Spring	-	-	-	-	-	-	5/15- 175
		-	-	-	-	-	-	7/10- 100
(A-11-23) 20d	Silver Spring	-	-	-	-	-	-	2/14-2, 100
		-	-	-	-	-	-	6/12-3, 220
(A-11½-11) 30dc	Cold Spring	-	-	-	-	-	-	5/17-4, 200
		-	-	-	-	-	-	7/11-1, 060
		-	-	-	-	-	-	11/11- 830

a/ Measured by personnel of Surface Water Branch, Geological Survey.
b/ Measured about 10 miles upstream from previous measuring point.

Table 9.--Fluctuations in discharge of selected springs in Mogollon Rim region--continued.

Spring no.	Name	Measured discharge in gallons per minute 1946	1947	1948	1949	1950	1951	1952
(A-12-7)								
14	Fossil Creek	6/12-19,125a/	6/26-19,200a/	-	-	-	-	2/15-18,600b/
	Spring	-	-	-	-	-	-	7/10-18,620b/
(A-12-26)								
19	Concho Springs	6/17- 1,325a/	6/12- 1,275a/	6/22-1,125a/	6/28-1,100a/	7/17-1,175a/	12/6-1,120	6/19- 1,120
		-	-	-	-	-	6/18-1,300a/	6/29- 1,050a/
(A-16-4)								
15da	Treeroot							
	Spring	-	-	-	-	-	-	2/12- 380
		-	-	-	-	-	-	7/9 - 260
15da	Bubbling Pond	-	-	-	-	-	12/11-4,125	2/12- 3,500
		-	-	-	-	-	-	7/9 - 4,150
		-	-	-	-	-	-	12/10-4,100
15dd	Turtle Pond	-	-	-	-	-	-	2/12- 160
		-	-	-	-	-	-	7/9 - 135
		-	-	-	-	-	-	12/10- 160
16ddd	Springs on							
	Spring Creek	-	-	-	-	-	-	2/12- 2,700
		-	-	-	-	-	-	7/9 - 2,400
		-	-	-	-	-	-	12/10-2,950
(A-17-3)								
5dbd	Summer's	-	-	-	-	-	10/10-2,700	2/16- 2,375
	Spring	-	-	-	-	-	-	6/18- 2,350
		-	-	-	-	-	-	12/12-2,275
(A-20-6)								
13	Sycamore Canyon at Packard Ranch	7/10- 5,125a/	6/24- 4,950a/	-	-	6/28-4,875a/	6/13-4,550a/	6/18- 5,000a/
13cc	Fulton Spring	-	-	-	7/29- 8	-	-	7/8 - 10

Table 10. --Analyses of water from representative springs in the Mogollon Rim region.

Spring no. a/	Name	Date of collection	Parts per million: Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25°C.)
WESTERN DIVISION															
(A-16-4) 15da	Frey Ranch Spring	2-12-52	15	61	26	16	287	6.4	36	0.0	1.4	303	259	12	54
15da	Bubbling Pond	12-11-51	17	56	24	9.2	275	5.1	18	0.2	1.1	266	233	8	47
(A-17-3) 5dbd	Summer's Spring	10-10-51	15	72	27	5.8	341	7.6	10	.2	1.5	307	290	4	54
EASTERN DIVISION															
(D-4-30) 30db	Clifton Hot Springs	1-10-44	58	860	41	2,750 b/	109	153	5,800	3.0	7.5	9,790 c/	2,310	70	16,50
(A-4-27) 20b	Ess ("S") Spring	6-18-52	25	13	5.7	4.1	69	5.6	1	.4	.1	89	56	14	11
(A-4½-20) 35ad	White River Salt Springs	9-20-51	22	384	103	2,730 d/	1,020	265	4,420	.5	-	8,450	1,380	80	13,90
(A-6-23) 4c	Columbine Terrace Springs	6-24-52	16	117	24	7.8	230	204	4	.4	.0	486	390	4	71

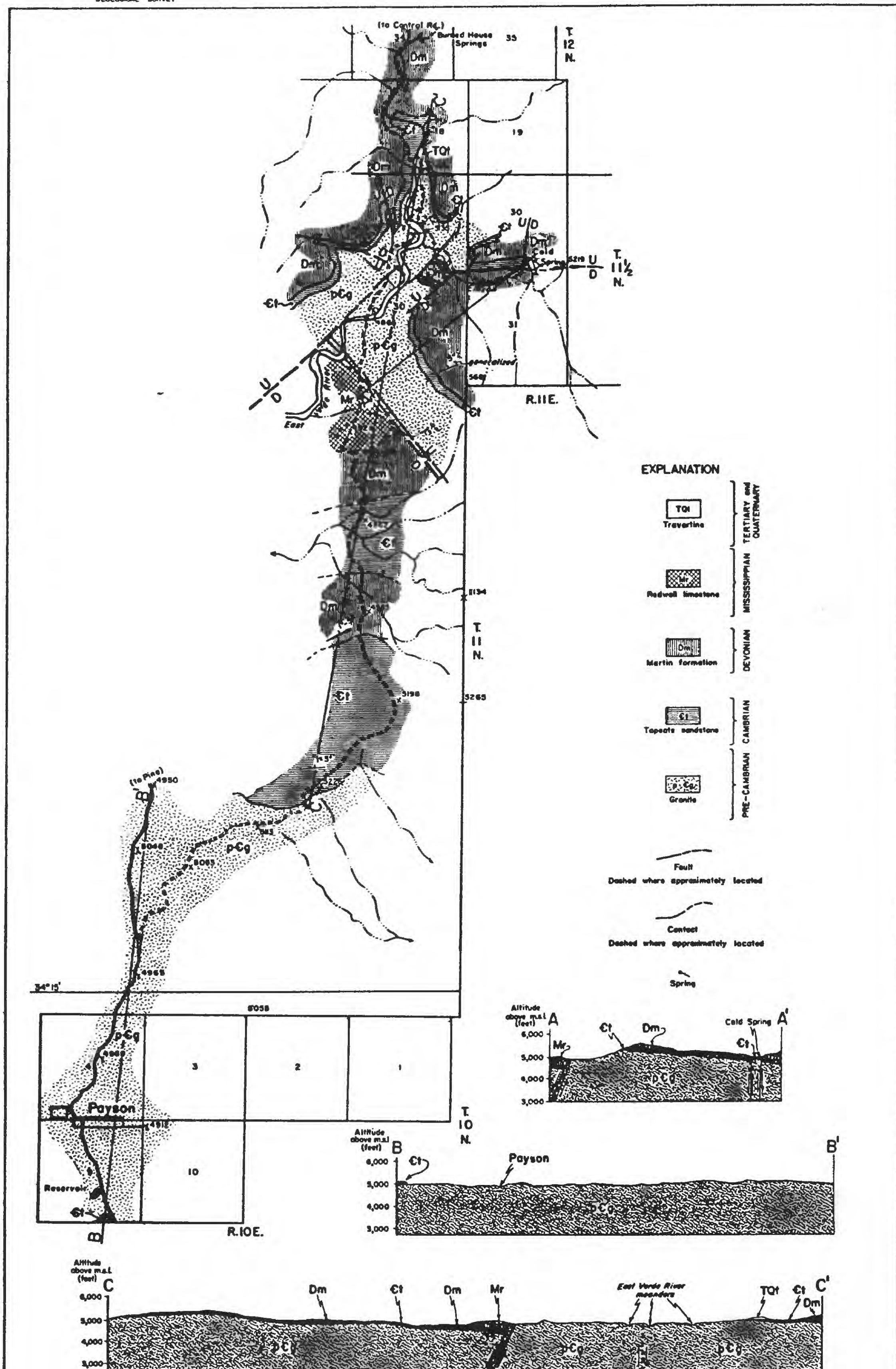
Table 10.--Analyses of water from representative springs in the Mogollon Rim region--continued.

Spring no. a/	Name	Date of collection	Parts per million: Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25°C.)
CENTRAL DIVISION															
(A-2-19) 18	Cassadore Spring	3-13-51	30	51	21	20	285	5.8	10	0.4	1.9	280	214	17	464
(A-5-16) 13	Salt Banks - Green Seep	12-8-51	45	496	286	10,000 e/	1,490	882	15,900	-	-	28,400f/	2,410	89	41,500
13	Salt Banks - Orange Spring	12-8-51	15	549	249	13,500 g/	2,020	1,130	20,800	-	-	37,300h/	2,390	92	52,300
(A-11-6) 3b	Verde Hot Springs	12-10-51	60	116	45	996	1,560	566	545	1.5	.3	3,100i/	474	82	4,660
(A-11-12) 20	Indian Gardens	5-17-52	8.9	68	27	3.2j/	333	4.1	2	.2	.1	278	280	2	497
(A-12-7) 14	Fossil Creek Springs	2-16-52	14	104	40	6.9	485	27	9	.1	.5	440	424	3	753
(A-12-8) 35c	Cottonwood Spring	7-18-46	-	56	34	18	370	2.9	8	.4	.5	302	280	-	557

Table 10. --Analyses of water from representative springs in the Mogollon Rim region--continued.

Spring no. a/	Name	Date of collection	Parts per million											Percent sodium	Specific conductance (micromhos at 25°C.)
			Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Hardness as $CaCO_3$		
(A-12-10)															
11cc	McGee Spring	10-18-52	11	58	17	.5	250	6.6	2	.1	.2	218	214	-	383
14a	East Verde Spring	10-18-52	11	30	10	1.6	136	5.8	1	.2	.1	127	116	3	207
(A-12-12)															
33baa	Tonto Spring	10-17-52	8.7	26	7.6	.7	111	3.1	2	.2	.3	104	96	2	174
NORTH FLOWING															
(A-9-23)															
18ad	Paige Spring	6-6-52	35	16	9.4=	4.6	96	4.9	3	.2	.8	121	78	11	162
(A-9-24)															
21ddd	Danstone Spring	6-13-52	24	10	5.8	2.3	56	4.7	1	.4	.4	77	49	9	99
(A-32-7)															
	Blue Spring	6-14-50	19	264	79	527	964	147	815	.2	3.2	2,340	984	-	3,940

a/ See table 8 for other pertinent data.
b/ Includes equivalent of 142 ppm potassium (K).
c/ Includes 0.19 ppm iron (Fe) and 0.74 ppm boron (B).
d/ Includes equivalent of 63 ppm potassium (K).
e/ Includes equivalent of 167 ppm potassium (K).
f/ Includes 17 ppm boron (B).
g/ Includes equivalent of 208 ppm potassium (K).
h/ Includes 26 ppm boron (B).
i/ Includes 7.2 ppm boron (B).
j/ Includes equivalent of .7 ppm potassium (K).



RECONNAISSANCE GEOLOGICAL MAP AND CROSS SECTIONS
OF AREA BETWEEN
PAYSON AND ELLISON CREEK, GILA COUNTY, ARIZONA

1 0 1 MILES
HORIZONTAL AND VERTICAL SCALE

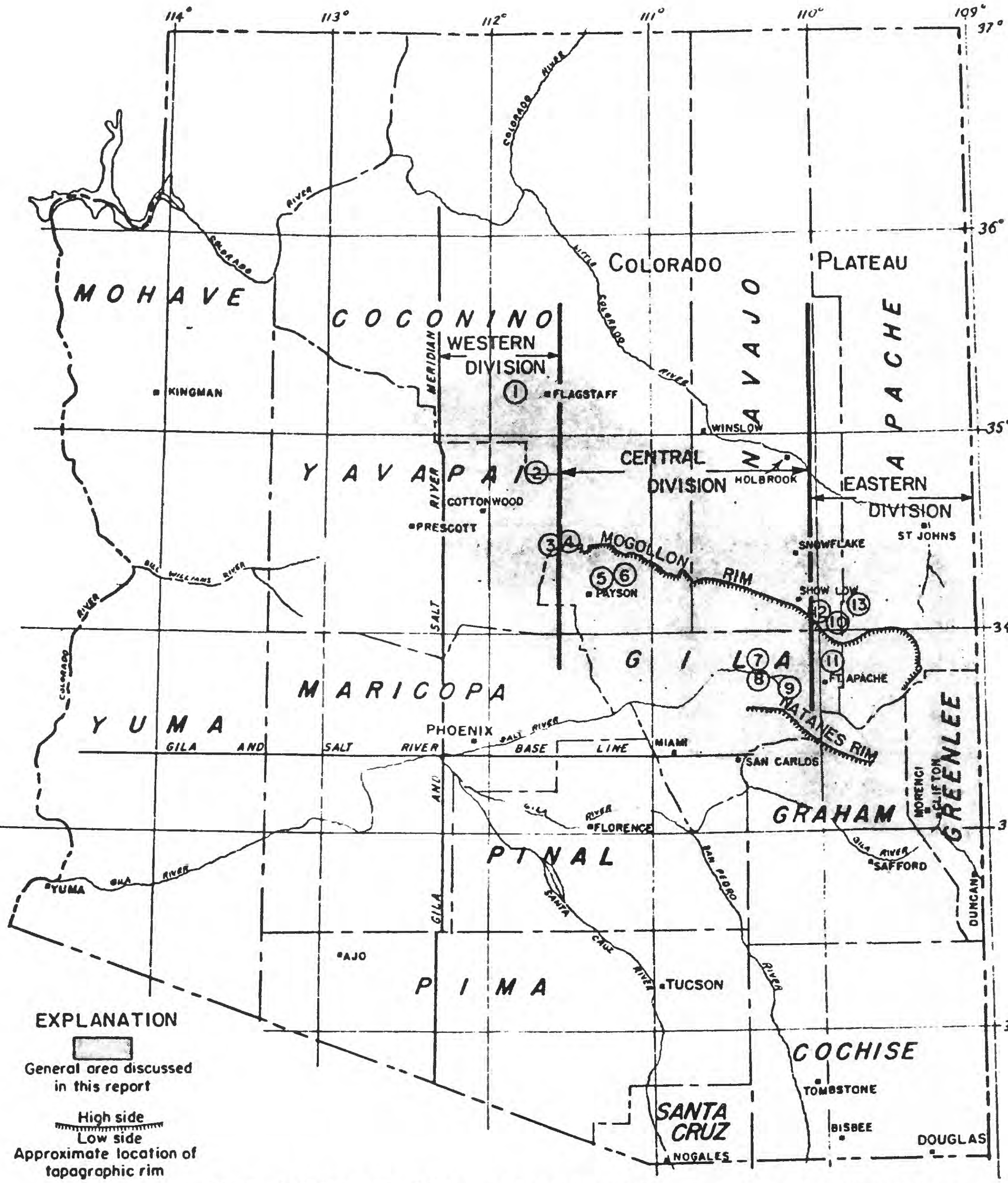


Figure-1. Index map of Arizona showing area investigated, location of escarpments, and locations of stratigraphic sections shown on Plate 2

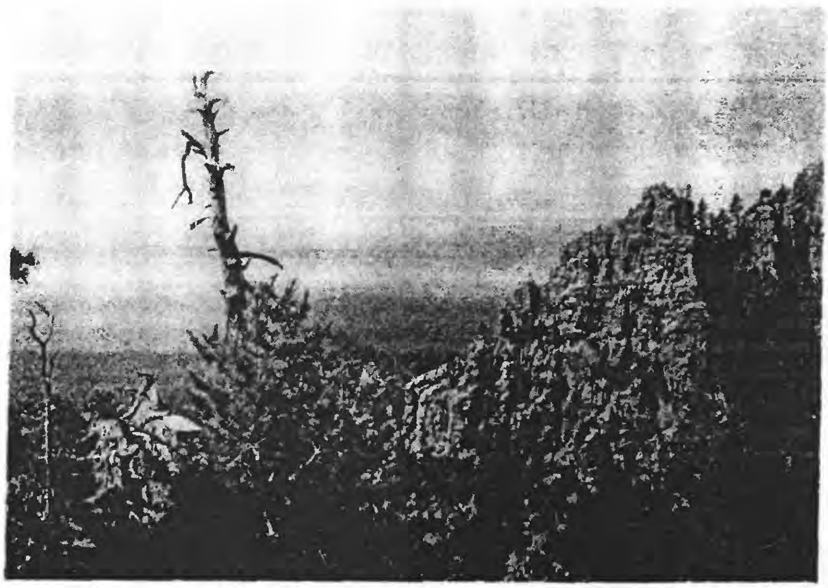
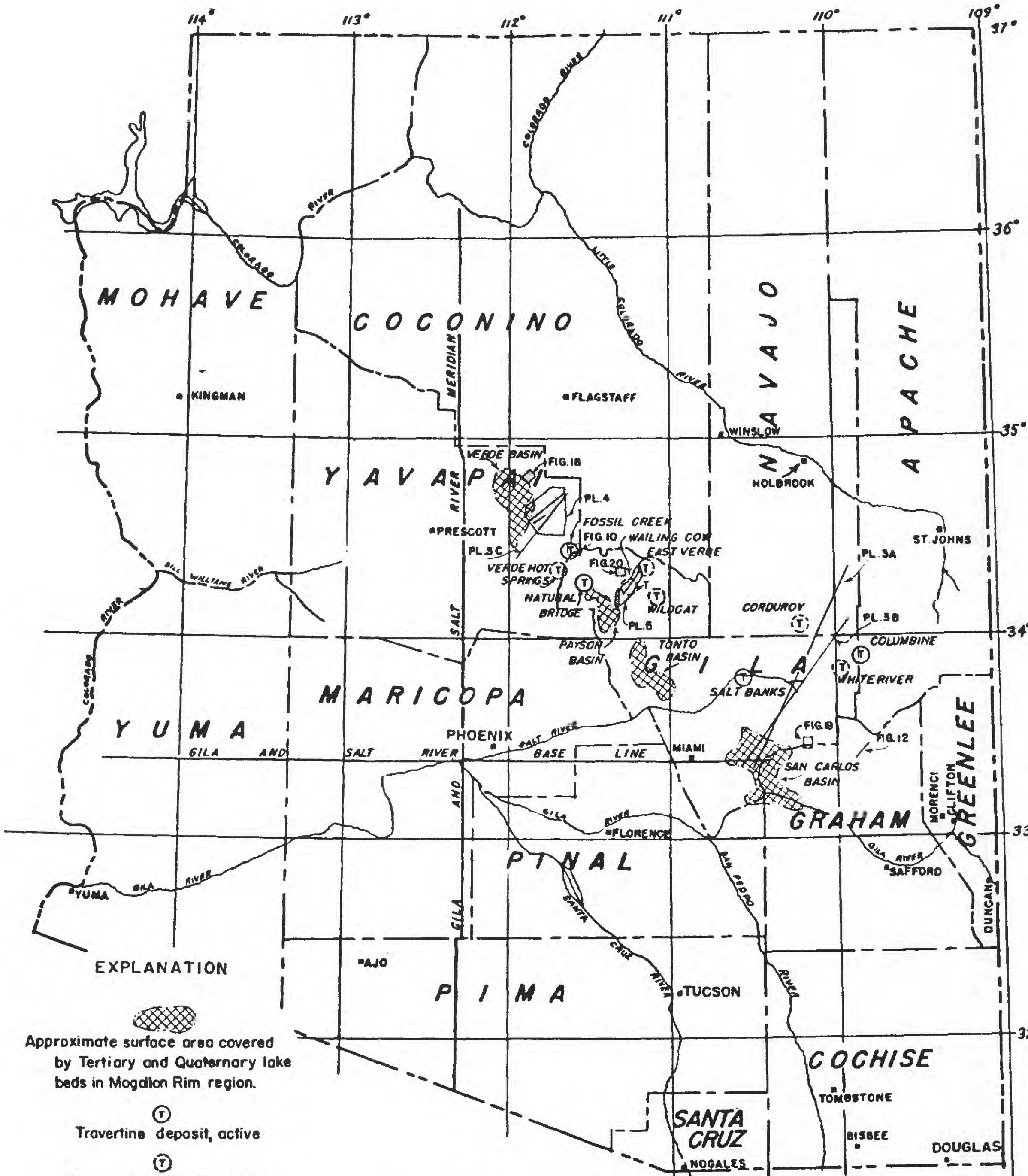


Figure 2. Characteristic Mogollon Rim topography. View is northwest from rim crest near Pine, Ariz. Jointing in Coconino sandstone in cliff is typical of conditions along the rim.



EXPLANATION

Approximate surface area covered by Tertiary and Quaternary lake beds in Mogollon Rim region.

Travertine deposit, active

Travertine deposit, inactive

Approximate location of geologic profile, figure number indicated.

Area individual map. Plate or figure number indicated.

Figure 3.- Index map of Arizona showing lake-bed basins, locations of travertine terraces, areas mapped, and location of geologic profiles.

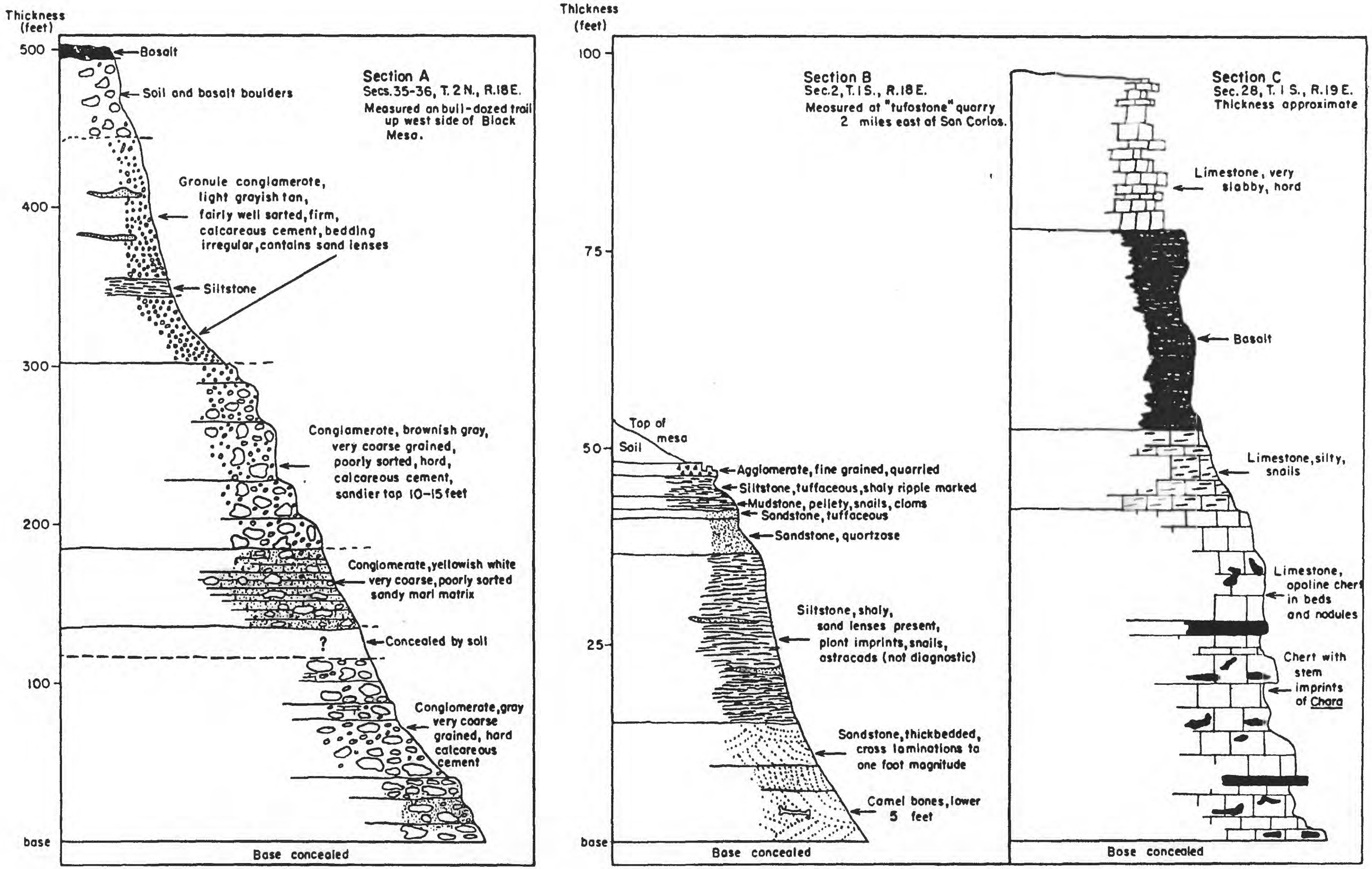


Figure 4.- Stratigraphic sections, lake beds probably equivalent to Gila conglomerate, San Carlos Indian Reservation, Arizona

Figure 5. Sodium sulfate quarry near Camp Verde, Ariz. Saliferous clays comprise the darker beds overlying the white salt strata. Two thin halite beds crop out near top of salt beds.

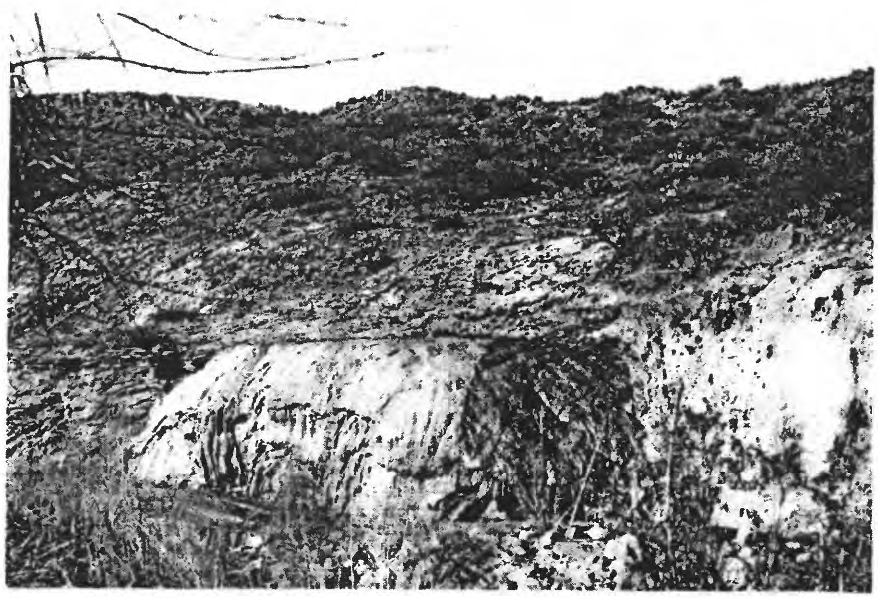


Figure 6. Salt Banks on Salt River, Ariz. Spring terrace about 15 feet high. Hill in background consists of quartzite and limestone of the Apache group.

Figure 7. View upstream on Fossil Creek showing inactive travertine terrace (upper center), and hill of Supai formation rocks (upper right). Foreground is underlain by volcanic rocks principally agglomerate. (S. F. Turner, photo)

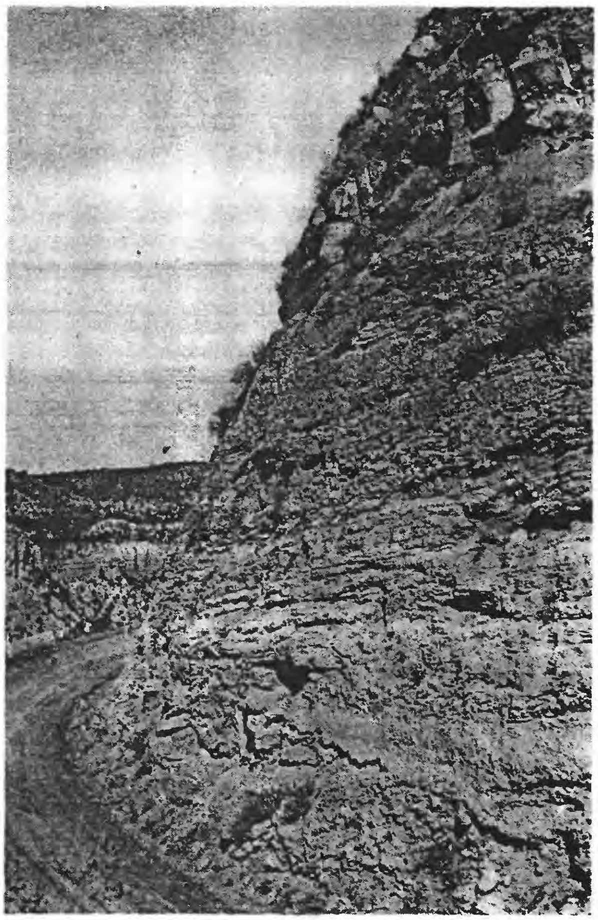


Figure 8. Corduroy terrace on Forestdale Creek showing travertine with basal conglomerate and basalt capping. Height of travertine from base of conglomerate to base of basalt about 30 feet.

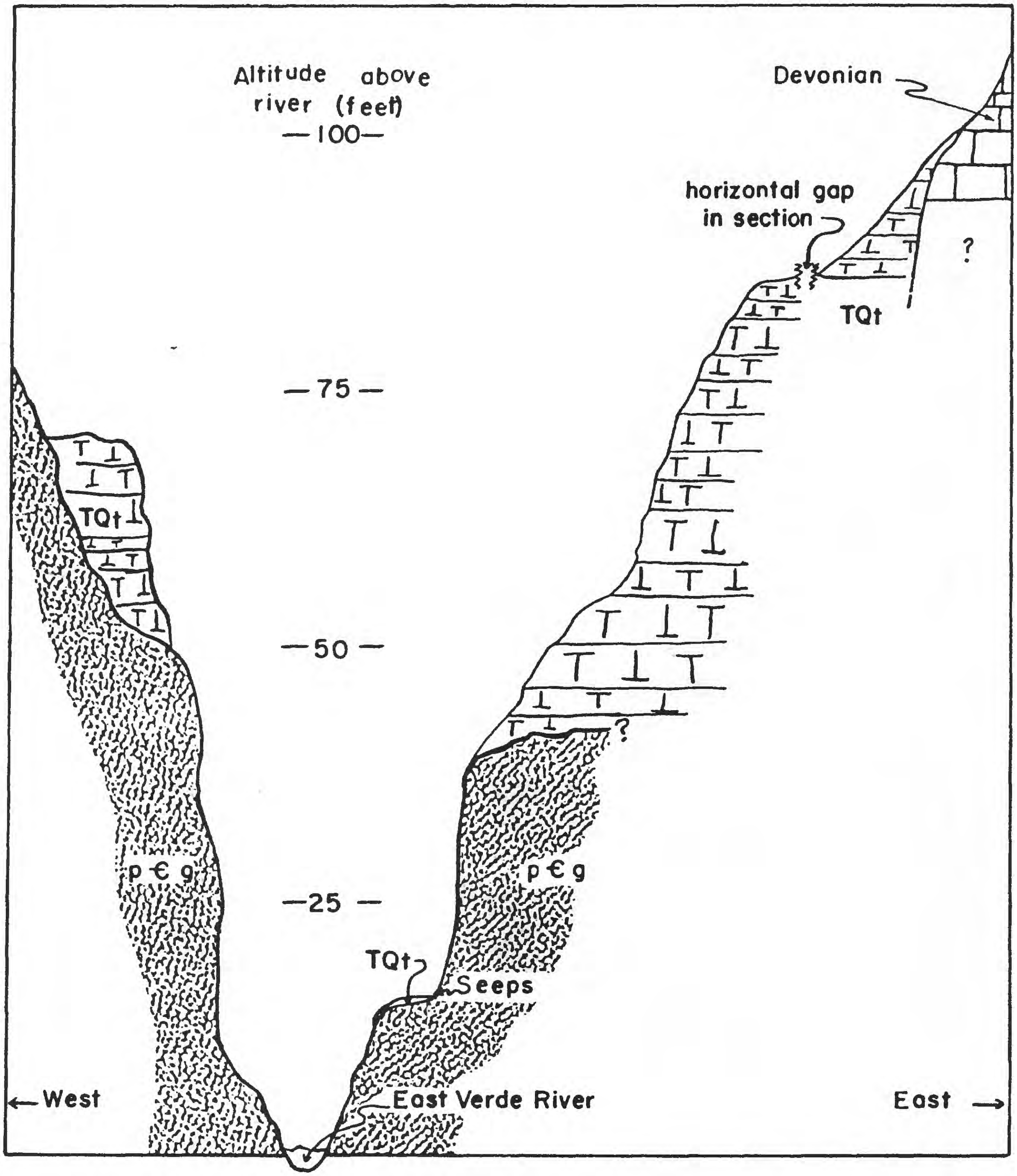


FIGURE-9. SECTION SHOWING OCCURRENCE OF TRAVERTINE ON EAST VERDE RIVER, ARIZ., NEAR ELLISON CREEK

horizontal scale compressed

TQt Tertiary and Quaternary travertine

pre-Cambrian granite p€g

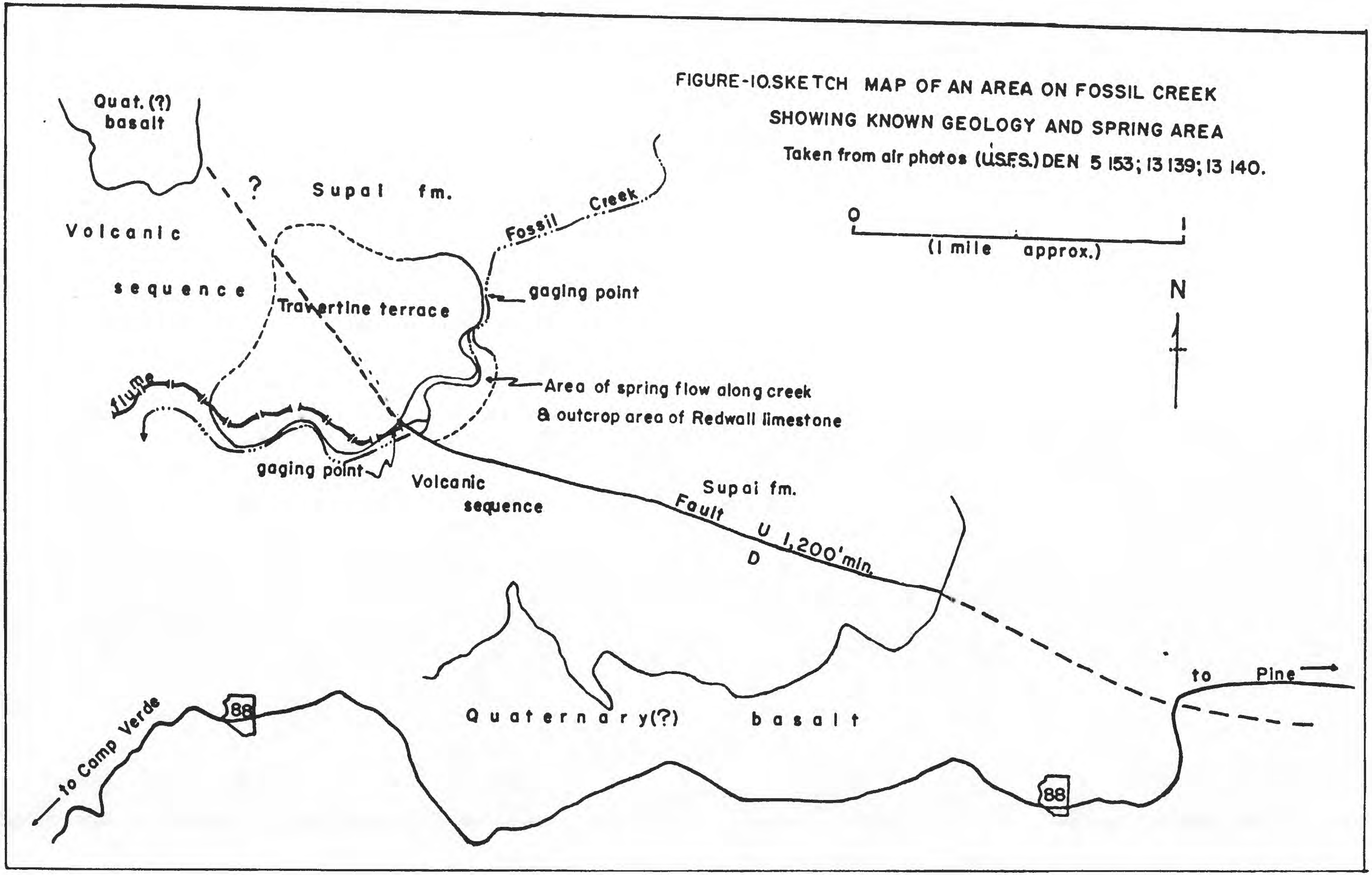
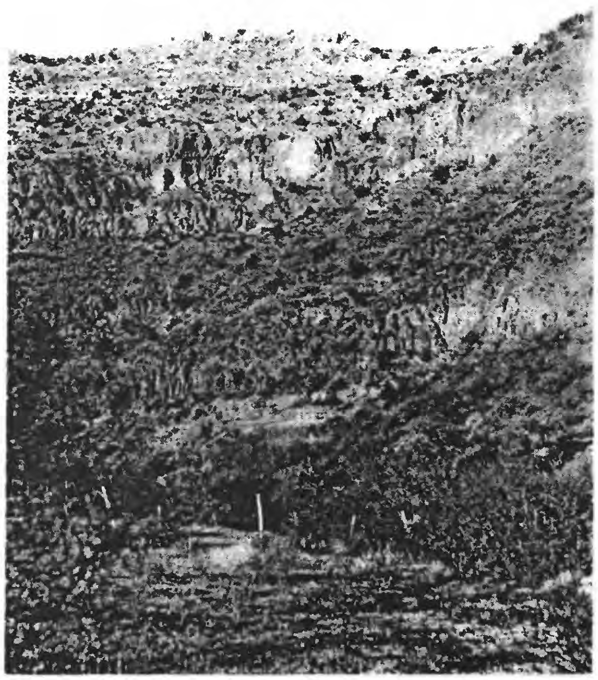


FIGURE-10. SKETCH MAP OF AN AREA ON FOSSIL CREEK SHOWING KNOWN GEOLOGY AND SPRING AREA

Taken from air photos (U.S.F.S.) DEN 5 153; 13 139; 13 140.

A. View northeastward from U. S. Highway 89-A near Cottonwood, Ariz. showing Verde formation overlying two basalt hills.



B. View in Oak Creek Canyon near Bubbling Pond Spring, showing Verde formation overlying basalt which rests on rocks of Supai formation.

Figure 11. Verde formation overlying basalt.

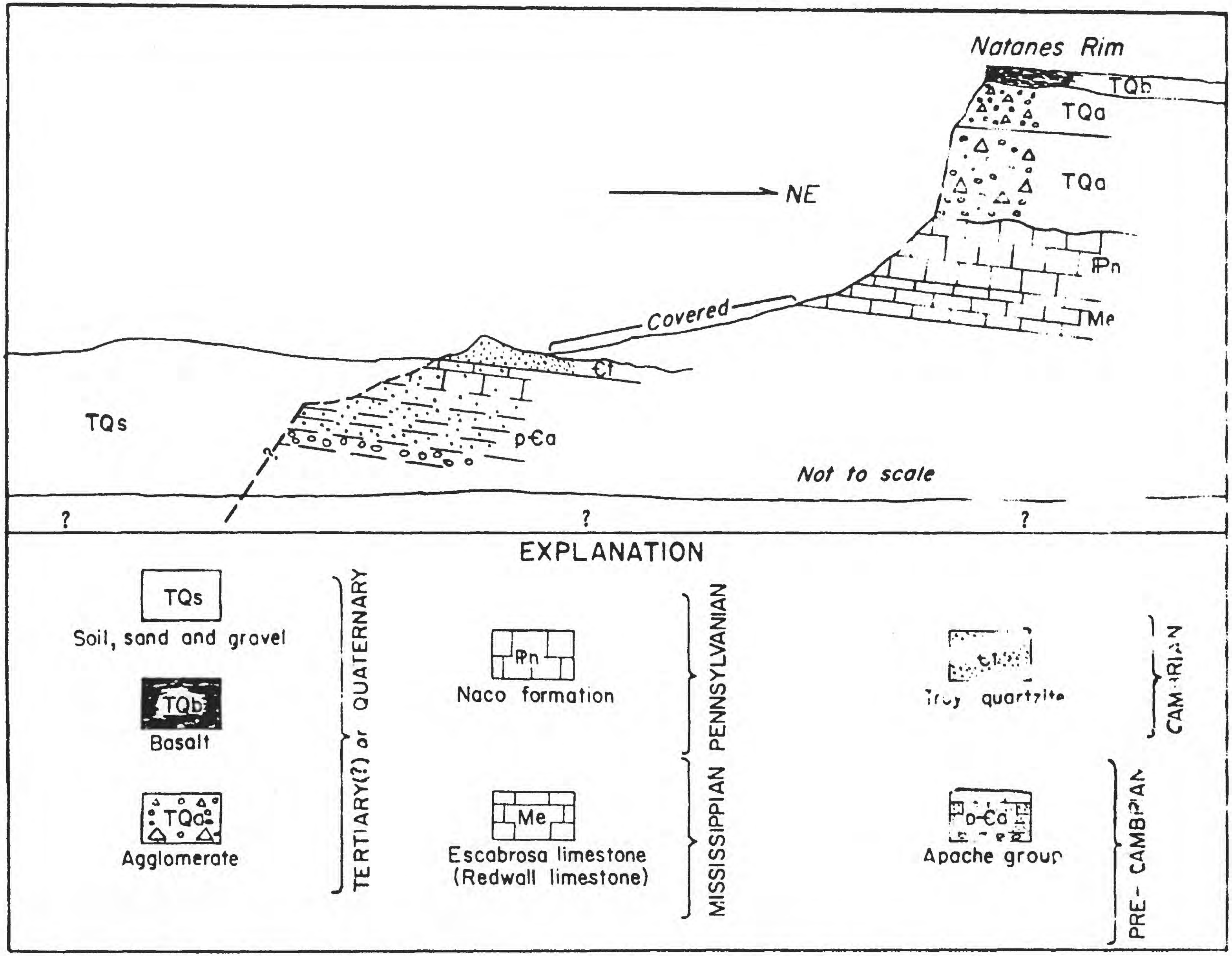


Figure 12.—Generalized geologic profile, Ash Flat area, San Carlos Indian Reservation, Arizona.

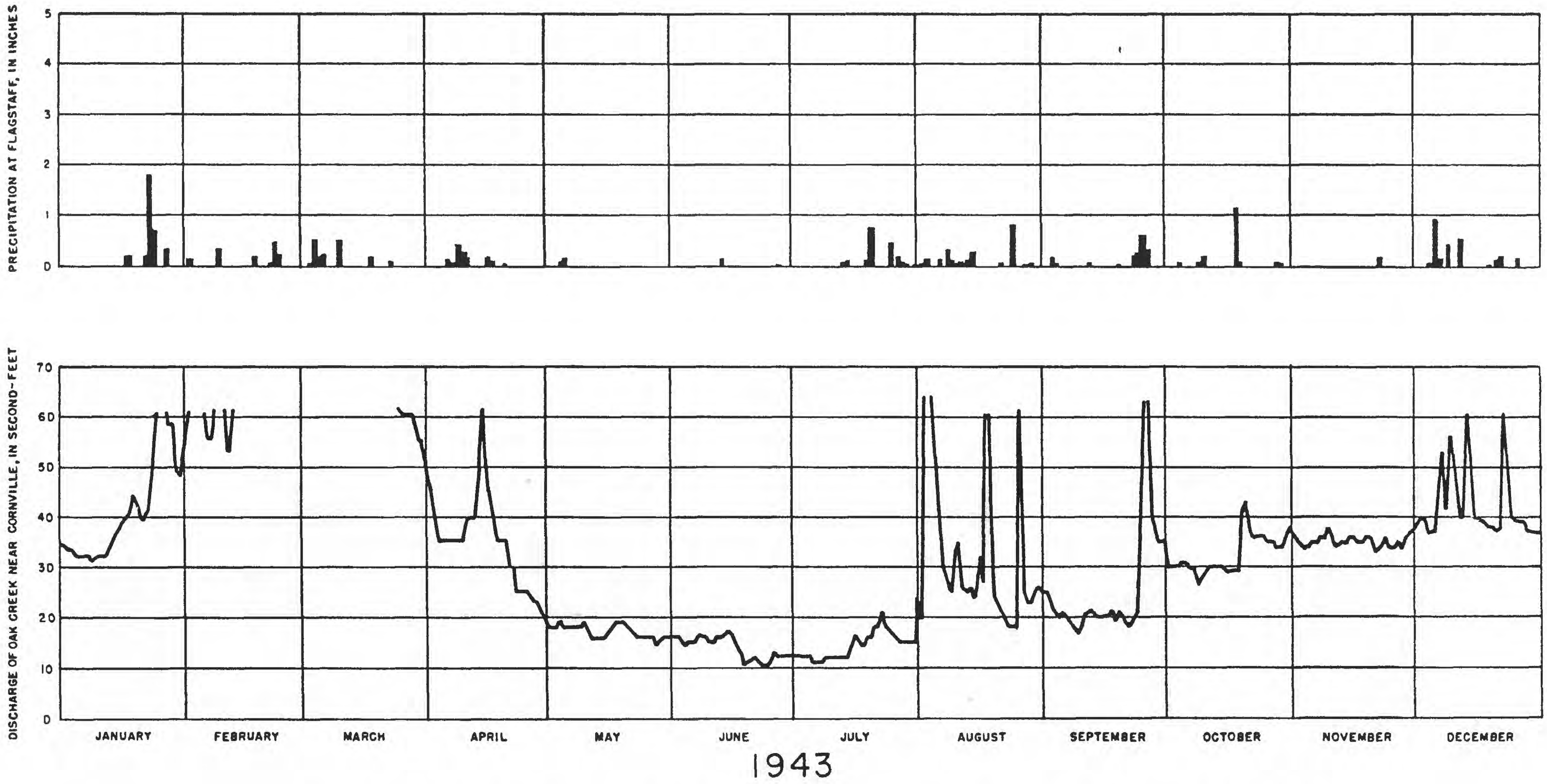


Figure-13. Representive graph showing relation between precipitation and stream discharge along Mogollon Rim.

A. Dried mud on pond bottom - November 1952, park near Pine.

B. Upper Bull Cienaga, Ft. Apache Reservation. Spring discharges about 100 gpm from basalt talus slide, center background outflow concealed by coarse, heavy growth, right foreground.

C. Mormon Lake near Flagstaff, October 1951 after several years of subnormal precipitation.

Figure 14. Park, cienaga, and lake, plateau portion of Rim region.

Figure 15. Salt Banks on Salt River, showing travertine deposited on pre-Cambrian quartzite near upstream end of terrace. Hill in background consists of quartzite and limestone injected with basalt.

A. Principal orifice discharging about 5, 000 gallons per minute.

B. Water from main orifice cascading over travertine terrace to North Fork (foreground).

Figure 16. Columbine Terrace on the White River.

Figure 17. Columnar jointing in basalt about 3 miles north of Lakeside, Ariz. Water-course shown local ponds only. Springflow 300 gpm upstream of locality shown goes underground in less than half a mile.

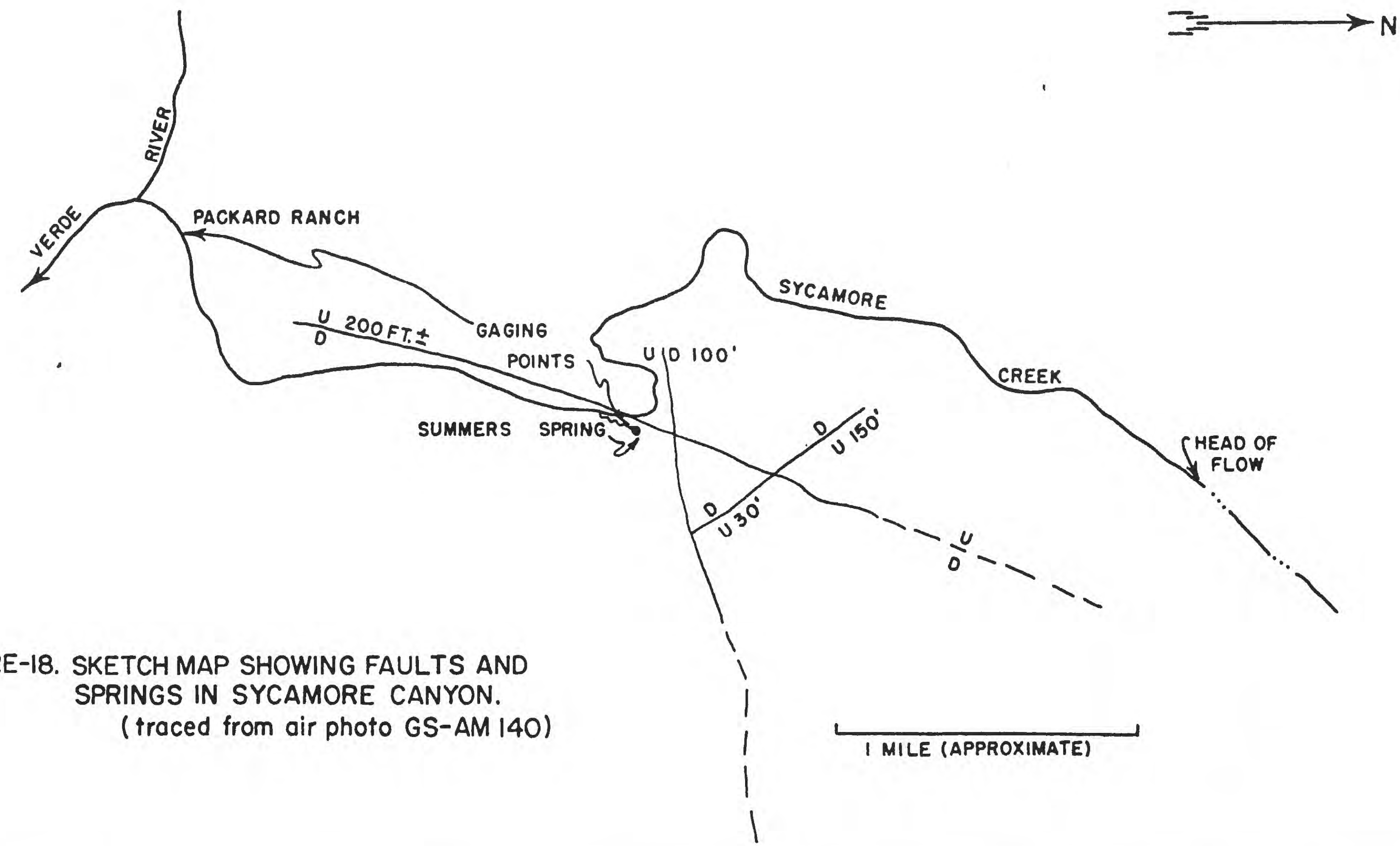


FIGURE-18. SKETCH MAP SHOWING FAULTS AND SPRINGS IN SYCAMORE CANYON.
(traced from air photo GS-AM 140)

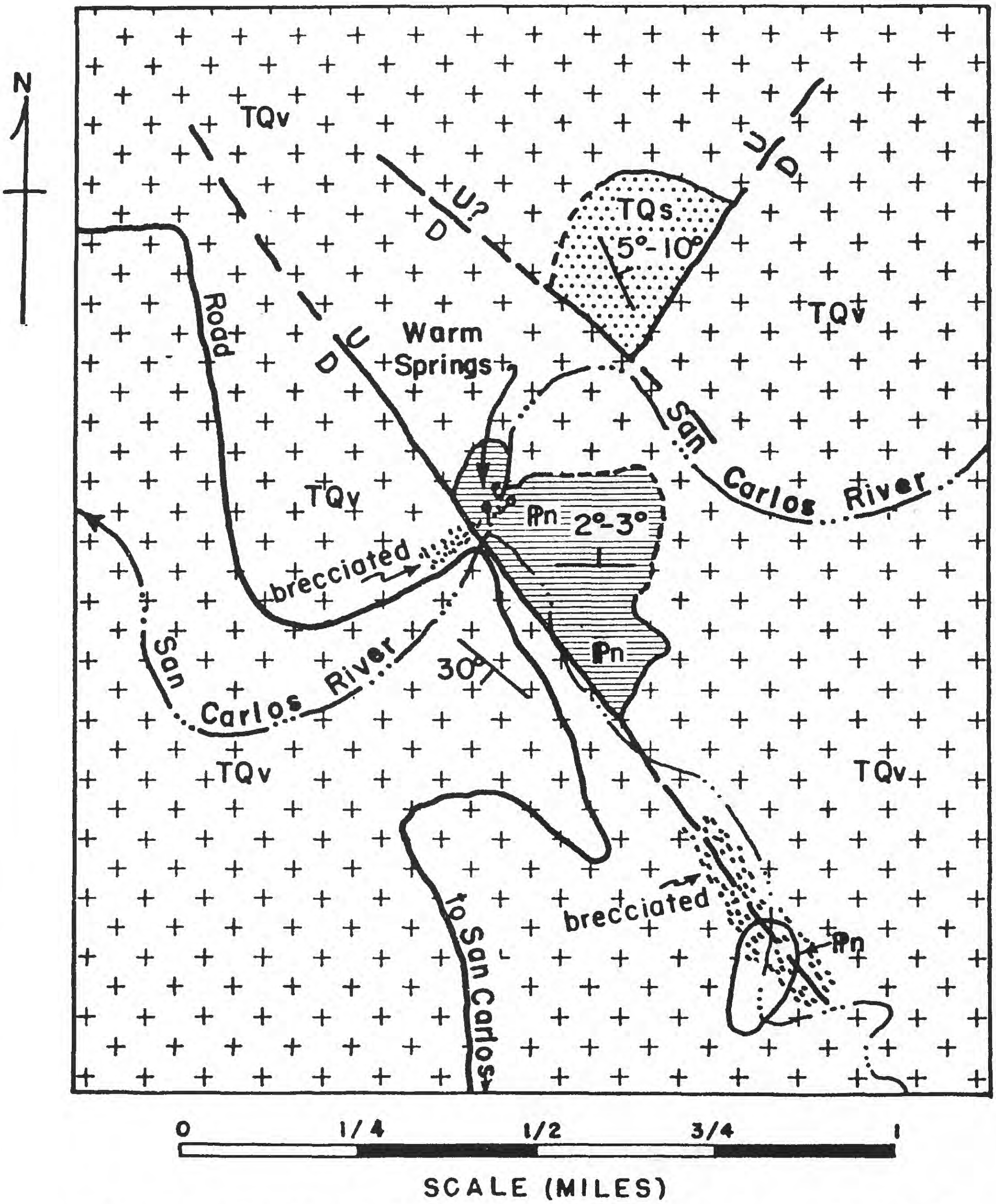


FIGURE-19. MAP OF WARM SPRINGS AREA NEAR SAN CARLOS, ARIZ., SHOWING GEOLOGY

EXPLANATION

	Explanation
TQv	TERTIARY AND QUATERNARY VOLCANIC ROCKS
TQs	TERTIARY AND QUATERNARY SEDIMENTARY ROCKS
Pn	PENNSYLVANIAN NACO FORMATION
U / D	FAULT
10°	ATTITUDE OF LAYERED ROCKS

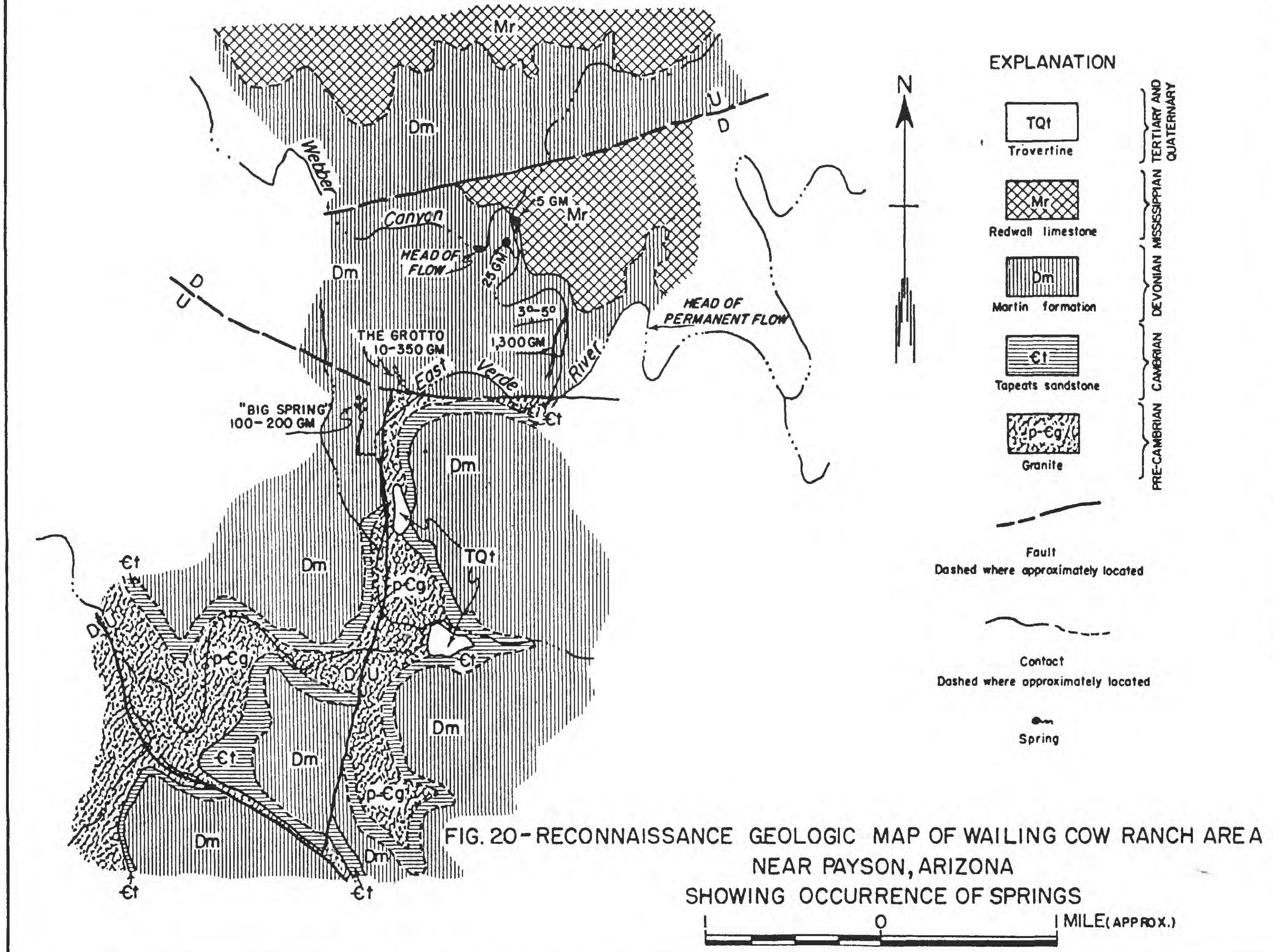


FIG. 20 - RECONNAISSANCE GEOLOGIC MAP OF WAILING COW RANCH AREA NEAR PAYSON, ARIZONA SHOWING OCCURRENCE OF SPRINGS

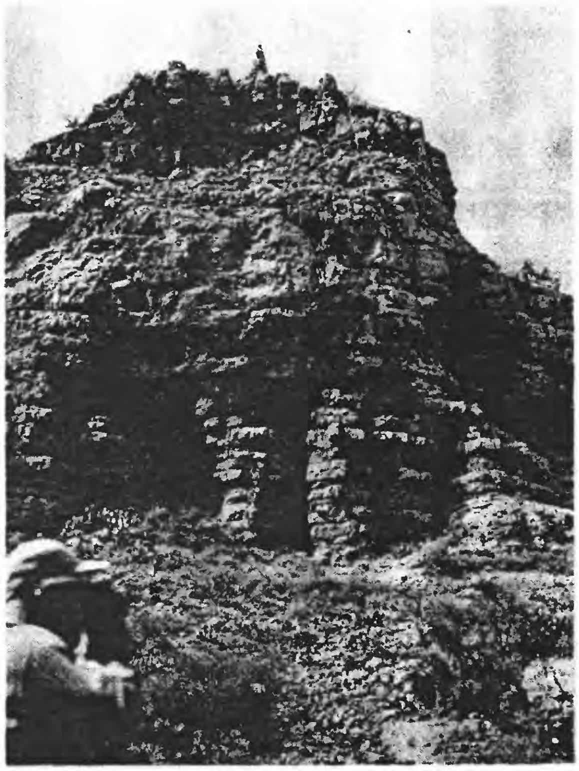


Figure 21. Redwall limestone exposure in Sycamore Canyon, showing characteristic solution openings.

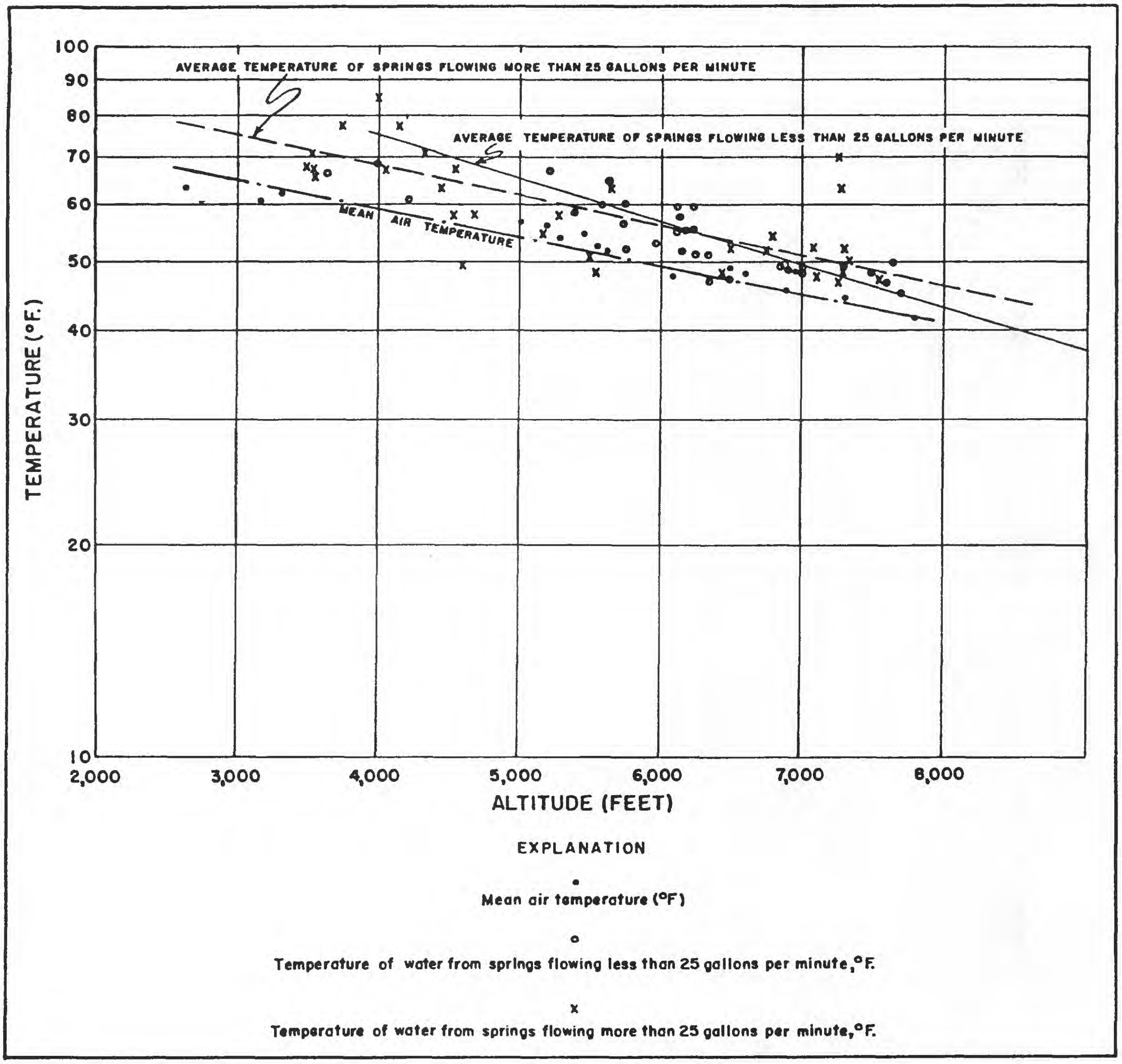


Figure-22. Graphs showing relations between mean annual air temperature and temperature of waters in rim region.

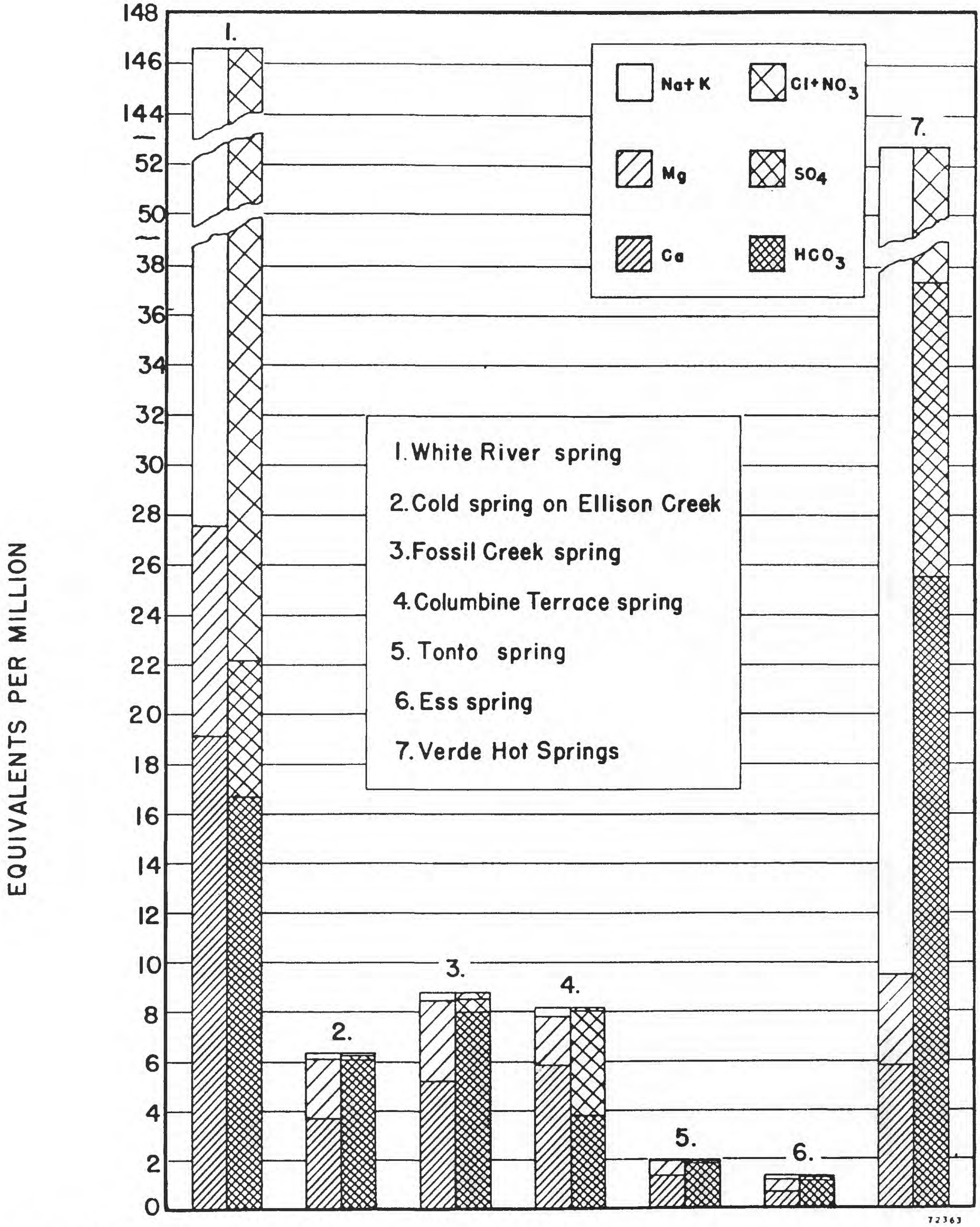


Fig. 23.-Analyses of water from seven springs in Mogollon Rim region, Arizona.

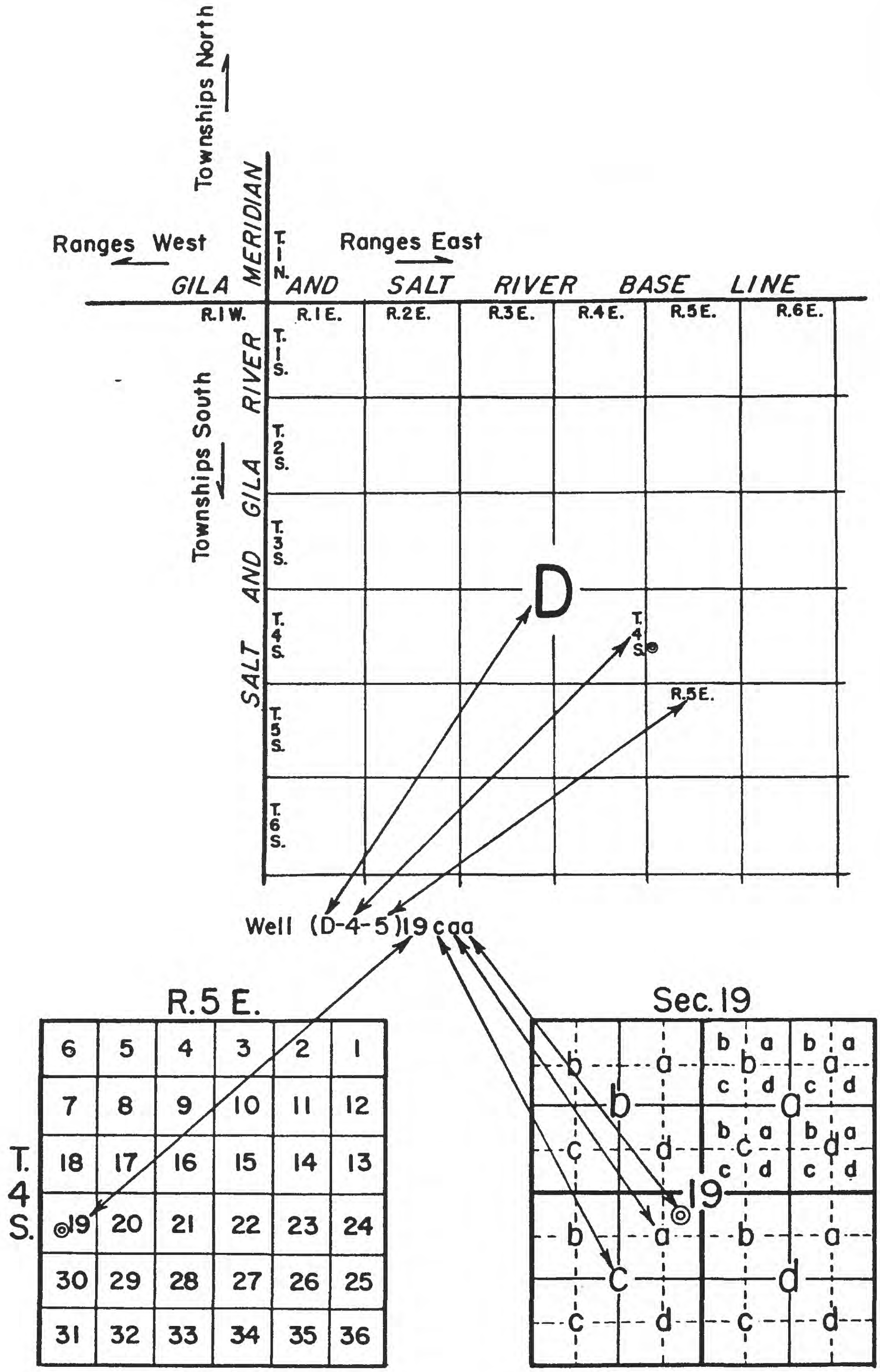


Figure-24 Explanation of standard well and spring numbering system, Arizona district (GW)