Relation of the Transmissive Character of the Sedimentary Rocks of the Colorado Plateau to the Distribution of Uranium Deposits

GEOLOGICAL SURVEY BULLETIN 1124

Prepared on behalf of the U.S. Atomic Energy Commission

Relation of the Transmissive Character of the Sedimentary Rocks of the Colorado Plateau to the Distribution of Uranium Deposits

By D. A. JOBIN

GEOLOGICAL SURVEY BULLETIN 1124

Prepared on behalf of the
U.S. Atomic Energy Commission

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library has cataloged this publication as follows :

Jobin, Daniel Alfred, 1922–

Relation of the transmissive character of the sedimentary rocks of the Colorado Plateau to the distribution of uranium deposits. Washington, U.S. Govt. Print. Off., 1962.

viii, 151 p. maps, diagrs. (1 fold. col. in pocket) tables. 24 cm. (U.S. Geological Survey. Bulletin 1124)

Prepared on behalf of the U.S. Atomic Energy Commission.

Bibliography : p. 106–109.

1. Rocks, Sedimentary. 2. Uranium ores—Colorado Plateau. I. Title. (Series)

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

CONTENTS

ILLUSTRATIONS

TABLES

RELATION OF THE TRANSMISSIVE CHARACTER OF THE SEDIMENTARY ROCKS OF THE COLORADO PLATEAU TO THE DISTRIBUTION OF URANIUM DEPOSITS

By D. A. Jobin

ABSTRACT

Two types of aquifers, sandstones of eolian and marine origin and sandstones and conglomerate of fluvial origin, together account for most of the regional transmissive capacity of the exposed rocks of the Colorado Plateau. Sandstones of eolian and marine origin are characterized by relatively moderate to great mean thickness and permeability and consequently, by relatively high uniform gradients of regional transmissive capacity. Sandstones and conglomerates of fluvial origin are characterized by relatively small to moderate thickness and permeability, abrupt and extreme fluctuations in local gradients of thickness and permeability, and consequently, by relatively low to moderate and less uniform gradients of regional transmissive capacity. Most known uranium deposits are in sandstones and conglomerates of fluvial origin in two major host rocks—the lower part of the Chinle formation of Triassic age and the lower part of the Morrison formation of Jurassic age.

Interbedded with the aquifers are relatively abundant and commonly thick mudstones and a few thin limestones. Both the mudstones and the limestones are characterized by small to almost no permeability and consequently have little or no intrinsic transmissive capacity. They chiefly function to confine fluid movement within both underlying and overlying aquifers.

Pathways for vertical movement of fluids through any considerable thickness of the succession of rocks exposed in the Colorado Plateau are restricted to strongly folded and fractured zones. In rocks younger than Paleozoic, strongly folded and fractured zones of sufficient vertical continuity to accommodate the passage of fluids are concentrated along the steeply dipping sides of major monoclines and in narrow zones surrounding igneous and salt intrusive masses.

Maps of the two major host rocks show the relation of horizontal transmissive character of each host rock to the mean horizontal transmissive character of its most uraniferous parts. Relatively little of the lower unit of the Chinle formation is hydrologically similar to its most uraniferous parts. In contrast, large areas of sandstones of the Morrison formation are similar in horizontal transmissive character to that of its most uraniferous parts. A classification of the lower sandstones of the Chinle and sandstones of the Morrison by the mean horizontal and vertical transmissive character of their most uraniferous areas resulted in outlining much smaller favorable areas. These areas are believed to be the most likely to contain undiscovered ore deposits.

A comparison of the distribution of uranium deposits with the variation in transmissive characteristics in the exposed rocks of the Colorado Plateau yields the following generalizations: The major host rocks are thin, have moderate to low permeability, low transmissivity, and steep local gradients in thickness, permeability, and transmissivity, and are almost invariably overlain by thick nontransmissive mudstones. As the mean size of uranium deposits increases and the number of deposits decreases, there is a corresponding increase in the mean transmissive capacity of the host rock. Within a host rock the range in size and total number of deposits seems to vary directly with the range in local horizontal transmissive capacity, and inversely with distance from zones most likely to have vertical transmissive capacity.

The data of this report, in the light of the known geologic history of the Colorado Plateau, suggest the following interpretations: (1) the major host rocks of uranium deposits have had an intermediate to low transmissive capacity throughout their history; (2) the selectivity both of the movement of the uranium-bearing solutions and of the places of deposition of the ore minerals was controlled in some measure by both the horizontal and vertical transmissive character of the host rock; (3) the spatial relations of ore deposits, their distribution in aquifers that are overlain by thick nontransmissive mudstones, and their systematic and close association with the structurally highest parts of local regions suggest that the overlying aquicludes and the evolution or reactivation of uplifted blocks during Late Cretaceous or early Tertiary time were the dominant controls.

INTRODUCTION

PURPOSE

Uranium deposits of the Colorado Plateau are concentrated in a few sedimentary rock units of similar lithology and stratigraphic setting. Reasons to explain this concentration are varied but have in common the supposition that uranium was carried to its present sites by fluids that had traversed the host rocks for distances as great as several miles. (For a review of the literature see McKelvey and others, 1956.) If this assumption is correct, knowledge of the transmissive capacity of the rocks of the Colorado Plateau will be essential to determine the probable routes of travel available to the ore-bearing solutions, and may make possible meaningful correlations between transmissive capacity and the distribution of ore deposits. The purpose of this report is twofold: to present data showing the existence and character of regional transmissivity gradients in the exposed rocks of the Colorado Plateau, and to relate these gradients to the distribution of uranium deposits.

SCOPE

The area of study, as outlined in figure 1, is coextensive with the Colorado Plateau structural province (Hunt, 1956) which includes most of western Colorado, northwestern New Mexico, northeastern Arizona, and southeastern Utah. The rocks exposed in this area, which is slightly larger than 130,000 square miles, range in age from Precambrian to Recent with sedimentary rocks of Mesozoic age predominating. The study is concerned mostly with the sedimentary

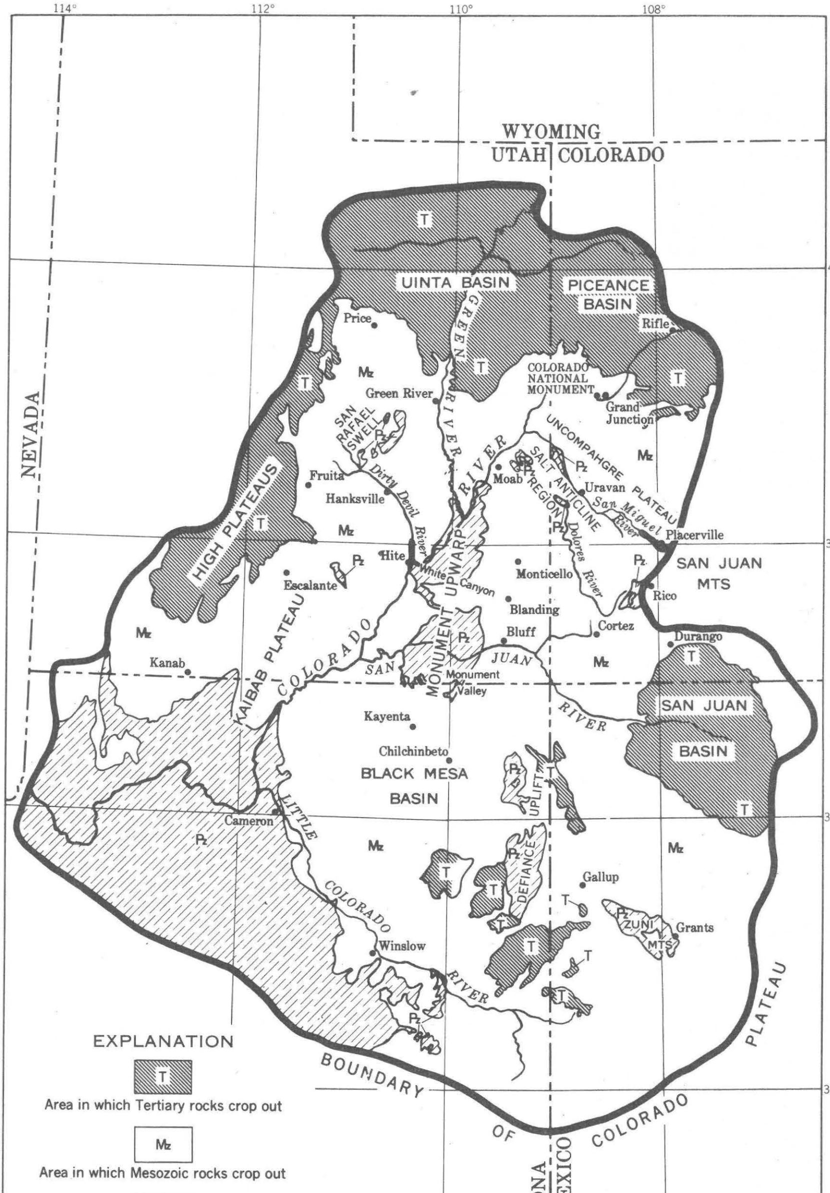


FIGURE 1.—Index map of the Colorado Plateau showing gross distribution of rock sequences.

rocks of Mesozoic age and particularly the principal ore-bearing units of this sequence: the lower sandstones of the Chinle formation, the

Entrada sandstone, the Todilto limestone, and sandstones of the Morrison formation.

Table 1 shows a generalized stratigraphic section of upper Paleozoic and Mesozoic strata in southeastern Utah and adjoining parts of Colorado, Arizona, and New Mexico, and includes all the stratigraphic units studied.

TABLE 1.—*Generalized section of upper Paleozoic and Mesozoic strata in southeastern Utah and adjoining parts of Colorado, Arizona, and New Mexico*

[Stratigraphic units marked with an asterisk (*) are considered to have a significant regional transmissive capacity and were sampled in this study]

System or series	Group	Formation	Member or tongue	Thickness (feet)	Character
Upper Cretaceous		*Mesaverde [1]		500–2,000	Sandstone, light-colored, broadly lenticular, interbedded with drab shales; crops out widely along margins of the region.
		Mancos		2,000–5,000	Shale, dark-blue to gray, limy and silty; scattered interbedded sandstone.
		*Dakota [1]		0–200	Sandstone and shale, gray and brown; form cliff; widespread.
Lower Cretaceous		*Burro Canyon [1]		0–250	Sandstone, light-colored, conglomeratic and green and maroon mudstone; mesa-capping; absent in western part of region.
Upper Jurassic		*Morrison	Brushy Basin [2]	300–500	Shale (or mudstone), varicolored, some sandstone lenses; forms slopes; widespread.
			Westwater Canyon [2]	0–350	Sandstone, light-colored; forms cliffs and benches; absent in northern part of region.
			Recapture [1]	0–680	Red shales and sandstones; form cliffs and benches; absent in northern part of region.
			Salt Wash [2]	0–400	Sandstone, light-colored, and red mudstone; form cliffs and benches; widespread.
	San Rafael	*Bluff		0–55	Sandstone, red, massive; forms cliff; absent in northern part of region.
		Summerville		0–400	Shale, red and gray; thin sandstone; form slopes; thickens westward; widespread.
		Curtis [3]		0–100	Sandstone, light-colored; absent in southern Utah.
		*Entrada [1]		50–1,000	Sandstone, light-colored, massive; forms cliff; thickens westward to red earthy sandstone.
		Carmel		0–600	Sandstone, red, earthy; thickens westward to gray and red shale; limestone and gypsum widespread.
Jurassic and Jurassic(?)	Glen Canyon	*Navajo		0–2,000	Sandstone, red, irregularly bedded; forms bench; absent in eastern part of region.
Jurassic(?)		*Kayenta		0–300	Sandstone, light-colored, massive, cliff-forming; absent in western Colorado.
		*Wingate		0–400	Sandstone, red, massive; forms cliff; absent in eastern part of region.

See footnotes at end of table.

TABLE 1.—*Generalized section of upper Paleozoic and Mesozoic strata in southeastern Utah and adjoining parts of Colorado, Arizona, and New Mexico*—Con.

System or series	Group	Formation	Member or tongue	Thickness (feet)	Character
Upper Triassic		Chinle	"A"	0–350	Siltstone, red, and sandstone; form ledges and slopes; widespread.
			Owl Rock	0–450	Limestone, gray, and red siltstone; form ledges and slopes; widespread.
			Petrified Forest	0–700	Claystone, variegated; forms slopes; widespread absent in northern Utah.
			*Moss Back [2]	0–150	Sandstone, light-colored, conglomeratic; forms cliff; fills channels (widespread).
			Monitor Butte	0–250	Gray claystone and sandstone; form slopes; widespread.
			*Shinarump [2]	0–250	Sandstone, light-colored, conglomeratic; fills channels; forms cliff (widespread).
Lower and Middle(?) Triassic		Moenkopi		0–700	Red siltstone and sandstone, ripple-marked; form slopes and ledges; widespread.
			Sinbad	0–200	Limestone; absent in eastern part of region.
				0–200	Siltstone, red, ripple-marked; forms slopes and ledges; thins eastward.
			Hoskinnini	0–120	Siltstone, red; forms steep slopes and cliffs; absent in northwestern part of region.
Permian		Kaibab; Cutler	*White Rim	0–230	Sandstone, white; forms cliffs; absent in western part of region.
			*De Chelly	0–850	Sandstone, light-colored; forms cliffs; absent in northern part of region.
			Organ Rock	250–800	Siltstone, red; forms steep slopes; absent in northern partof region.
			*Cedar Mesa	0–1,250	Sandstone, light-colored; forms cliffs and benches; thickens northward.
Pennsylvanian and Permian(?)		*Coconino	Halgaito	0–500	Red siltstone and sandstone; absent in northern part of region.
		Rico		300–500	Red sandstone and siltstone, light-gray limestone; form cliffs and ledges; widespread.

[1] Uranium-bearing stratigraphic units of minor importance.
[2] Uranium-bearing stratigraphic units of major importance.
[3] Equivalent to the uranium-bearing Todilto limestone of the Grants area, McKinley and Valencia Counties, N. Mex.

BASIC CONCEPTS AND HYDROLOGIC TERMINOLOGY

Several concepts, terms, and units of measurement which may not be entirely familiar to most readers are used in this report. Therefore, a brief discussion of these concepts and terms is given here.

PERMEABILITY

Permeability is a measure of the ability of a porous medium to transmit fluids. In sedimentary rocks this ability to transmit fluids is largely determined by the interconnection of the pores and other openings of the rock, although the geometry of the pores, the physical state and chemical character of the fluids being transmitted, and the composition of the minerals lining the pores also may effect permeability considerably. A commonly used unit of measurement for permeability, and the unit used in this report, is the darcy. Muskat (1937, p. 71) defines the darcy as "the volume of a fluid of unit viscosity passing through a unit cross section of the medium in unit time under the action of a unit pressure gradient." All units are expressed in the cgs system. Permeability, thus defined, is a mass property of a porous medium and is independent of the gross dimensions of the porous medium.

TRANSMISSIVITY

In order to compare the areal variations of the transmissive capacity of a rock unit, and to compare the transmissive capacity of several different units within a specific area, it was necessary to devise a parameter, analogous to permeability, which would characterize the transmissive capacity of an entire rock unit at a given locality. Theis (1935) first proposed such a parameter, and named it transmissibility. Transmissibility is expressed quantitatively by a coefficient of transmissibility defined as the product of mean field permeability, in gallons per day per square foot at the prevailing water temperature, and the saturated thickness, in feet, of an aquifer.

Unfortunately, the coefficient of transmissibility as defined by Theis refers to specific conditions of both fluid and transmitting medium which without redefinition restrict its applicability. For this reason, and in order to avoid any confusion of meaning, a more general parameter, transmissivity, is proposed and is expressed quantitatively by the coefficient of transmissivity which is defined as the product of mean permeability and total thickness of the transmitting medium. In this study, the coefficient of transmissivity, or more simply transmissivity, is expressed in units of darcy-feet. The term "transmissive capacity" is synonymous.

MISCELLANEOUS TERMS

Hydrologic unit.—One or several laterally or vertically contiguous formations, members, or beds of similar lithologic character.

Permeability profile.—A general term used to describe the aggregate of permeability measurements made within one hydrologic unit at a single locality.

Horizontal transmissivity.—The capacity of one or more hydrologic units to transmit fluids parallel to their gross bedding plane. In areas of predominantly flat lying beds such as the Colorado Plateau, this is virtually the same as transmissive capacity parallel to the earth's surface.

Vertical transmissivity.—The capacity of one or more hydrologic units to transmit fluids perpendicular to their gross bedding plane.

Intrinsic permeability.—The permeability attributable to the interconnected pores and dependent on their size and distribution. It specifically excludes permeability attributable to macroscopic fractures or solution openings.

Transmissive character.—A general term used to describe the aggregate effect on transmissivity of permeability and thickness and the gradients present in these factors.

PLAN OF STUDY

As the stratigraphic units recognized in the region of study are numerous and extensive, it seemed desirable, at the start of the investigation, to make as many simplifying assumptions as possible so as to focus the work in the most efficient manner. Separate treatment of all recognizable sedimentary units would unreasonably complicate the hydrologic picture. Therefore, stratigraphically separable units having very similar lithologic characteristics and vertical contiguity were treated as single hydrologic units.

The study was further simplified by limiting sampling to rock largely composed of sandstone. The elimination of shale, mudstone, siltstone, evaporites, and limestone from the sampling is not based on an assumption of their impermeability; all sedimentary rocks are permeable to some degree. However, the intrinsic permeability of these rocks is so small when compared to that of the sandstones that, in considering either local or regional transmissive capacity, little risk of error is involved in using a theoretically determined intrinsic permeability.

Thin discontinuous sandstone units of limited areal extent also were not sampled. As a rule, strata less than 5 feet thick, or with an exposed or inferable lateral continuity of less than several hundred feet, were excluded. Generally, these rock units are well cemented, and even where not cemented they have little regional transmissive capacity because of their limited thickness and areal extent.

Because few data [1] on the local and regional variations in permeability were available for the sandstones of the Colorado Plateau,

[1] Gordon Davis of the U.S. Geological Survey provided several sets of aquifer-test data from which permeability could be calculated for wells in the Navajo sandstone of northeastern Arizona. R. A. Cadigan of the U.S. Geological Survey provided more than 2,000 sets of grain-size analysis data for Colorado Plateau sandstones of Mesozoic age.

the investigation was carried out in a stepwise sampling and measurement program. First, a study was made of the magnitude and spatial variation of permeability of representative sandstone units. This was carried out in conjunction with a program for determining the most useful laboratory methods available for measuring permeability, including an analysis of the errors inherent in each method used. The results of the preliminary work were then used to determine the probable number of samples it would be necessary to collect from the several types of hydrologic units sampled in order to detect regional variations in permeability. The preliminary analysis also provided some guidance as to the most economical spacing of sample localities.

The second phase of the investigation consisted largely of the collection of samples from all the hydrologic units that were judged to have a regional transmissive capacity, and the measurement of their permeability. Concurrently, data on the thickness and continuity of the hydrologic units were compiled from the literature and files of the U.S. Geological Survey.

FIELDWORK

Fieldwork, which was done intermittently during 1953, 1954, and 1955, consisted largely of the collection of sets of representative samples of the exposed relatively transmissive hydrologic units of the Colorado Plateau. Most of the samples consisted of blocks of relatively unweathered rock about the size of a common building brick. In unjointed rocks, where block samples were not readily available, a portable diamond drill capable of cutting a ¾-inch-diameter core about 7 inches long was used to obtain samples. Little difficulty was found in obtaining samples of relatively unweathered rock in most areas of the Colorado Plateau owing to the abundance of new road cuts traversing the exposed rock section and of bulldozer cuts for exploratory mining operations.

Selection of samples from a specific hydrologic unit was guided by many interrelated stratigraphic factors. A preliminary set of closely spaced samples from representative types of hydrologic units provided initial guidance as to the variation of permeability with respect to lithology. Using this experience as a guide, the number of samples selected for each permeability profile was governed by the number of strata making up the hydrologic unit, thickness of the strata, number and complexity of the sedimentary structures within each stratum, and the heterogeneity of textures within sedimentary structures. As hydrologic units of marine or eolian origin have a relatively uniform lithology locally, these rocks were sampled at regular intervals throughout their thickness. Lack of closely spaced jointing and the relatively unconsolidated nature of these rocks made the task of obtaining good samples difficult. On the other hand, the more complex lithology of rocks of fluvial origin necessitated a more complex and subjective sampling procedure but, as these rocks are relatively well consolidated and well jointed, usable samples were fairly easy to obtain.

LABORATORY WORK

The laboratory work was carried out in two stages. Stage 1 consisted of a series of measurements of permeability, designed to reveal the spatial variations of permeability in representative hydrologic units, and the most practical means of measuring these variations. Stage 2 consisted almost entirely of routine permeability measurements made in the manner, and with the frequency, suggested by stage 1 results.

The specific questions the laboratory measurements of stage 1 were designed to answer were: What is the precision with which permeability can be measured using a permeameter designed for rapid determinations? how large is the variation in permeability in sandstones within distances measured in inches, several feet, miles, and tens of miles? is the permeability in sandstones directional? and if so, what is the magnitude and constancy of the differences? is there a significant difference in permeability determined by use of an inert gas or a liquid? and can permeability be reasonably well approximated by use of a formula computed with the common parameters of grain-size analysis?

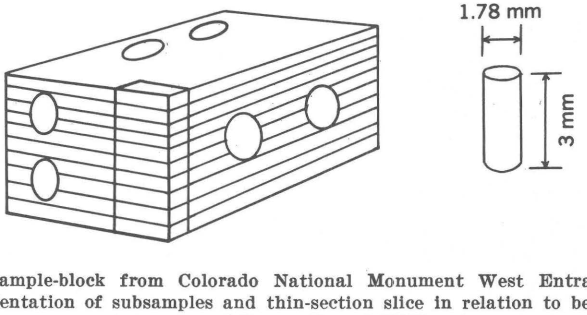


FIGURE 2.—Sample-block from Colorado National Monument West Entrance samples, showing orientation of subsamples and thin-section slice in relation to bedding. Each subsample was measured for permeability to N_3 and HOH, using permeameters shown in figure 3, and material around subsamples was mechanically analyzed. Only 3 subsamples were cut from each of the samples obtained elsewhere. [Measurements shown are cm, not mm.]

631709 O—62——2

Figures 2 and 3 illustrate the sampling and measurement program used.

COMPILATION METHODS

UNITS OF MEASUREMENT

In order to apply most standard statistical techniques, including analysis of variance designs used extensively in this study, the data to be analyzed must approximate normal distributions (Cochran, 1947). Permeability measurements, however—the chief data treated statistically in this study—have an approximately log-normal distri-

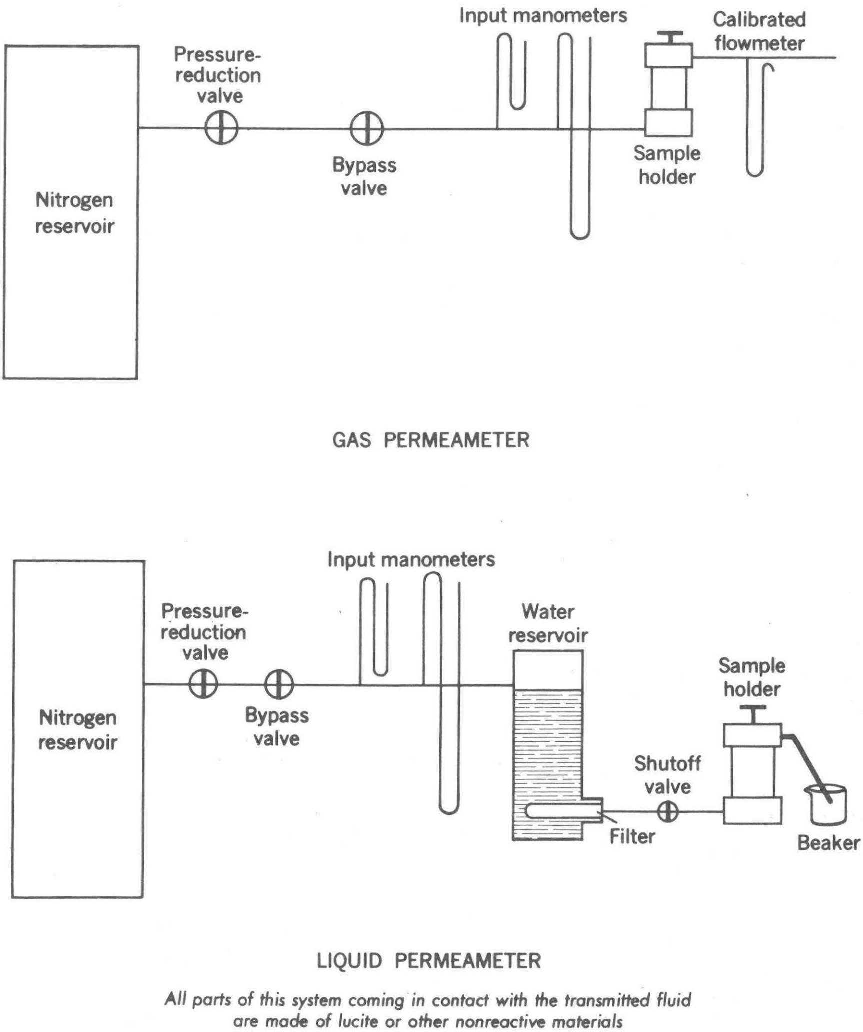


FIGURE 3.—Schematic diagrams of gas and liquid permeameters.

bution (Law, 1944; Ohle, 1951). Therefore, all permeability values used in estimating specific parameters of permeability, such as the arithmetic mean, standard deviation, and the standard error of the mean, or those used in the several statistical techniques for the analysis of permeability data have been transformed into common logarithms. Subsequently, and solely as a matter of convenience, when the estimated parameters were used in compiling maps showing transmissivity and permeability variations, the common logarithms were transformed to natural logarithms to allow the use of small whole numbers for contour intervals.

PROCEDURE

Determining the transmissive capacity of eolian and marine sandstones presents few problems. These units are typically tabular or wedged shaped and are characterized by relatively uniform gradients of permeability and thickness. The coefficient of transmissivity at any location in such rocks is determined simply and is equal to the product of mean permeability in darcys and thickness in feet.

Determining transmissive capacity in fluvial sandstones is more difficult. In these rocks large local gradients in both thickness and permeability tend to obscure the regional gradients. Consequently, averaging techniques were required to obtain measures of thickness and permeability on which reliable regional gradients could be based.

The techniques used to obtain an average thickness of sandstones varied to some extent with the hydrologic unit under consideration. Sandstones of the Morrison formation, which include the Salt Wash sandstone member over most of the area of study as well as the Westwater Canyon sandstone and Recapture shale members in northwestern New Mexico, had previously been studied quantitatively (Craig and others, 1955). From this study measurements were available of the thickness of sandstone and mudstone at 5 closely spaced locations at each of 64 well separated outcrops. These thickness and continuity data were used to calculate the mean thickness and the standard deviation of thickness for sandstones of the Morrison at each of the 64 outcrops.

Thickness and continuity data on the lower sandstones of the Chinle were not so readily obtained. A large number of measured sections, mostly in southeastern Utah, were available from the files of the U.S. Geological Survey office at Grand Junction, Colo. Many measurements in the Navajo-Hopi Indian Reservation of northeastern Arizona and northwestern New Mexico were also obtained from ground-water studies in that area (Harshbarger and others, 1957). Thickness data from these measured sections, together with a few from published reports, were plotted on a map and the average thickness and standard deviation of thickness were obtained by a moving-average technique. A grid was generated by marking off 40-mile intervals in the cardinal directions from an arbitrary origin—the point where Colorado, Utah, Arizona, and New Mexico meet. A circular template with a 40-mile radius was placed on each grid point and the values falling within the circumference of the template were used to find the mean thickness and its standard deviation.

The dimensional data for sandstones of the Dakota, Burro Canyon, Kayenta, and Mesaverde formations, which are also in part of fluvial origin, were not amenable to this treatment as the available measured sections were fewer and more widely spaced. For these units thickness was obtained from the measured sections, and no attempt was made to compute their standard deviation.

The mean permeability and standard deviation of permeability of sandstones of the Morrison and of the lower sandstones and conglomerates of the Chinle were also determined by use of a moving-average system. The same grid that was used in determining mean thickness and standard deviation of mean thickness was used in determining the mean and standard deviation of permeability. Because of the small number of samples per profile used in obtaining an estimate of the parameters of the grain-size analysis, and the uncertainties of correlation of the permeability computed from these parameters with measured permeability, it seemed desirable to give more weight to measured permeability than to computed permeability (p. 136). Consequently, and as each measured permeability profile contained on the average twice as many samples as those from computed profiles, each measured mean permeability was weighted twice. This also provided a means of cross checking estimates of permeability, as at least one measured mean fell within most circles that were averaged.

In all other units, including the eolian and marine units, the numbers of both measured and computed permeability means were too few to use the moving-average system. In these units the measured means were used as primary control, and the computed means were used to guide interpolation between areas of measured permeability.

In every hydrologic unit sampled, the reliability of measured permeability was judged by a control chart with a specified acceptance level of standard deviation of the mean (American Society for Testing Materials, 1951). All sets of permeability samples with a standard error of the mean above 0.40 $\log_{10}$ millidarcys were considered to have an inadequate number of samples and, where possible, additional samples were added until the standard error of the mean was reduced below this level. By this method the contour interval of 1.0 $\log_e$

millidarcys, the most convenient interval and scale for the ranges of permeability involved, could be used with at least some assurance of reliability. The control charts for all formations tested are shown on figure 4.

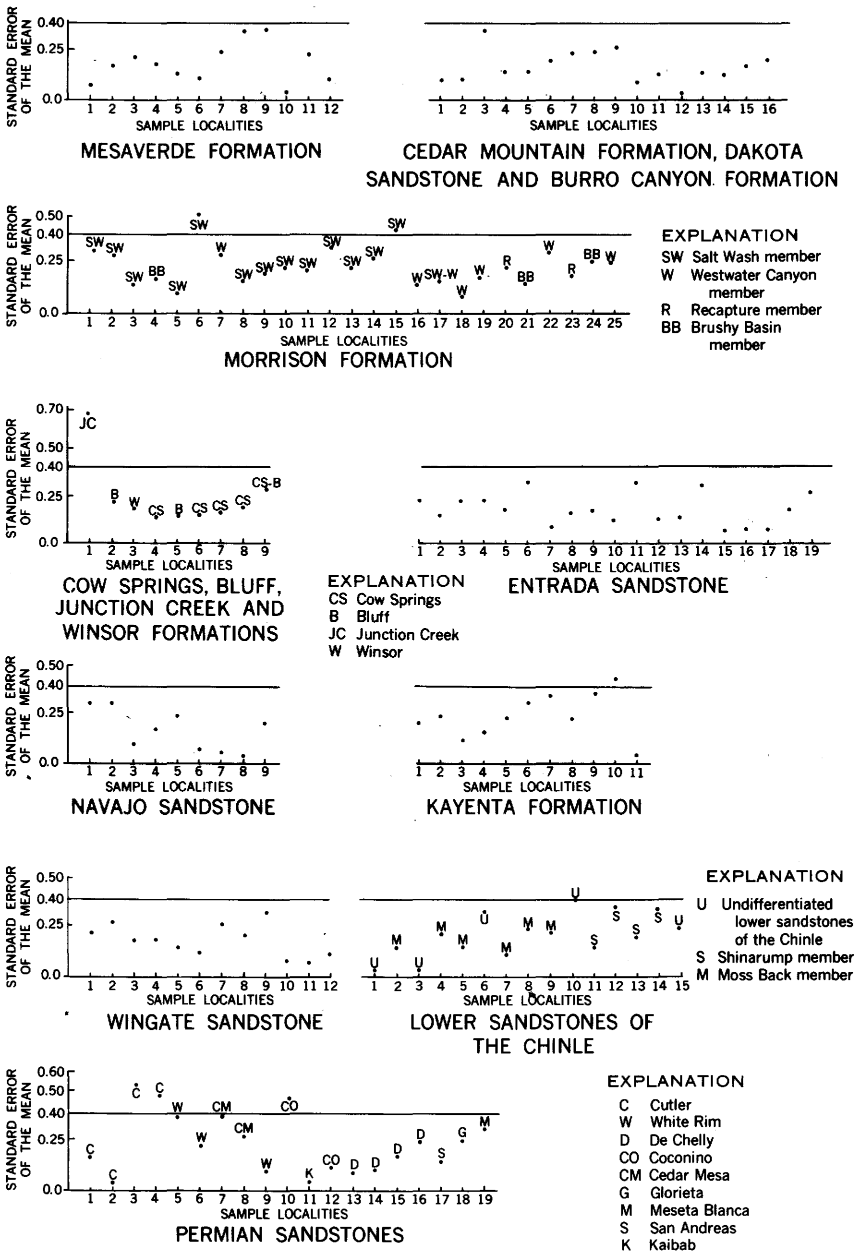


FIGURE 4.—Control charts for sampling density (The sample locality numbers refer to those listed on p. 142–146.)

ACKNOWLEDGMENTS

This project is a part of an extensive program of geologic investigation of uranium on the Colorado Plateau undertaken by the Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission. The project owes much, both in technique and fundamental approach, to an earlier study by Phoenix (1956) on the permeability of the "ore-bearing sandstone" of the Morrison formation. Invaluable aid in statistical methods and particularly in devising an empirical formula to compute permeability from grain-size analysis parameters was given the writer by R. A. Cadigan of the U.S. Geological Survey.

Plans for the design, and precautions as to the use, of a universal permeameter capable of using either gases or fluids as the transmitted medium were made available by G. L. Gates and F. C. Morris of the U.S. Bureau of Mines, San Francisco, Calif.

W. David Lumpkin assisted both in the field and the laboratory throughout most of the investigation.

RESULTS OF PRELIMINARY EXPERIMENTS

The results of the first stage of the sampling and measurement program are summarized below. Although only a brief statement of results will be given here, the data of each analysis may be found in appropriate tables and sections of "Statistical analysis of methods and data."

The first stage of sampling and measurement was exploratory in nature. It was designed to yield probability-stated estimates of the amount of variation (including operator variation) in permeability measurements which could be assignable to the various techniques used to determine permeability and to local and regional permeability gradients.

First, it was determined that the permeameter used in the experiment could be read with sufficient precision and operator variation was sufficiently small that slight differences in permeability between similarly oriented subsamples, separated by several inches within the same sample, could be detected (tables 11–21). These conclusions justified elimination of replicate runs on routine permeability determinations except where the results of the several subsamples seemed to be obviously anomalous.

Second, within the samples of sandstones tested, both fluvial and eolian, significant differences exist between the permeability of three subsamples cut so as to be mutually perpendicular (p. 116). These differences are large when compared to the differences attributable to operator variance and the precision of measurement, but they are small when compared to the differences between adjacent samples within the same permeability profile (table 12). The total variation owing to operator variance and lack of precision in measurement averages about 1 to 2 percent; the differences between subsamples average about 5 to 10 percent, and the differences between adjacent samples are about 10 to 20 percent. For these reasons, and because crossbedding is characteristic of the strata involved in this study, the mean permeability of three mutually perpendicular subsamples was used as the mean permeability of the sample.

Third, the variation in mean permeability between the closely spaced samples of one permeability profile of the units tested suggested that a vertical sampling density of about 6 to 12 samples for units of marine or eolian origin and 8 to 20 for those of fluvial origin would be necessary in order to measure the mean permeability of the profile with a standard error of the mean below 0.40 $\log_{10}$ millidarcys (fig. 5, table 9).

Fourth, although there is a wide range of permeability values within any permeability profile, the regional gradient of arithmetic mean permeability in sandstones of both fluvial and eolian or marine origin is very gradual (tables 22–25). Within distances of less than 50 miles, where the permeability-profile samples were collected about parallel to the basin of deposition of the sediments being sampled, regional mean permeability gradients are generally less than 0.01 $\log_{10}$ millidarcys per mile. For this reason, the permeability profiles used to outline regional permeability could be spread rather widely over the outcrop areas. Although the spatial distribution of outcrop pattern controlled the spacing of sample points to a larger degree than desirable, a spacing of 50 miles or less was maintained wherever possible for the more uniform sandstones, and about 30 miles for the more heterogeneous sandstones.

Fifth, after applying an empirical correction factor to the permeability values determined with nitrogen, no significant differences were found between measurements made with liquid and gas permeameters on suites of samples from five representative hydrologic units (tables 8–10). The correction factor, though not a constant, is a consistent one which varies as a function of the magnitude of permeability, and is believed to be chiefly due to the difference in flow behavior of the two transmitted fluids.

Finally, although it has not been possible, using standard grain-size-analysis parameters, to devise a formula that will yield permeability values strictly comparable to those obtained with the permeameter, it has been possible to achieve a high degree of correlation between the values derived by the two methods (tables 28–30). By eliminating from consideration the few grain-size analyses with kurtosis

$>20\phi$ units and standard deviation $<1.0\phi$ units, the correlations are good enough so that the permeability estimated from grain-size-analysis data can be a guide to interpolation between measured permeability profiles.

HORIZONTAL TRANSMISSIVITY

In the following sections, the transmissive character of the exposed sedimentary rocks of the Colorado Plateau is shown largely by a series of diagrams that outline the regional gradients of thickness, permeability, and transmissivity. The regional stratigraphic relations of the different hydrologic units are shown in tabular form and are accompanied only by a brief discussion of the regional trends and character of each hydrologic unit. Most of the stratigraphic relations shown on the tables are well established in the literature of the Colorado Plateau; for those few currently in doubt, the correlations used are those of W. L. Newman and E. M. Shoemaker (written communication, 1955).

PRE-PERMIAN ROCKS

Sedimentary rocks of pre-Permian age were not studied in this investigation, primarily because of the few exposures. Where exposed, they consist of an assemblage of limestones, fine-grained clastic materials, and some interbedded evaporites. Rocks of this character are generally of low permeability except where they are highly fractured or cavernous.

There is little reason to doubt, however, that the limestones may possess appreciable local transmissivity. In at least one area, where the Blue Springs issue from the Redwall limestone near the mouth of the Little Colorado River, a flow of about 90,000 gpm (gallons per minute) has been recorded (Brown and Halpenny, 1948). Another permeable zone lies in northwestern New Mexico and southwestern Colorado where sandstones of Permian age crop out in the Animas River valley. Bass (1944) believes that these sandstones have little areal extent and were deposited in a narrow belt paralleling the shoreline of the San Luis-Uncompahgre upland of late Paleozoic time. Other sandstones of pre-Permian age with low but erratic gradients of permeability have been penetrated by oil wells drilled in southeastern Utah (Wengerd, 1955).

PERMIAN ROCKS

The oldest sedimentary rocks that crop out extensively on the Colorado Plateau are Permian in age. The stratigraphic and hydrologic character for representative parts of the area studied is shown in table 2.

TABLE 2.—*Exposed sedimentary rocks of Permian age*

Area	Formation		Member or tongue	Thickness (feet)	Hydrologic unit	Remarks
Southwestern Colorado and southeastern Utah	Cutler		White Rim Organ Rock Cedar Mesa Halgaito tongue	0–230 0–400 0–1,200 0–75	Upper unit	Sampling, except for exploratory work, restricted to sandstones of the White Rim and Cedar Mesa. Halgaito tongue is sandy in part but owing to high clay content and heterogeneity of sorting is of low permeability, generally less than 1.0 millidarcys.
	Rico			300–500	Lower unit	Not sampled but very low intrinsic permeability; dominantly fine grained clastic rocks and limestone.
Northern Arizona and southern Utah	Kaibab limestone Toroweap			0–350 ------------	Upper unit	Not sampled; very low intrinsic permeability.
	Coconino	Cutler	De Chelly Organ Rock Cedar Mesa Halgaito tongue	0–700	Upper unit	Sandstone units are patchily cemented with calcite and iron oxides which are fine grained to very fine grained, well sorted, and contain little interstitial clays.
	Hermit shale Supai			0–700 1,000–2,000	Lower unit	Virtually nontransmissive shales and siltstones.
South-central Utah	Kaibab limestone			0–150	Upper unit	Absent over much of the area.
	Coconino and Cedar Mesa			100–800	Upper unit	Fine grained to very fine grained sandstone and a patchy distribution of calcite and iron oxide cement. Low clay content and well-sorted character make this unit an excellent aquifer.
Northwestern New Mexico	Cutler (undivided)	San Andres		0–100	Upper unit	No measurable permeability, that is, less than 0.5 millidarcys.
		Glorieta		0–300		Well sorted clean medium- to fine-grained sandstone; major aquifer in this area; well cemented and has only moderate permeability except where fractured.
		Yeso	San Ysidro Meseta Blanca	------------ ------------		Moderately well sorted sandstone interbedded with siltstone. Sandstone units have fair permeability.
	Supai	Abo		0–500+	Lower unit	Not sampled; dominantly shale and siltstone in Colorado Plateau although contains some earthy sandstones.

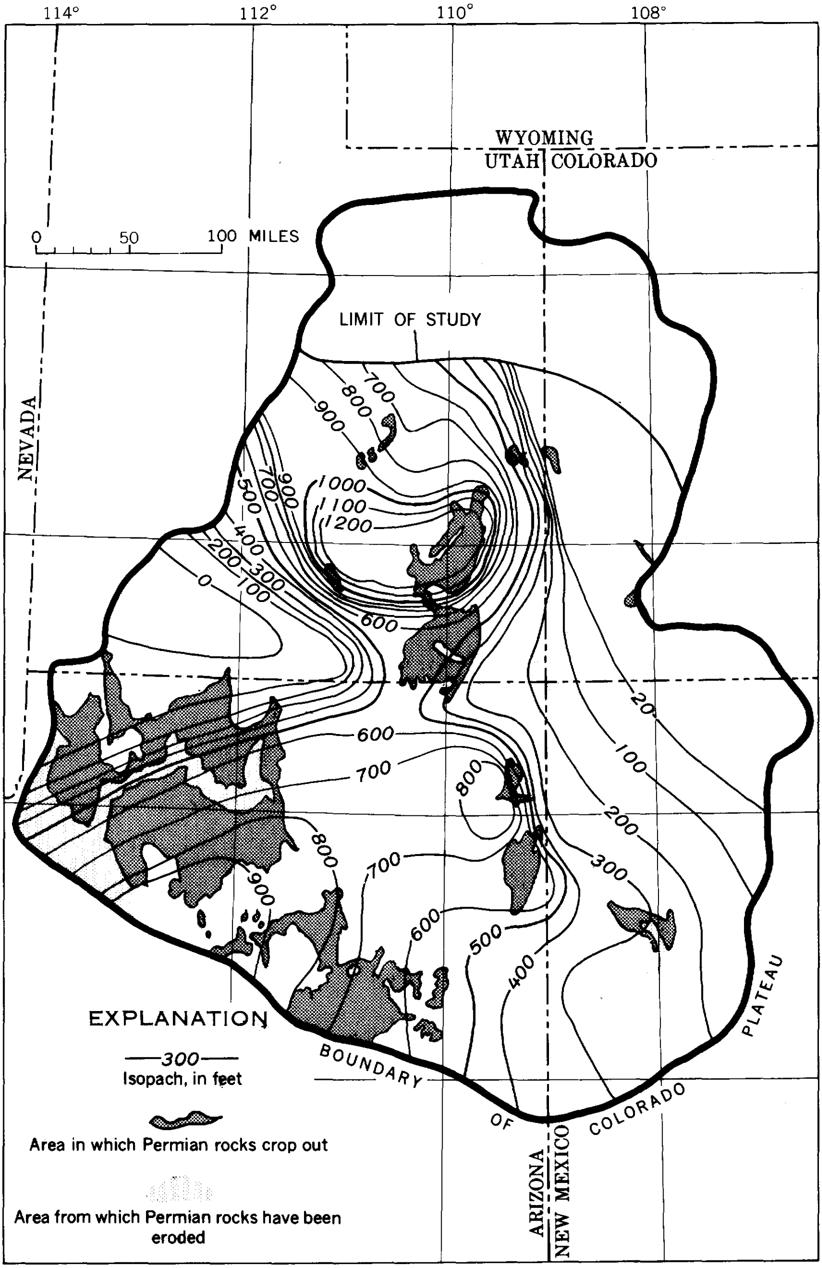


FIGURE 5.—Isopach map of Permian sandstones. Compiled from Baker (1946), Baker and Reeside (1929), Bass (1944), McKee (1934, 1952), and Reed (1950).

LOWER UNIT

The lowermost part of the Permian system—the Rico, Abo, Supai, and Hermit formations—is mainly interbedded fine clastic materials containing minor amounts of limestone. Together these formations comprise a hydrologic unit of little or no significant regional transmissive capacity on the Colorado Plateau. The Abo formation, however, does contain some lenticular conglomerates and sandstones of low permeability which are more widespread to the southeast and east. There they contain copper deposits, some of which contain uranium.

UPPER UNIT

The uppermost Permian rocks are more diverse than the lower unit in both lithology and hydrologic character. In southwestern Colorado and northwestern New Mexico the upper unit is the Cutler formation. The Cutler of this area is composed of a thick dominantly fluvial red-bed assemblage of interbedded mudstone, siltstone, and poorly sorted sandstones and conglomerates. To the west, approximately coincident with the Colorado-Utah State line, and to the south, near the Zuni Mountains, the Cutler includes the White Rim and Cedar Mesa sandstones and grades into and interfingers with the Coconino and Glorieta sandstones. The Coconino, Glorieta, White Rim, and Cedar Mesa sandstones, thick wedge- or tongue-shaped units, are believed to be of eolian origin. These sandstone units, in turn, appear to thicken and coalesce westward in north-central Arizona. In both north-central Arizona and the Zuni Mountains area a limestone unit, the Kaibab and San Andres limestones respectively, commonly overlies these sandstones.

An isopach map of the total permeable sandstones in the upper unit and their gross outcrop pattern is shown in figure 5. It does not include the thin discontinuous sandstone beds in the red-bed assemblage of southwestern Colorado and northwestern New Mexico. Isopermeability and isotransmissivity maps of the same unit are shown in figures 6 and 7.

Perhaps the most striking hydrologic characteristic of these sandstones is a relatively high uniform permeability as evidenced by the low standard deviation of permeability within permeability profiles (table 31). This characteristic and the relatively great thickness and the lack of interstitial clays indicate that this unit has an excellent regional transmissive capacity. Local highs occur in New Mexico, northeastern Arizona, and southeastern Utah.

The marked positive correlation between isopleths of thickness and permeability of the Permian sandstones probably reflects the areal variation in stability and duration of the dune-forming environment.

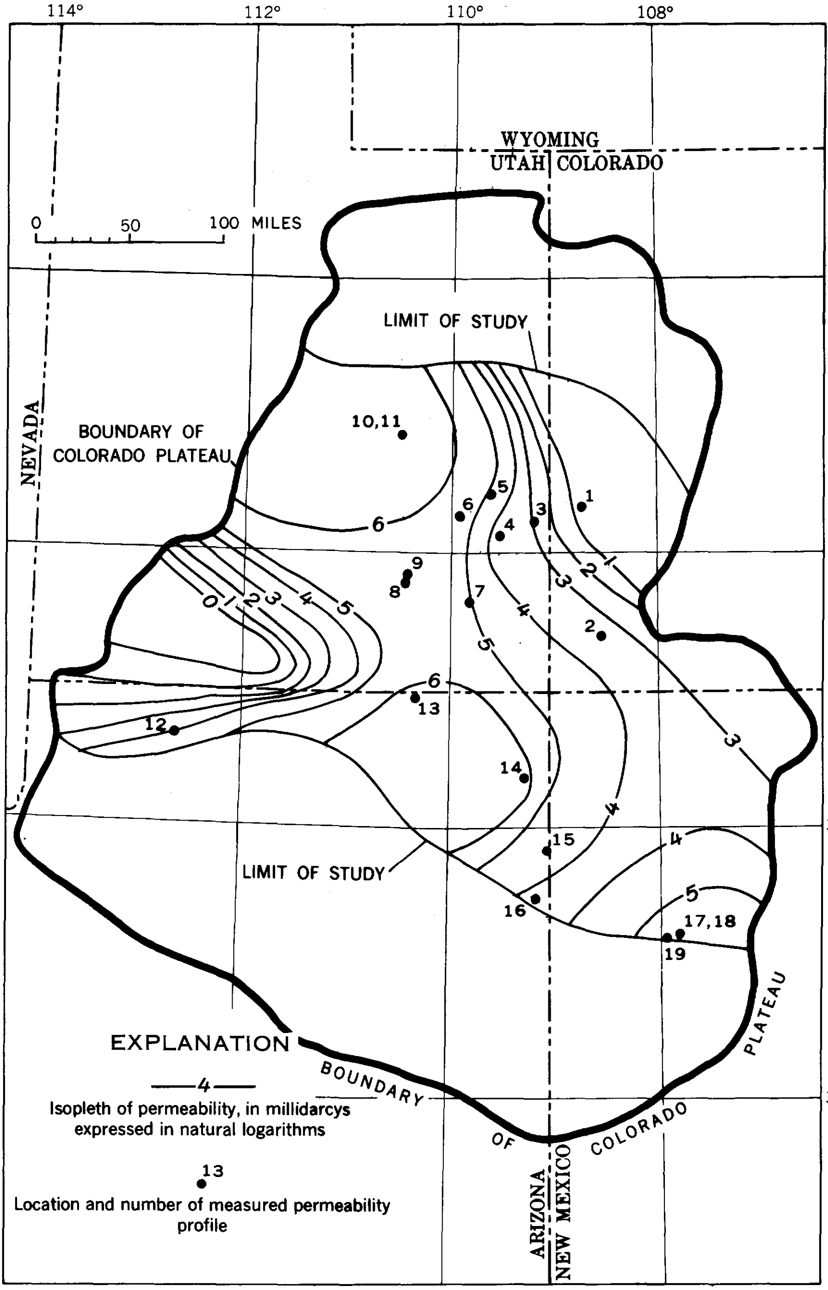


FIGURE 6.—Isopermeability map of Permian sandstones. Location numbers are given in table 31.

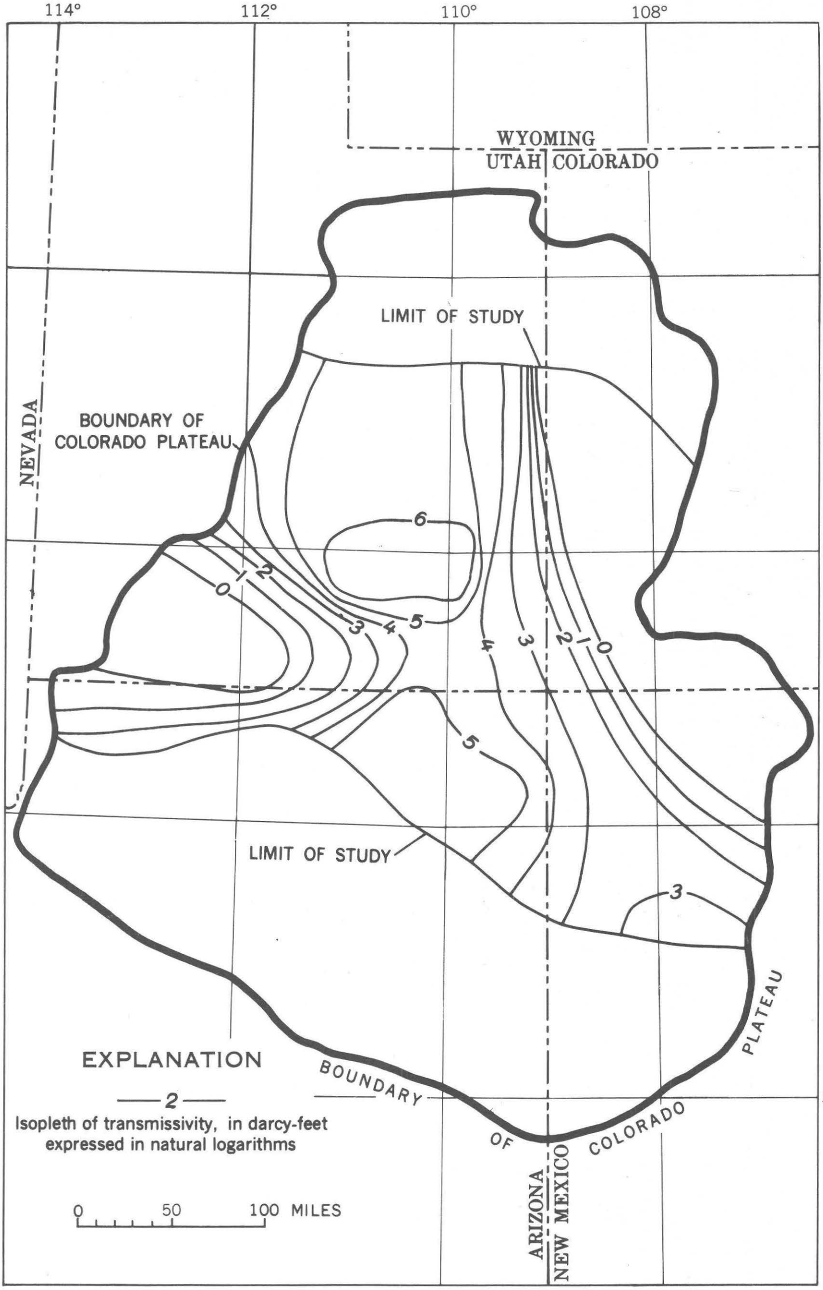


FIGURE 7.—Isotransmissivity map of Permian sandstones.

Stable and long-lasting conditions which are conducive to dune formation have resulted in the deposition of thick, well-sorted, and therefore relatively permeable, sandstones over wide areas. Less stable conditions with alternating periods of eolian and fluvial regimen in areas peripheral to the main dune deposits have resulted in the deposition of thinner less well sorted, and therefore less permeable, sandstones.

TRIASSIC ROCKS

MOENKOPI FORMATION

The Moenkopi formation is the basal hydrologic unit of Triassic age in southern Utah and northern Arizona (table 3). It is composed mainly of fine-grained clastic rocks although minor amounts of limestone and poorly sorted sandstone make up about 10 percent of the total volume (G. A. Williams and others, written communication, 1955). Taken as a whole, the Moenkopi formation is an aquiclude. The permeable parts of the unit are confined to the sandstones which, although thin, are widespread. A few exploratory permeability measurements on samples of the sandstones indicate that these too have a low permeability and so contribute little to regional transmissive capacity.

LOWER SANDSTONES OF THE CHINLE FORMATION

Above the Moenkopi formation, or near the base of the sedimentary rocks of Triassic age where the Moenkopi is absent, are widespread thin lenticular strata of sandstone and conglomeratic sandstone (fig. 8).

In most areas there is only one stratum, but no stratum is continuous over the entire region (Stewart, 1957). The two most extensive and distinctive sandstones and conglomeratic sandstones have been named the Shinarump and Moss Back members of the Chinle formation (Stewart, 1957).

The Shinarump seems to have been deposited from several distributary systems which extended inward in a tonguelike fashion from the southwestern to southeastern periphery of the basin of Chinle deposition, whereas the Moss Back seems to have had a single major source on the eastern periphery of the basin of deposition (Stewart, oral communication, 1955). The major directions of transport were to the north and northwest for the Shinarump and to the west and northwest for the Moss Back (fig. 8). Other minor sandstone strata near the base of the Triassic include parts of the Temple Mountain, Monitor Butte, and Church Rock members of the Chinle formation (Stewart, 1957). These minor sandstones and conglomeratic sandstones are almost exclusively found in areas that contain the Moss Back member as the chief component of the lower Chinle hydrologic unit.

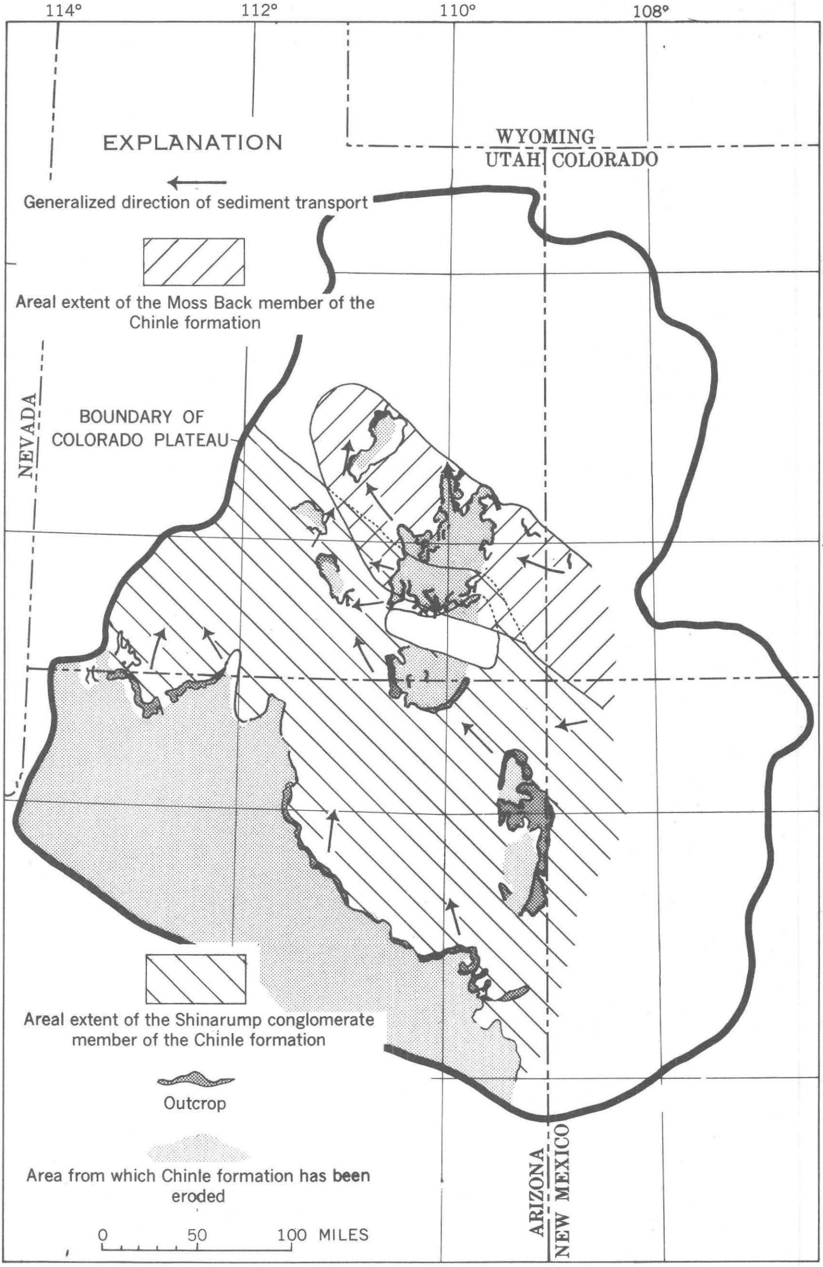


FIGURE 8.—Gross outcrop pattern of the lower sandstones of the Chinle formation. Modified after Finch (1955), and Stewart and others (1959).

TABLE 3.—*Exposed sedimentary rocks of Triassic age*

Area	Group	Formation	Member	Thickness (feet)	Hydrologic unit	Remarks
Southwestern Colorado and southeastern Utah	Glen Canyon	Wingate sandstone		0–300	Wingate sandstone	Moderately well sorted very fine grained sandstone; good aquifer.
		Chinle	"A" of Gregory (1917, p. 42–43) Owl Rock	0–900	Upper mudstones	Dominantly siltstone and mudstone interbedded with thin limestones. Some poorly sorted sandstones especially near top of the section.
			Moss Back Monitor Butte Shinarump	0–50 0–200 0–175	Lower sandstones	Interbedded lenticular sandstone and mudstone.
		Moenkopi		0–1, 100	Moenkopi	Mudstone and siltstone unit; includes some poorly sorted sandstones.
Northern Arizona and southern Utah	Glen Canyon	Wingate sandstone	Lukachukai Rock Point	0–500	Wingate sandstone	Moderately to well-sorted, very fine grained sandstone; lower part contains abundant siltstone.
		Chinle	Church Rock Owl Rock Petrified Forest	700–1, 000	Upper mudstones	Mudstone, siltstone, limestone, and thin poorly sorted sandstones; a good aquiclude in most parts of area.
			Moss Back Monitor Butte Shinarump	0–50 100–200 0–250	Lower sandstones	One or more thin, but widespread, lenticular sandstones interbedded with mudstone; sandstones moderately poorly sorted.
		Moenkopi		100–1, 500	Moenkopi	Mudstone, shale, and limestone. Some poorly sorted thin sandstones.

South-central Utah	Glen Canyon	Wingate sandstone		300	Wingate sandstone	Moderately well sorted, very fine grained sandstone; good aquifer.
		Chinle	"A" of Gregory Owl Rock	} 300–600	Upper mudstones	Interbedded siltstones, limestones, mudstones, and poorly sorted very fine grained sandstones; an aquiclude in most places.
			Moss Back Monitor Butte Shinarump	0–50 0–100 0–20	Lower sandstones	Lenticular sandstone interbedded with mudstone. Sandstone is moderately to poorly sorted, fine to medium grained, containing stringers of conglomerate.
		Moenkopi		700–1, 000	Moenkopi	Siltstone and mudstone containing persistent middle limestone unit and few thin sandstone units.
Northwestern New Mexico	Glen Canyon	Wingate sandstone	Lukachukai Rock Point	} 0–300	Wingate sandstone	Moderately well sorted, fine-grained sandstone; grades into siltstone or sandy siltstone at base.
		Chinle	(Undifferentiated)	900–1, 500	Upper mudstones	Dominantly interbedded siltstone, mudstone, and limestone. Excellent aquiclude.
			Shinarump	0–50	Lower sandstones	Moderately to poorly sorted, fine-to medium-grained sandstone; very heterogeneous.

631709 O—62——3

Figure 9, constructed by means of the previously described moving-average technique, shows the lower sandstones of the Chinle.

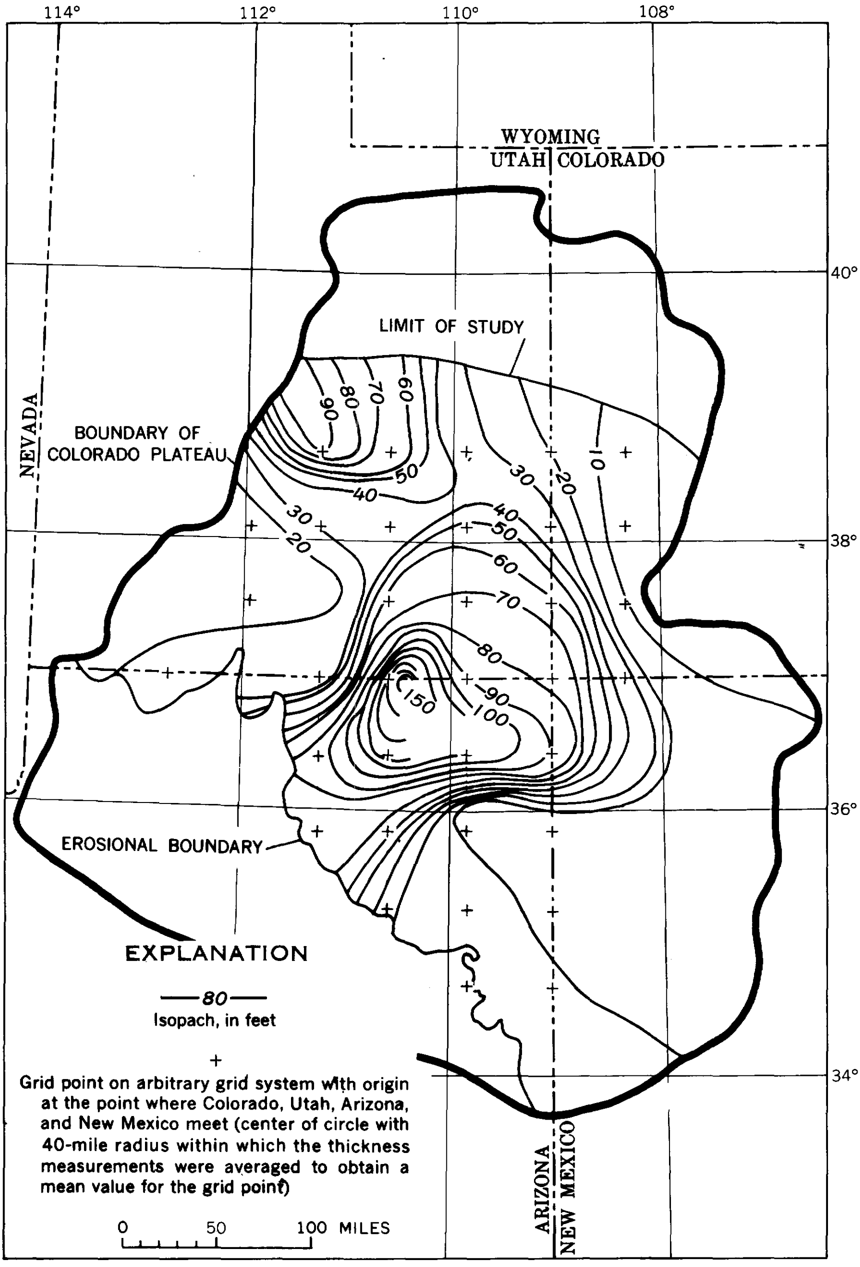


FIGURE 9.—Isopach map of lower sandstones of Chinle formation. Compiled from Gregory (1917, 1938), Harshbarger and others (1957), and Stewart and others (1959).

Two features stand out on this map: a lobe of thicker than average deposits that trends southeastward from central Utah and a large irregular area of thick deposits that centers in northeastern Arizona. The southeastward-trending lobe largely represents a local thickening of the Moss Back member, although the presence of sandstones in the underlying Temple Mountain and Monitor Butte members of the Chinle formation also contributes to this thickening. The irregular area of thick deposits in northeastern Arizona consists of deep channel deposits of the Shinarump.

An isopermeability map (fig. 10) of the lower sandstones of the Chinle formation indicates a general increase in permeability from western Colorado to northwestern Arizona. The gradient is relatively steep along the Colorado-Utah border and in southwestern Utah, and shows a pronounced plateau between these areas. The trend of the permeability gradient in northeastern Arizona and northwestern New Mexico is not well defined, owing to the lack of measurements, but it seems to indicate increasing permeability to the south.

A comparison of the isopermeability map (fig. 10) with maps showing the distribution and thickness of the major sandstone members of the Chinle formation (figs. 8, 9) shows the following relations: First, the Shinarump member as a whole is more permeable than the Moss Back member; second, the parts of the hydrologic unit that are near the principal source areas of the Shinarump are in general relatively thin and have high permeabilities, whereas the part of the hydrologic unit near the principal source area of the Moss Back is also thin but has low permeability; third, the thickest part of the hydrologic unit, where it is composed entirely of Shinarump, has a moderate to low permeability when contrasted to the remainder of the hydrologic unit underlain by Shinarump, whereas the thickest part of the hydrologic unit where it is composed chiefly of Moss Back has a high permeability when contrasted with the remainder of the hydrologic unit chiefly underlain by Moss Back.

In most conglomerate or sandstone, intrinsic permeability depends primarily on the amount and distribution of cementing material and on the range and proportions in the distribution of grain sizes. Although available data are not plentiful it is of interest to sort out the influence each of these factors seems to have had on the permeability of the lower sandstones of the Chinle formation.

The limited amount of data available from the grain-size analyses of samples collected for this study show no readily apparent systematic regional variation in sorting, cementation, or mean grain size for the unit as a whole. Between members, however, the Moss Back seems slightly more cemented and better sorted than the Shinarump and also seems to have a smaller mean grain size. In addition, within that

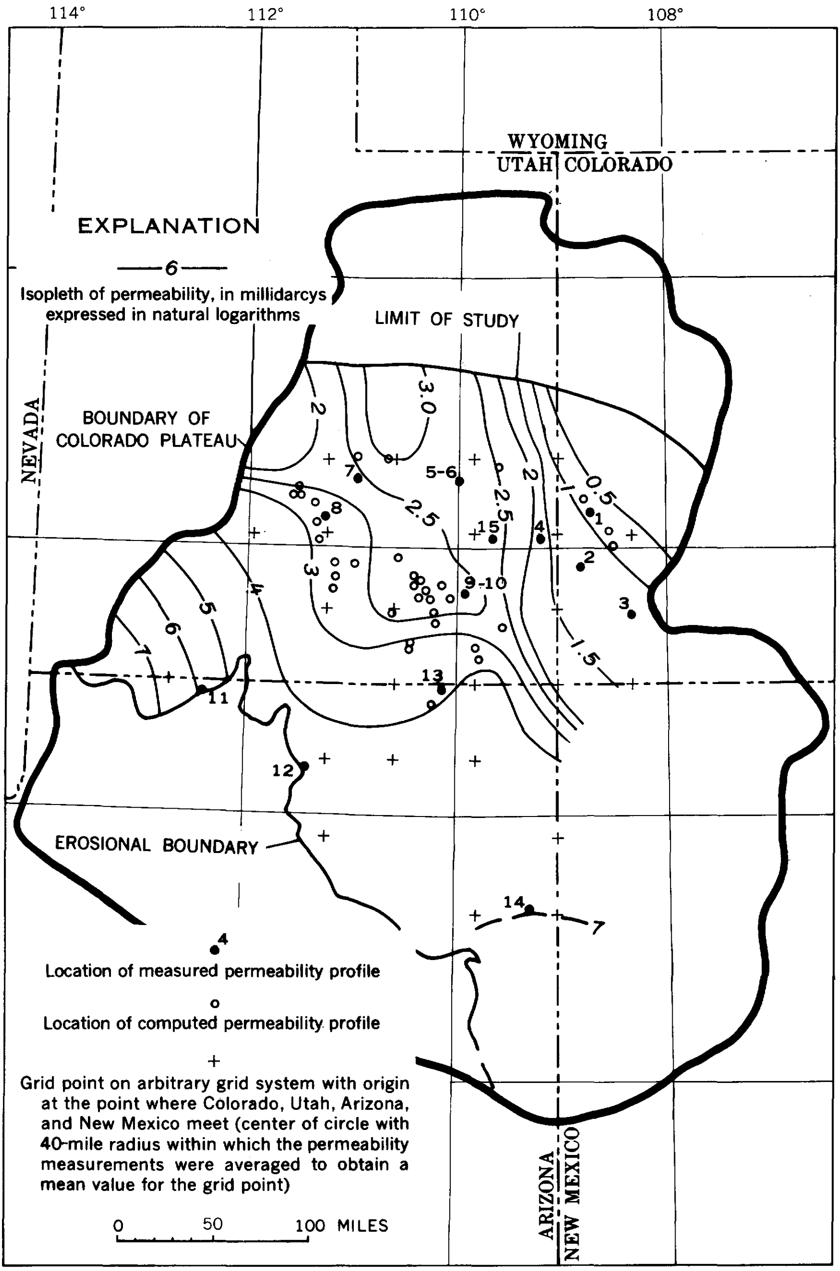


FIGURE 10.—Isopermeability map of the lower sandstones of the Chinle formation. Location numbers are given in table 31.

part of the unit composed only of Shinarump, neither cementation nor the degree of sorting seems to vary systematically. Average grain size of the Shinarump, however, is larger in areas nearest to the postulated source areas. In that part of the unit underlain mainly by Moss Back, both the degree of cementation and the degree of sorting seem to vary systematically. More abundant cement and a slightly wider range of particle size is evident in the areas nearest the postulated source area.

In comparing these factors the most apparent factor contributing to the higher mean permeability of the Shinarump as contrasted to the Moss Back seems to be the larger average grain size of the Shinarump. This factor is in part negated by slightly poorer sorting in the Shinarump but reinforced by a higher average content of cement in the Moss Back. The gradient of permeability between highest values in areas nearest the source and lower values at greater distances from the source in the Shinarump seems to be chiefly the result of the larger mean grain size found in the Shinarump in areas nearest the postulated source areas.

In the Moss Back, however, permeability is higher in central Utah, where it is at a greater distance from the chief source area, than in southwestern Colorado, at a lesser distance from the source area. The low permeability of the areas closest to the postulated source areas for the Moss Back is chiefly the result of two factors: a greater degree of cementation in these areas, and the greater amount of interstitial clays. A partial explanation may also lie in the apparent increase in arkosic material and grain size of the lower sandstones of the Chinle of the San Rafael Swell area of central Utah (R. A. Cadigan *in* Stewart and others, 1959). Although these data are derived from a small number of samples they would at least suggest that the Moss Back of central Utah may also have had local source areas in north-central Utah.

An isotransmissivity map (fig. 11) of lower sandstones of the Chinle shows many of the same trends as the isopermeability map. The dominant gradient of transmissivity is from high values in northwestern Arizona to low values in southwestern Colorado. The White Canyon area of southeastern Utah (fig. 1) appears as a region of higher transmissivity surrounded by lower values. The transmissivity gradient seems generally to flatten in an area centering in east-central Utah over the San Rafael Swell. The change in trend of isopleths of permeability in northeastern Arizona is paralleled by a change in trend of isopleths of transmissivity.

In interpreting the transmissivity trends, it should be noted that, although over most of the Colorado Plateau the lower part of the Chinle is composed of virtually a single sandstone, in the White Canyon area of southeastern Utah the lower Chinle comprises two overlapping major sandstones. That this poses no serious interpre-

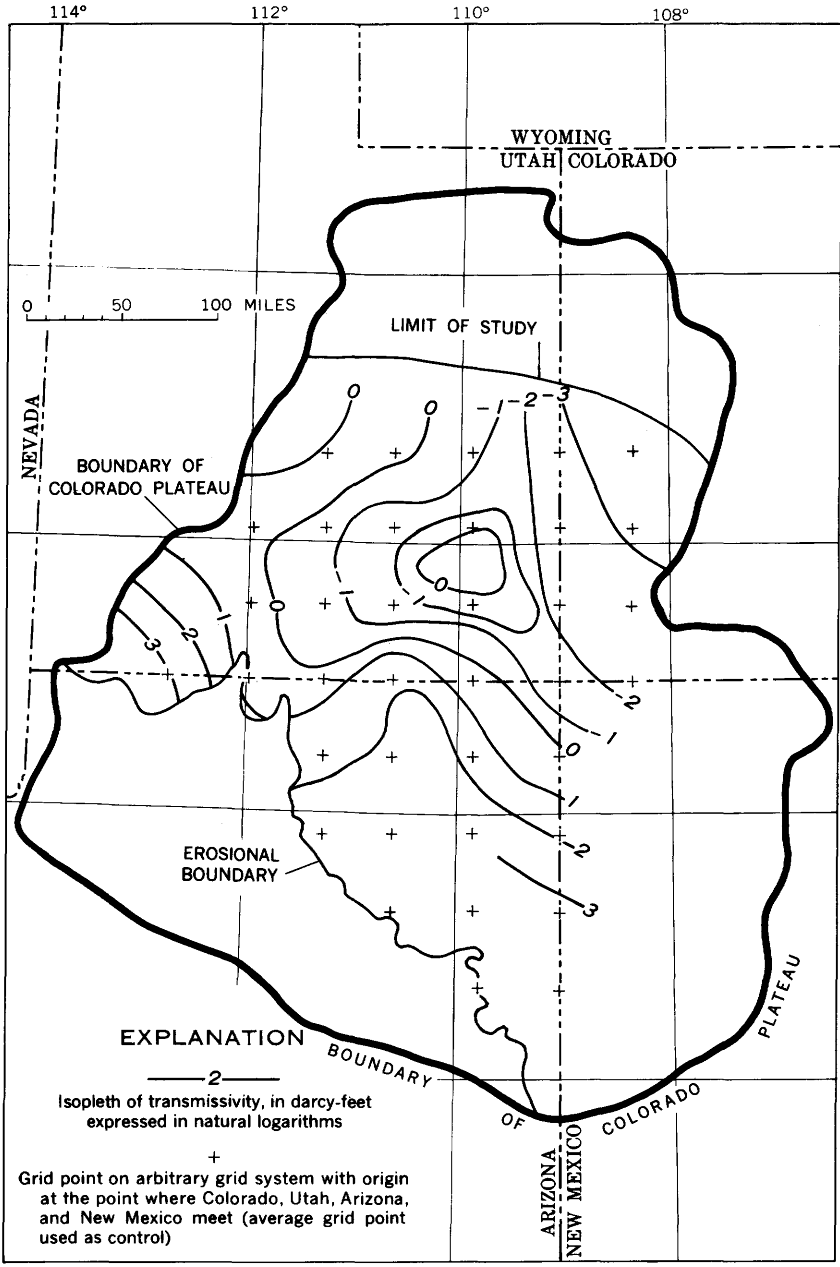


Figure 11.—Isotransmissivity map of the lower sandstones of the Chinle formation.

tive problems, however, is shown by a consideration of the thickness of these sandstones. As the thickness gradient of the Shinarump decreases northward in the area of overlap, that of the Moss Back increases and, in effect, there is little change in the regional gradient

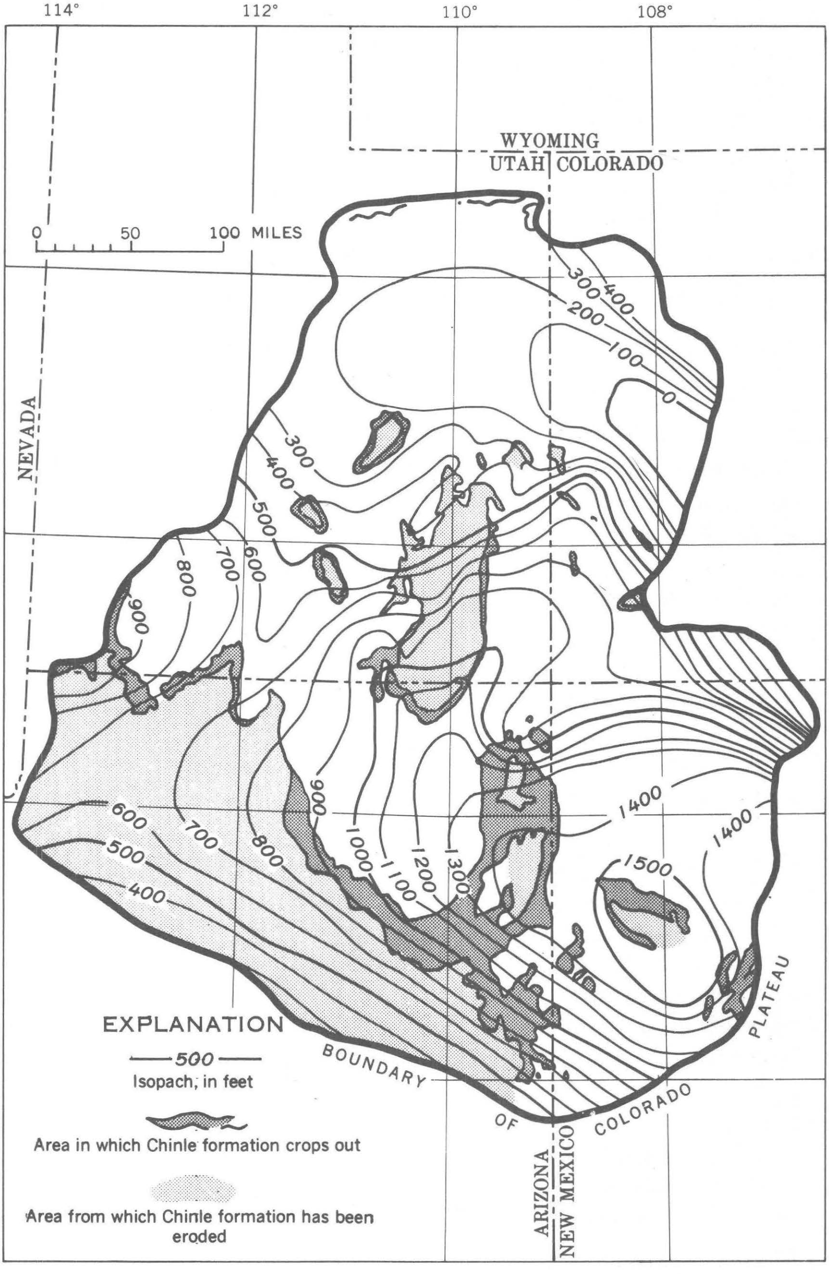


FIGURE 12.—Isopach map of the mudstone and siltstone unit of the Chinle formation. Data compiled by W. L. Newman and E. M. Shoemaker, 1954.

of total thickness which shows a gradual thinning to the northeast. The increase in transmissivity of this area is then almost entirely due to a local flattening of the regional gradient of permeability.

In summary, isopleths of permeability and transmissivity generally trend at high angles to directions of sediment transport; these isopleths indicate increasing permeability and transmissivity in the direction of the source of the Shinarump but decreasing permeability and transmissivity in the direction of the source for the Moss Back. Regional anomalies, flattenings or even slight reversal in the permeability and transmissivity gradients, are located in the San Rafael Swell and White Canyon areas, Utah.

MUDSTONES AND SILTSTONES OF THE CHINLE FORMATION

Above the Shinarump member and other basal sandstones and conglomerates of the Chinle lies a thick unit of interbedded shale, mudstone, and siltstone intercalated with minor amounts of sandstone and freshwater limestone. This part of the Chinle, which extends as a thick blanket over the entire Colorado Plateau (fig. 12), is perhaps the most effective aquiclude in the Colorado Plateau. In a few places, however, particularly in southwestern Colorado and eastern Utah, a thin coherent silty to very fine sandy unit is present at the top of the Chinle. Locally this part of the Chinle is weakly transmissive.

WINGATE SANDSTONE

The Wingate sandstone, the basal formation in the Glen Canyon group, is the uppermost formation of Triassic age over most of the Colorado Plateau. It is typically a highly crossbedded relatively well sorted sandstone, and is thought to be dominantly of eolian origin (Baker and others, 1936). The areal extent of the Wingate sandstone and the distribution of outcrops are shown in figure 13. Isopermeability and isotransmissivity maps (figs. 14, 15) both show roughly concentric gradients; the most permeable sediments coincide approximately with the thickest, and therefore most transmissive, deposits near the central part of the basin of deposition. The transmissivity high is slightly off center and is in southeastern Utah and northeastern Arizona. Owing to a moderately high permeability and great thickness, the Wingate sandstone is a relatively good transmissive unit over most of the Colorado Plateau.

The Wingate sandstone has the most uniform permeability of any of the sandstones of the Colorado Plateau (table 31). This is explainable as being a function of relatively uniform grain size over the entire area and similarity in character and amount of interstitial matrix material. Owing to the uniform permeability, isopleths of thickness and transmissivity are about parallel.

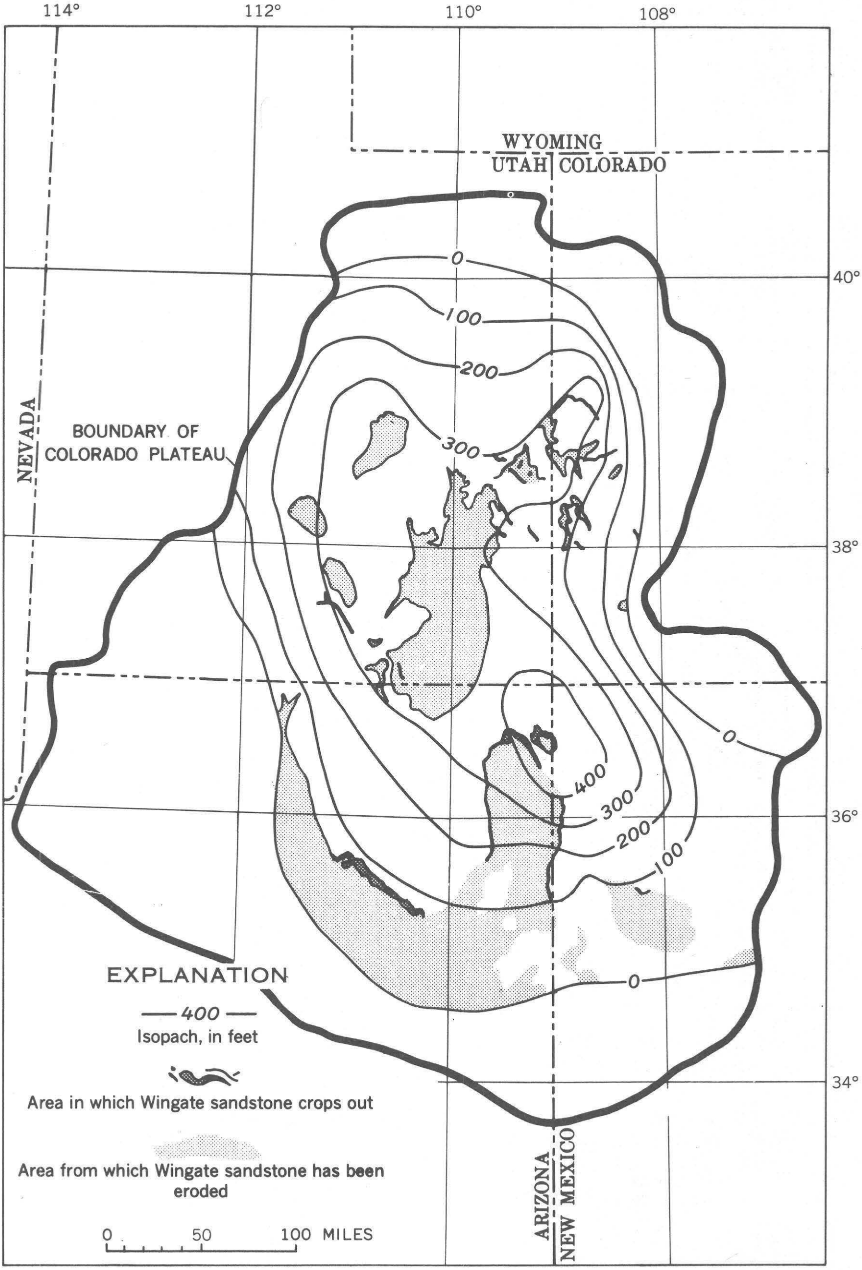


FIGURE 13.—Isopach map of the Wingate sandstone. Data compiled by W. L. Newman and E. M. Shoemaker, 1954.

Although the data are few, the isopleths of permeability show an interesting positive correlation with distance from the peripheral

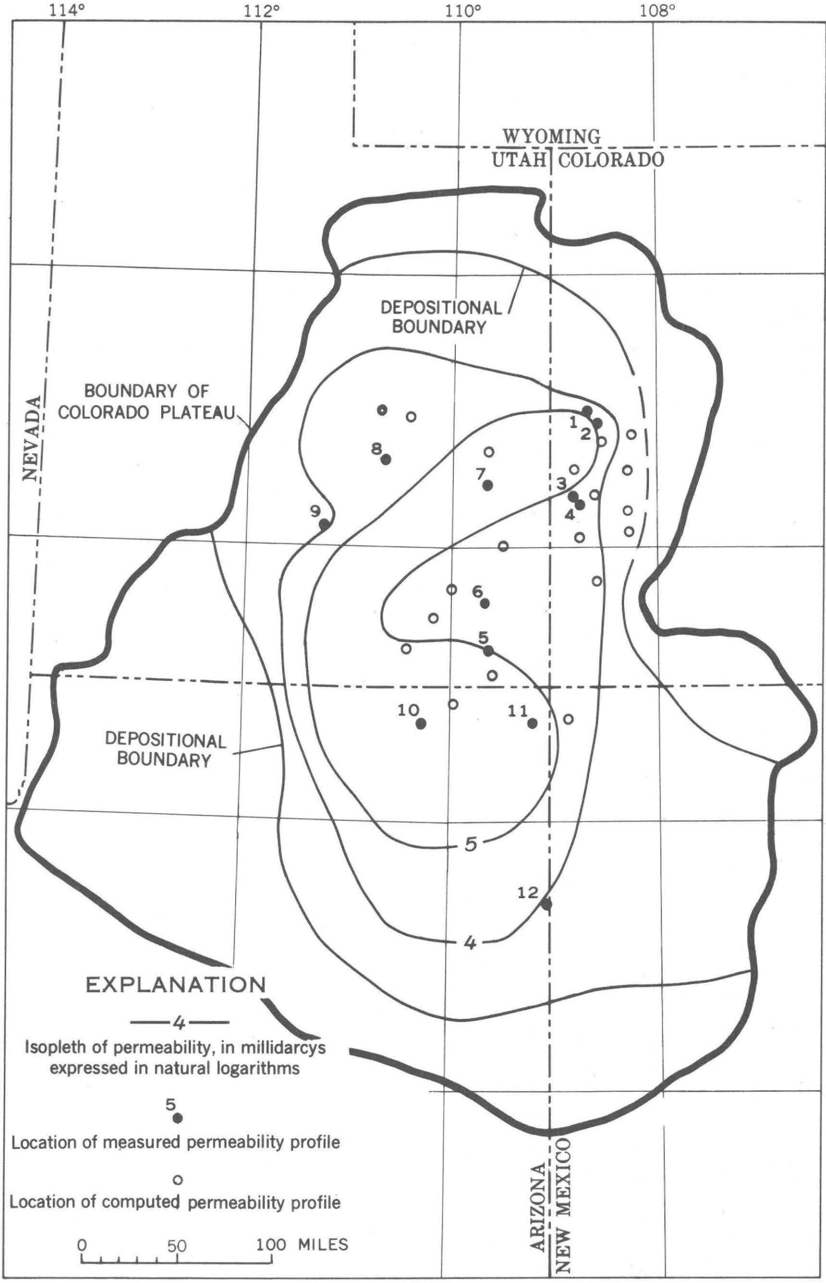


FIGURE 14.—Isopermeability map of the Wingate sandstone. Location numbers are given in table 31.

parts of the plateau. As Harshbarger and others (1957, p. 23) have postulated, a general westward migration of dunes took place during

Wingate time from the north, east, and southeastern peripheral areas of the plateau, and permeability trends apparently reflect the better

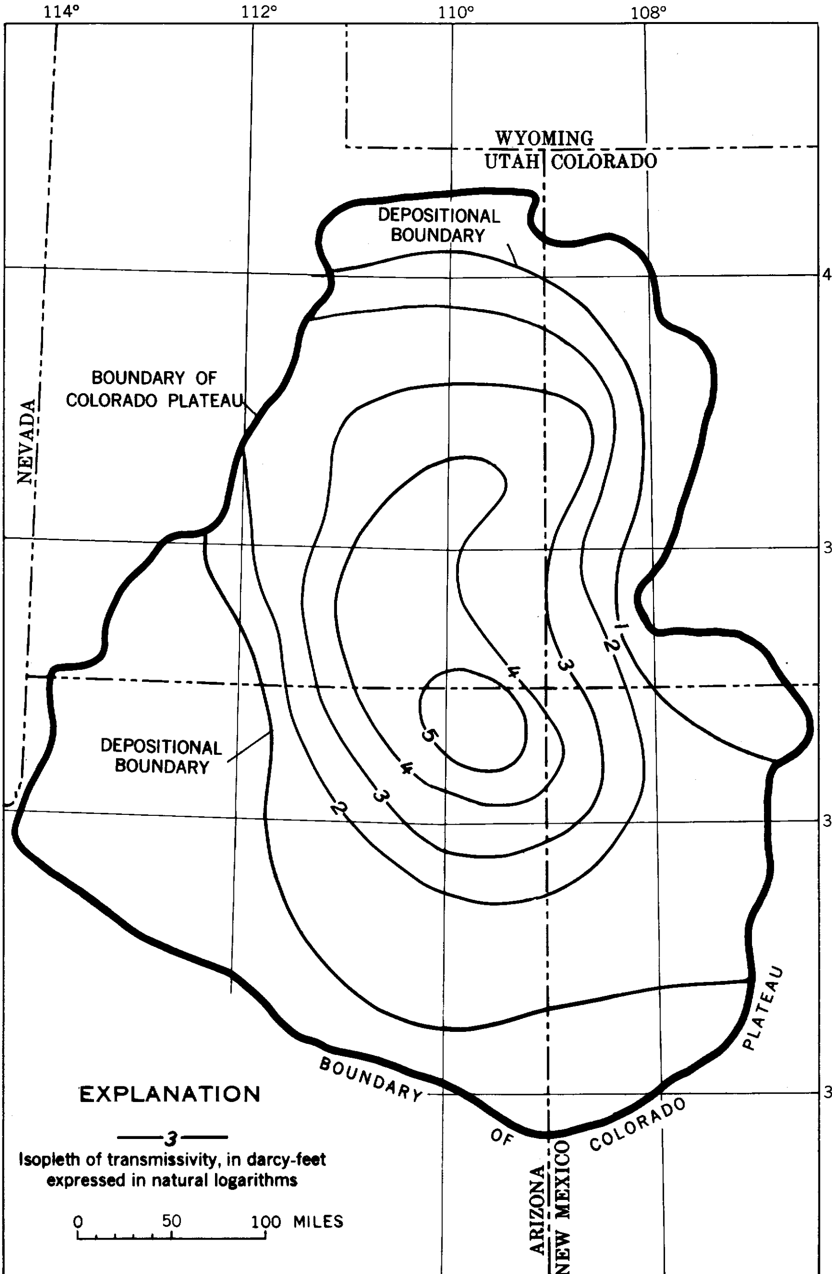


FIGURE 15.—Isotransmissivity map of the Wingate sandstone.

sorting of the latest Wingate dunes that were deposited in the central part of the basin. Admixture of fluvial sediments, and consequently poorer sorting, must also contribute to the lower permeability of the peripheral zones.

JURASSIC(?) AND JURASSIC ROCKS

KAYENTA FORMATION

The Kayenta formation of Jurassic(?) age, the middle member of the Glen Canyon group, is chiefly sandstone of fluvial origin and includes lesser amounts of siltstone and mudstone (table 4). The areal extent of the Kayenta and the distribution of outcrops are shown in figure 16; isopermeability and isotransmissivity maps are shown in figures 17 and 18.

The Kayenta formation is moderately permeable over most of its extent. This uniformity of permeability is largely a result of the relative uniformity of grain size in much of the Kayenta. The Kayenta would probably be more permeable were it not for the many interbedded seams of silt and clay and for the moderately large amounts of cementing material.

The isopleths of permeability trend generally southwest; the area of highest permeability is an elongate tongue which projects from the southwest inward into the basin of deposition. On the southeast side of this high the gradient of permeability seems to decrease systematically. As the Kayenta is believed to be deposited from streams draining to the southwest (Stewart and others, 1959), the permeability high probably coincides with the course of the dominant distributary system from which the Kayenta was deposited.

Similar to the Wingate, the Kayenta has gradients of transmissivity that crudely parallel the gradients of thickness; the area of highest transmissive capacity is slightly to the south and west of the center of the basin of deposition. As the Kayenta of this area has large components of reworked Wingate sandstone, which is more permeable than the Kayenta, the coincidence of permeability highs in the Wingate and Kayenta might be partly attributed to a local dominance of reworked Wingate sandstone.

The regional transmissivity of the Kayenta, as shown in figure 18, is probably somewhat exaggerated because of the methods used in estimating mean permeability. The magnitude of the decrease in permeability that would result from the numerous crosscutting sedimentary structures and thin mudstone beds in the Kayenta can only be estimated, but these features certainly lower the mean permeability of the beds in which they occur, and certainly lower the regional transmissivity considerably. In many areas of the Colorado Plateau the permeability of the Kayenta is so reduced by these factors that the

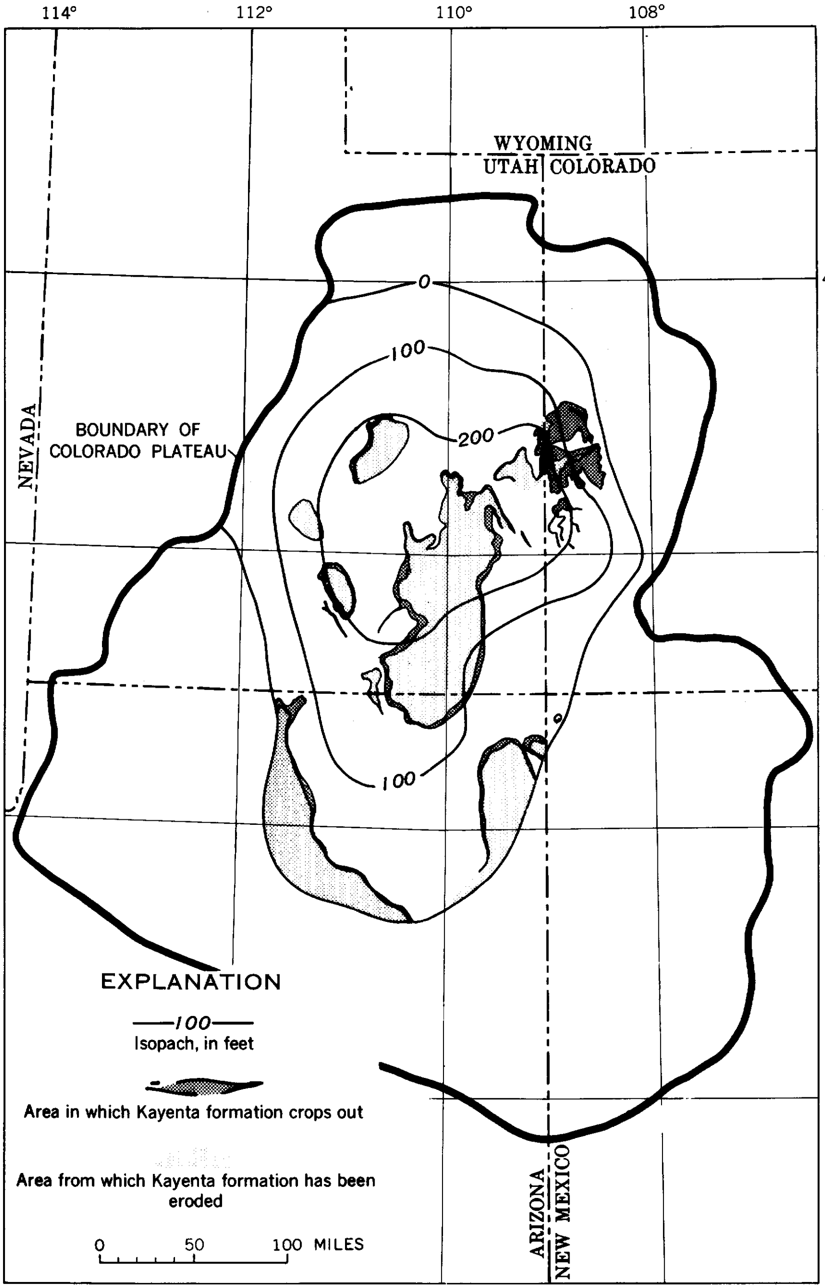


FIGURE 16.—Isopach map of the Kayenta formation. Data compiled by W. L. Newman and E. M. Shoemaker, 1954.

Kayenta acts as an aquiclude for the overlying highly permeable Navajo sandstone.

TABLE 4.—*Exposed sedimentary rocks of Jurassic(?) and Jurassic age*

Area	Group	Formation	Member or tongue	Thickness (feet)	Hydrologic unit	Remarks
Southwestern Colorado and southeastern Utah.	San Rafael.	Morrison	Brushy Basin	200–500	Mudstones of the Morrison.	Dominantly mudstone interbedded with few sandstones at base of unit.
			Salt Wash	0–350	Sandstones of the Morrison.	Alternating layers of lenticular well-sorted fine- to medium-fine-grained sandstone and mudstone.
		Junction Creek sandstone.		0–250	Cow Springs, Bluff, Winsor and Junction Creek.	Clear fine- to very-fine-grained sandstones, and widespread but thin, siltstone and mudstones.
		Summerville-Wanakah	Marl Bilk Creek sandstone.	0–150	Summerville and Wanakah.	Mudstone and siltstone interbedded with thin sandstones and gypsum.
			Pony Express limestone.		Todilto and Pony Express.	Thin limestone unit.
		Entrada sandstone	Moab tongue	0–200	Entrada sandstone	Moderately clean medium-fine- to fine-grained; fair aquifer.
		Carmel		0–50	Carmel	Sandy mudstone; good aquiclude where thickest.
	Glen Canyon.	Navajo sandstone		0–500	Navajo sandstone	Clean well-sorted fine-grained sandstone.
		Kayenta		0–200	Kayenta	Poorly sorted, dirty sandstone.
Northern Arizona and Southern Utah.	San Rafael.	Morrison	Brushy Basin	0–100	Mudstones of the Morrison.	Good aquiclude where thick.
			Westwater Canyon. Recapture Salt Wash	0–350	Sandstones of the Morrison.	Poorly sorted conglomeratic clayey sandstone interbedded with some mudstone.
		Winsor / Cow Springs; Bluff sandstone		0–300	Cow Springs, Bluff, Winsor, and Junction Creek.	Well-sorted relatively clean sandstone.
		Summerville		0–200	Summerville and Wanakah.	Persistent mudstone and siltstone; nontransmissive.
		Entrada sandstone		0–400	Entrada sandstone	Largely earthy sandstone of moderate permeability.
		Carmel		100–300	Carmel	Siltstone unit; very low transmissive capacity (1.0 millidarcys permeability).

	Glen Canyon.	Navajo sandstone			500–2,000	Navajo sandstone	Clean well-sorted medium-fine-grained sandstone.
		Kayenta	Moenave		0–150	Kayenta	Poorly sorted dirty sandstone interbedded with some mudstone.
South-central Utah.		Morrison			0–300	Sandstones of the Morrison.	Poorly sorted conglomeratic sandstone.
	San Rafael.	Winsor			0–300	Cow Springs, Bluff, Winsor, and Junction Creek.	Clean well-sorted fine-grained sandstone.
		Summerville			200–300	Summerville and Wanakah	Siltstone and mudstone unit.
		Curtis			0–300	Todilto, Curtis, and Pony Express.	Gypsiferous shale, limestone, and thin beds of calcareous sandstone.
		Entrada sandstone			300–700	Entrada sandstone	Largely earthy sandstone, poor aquifer.
		Carmel			200–600	Carmel	Sandy siltstone and limestone.
	Glen Canyon.	Navajo sandstone			1,000–2,000	Navajo sandstone	Clean well-sorted fine-grained sandstone.
		Kayenta			100–200	Kayenta	Poorly sorted sandstone interbedded with mudstone.
Northwestern New Mexico.		Morrison		Brushy Basin Westwater Canyon. Recapture Salt Wash	0–600	Sandstones of the Morrison.	Dominantly earthy conglomeratic sandstones interbedded with some mudstone.
	San Rafael.	Bluff sandstone Cow Springs.			0–500	Cow Springs, Bluff, Winsor, and Junction Creek	Well-sorted relatively clean fine-grained sandstone.
		Summerville			0–200	Summerville and Wanakah	Siltstone and mudstone of low permeability.
		Todilto limestone			0–100	Todilto and Pony Express	Thin limestone having little intrinsic permeability.
		Entrada sandstone			100–200	Entrada sandstone	Mainly moderately well-sorted fine to very fine-grained sandstone.
		Carmel			0–25	Carmel	
	Glen Canyon.	Navajo sandstone			0–25	Navajo sandstone	Glen Canyon group present only in extreme northwestern part of New Mexico.
		Kayenta			0–25	Kayenta	

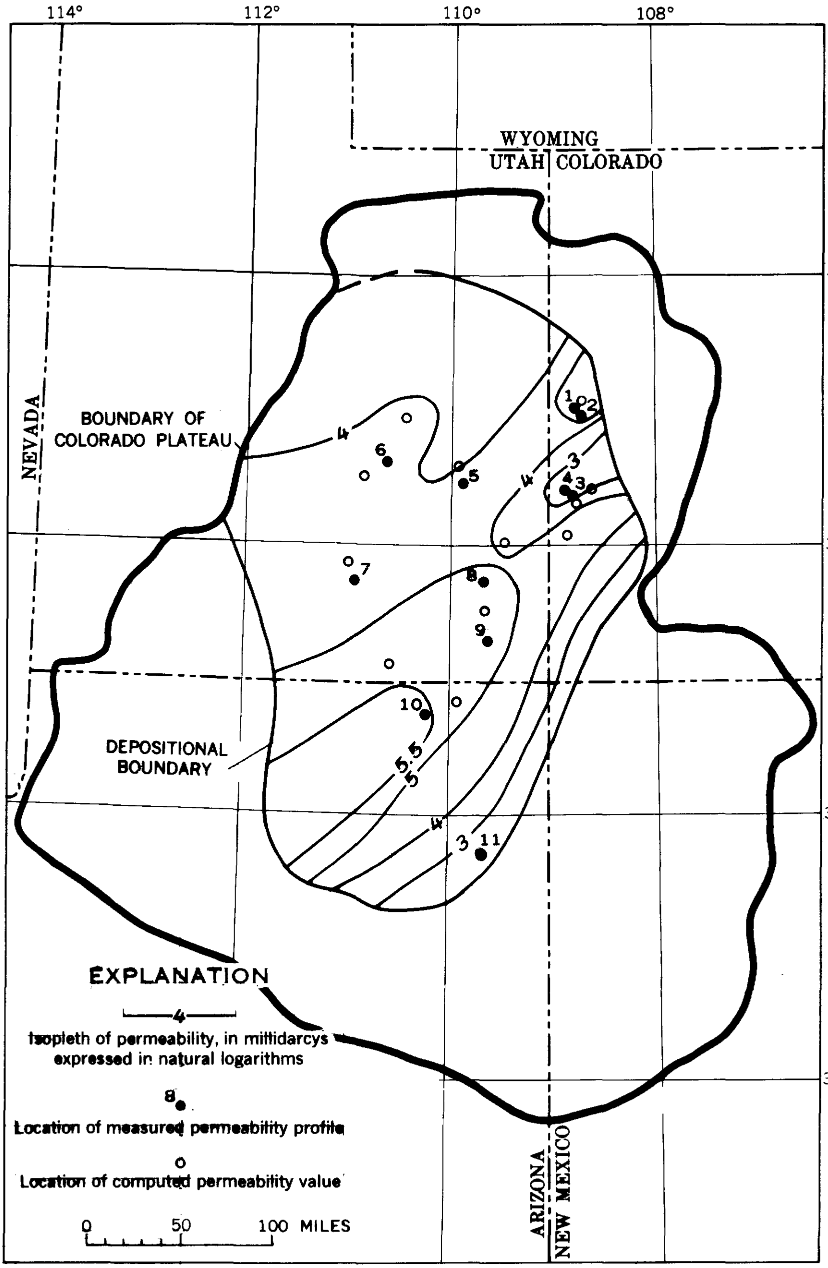


FIGURE 17.—Isopermeability map of the Kayenta formation. Location numbers are given in table 31.

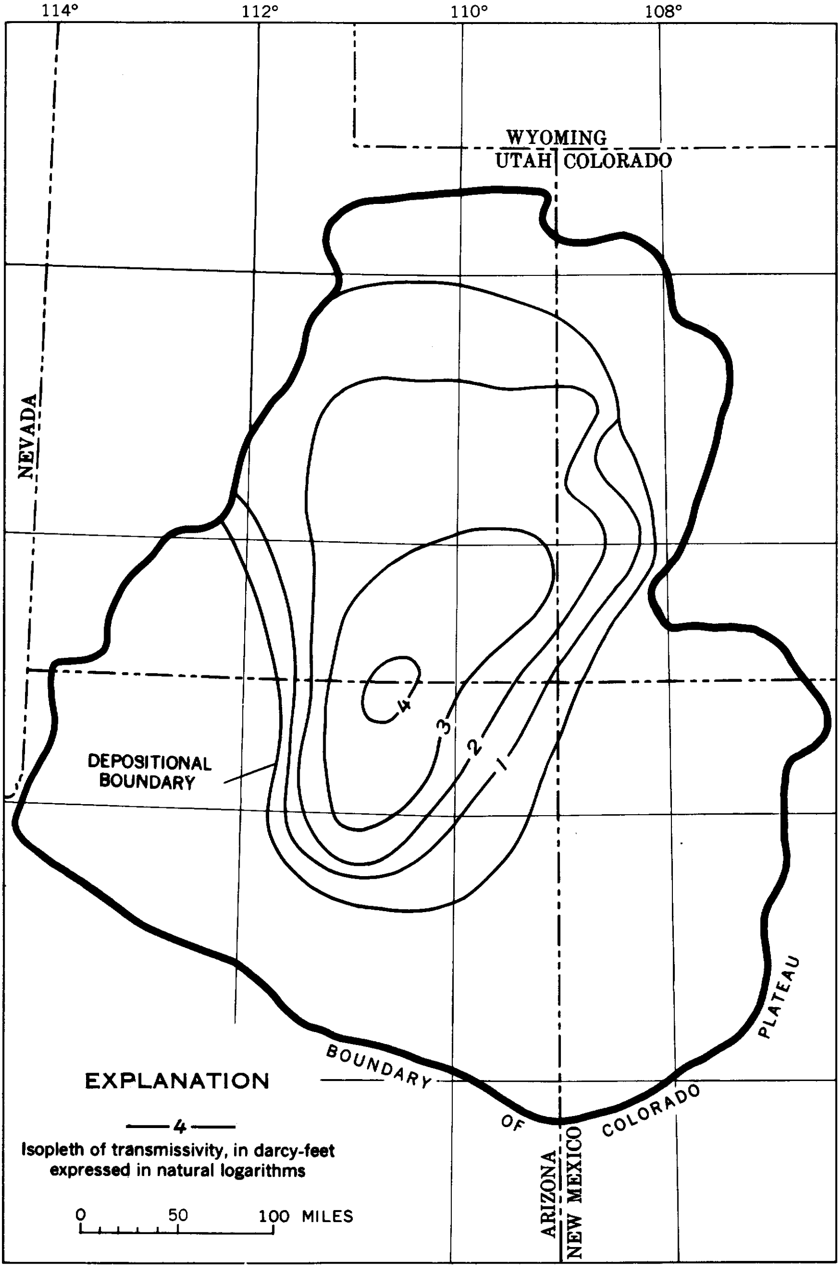


FIGURE 18.—Isotransmissivity map of the Kayenta formation.

631709 O—62——4

NAVAJO SANDSTONE

The Navajo sandstone, the uppermost formation in the Glen Canyon group, is a thick eolian sandstone that extends over much of southeastern Utah and northern Arizona. In gross aspect, it resembles a large asymmetrical fan whose apex centers over northwestern Arizona and southwestern Utah (fig. 19). Internally, it is largely composed of cosets of large-scale crossbedded units of clean well-sorted very fine- to medium fine-grained sandstone. The planar surfaces separating cosets are commonly developed in sandy material; clay layers are rarely present.

Permeability is relatively high throughout the Navajo (fig. 20). The thicker parts of the fan, however, are slightly more permeable than the peripheral regions (fig. 20).

The Navajo sandstone, because it is uniformly thick and well sorted, has the largest transmissive capacity of all the hydrologic units of the Colorado Plateau (fig. 21). For this reason, and because in many areas it has a favorable structural and topographic position, the Navajo is one of the most widely used aquifers in the Colorado Plateau.

A number of water wells in the Navajo sandstone for which pumping-test data were available (Gordon Davis, written communication, 1955) afforded a means of comparing permeability measured by ground-water flow into a well with permeability as estimated from permeameter measurements. Mean permeability derived from the pumping-test data from several closely spaced wells is 5.4 $\log_e$ millidarcys. After applying the correction factor appropriate to converting measurements made with gas to measurements made with water, the permeameter and pumping-test measurements are, for all practical purposes, identical.

SAN RAFAEL GROUP AND COW SPRINGS SANDSTONE

The San Rafael group and the partly correlative Cow Springs sandstone of Late Jurassic age overlie the Glen Canyon group. The San Rafael group is composed of many formations of diverse character; several are thin and of small areal extent (table 4).

The hydrologic character of the San Rafael group and the Cow Springs sandstone is variable but the unit may be separated into a smaller number of hydrologic units. From the base upward these are: (1) a relatively impermeable, silty or limy unit, composed of the Carmel formation and basal siltstone of the Entrada sandstone; (2) a moderately thick and permeable sandstone unit, the Entrada sandstone; (3) a thin dominantly limestone or siltstone unit of relatively low intrinsic permeability composed of the Summerville, Curtis, Todilto, and Wanakah formations; and (4) a highly permeable sand-

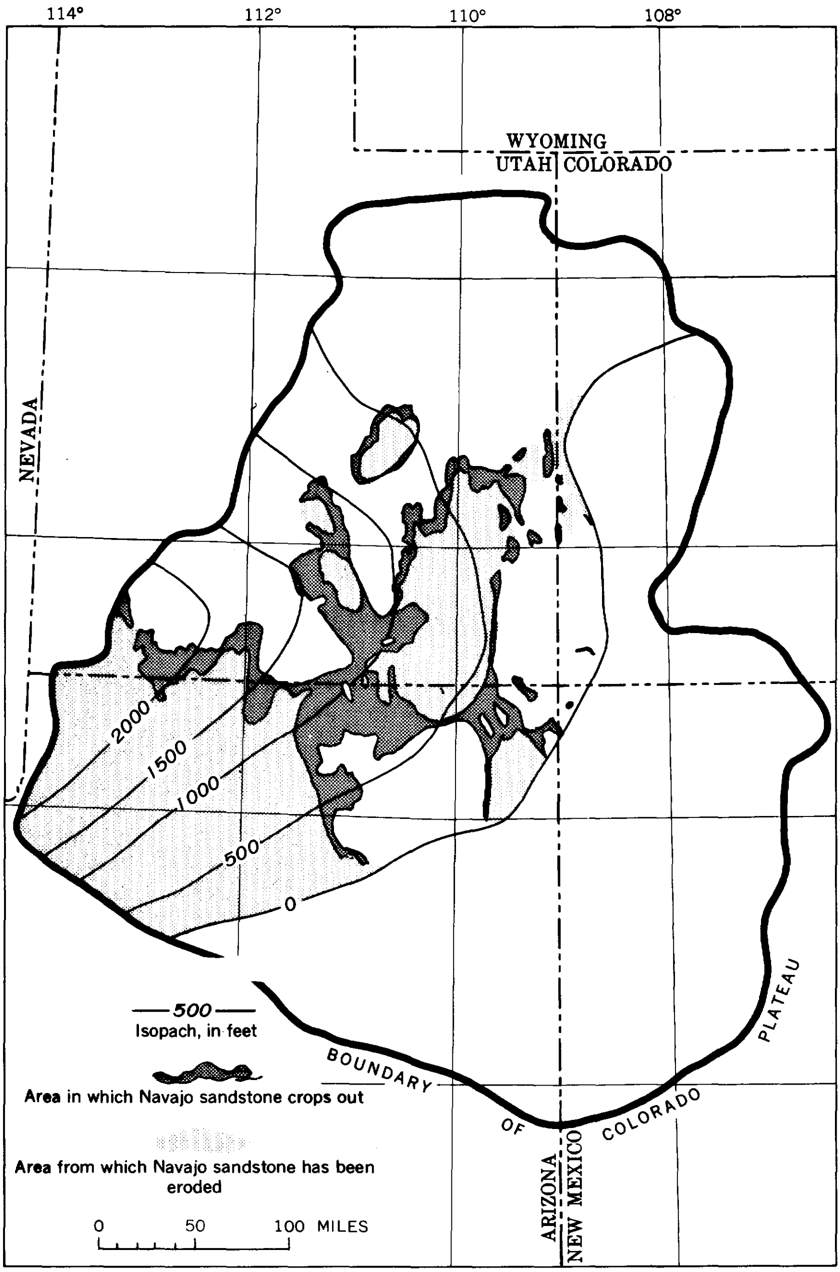


FIGURE 19.—Isopach map of the Navajo sandstone. Data compiled by W. L. Newman and E. M. Shoemaker, 1954.

stone unit, the Cow Springs, Bluff, and Junction Creek sandstones. In northwestern New Mexico and northeastern Arizona the Cow Springs

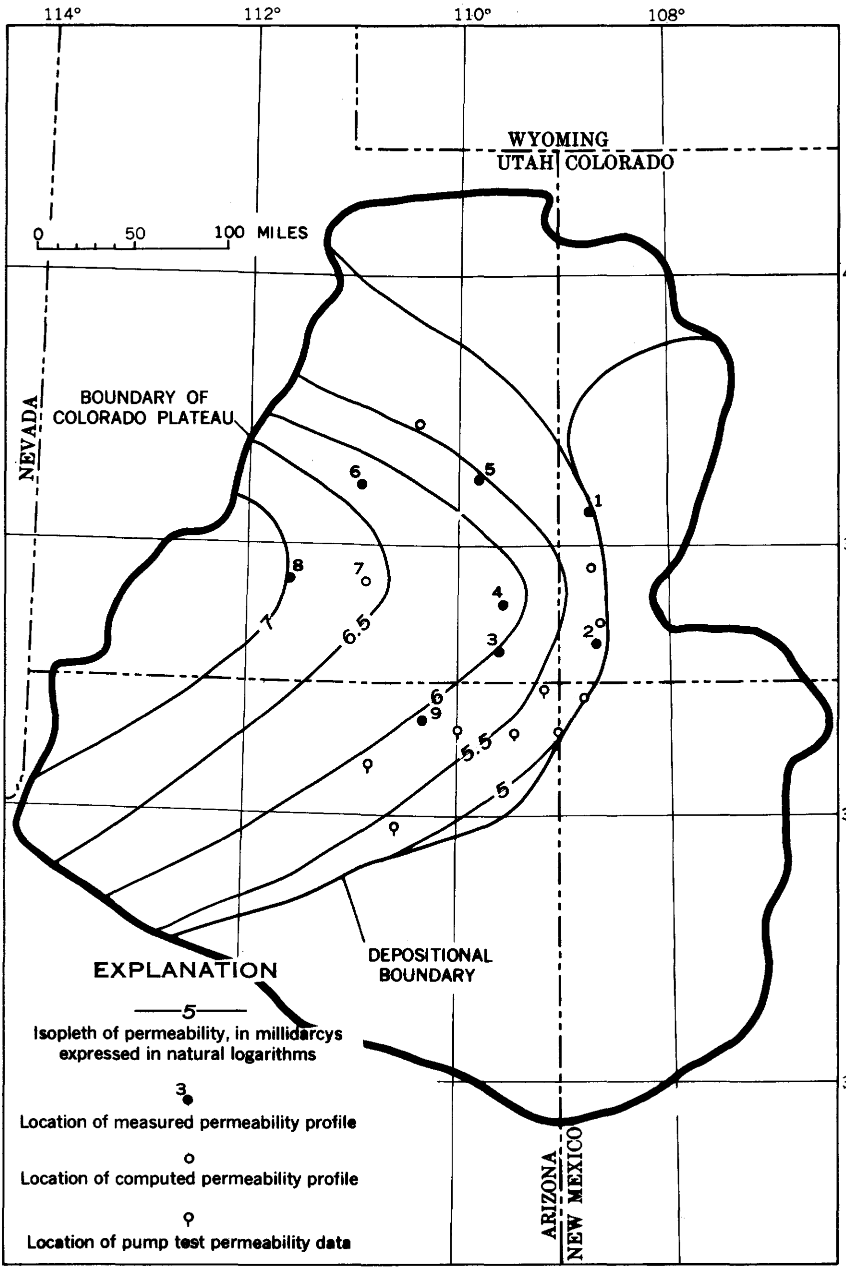


FIGURE 20.—Isopermeability map of the Navajo sandstone. Location numbers are given in table 31.

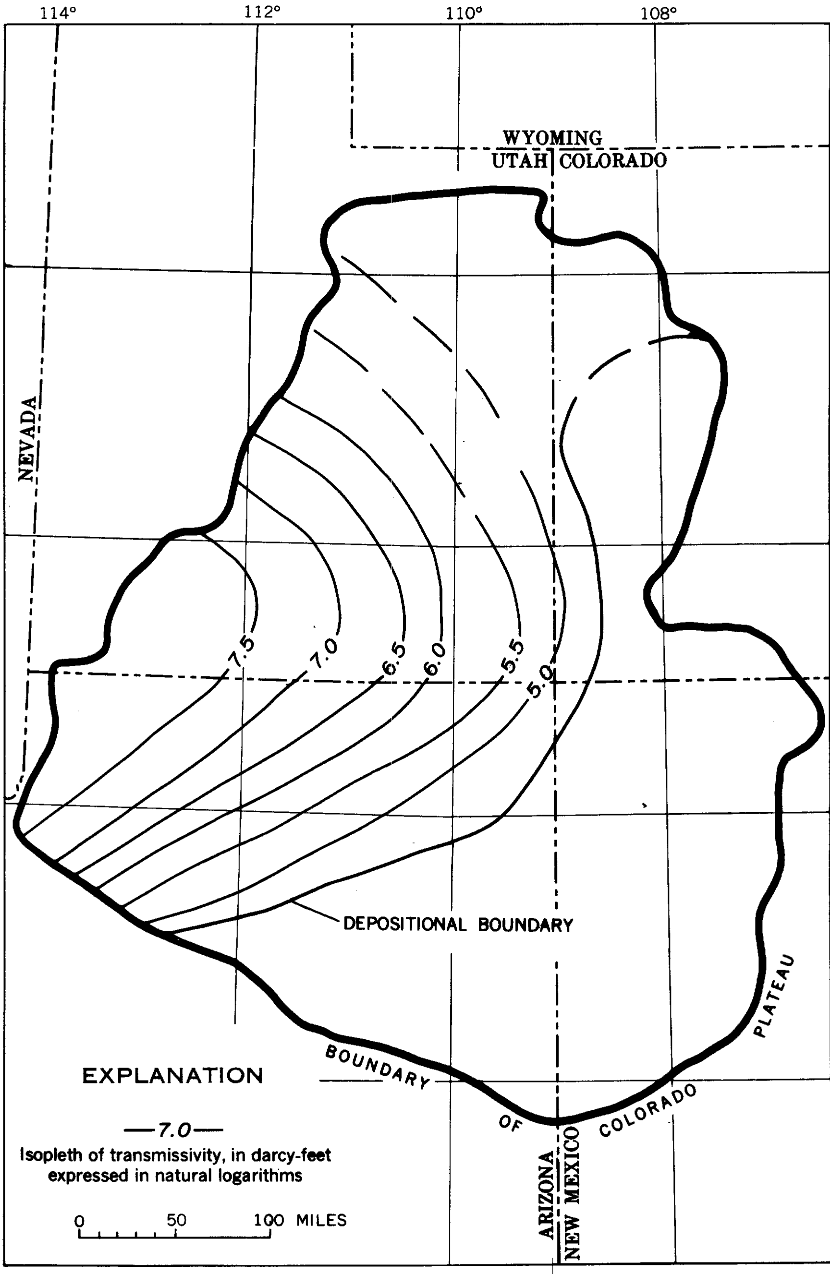


FIGURE 21.—Isotransmissivity map of the Navajo sandstone.

intertongues with all the previously named formations of the San Rafael group as well as with the overlying Morrison formation (Harshbarger and others, 1957, p. 48).

CARMEL FORMATION AND LOWER SILTSTONES OF ENTRADA SANDSTONE

The basal hydrologic unit of the San Rafael group extends as a relatively thin layer—50 to 100 feet thick—over most of the Colorado Plateau. Both the Carmel formation and siltstones of the lower Entrada sandstone thicken appreciably northwestward, however, and reach a maximum exposed thickness of 500 to 600 feet in the southwestern part of the San Rafael Swell.

Representative samples of this unit invariably were relatively impermeable (table 31). Two samples from locally sandy Carmel or lower Entrada had appreciable but relatively low permeabilities. As the extent and frequency of the more sandy beds is slight, the unit composed of the Carmel formation and lower siltstones of the Entrada sandstone is an aquiclude of moderate effectiveness.

ENTRADA SANDSTONE

An isopach map of the Entrada sandstone showing the distribution of outcrops is given in figure 22, and isopermeability and isotransmissivity maps are shown in figures 23 and 24.

The Entrada sandstone is divisible into two facies, each of large areal extent: a red earthy sandstone facies in central and southwestern Utah; and, gradational into it, a relatively clean sandstone facies in southeastern Utah, southwestern Colorado, northwestern New Mexico, and northeastern Arizona (Craig and others, 1955; this report, table 4). Recent work in the Navajo and Hopi Indian Reservation of northeastern Arizona and northwestern New Mexico has shown that one or more tongues of the red earthy facies extend into this area and at places separate the clean sandy facies into an upper and lower unit (Harshbarger and others, 1957).

The permeability of the Entrada reflects rather closely the proportions of clean sandy and earthy material present at any one locality. The clean sandy Entrada of northeastern New Mexico, southwestern Colorado, and east-central Utah has a relatively moderate permeability, whereas the earthy Entrada to the west and northwest in central Utah has a lower permeability with a regional low centered over the San Rafael Swell area.

Isopleths of transmissivity of the Entrada in general show the same trends as the isopleths of permeability except that the general thickening of the Entrada to the northwest tends to compensate for the lower permeability in that area. Local highs are centered over an area of thicker than average and more permeable, well-sorted sandstone along the northern part of the Arizona-New Mexico State line, near Gallup, N. Mex., and in an area centered over the central part of the Colorado-Utah State line, southeast of Moab, Utah. Variations in thickness and permeability in the Entrada in the Placer-

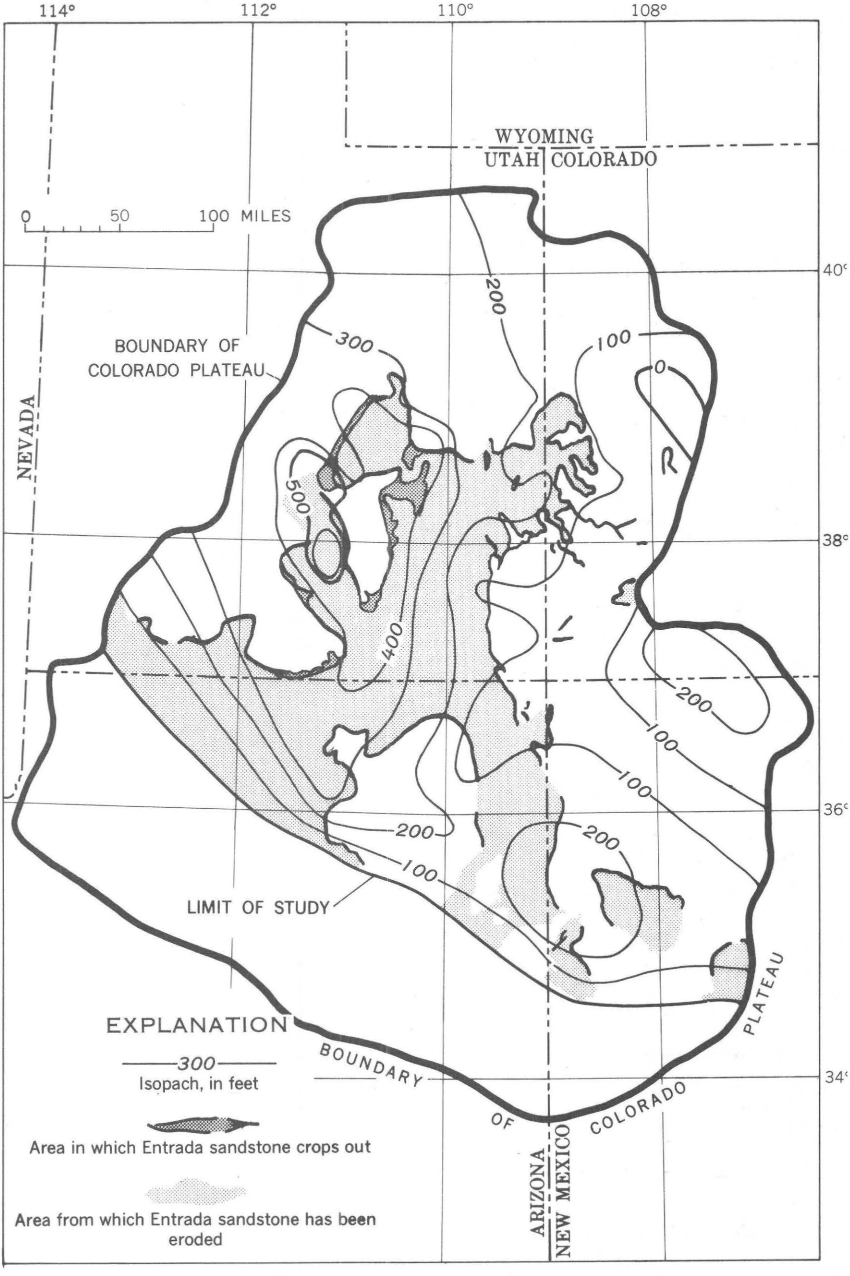


FIGURE 22.—Isopach map of the Entradà sandstone. Data compiled by W. L. Newman and E. M. Shoemaker, 1954.

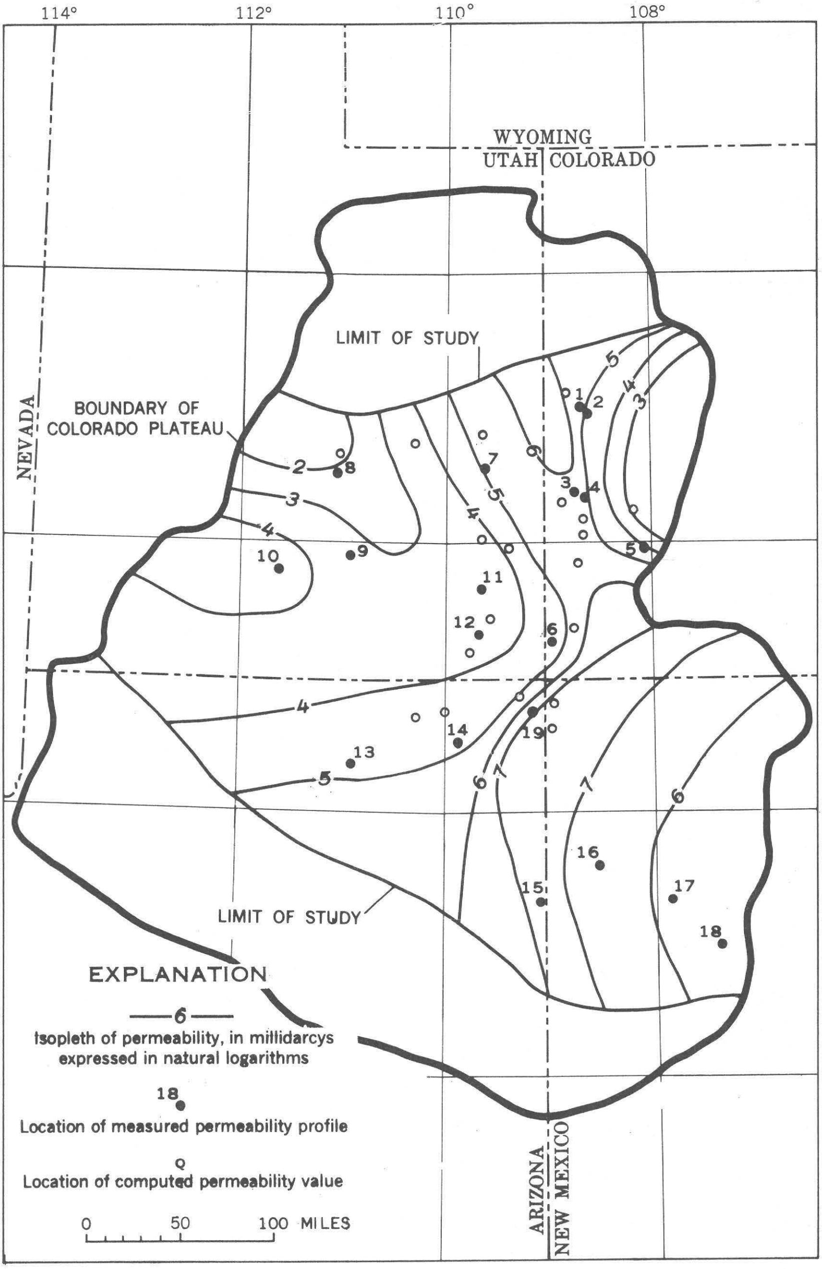


FIGURE 23.—Isopermeability map of the Entrada sandstone. Location numbers are given in table 31.

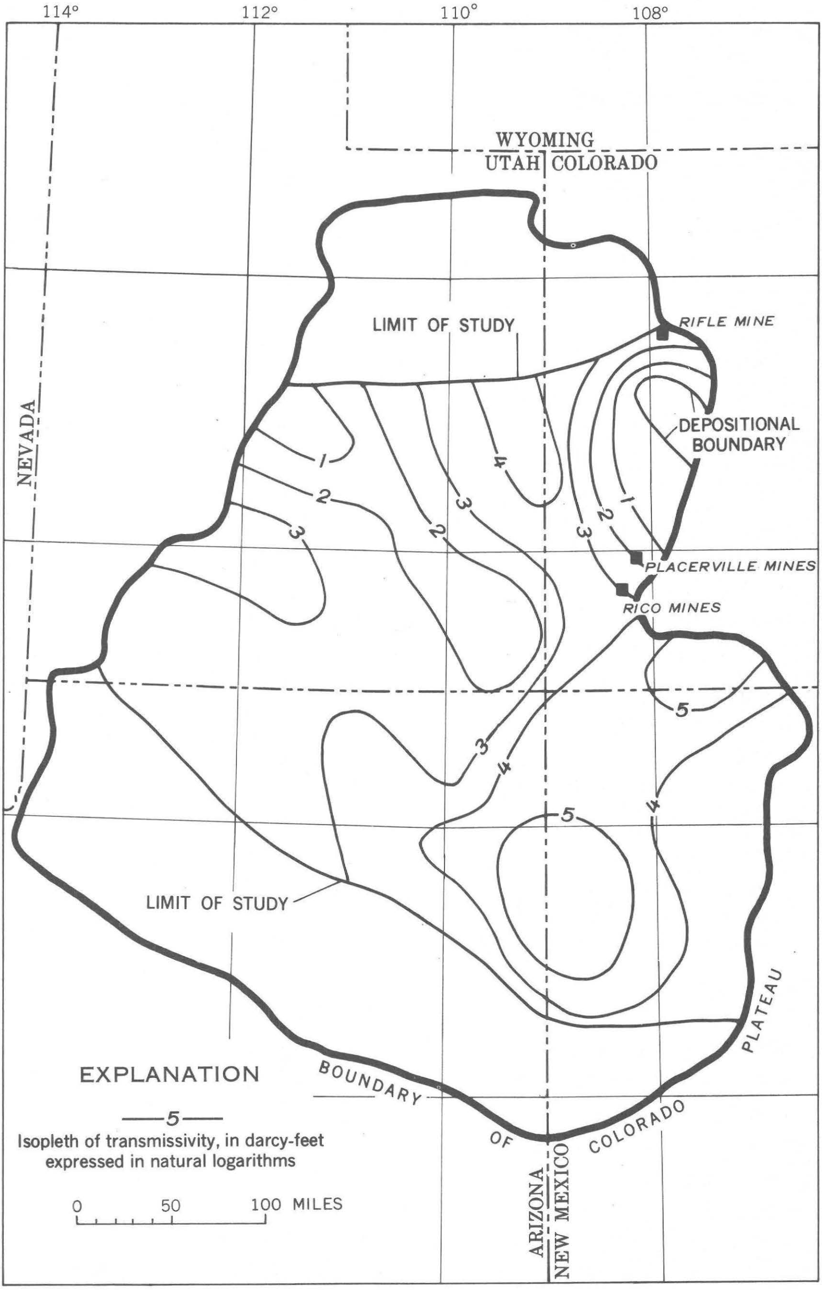


FIGURE 24.—Isotransmissivity map of the Entrada sandstone.

ville, Rico, and Rifle mining districts in Colorado are small and resulting variation in transmissivity is limited to 1 order of magnitude (from 2.0 to 3.0 $\log_e$ darcy-feet).

TODILTO LIMESTONE, SUMMERVILLE AND CURTIS FORMATIONS, AND PONY EXPRESS MEMBER OF THE WANAKAH FORMATION

The areal extent and distribution of outcrops of the Curtis and Todilto formations and the Pony Express member of the Wanakah formation are shown in figure 25. Although the distribution of these units in the middle limestone and siltstone hydrologic unit is areally restricted and the intrinsic permeability is slight, each of the stratigraphic units, and in particular the Todilto limestone, contains uranium deposits.

The Todilto limestone and its probable equivalent, the Pony Express member of the Wanakah formation, have little intrinsic permeability. Typical exposures are of a lower thin dense crystalline platy limestone grading upward into a coarsely crystalline "crinkly" limestone (Rapaport and others, 1952). On the periphery of the basin of deposition, the limestones grade into sandy limestone and mudstone (Harshbarger and others, 1957), and near the center of the basin the limestones are overlain by a thick gypsum member (Rapaport and others, 1952). Extensive small-scale folds and slippage along minute clay partings, both believed to be penecontemporaneous with deposition (Gruner *in* Rapaport and others, 1952), have crinkled the Todilto, particularly the upper part. Later fracturing of probable Late Cretaceous or early Tertiary age is prominent wherever the Todilto crops out. For this reason the Todilto is assumed to have some transmissive capacity, at least locally, in the vicinity of most intensive differential uplift.

The Curtis formation, which is composed of coarse-grained glauconitic marine sandstone, limestone, and shale, has little transmissive capacity in the area studied. A few samples, taken from the thin glauconitic sandstone of the San Rafael Swell, Utah, and from probable sandstone of the Curtis at the Skull Creek mine, Colorado, (fig. 25), however, have relatively high to intermediate permeabilities.

The Summerville and Wanakah formations, exclusive of the Pony Express member of the Wanakah, comprise a widespread relatively thin but continuous unit of interbedded siltstones, mudstones, and sandstones over most of the central part of the Colorado Plateau. They comprise the only members of this hydrologic unit in much of westernmost Colorado and southeastern Utah where the Curtis formation and Todilto limestone are absent. The predominance of siltstone and mudstone precludes this part of the middle limestone and siltstone hydrologic unit from having any significant regional transmissivity; however, in a small area in northwestern New Mexico, where the Summerville interfingers with the Cow Springs sandstone, there is a gradation from virtually no transmissive capacity to a relatively moderate transmissive capacity approaching that of the Cow Springs sandstone.

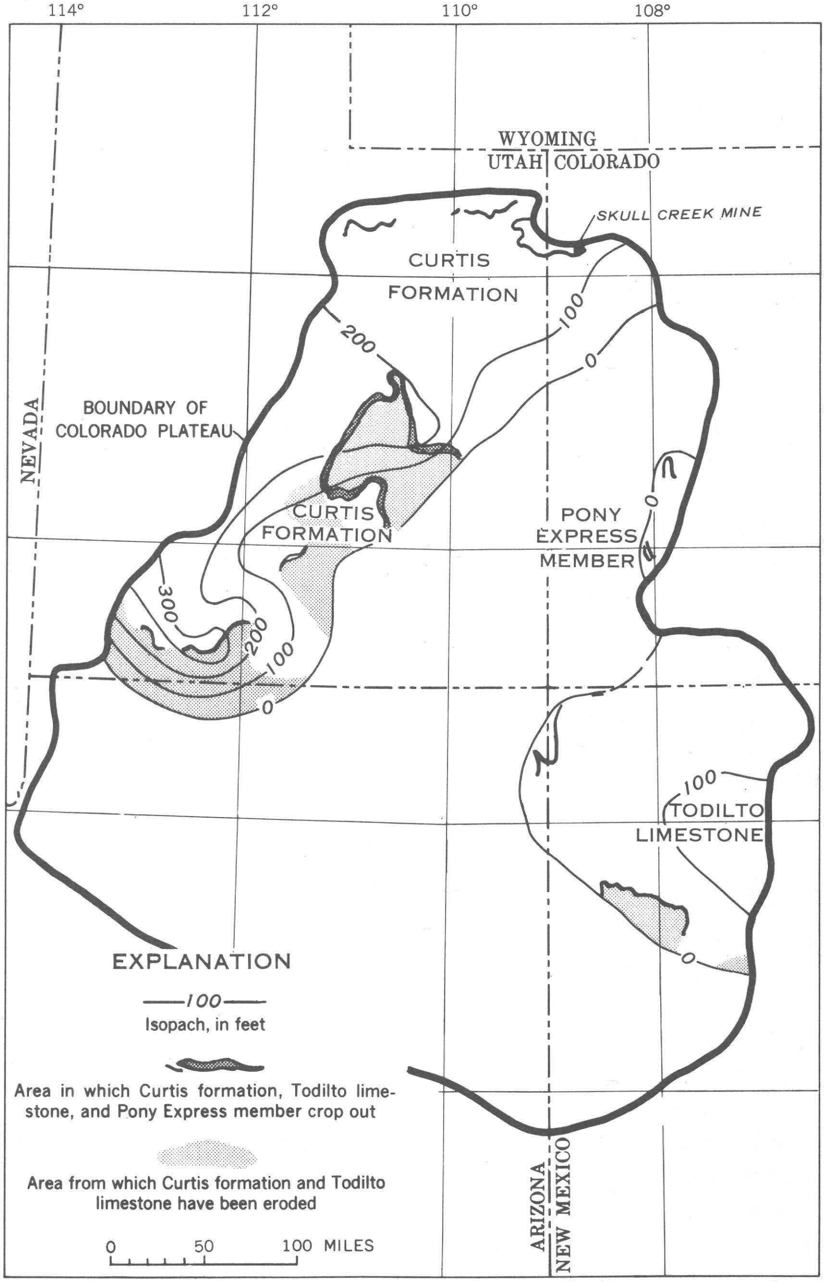


FIGURE 25.—Isopach map of the Todilto limestone, Curtis formation, and Pony Express member of the Wanakah formation. Modified from data compiled by W. L. Newman and E. M. Shoemaker, 1954.

COW SPRINGS, BLUFF, AND JUNCTION CREEK SANDSTONES, AND WINSOR FORMATION

The probable areal extent, thickness, and distribution of outcrops of the Cow Springs sandstone and its correlatives, the Winsor formation, and the Bluff and Junction Creek sandstones, are shown in figure 26 with the general location of the different formations in the hydrologic unit indicated by name. Except for the Winsor formation, this unit is chiefly composed of large-scale high-angle crossbeds of well-sorted medium- to medium-fine-grained sandstone.

The Winsor formation, although tentatively correlated with the Cow Springs sandstone (Harshbarger and others, 1957), is thought by Gregory (1951) to be of marine or at least subaqueous origin. Limited observation and sampling indicate that the Winsor is a slightly finer-grained and better-sorted sandstone than the Cow Springs and contains less interstitial clay.

Isopleths of permeability (fig. 27) shows the same general coincidence of permeability highs with the thicker parts of the unit as have most of the other sandstone units discussed. There is also a parallelism of thickness and permeability gradients which, as the thickest parts of the unit are also the most permeable, results in rapid changes in the gradient of transmissivity (fig. 28).

MORRISON FORMATION

The Morrison formation of Jurassic age overlies the San Rafael group in most areas of the Colorado Plateau. It is chiefly a mudstone intercalated with sandstone strata; in gross aspect it resembles a large compound fan (fig. 29). Craig and others (1955) divided the compound fan into several separate fan-shaped bodies whose thicker parts are near their respective apices.

The Morrison can be divided into two partly overlapping hydrologic units: a lower one, the unit of sandstones of the Morrison (fig. 30), in which almost all the sandstone strata are concentrated, and an upper one, the mudstone unit of the Morrison (fig. 31), which is almost entirely mudstone. Although both units are present throughout the central part of the Colorado Plateau, sandstones of the Morrison constitute almost the entire formation near the apices of the fan, which are in northeastern Arizona and northwestern New Mexico; the formation is almost entirely mudstone in northeastern Utah and northwestern Colorado.

The sandstones in the lower unit, which includes those of the Recapture, Westwater Canyon, and Salt Wash members of the Morrison formation, are believed to be of fluvial origin (Craig and others, 1955). These sandstones form a vertical series of broad lensoid ledges separated by mudstone. Although the proportion of sandstone to

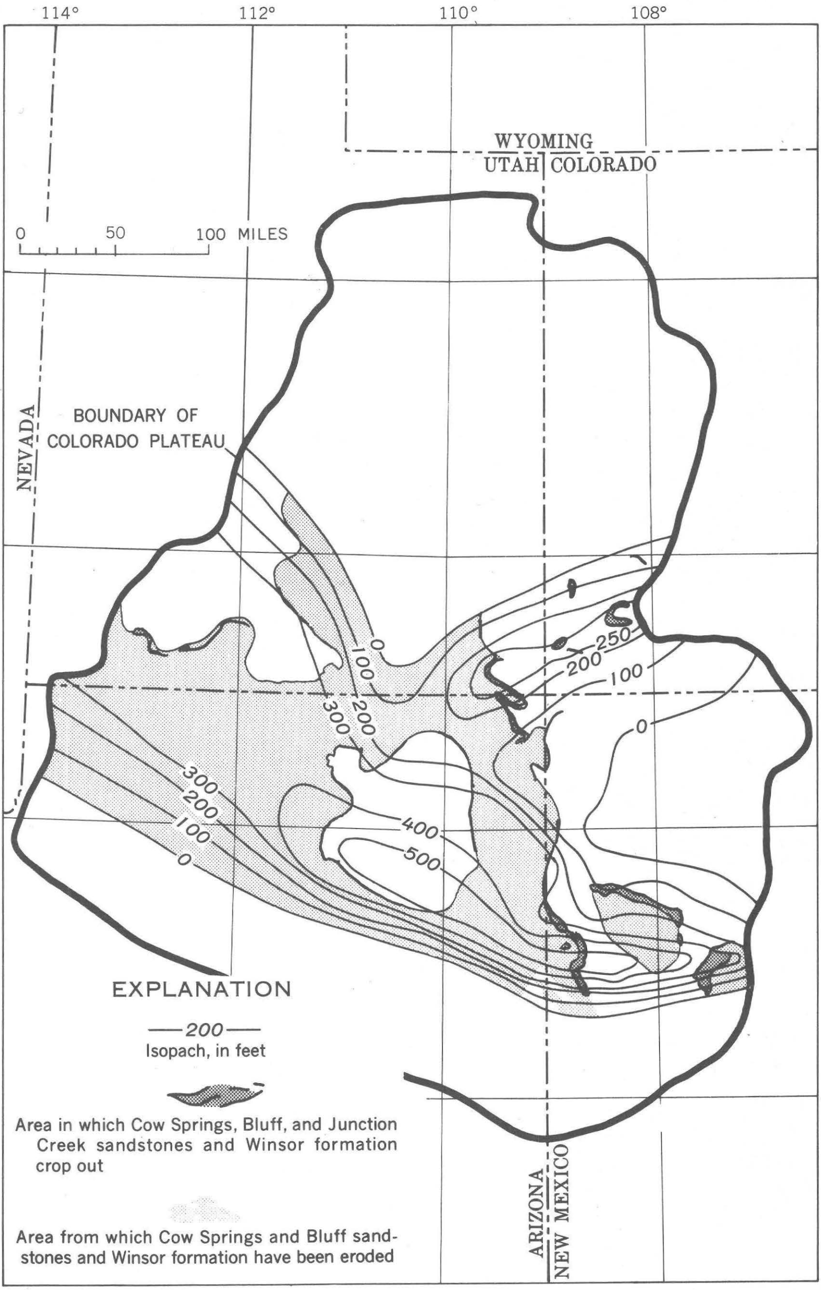


FIGURE 26.—Isopach map of the Cow Springs, Bluff, and Junction Creek sandstones, and the Winsor formation. Modified from data compiled by W. L. Newman and E. M. Shoemaker, 1954.

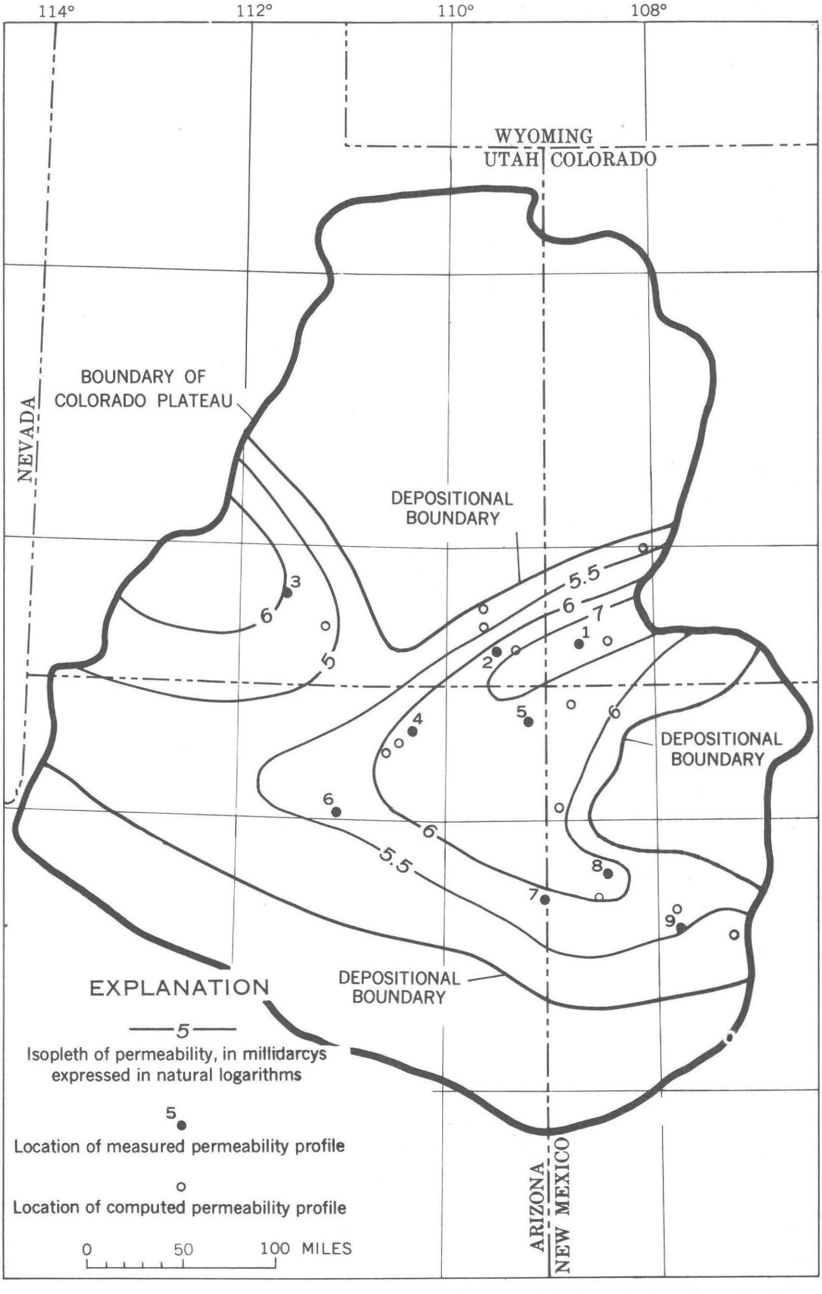


FIGURE 27.—Isopermeability map of the Cow Springs, Bluff, and Junction Creek sandstones, and the Winsor formation. Location numbers are given in table 31.

mudstone varies from place to place as does the scale of the lensing, the unit generally is a cliff former and bench former in which the sandstone forms a series of from 3 to as many as 10 laterally discontinuous ledges separated by mudstone slopes.

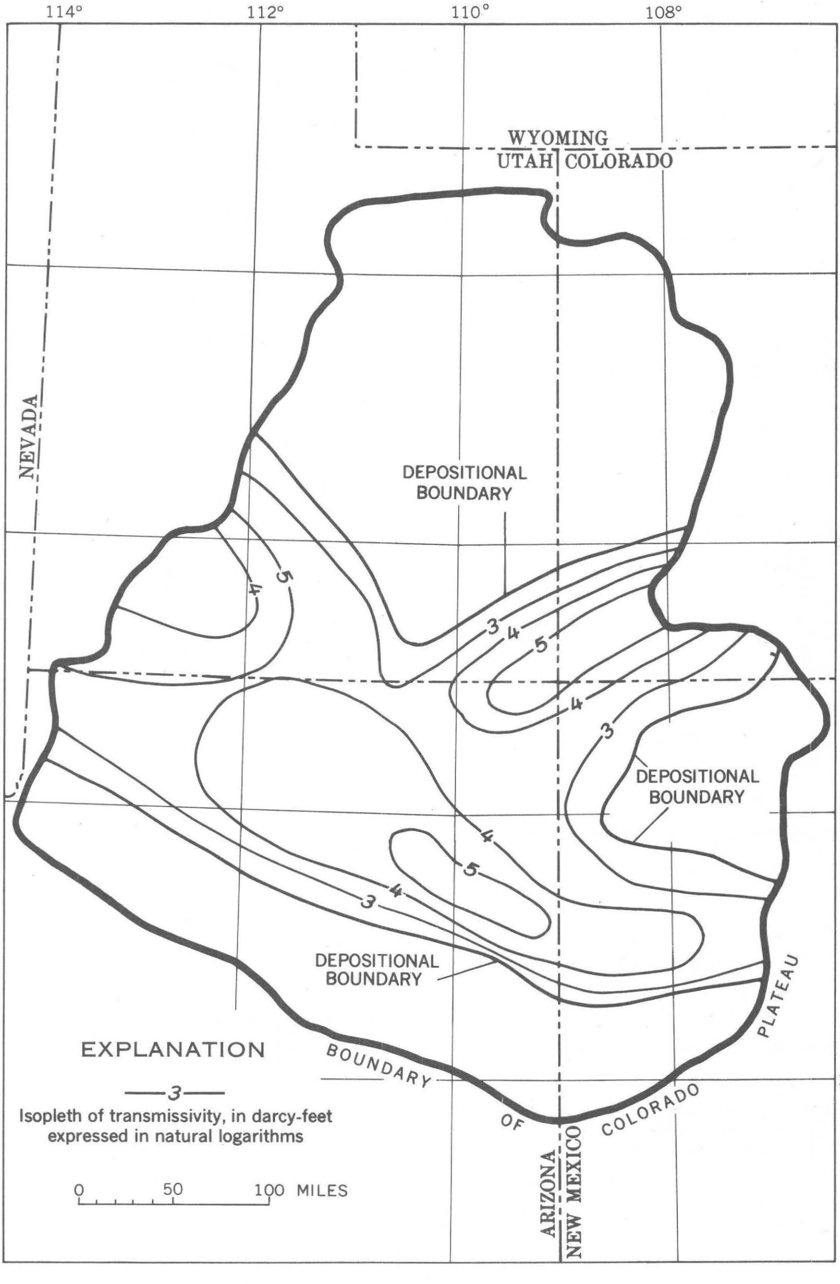


FIGURE 28.—Isotransmissivity map of the Cow Springs, Bluff, and Junction Creek sandstones, and the Winsor formation.

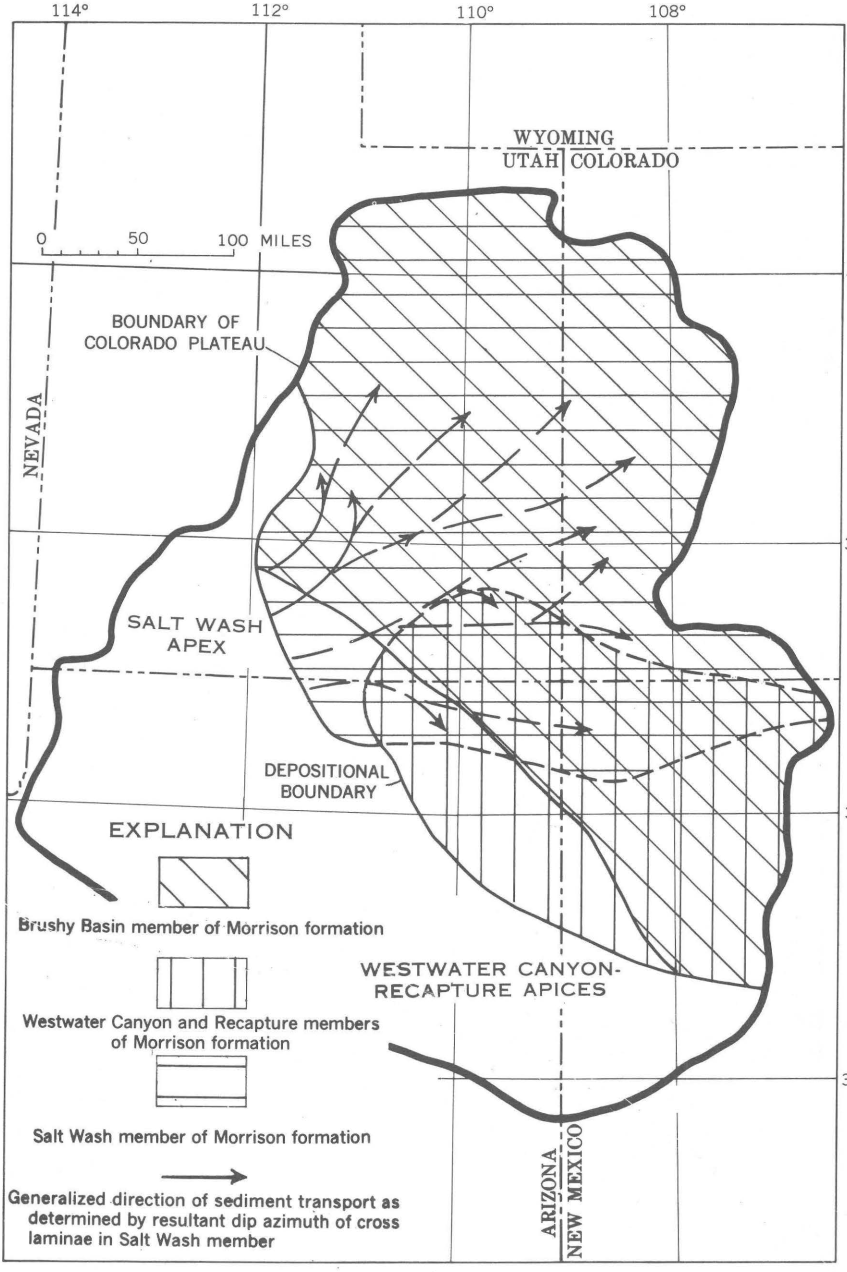


FIGURE 29.—Areal distribution of members of the Morrison formation. Data adapted from Craig and others (1955).

A typical sandstone ledge is composed of one or more discrete cosets of cross strata or massive sandstone strata; the successive cosets or strata either rest directly on those beneath or are separated by a thin mudstone seam. Truncation of underlying cosets or massive

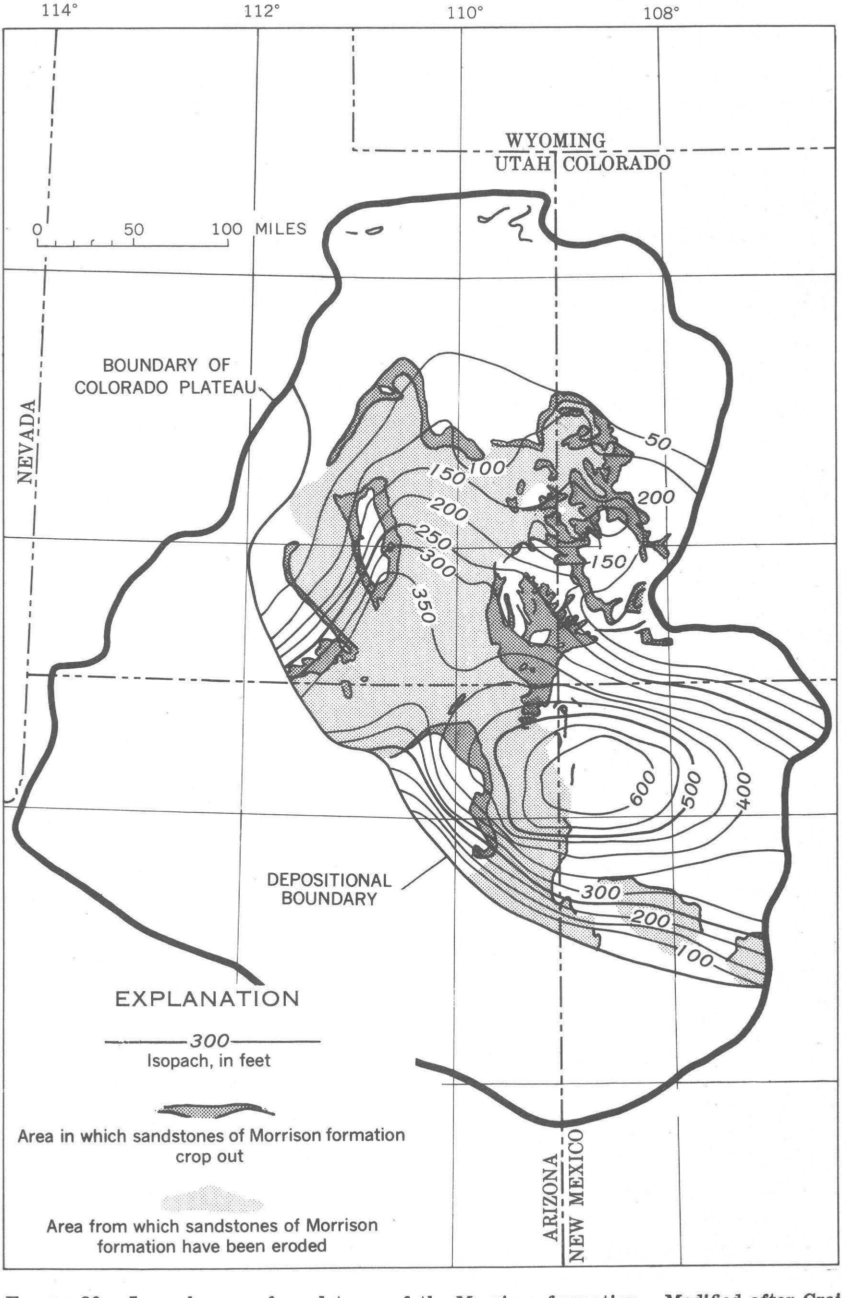


FIGURE 30.—Isopach map of sandstones of the Morrison formation. Modified after Craig and others (1955).

631709 O—62——5

strata by the succeeding units is common and individual cosets are themselves composed of a complex of crosscutting festoon, wedge, and low-angle crossbeds typical of fluvial deposits (McKee and Weir, 1953).

The Brushy Basin member of the Morrison formation is largely mudstone except in the southeastern part of the Colorado Plateau where the Morrison, including the Brushy Basin, is dominantly sandstone. The composition, continuity, and relatively great thickness of this mudstone unit make it an effective aquiclude.

Although the Salt Wash, Recapture, and Westwater Canyon members are similar in lithology, had adjacent source areas, and overlap in part, the isopleths of their combined permeability can be most easily understood by first considering the effects attributable to each. In general, the permeabilities of the Salt Wash and Westwater Canyon are comparable and are somewhat higher than those of the Recapture. A comparison of mean permeability with grain-size analyses data shows that the lower permeability of the Recapture is due to a finer mean grain size and slightly larger standard deviation of grain size. The similar permeability of the Salt Wash and Westwater Canyon does not result from similar grain size and standard deviation of grain size, but rather is largely due to the compensating effect that differences in these factors have had on the respective permeability of each sandstone. Sandstones of the Salt Wash are the better sorted of the two but on the other hand are finer grained. The differences in permeability between these sandstones have also been narrowed by the greater degree of cementation of the Salt Wash.

Isopleths of mean permeability (constructed as described on p. 12) for the sandstone strata of the lower unit of the Morrison formation show roughly concentric trends in which either decreasing or increasing values of permeability extend outward north-northeastward from the apices of the depositional fans (figs. 29, 32). Sandstones of the Salt Wash had their main source somewhere west-southwest of south-central Utah, as evidenced by coarser grain size and poorer sorting in this direction (Craig and others, 1955). Isopleths of permeability increase in value in this direction; the increase in grain size and decrease in cementing material, together more than compensate for the decrease in permeability resulting from the poorer sorting. Southeastward from the apex of the Salt Wash fan, in the area of overlap between the Salt Wash and the virtually coextensive Recapture and Westwater Canyon members, permeability decreases systematically. In the area of overlap the decrease in permeability results chiefly from the increase in the proportion of Recapture to Salt Wash and Westwater Canyon members. The decrease in permeability, due to the finer grained and less well sorted

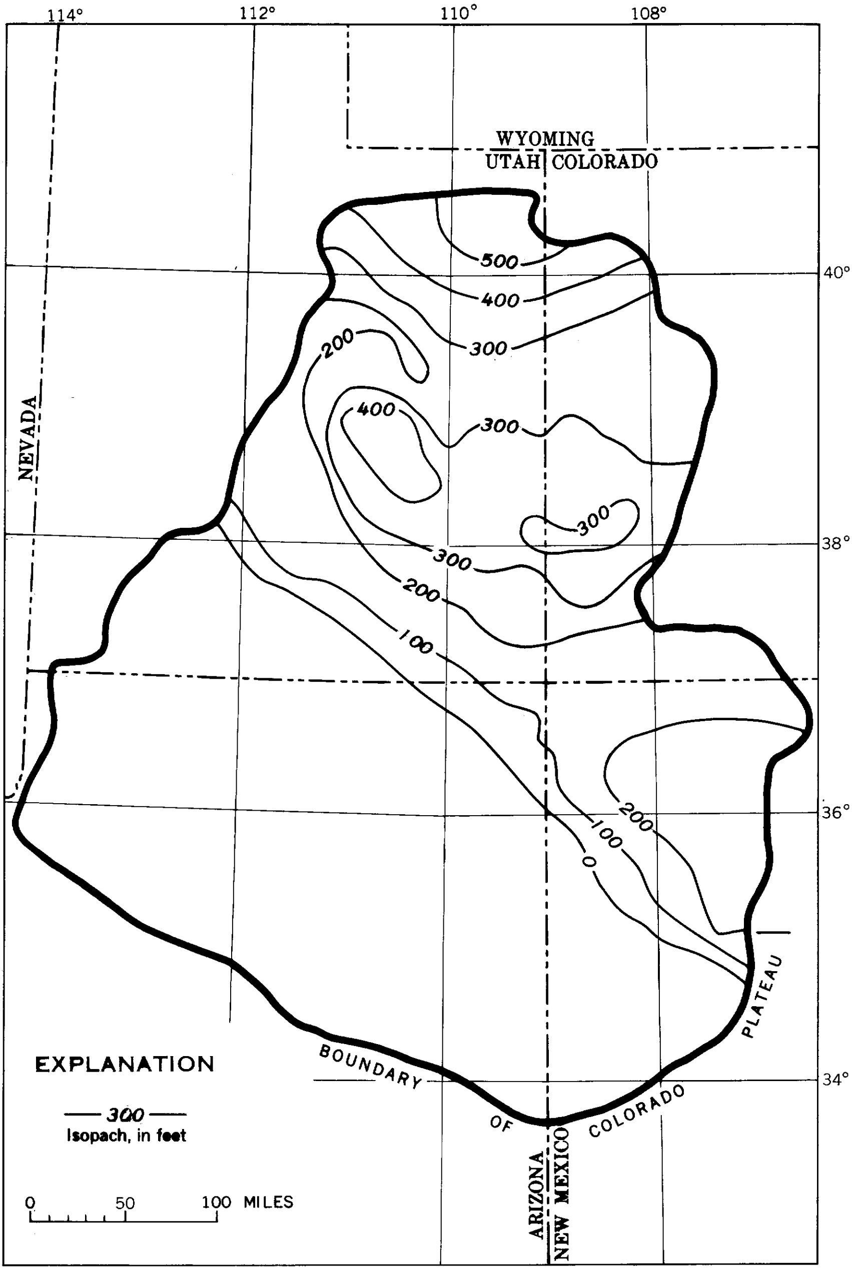


FIGURE 31.—Isopach map of the Brushy Basin shale member of the Morrison formation. The Brushy Basin member of the Morrison formation is virtually coextensive with the "upper mudstone unit" of the Morrison formation. Data compiled by W. L. Newman and E. M. Shoemaker, 1954.

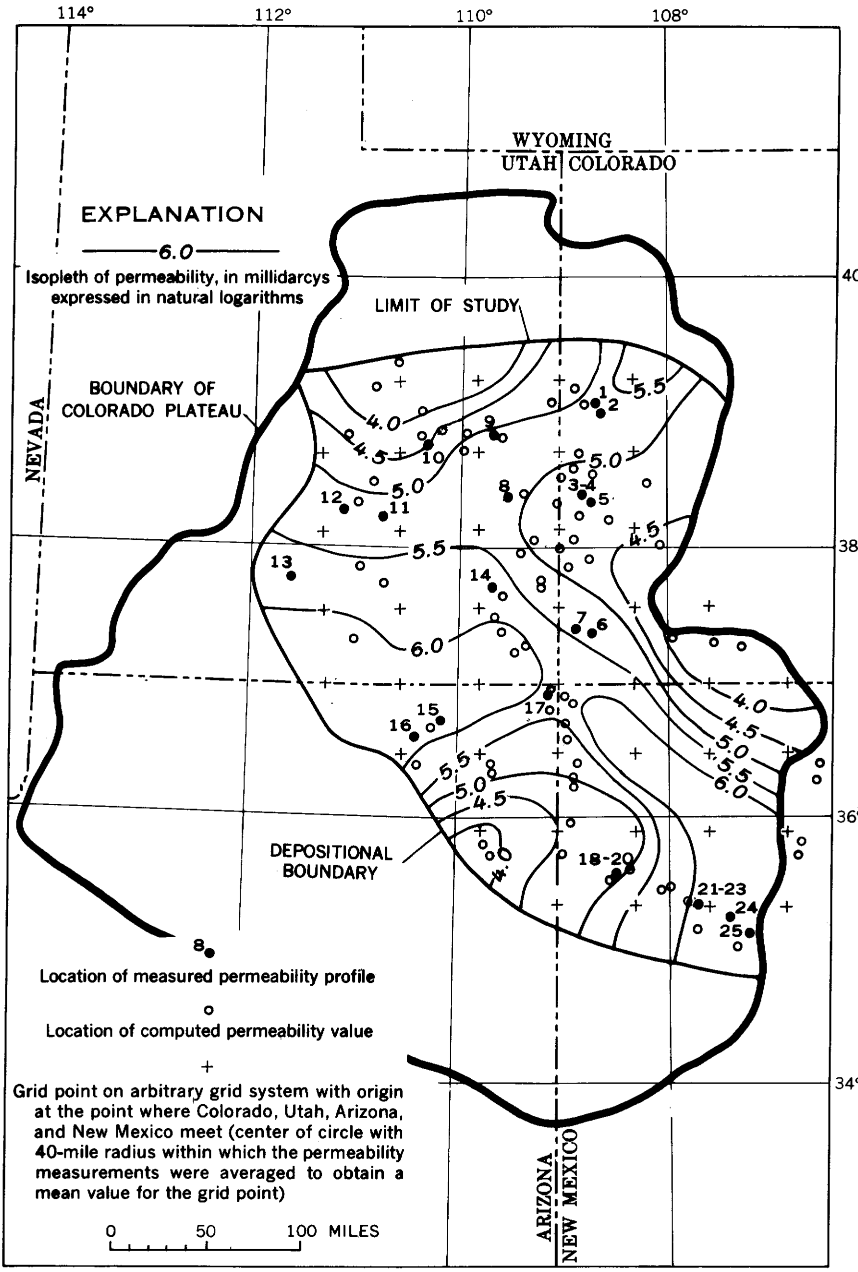


Figure 32.—Isopermeability map of sandstones of the Morrison formation. Location numbers are given in table 31.

Recapture, is also reinforced by a decrease in the degree of sorting of sandstones of the Westwater Canyon in this direction. The area of low permeability outlined by the 5.0 isopleth just west of the Arizona-New Mexico boundary, approximately outlines the conglomeratic and

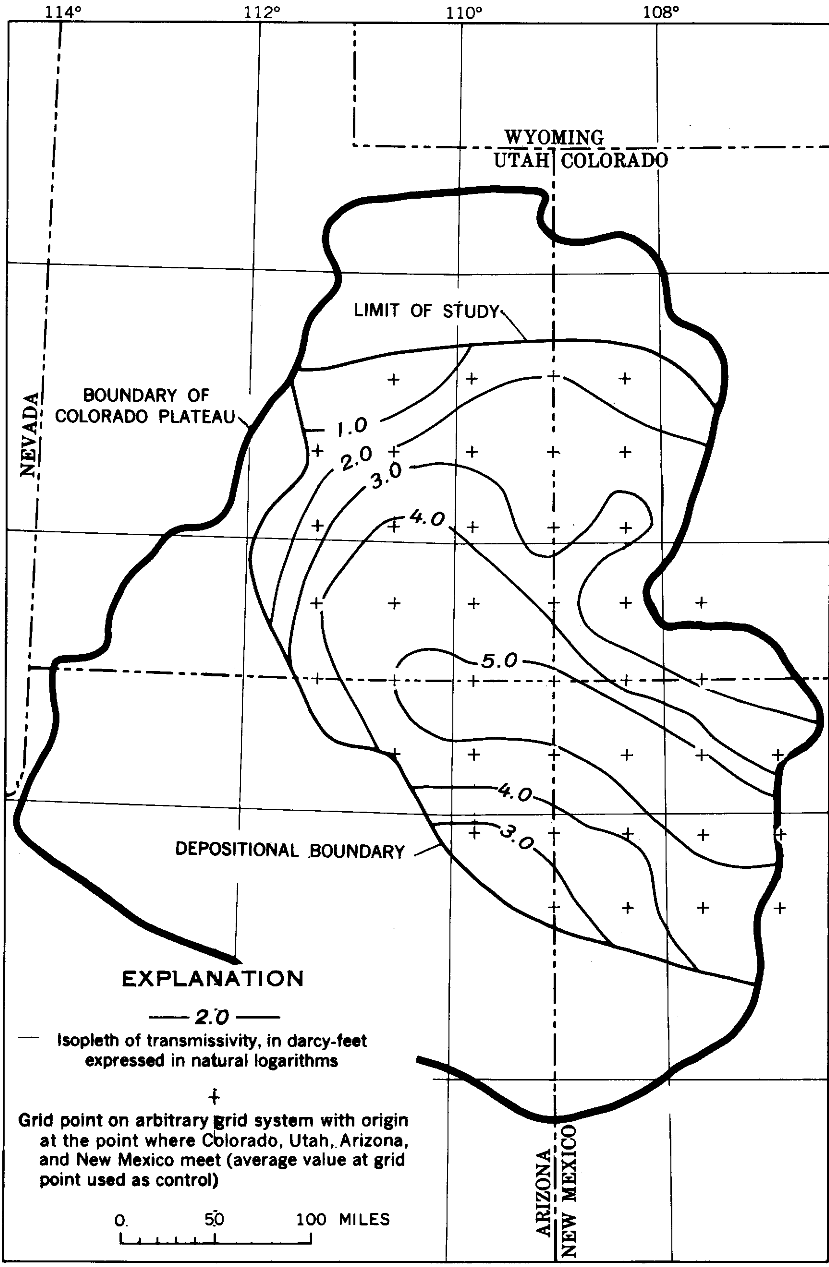


FIGURE 33.—Isotransmissivity map of sandstones of the Morrison formation.

claystone-sandstone facies of the Westwater Canyon and Recapture members as shown by Craig and others (1955).

Eastward from the regional low, the mean permeability increases in northwestern New Mexico. This increase is the result of the interaction of three factors: an increase in the proportion of Westwater Canyon to Recapture, a decrease in grain size, and a decrease in standard deviation of grain size. In this instance the slight decrease in grain size is more than compensated for by the better sorting and results in an increase in permeability with distance from the source area. Farther to the northeast in north-central New Mexico this trend is again reversed as decreasing grain size becomes the dominant factor in lowering permeability.

Isopleths of transmissivity of sandstones of the Morrison are somewhat asymmetric in that an elongate high trends southeastward from northeastern Arizona and southeastern Utah into northwestern New Mexico (fig. 33). This regional high is a result of the coincidence of a relatively great thickness of Salt Wash and Westwater members in the area of overlap of the several members of the Morrison, together with the regional permeability highs associated with these sandstones. The transmissive capacity of the lower part of the Morrison decreases rather regularly in all directions away from this high.

The average transmissive capacity of a single stratum of sandstones of the Morrison has been roughly determined by dividing the total transmissive capacity for the unit in each area in which measurements were available by the average number of strata present, and then contouring the resulting values (fig. 34). The most obvious feature of the resulting map is the uniformity in transmissive capacity. A comparison of the average transmissive capacity of a sandstone stratum of the Morrison with that of the lower sandstones of the of the Chinle shows that, although the sandstones of the Morrison have a slightly greater transmissive capacity, both have capacities of the same order of magnitude.

CRETACEOUS ROCKS

The stratigraphic sequence and lithologic character of the widely distributed Cretaceous sedimentary rocks of the Colorado Plateau are shown in table 5. The distribution of outcrops and sampled localities are shown in figure 35. For the purposes of hydrologic description the rocks of Cretaceous age can be grouped into three categories: a generally thin and somewhat discontinuous lower unit of lenticular sandstone and conglomerates interbedded with some shales; a thick middle shale and silty shale unit that extends over the entire Colorado Plateau and is an excellent aquiclude; and a generally thick upper unit of lenticular sandstones. The sandstone lenses

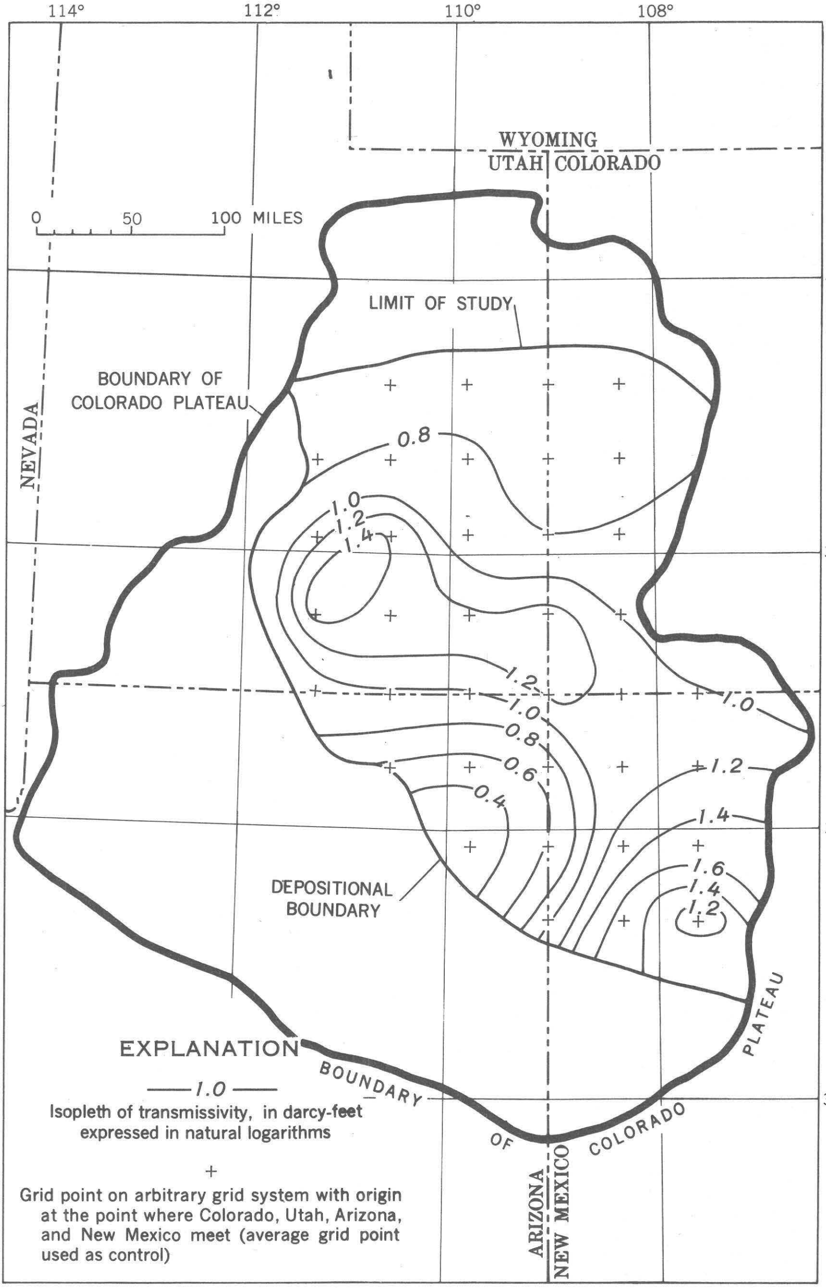


Figure 34.—Approximate average transmissive capacity of a single sandstone stratum of the Morrison formation.

in the upper hydrologic unit were deposited along the margins of the Upper Cretaceous epicontinental sea and are generally much larger than the sandstone lenses of fluvial origin in the lower hydrologic unit.

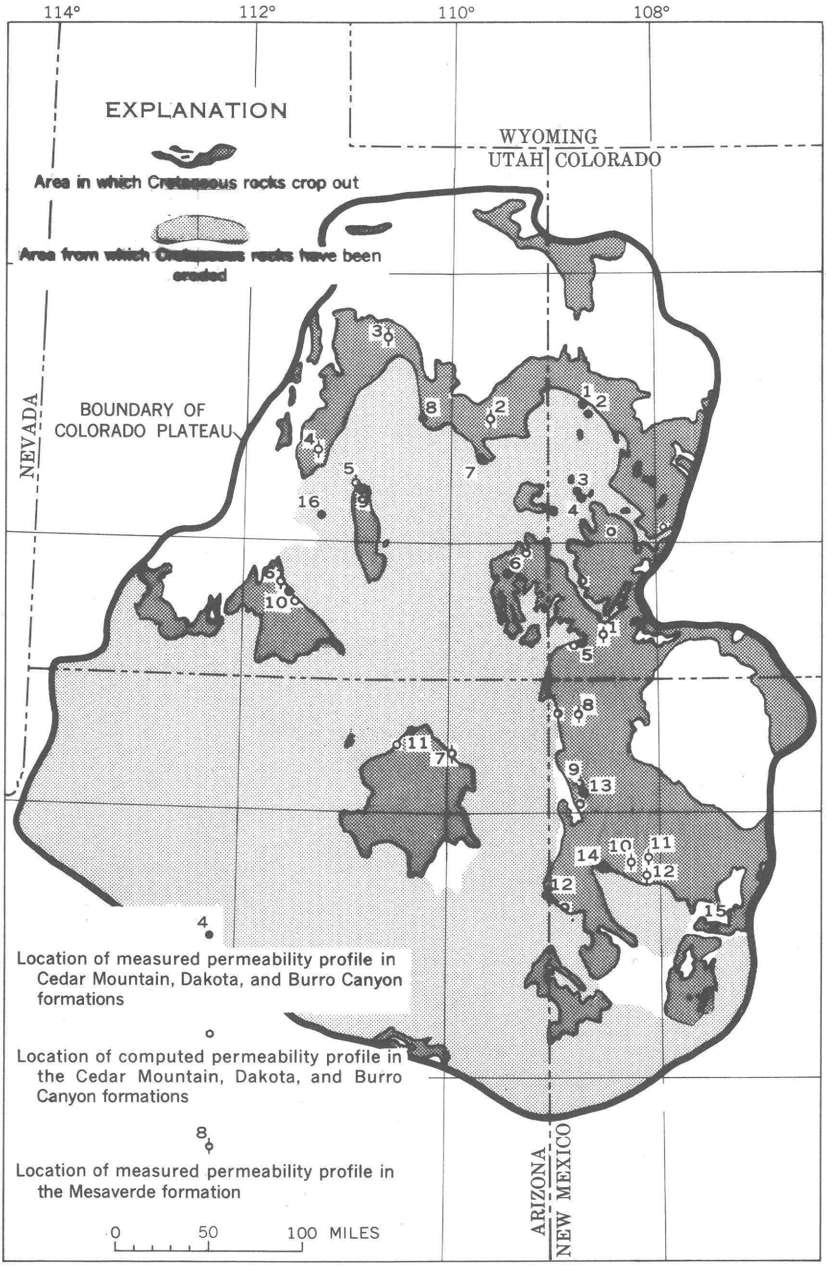


FIGURE 35.—Cretaceous outcrop pattern with sample localities. Location numbers are given in table 31.

TABLE 5.—*Exposed sedimentary rocks of Cretaceous age*

Area	Formation or group		Thickness (feet)	Hydrologic unit	Remarks
Southwestern Colorado and southeastern Utah.	Mesaverde		400–700	Upper	Well-sorted clean fine-grained sandstone interbedded with shale.
	Mancos shale		2,000–3,000	Middle	Silty shale and mudstone; an excellent aquiclude.
	Dakota sandstone		50–150	Lower	Poorly sorted conglomeratic sandstone, highly lenticular; poor to good aquifer.
	Burro Canyon conglomerate		700–1,100		
Northern Arizona and southern Utah.	Mesaverde	Straight Cliffs	700–1,100	Upper	Well-sorted clean fine-grained sandstone interbedded with shale.
	Mancos shale	Tropic shale	2,000–3,000	Middle	Shale and mudstones; excellent aquiclude.
	Dakota sandstone		20–100	Lower	Lenticular conglomeratic sandstones, poorly sorted; silt and clayey material.
	Burro Canyon formation		0–200		
South-central Utah.	Mesaverde	Straight Cliffs	400–1,100	Upper	Well-sorted clean fine-grained sandstone and interbedded mudstone. Lenticular on large scale.
	Mancos shale	Tropic shale	2,000–3,000	Middle	Shale and mudstone unit; excellent aquiclude.
	Dakota sandstone		20–60	Lower	Fine-grained silty sandstone; fair to poor aquifer.
	Cedar Mountain of Stokes (1944)		0–300		Lower 20–30 ft is conglomeratic sandstone, remainder is mudstones.
Northwestern New Mexico.	Mesaverde		400–1,000	Upper	Fine-grained clean sandstone, broadly lenticular; excellent aquifer.
	Mancos shale		700–2,000	Middle	Shale and mudstone; excellent aquiclude.
	Dakota sandstone		50–100	Lower	Fine-grained clean to dirty lenticular sandstones.

LOWER UNIT

The lowest hydrologic unit is comprised of the Burro Canyon formation, Cedar Mountain formation, and the Dakota sandstone. The geometry and composition of the different stratigraphic parts of this unit are very similar, and in areas of overlap the parts are generally difficult to distinguish from one another. The unit strongly resembles the lower sandstones of the Morrison formation both in dimensions of individual strata and in the arrangement of sedimentary structures within the strata. Most of the lower unit of the Cretaceous, however, is considerably coarser grained and less well sorted than sandstones of the Morrison. An isopach map (fig. 36) of the sandstone and conglomerate of this unit was constructed from the available measured sections in the literature, but owing to the small number of measured thicknesses and to the lenticular nature of this unit, the map is only a rough estimate of average thickness.

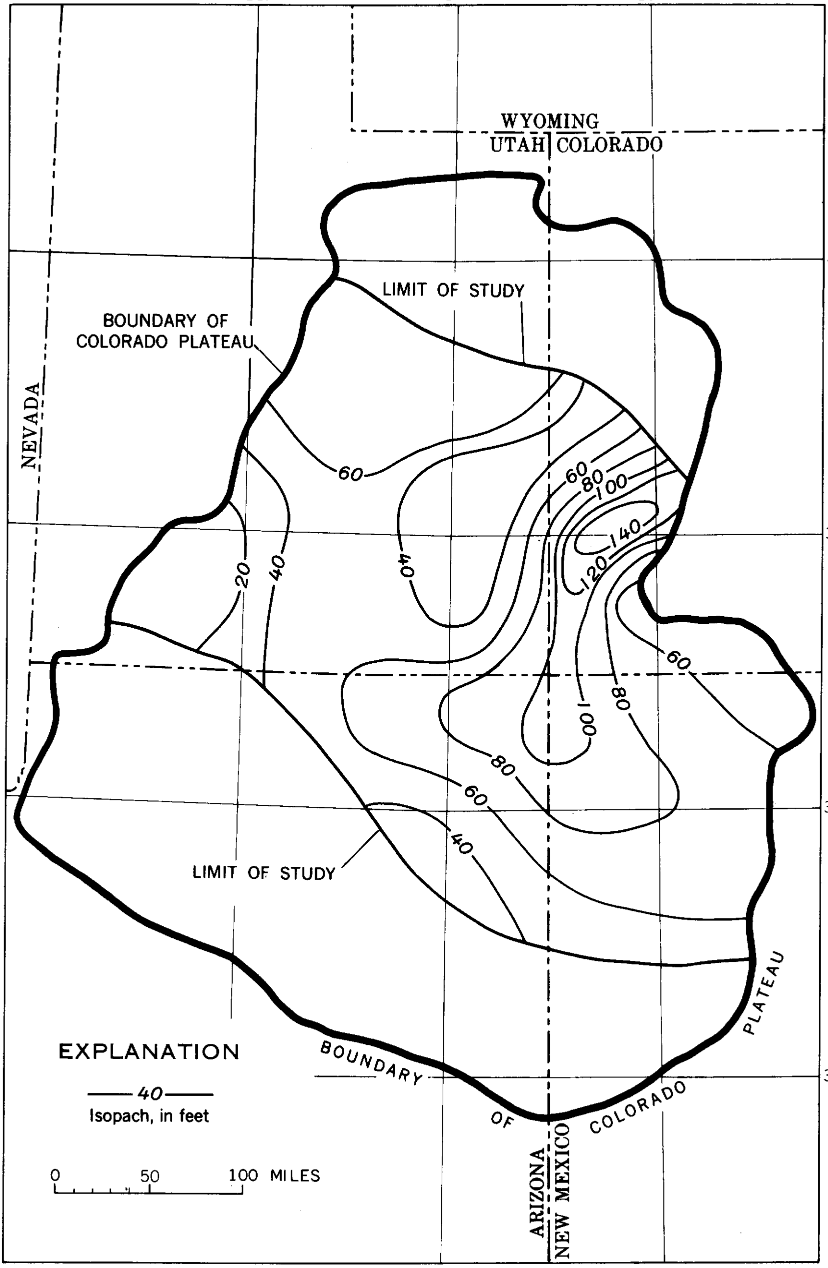


FIGURE 36.—Isopach map of the Burro Canyon and Cedar Mountain formations and the Dakota sandstone. Data from L. C. Craig and C. N. Holmes (written communication, 1953) and Stokes (1944).

Isopleths of both permeability and transmissivity show roughly coincident high values centered along the Colorado-Utah and Arizona-New Mexico State lines (figs. 37, 38). The regional high is an area of thicker than average sandstones and conglomerates, and coincides with the area of thickest deposits of Burro Canyon formation. The permeability and transmissivity lows are also coincident and lie in central Utah. In this area the Burro Canyon formation is absent and the unit is composed mainly of the Cedar Mountain formation.

The Dakota sandstone is present in most of the area of study. It attains its greatest thickness and permeability in northeastern Arizona and northwestern New Mexico where it is the only formation of the lower hydrologic unit present.

MIDDLE UNIT

The Mancos shale and the correlative Tropic shale make up the middle hydrologic unit of the Cretaceous sedimentary rocks; they are thick marine shales and silty shales that extend over the entire Colorado Plateau. This unit varies in thickness from about 700 feet along the western border of the plateau to about 6,000 feet in western Colorado (Pike, 1947). Like the upper mudstones of the Chinle formation and the mudstone unit of the Morrison, it is an excellent aquiclude.

UPPER UNIT

The Mesaverde formation and the equivalent Straight Cliffs sandstone comprise a hydrologic unit which overlies and intertongues with the Mancos and Tropic shales over the entire area of the Colorado Plateau (table 5). This hydrologic unit consists of alternating shale and widespread large-scale lenticular moderately well sorted sandstones.

An isopach map of the sandstones was constructed from published measured sections (fig. 39). Although numerous sections were available around the periphery of the plateau area, the interior has largely been stripped of Upper Cretaceous sedimentary rocks by erosion so that the isopach map must be interpreted with caution.

Isopleths of permeability trend mainly northwest and increase slightly in magnitude toward the southwest (fig. 40). The gradual southwestward increase in permeability, which reaches a regional high near the Arizona-Utah border, seems to be largely due to an increase in mean grain size. The increase in permeability expectable from the increase in mean grain size is somewhat, but not entirely, offset by greater differences in standard deviation of grain size.

Isopleths of permeability of sandstones of the Mesaverde and Straight Cliffs crudely parallel the southwestern margin of their basin

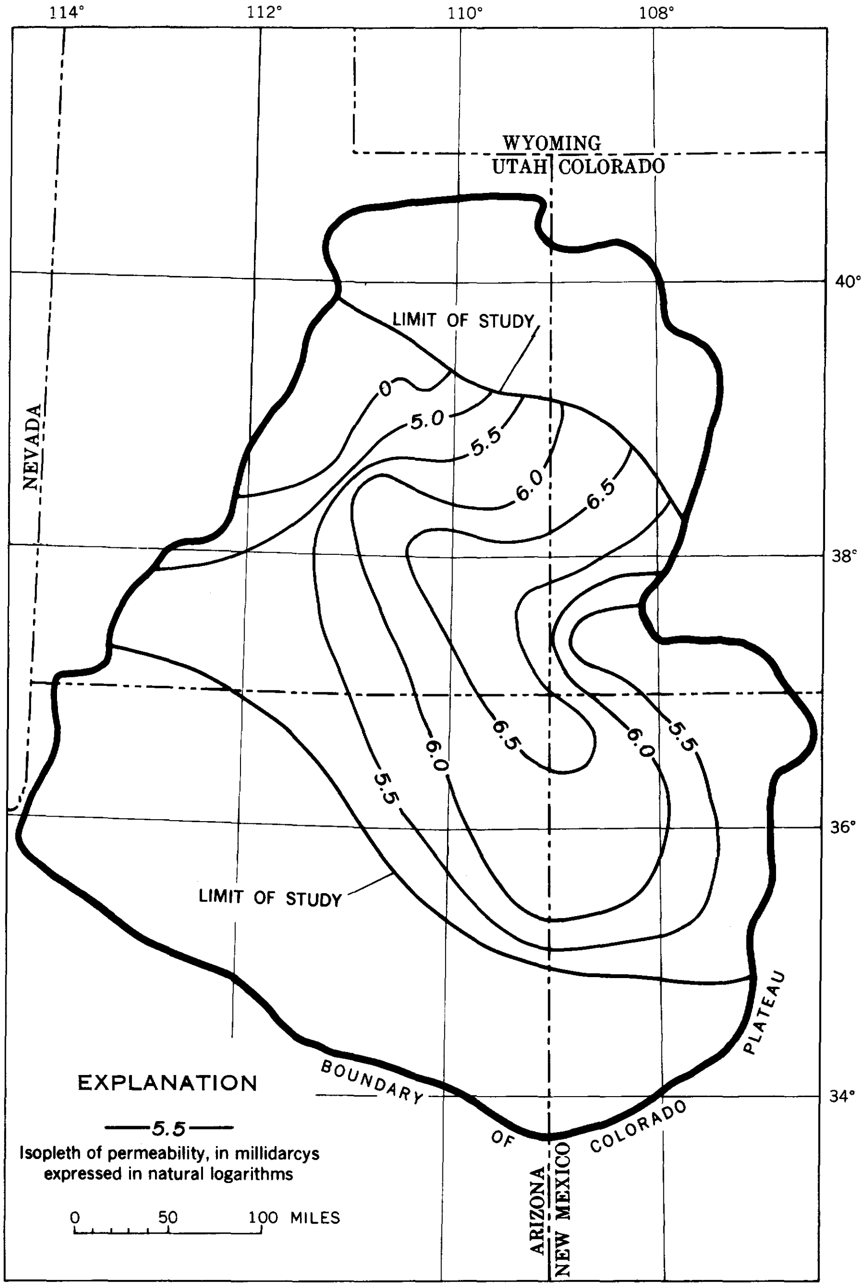


FIGURE 37.—Isopermeability map of the Burro Canyon and Cedar Mountain formations, and the Dakota sandstone.

of deposition (Pike, 1947; Sears and others, 1941). The permeability decreases inward with distance from the basin margin. The small range in mean permeability is due to the small range in mean grain size and to the relatively small range of grain sizes in this hydrologic

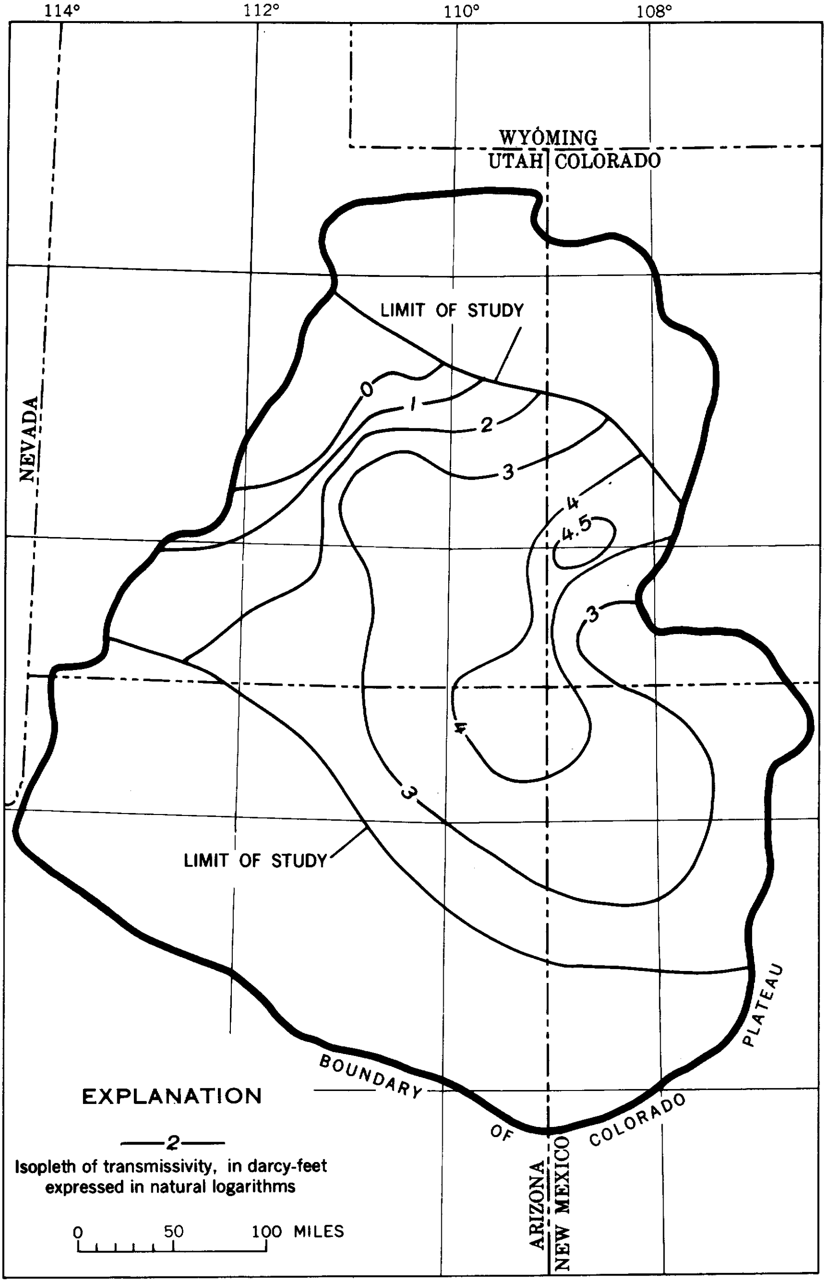


Figure 38.—Isotransmissivity map of the Burro Canyon and Cedar Mountain formations, and the Dakota sandstone.

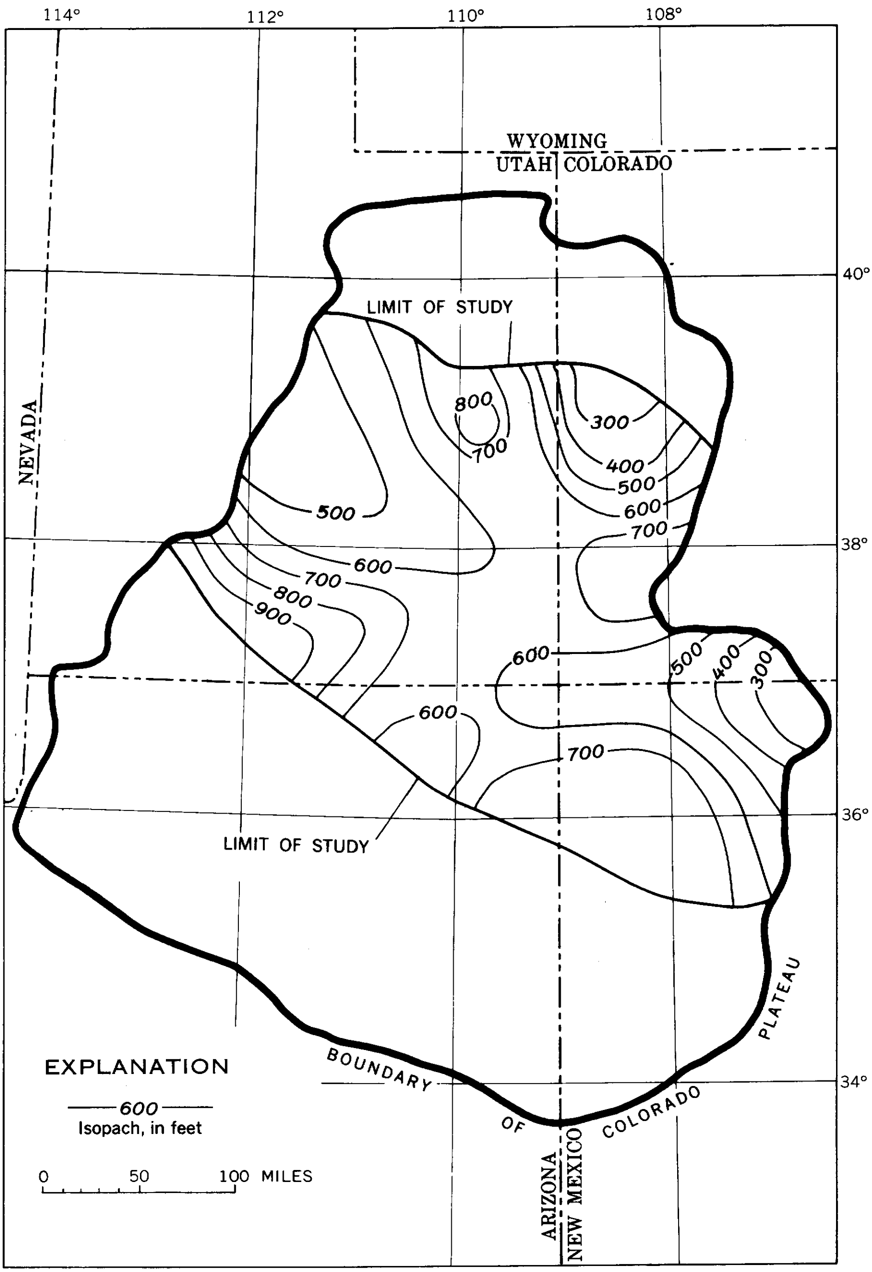


FIGURE 39.—Isopach map of sandstones of the Mesaverde formation and Straight Cliffs sandstone. Data from Fisher (1936), Gregory and Moore (1931), Hunt (1955), Pike (1947), Reeside (1924), Richardson (1909), Sears and others (1941), and Spieker 1946).

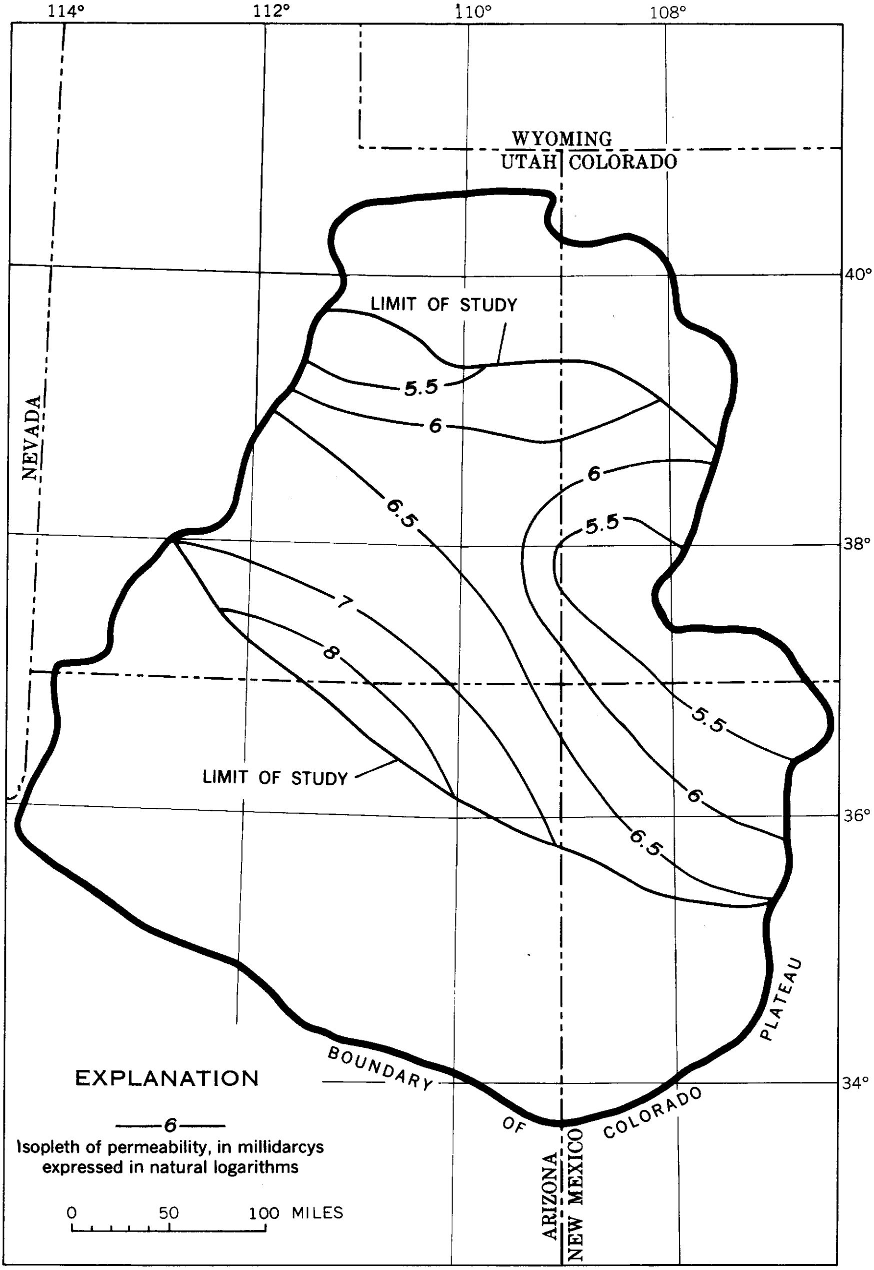


FIGURE 40.—Isopermeability map of sandstones of the Mesaverde formation and Straight Cliffs sandstone.

unit. As the position of the shoreline oscillated back and forth several times across the southwestern parts of the Colorado Plateau, similar climatic, geomorphic, and energetic conditions responsible for the supply and sorting of sediments, were operative over wide areas and deposited a series of sandstones which, although differing individually, have in total a relatively homogeneous mean permeability.

Isopleths of transmissivity also trend northwest and increase in magnitude to the southwest (fig. 41). The strong southwestward increase in transmissivity is due to the reinforcing effects of increasing thickness and permeability in this direction.

As there are commonly 3 to 10 relatively thick sandstone lenses in the upper hydrologic unit, its total transmissive capacity is very large when compared with that of other hydrologic units. Although there is considerable variation between areas, in any one area no more than about one-fifth of the total transmissive capacity is generally attributable to an individual stratum.

VERTICAL TRANSMISSIVITY

In most areas of the Colorado Plateau the exposed rocks consist of an irregularly alternating sequence of many relatively permeable and impermeable layers. If geologically reasonable hydrologic conditions are assumed, the movement of fluids vertically through an areally restricted part of such a sequence can only take place by means other than intrinsic permeability. By definition fluid will not flow across intrinsically impermeable layers, but if the impermeable layers have been strongly folded or extensively fractured or both, a considerable degree of secondarily induced permeability is possible. It follows that the evaluation of the vertical transmissive capacity of strata of alternating permeable and impermeable rocks, although influenced in part by the thickness, intrinsic permeability, and relative positions of the layers, will be primarily determined by the extent to which the layers have been strongly folded and by the continuity and amount of separation of fractures that transect the impermeable layers.

VERTICAL SEQUENCE, THICKNESS, AND INTRINSIC PERMEABILITY

A summary of the vertical sequence, thickness, and intrinsic permeability of the sedimentary rocks exposed in representative parts of the Colorado Plateau is shown in plate 1. Although both the total exposed thickness and the intrinsic permeability vary from area to area, the sequence and its permeability are notably consistent. From the base of the sections upward the sequence consists of: (1) a relatively thick and impermeable mudstone interval having as many as two interbedded wedge-shaped moderately permeable sandstone units in the lower part and a thin widespread sheet of sandstone of relatively

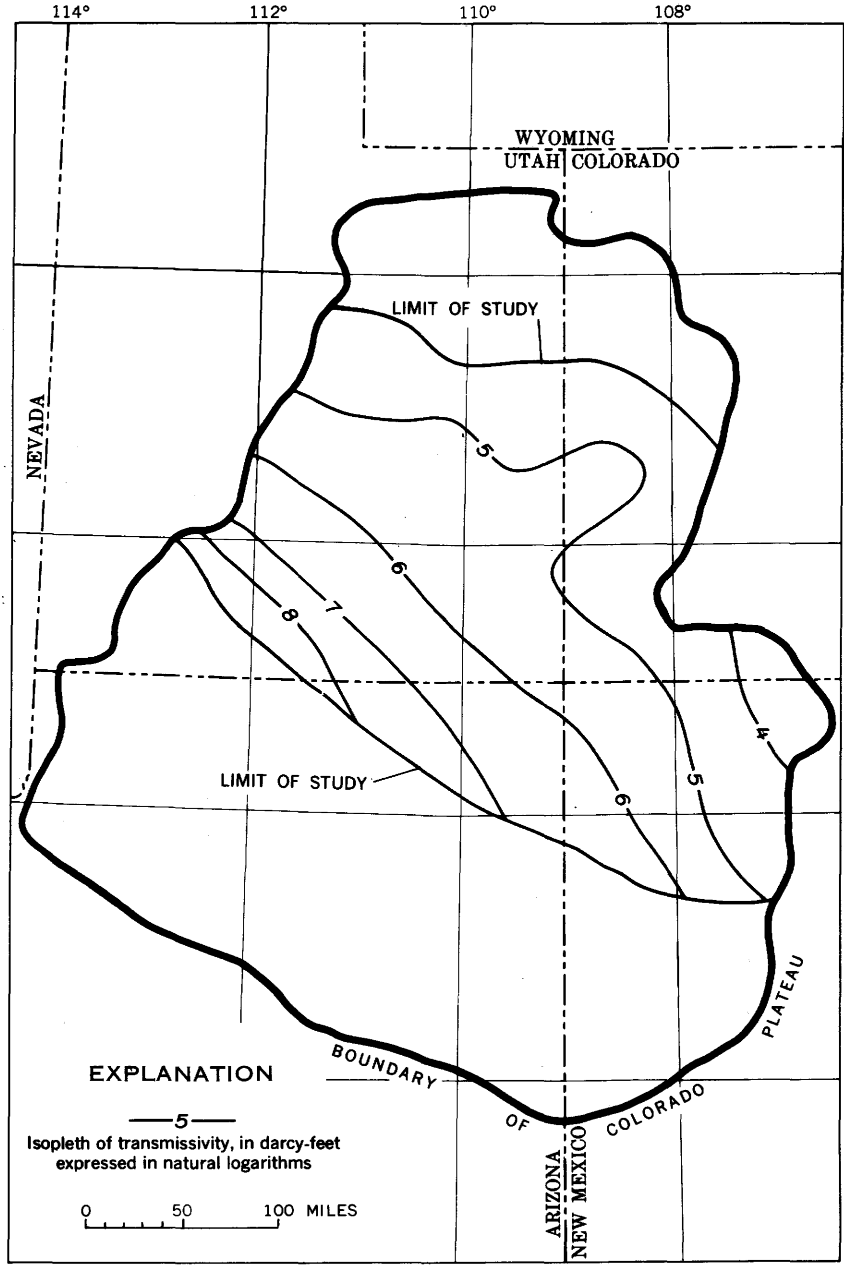


FIGURE 41.—Isotransmissivity map of sandstones of the Mesaverde formation and Straight Cliffs sandstone.

low permeability in the upper part; (2) a moderately thick interval of sandstones which is moderately permeable at the base and highly

631709 O—62——6

permeable at the top; (3) a thin interval of thin discontinuous moderately permeable sandstones interbedded with thin impermeable mudstones; (4) a thick mudstone or shale interval having a thin widespread moderately permeable sheet of sandstone near its base; and (5) a thick interval of moderately thick and permeable sandstones interbedded with thick and impermeable mudstones and shales.

It is also notable that the total proportion of permeable sandstones in the exposed rocks decreases rather regularly from the southwest to the northeast. In southeastern Utah and northwestern Arizona permeable sandstones account for about 40 to 50 percent of the exposed rocks, whereas in the Uravan and Grand Junction areas of southwestern Colorado permeable sandstones account for only 10 to 15 percent of the exposed rocks.

The most significant characteristic contributing to vertical fluid movement through these rocks, however, is the interlayering of permeable with impermeable hydrologic units. No single permeable hydrologic unit or vertical sequence of permeable hydrologic units constitutes more than 20 percent of the exposed rocks and commonly it constitutes less than 10 percent.

DISTRIBUTION OF FAULTS AND FRACTURES

It is assumed, on the basis of admittedly limited stratigraphic evidence and isotopic age determinations of uranium minerals, that many if not most, of the present loci of strong folding and extensive fracturing predate the emplacement of uranium deposits. For many of the monoclinal areas and salt intrusive bodies this is clearly true. There are, however, conflicting views as to whether the laccolithic igneous intrusions predate or postdate the emplacement of uranium deposits. Consequently, the present distribution of folds and fractures, while undoubtedly differing in degree and probably in detail from the distribution at the time of ore emplacement, is only a permissive estimate of the distribution of folds and fractures at the time of ore emplacement.

Few if any quantitative data on the distribution of fractures within the exposed sedimentary-rock units of the Colorado Plateau are presently available or readily obtainable. Consequently, the following discussion indicates only the general nature of fracture distribution in these rocks and speculates about its probable effects.

WITHIN UNITS

In general, the more highly cemented rocks of the Colorado Plateau, primarily pre-Mesozoic rocks and Mesozoic fluvial sandstones and conglomerates, are highly fractured where exposed. In addition to these units, the thin limestones of the Todilto limestone and Pony

Express member of the Wanakah formation are commonly highly fractured, although many of these fractures are probably due to slumping of recent origin. The thicker eolian and marine Mesozoic sandstone units are also fractured locally, but few large fractures are visible in these rocks. The Entrada formation, in particular, commonly does not have prominent fractures.

Examples of how different strata have responded to differential stress may be seen along most of the major tectonic uplifts, salt intrusive masses, and monoclines of the Colorado Plateau. Evaporites, as would be expected, show the most evidence of plastic deformation. Classic examples of this type of deformation are found in the Paradox member of the Hermosa formation of Pennsylvanian age in the "salt anticlines" of southwestern Colorado and southeastern Utah (Dane, 1935; Cater, 1954). Excellent examples of thinning accomplished mainly by intergranular movement can be observed at several places along the northeast part of the Uncompahgre Plateau. These examples of thinning are evident where the Precambrian metamorphic rocks have been displaced several hundred feet by normal faults, and where the overlying Wingate, Kayenta, and Entrada formations have responded to this movement by marked thinning and draping over the fault without the formation of faults or even many large visible fractures. In the same area the overlying more competent Salt Wash member and Dakota and Burro Canyon formations are well fractured. Although the mudstone and shale of the Chinle of this area also have generally adjusted to the unbalanced stress by intergranular movements, a few visible and sometimes open fractures have formed.

The magnitude of increase in transmissive capacity of fractured rocks over unfractured rocks can be seen by a comparison of the water-consumption data for drill holes. In several areas in southwestern Colorado and southeastern Utah fractured and unfractured rock of the Salt Wash member has been extensively drilled. Analysis of four of these areas showed that known fractures increased the transmissive capacity of the Salt Wash by a factor of from 3 to 5. This is but a minimum estimate as only the effects of relatively large fractures could be detected in this analysis.

BETWEEN UNITS

The degree to which faults and other fractures that extend through a considerable vertical sequence of rocks differ in intensity from one place to another in the Colorado Plateau is difficult to determine. Thick exposures of sedimentary rocks are generally limited to the margins of the major tectonic elements (fig. 49); little information is available outside these areas. Although a quantitative evaluation is thus not feasible, some generalization is possible.

The pre-Mesozoic rocks, where exposed, are generally well jointed regardless of lithologic type. The Paradox member of the Hermosa formation, which underlies many uranium-producing districts in the Colorado Plateau, is an important exception. The Paradox is chiefly composed of shale and evaporites and, in the Paradox Basin, is estimated to have been at least 2,000 feet thick when deposited (E. M. Shoemaker, oral communication, 1954). Locally, in southwestern Colorado, where it crops out in the thickened cores of the salt anticlines, it has been drilled to depths in excess of 10,000 feet. As it is doubtful if rock of this character would ever have open fractures except at shallow depths, the Paradox would be a formidable barrier to upward-moving solutions. Nevertheless, hydrothermal copper-silver veins, present locally as at the Cashin mine in southwestern Colorado (R. P. Fischer, 1936), may have been formed by solutions that moved upward along fractures through the Paradox member, suggesting that the Paradox member is susceptible to fracturing.

Rocks of Mesozoic age, mudstones and shale as well as sandstones, exposed along the margins of major tectonic elements are either faulted, jointed, or opened up by intergranular movements to such a degree that vertical movement of fluids through the entire sequence is easily possible. Away from these areas, vertical permeable zones are almost entirely restricted to the relatively competent sandstones and limestones. Thus, from a purely qualitative analysis it would seem that present vertical transmissive capacity through any extensive thickness of the exposed sedimentary rocks of the Colorado Plateau is restricted to the disturbed areas surrounding the intrusive masses of salt and igneous rock and along major monoclinal folds and faults.

URANIUM DISTRIBUTION AND TRANSMISSIVE CHARACTER OF HOST ROCKS

GENERAL CONSIDERATIONS

Although the principal host rocks of uranium deposits underlie much of the Colorado Plateau, the samples gathered to determine transmissivity characteristics and the data collected on the distribution of uranium are primarily from areas where the host rock crops out. This raises the question of how reliably either the transmissive character of a host rock as a whole or the distribution of the uranium it contains can be estimated from the data used in this report. If the structural elements and the erosional history which together determine the location of present outcrops can be shown to be substantially independent of the structural elements and depositional history, which together determined the hydrologic character of the host rocks, then the transmissivity data of this report can be considered representative and usable without further qualification. If a similar independence can be assumed for the processes that determined where the host rocks presently crop out and for the processes that determined the present location of uranium deposits, then the uranium-deposit distribution data of this report can also be considered representative and need no further qualification.

The occurrence of widely scattered areas in which the host rocks crop out and the regularity of lithologic variation between outcrops can be cited as prima facie evidence of the large area over which sedimentation was going on, and also that sedimentation processes were not dominated by either local contributions in source material or appreciable discontinuities in energy relations. It is true, however, that large proportions of the host rocks presently exposed are found immediately adjacent to major tectonic structures.

Although the date of origin of many of these structures has not been definitely established, many of these structures are known to have been active before the deposition of the host rocks and could have influenced both deposition and denudation of the host rocks. Detailed stratigraphic studies (Craig and others, 1955; Harshbarger and others, 1957; Stewart and others, 1959) indicate that although one structure or set of structures may have locally noticeably affected the thickness and type of sediment deposited they had no overriding effect on the regional pattern of sedimentation.

The intensive prospecting by both private enterprise and Federal agencies during the last few years is considered a sufficient guarantee that the distribution of ore deposits within outcrops is sufficiently well known, and that their distribution in areas in which the host rocks are at shallow depths is reasonably well known. As the outcrops of the host rocks are largely along the flanks of the major tectonic features, the distribution of deposits in these areas must be assumed to be representative of all deposits unless there is some evidence of a correlation of numbers of deposits with distance from the crests or bounding faults of these tectonic features; compilation of distribution data for uranium deposits and outcrop areas relative to major tectonic features has shown that a negative correlation exists (table 32). This precludes the possibility that the distribution of deposits in and near the areas where the host rocks crop out will statistically represent the distribution of all deposits. On the other hand, it does assure that this distribution is representative of areas of closely spaced and economically significant ore deposits—those areas that have yielded most of the uranium ore produced and are therefore a highly significant population to study.

On the supposition that the gross distribution of uranium deposits and the regional permeability and horizontal and vertical transmissivity trends of the uranium host rocks of the Colorado Plateau have not changed appreciably since the ore was deposited, and can be reliably estimated, several comparisons have been made. Isopleths of mean permeability, transmissivity, and a classifying function computed from horizontal transmissivity and the standard deviation of permeability and aquifer thickness were each superposed on a map showing the distribution of areas of closely spaced ore deposits. In addition, the gross distribution characteristics of the deposits in each host rock were analyzed in several ways. These several compilations were made to demonstrate the degree of correlation that exists between the distribution of known ore deposits and the different measurable hydrologic characteristics of the host rocks. Finally, an attempt was made to classify the extent to which each of the major host rocks departs from the mean measurable hydrologic characteristics of its most productive mining areas.

No attempt was made to appraise the effects that local variations in recharge, discharge, and structural attitude would have had on the flow of ground water when the ore was deposited. Although these factors undoubtedly affected the size, shape, and position of ore bodies, the data necessary for their evaluation are presently so scanty and conjectural that their influence can be only surmised.

MAJOR PRODUCING HYDROLOGIC UNITS

LOWER SANDSTONES OF THE CHINLE FORMATION

SPATIAL DISTRIBUTION OF DEPOSITS

One of the most striking characteristics of the uranium deposits of the Colorado Plateau is the close adjustment to the physical character of enclosing sedimentary rocks of both the gross and detailed distribution habits of the deposits. Although the mineralogy of the ores may vary from district to district, the habit of deposits within the same lithofacies of the host rock appears remarkably similar.

A recent resource appraisal of the uranium deposits in the San Rafael Swell region of central Utah (H. S. Johnson, 1957) has provided distribution data for a representative sample of the deposits in the lower sandstones of the Chinle. These data, summarized in figure 42, show that uranium in this hydrologic unit is typically found in a great many small deposits, although a few large deposits have produced most of the ore and contain most of the reserves.

In view of the often repeated but so far unverified assertions made by many geologists as to the random or systematic nature of the distribution of ore deposits with respect to outcrop pattern or to tectonic features, some scheme of quantifying these relations seemed desirable.

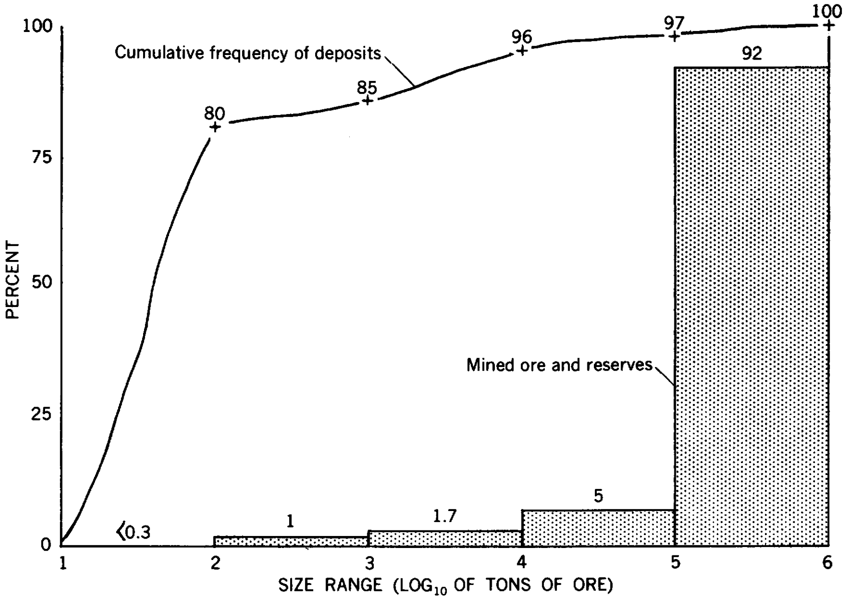
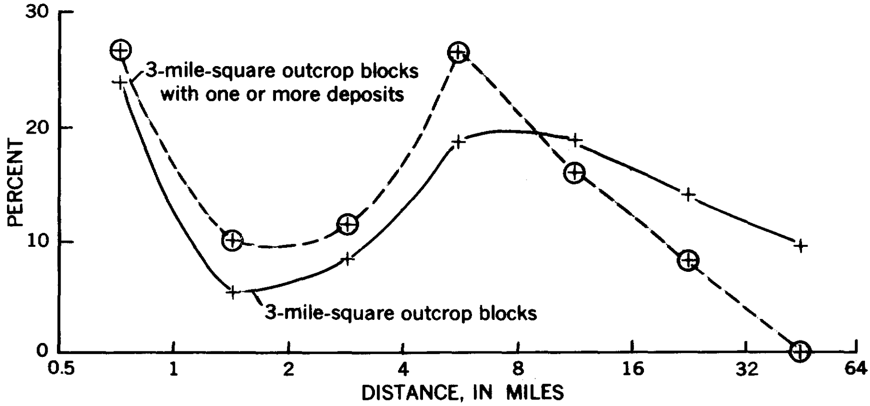


FIGURE 42.—Size distribution of uranium deposits in lower sandstones of the Chinle formation of the San Rafael Swell. Modified after H. S. Johnson (1957, p. 48).

Accordingly, data were combined from two previously compiled maps—one showing the major structural features of the Colorado Plateau (Luedke and Shoemaker, 1952) and the other showing the outcrop patterns of the principal producing stratigraphic units and the distribution of uranium deposits on which deposits containing over 1,000 tons of ore were distinguished as a separate group (Finch, 1955). The resulting map was then divided into approximately 3-mile squares by quartering the township land-survey network. Only those quarter-township subdivisions, hereafter called outcrop blocks, in which the lower sandstones of the Chinle crop out over about one-third to one-quarter or more of the area of the square were used in the subsequent measurement. Measurements were made of the frequency with which all deposits, and deposits over 1,000 tons, occur within outcrop blocks, and the shortest straight-line distance from the center of each outcrop block to the closest major tectonic feature was considered to be the locus of through-going fractures. Table 32 contains the raw data of the analysis: A list of the fracture zones from which distances were measured, the frequency of all outcrop blocks, and the frequency of deposits within blocks as a function of distance of the outcrop block from major fracture zones. For ease of measurement and clarity of presentation, the data were grouped into logarithmic distance classes. Figure 43, which summarizes these data, shows that the percentage of outcrop blocks containing uranium deposits decreases with increasing distance from major fracture zones. Furthermore, there is an even greater decrease in percentage of mineralized blocks with increasing



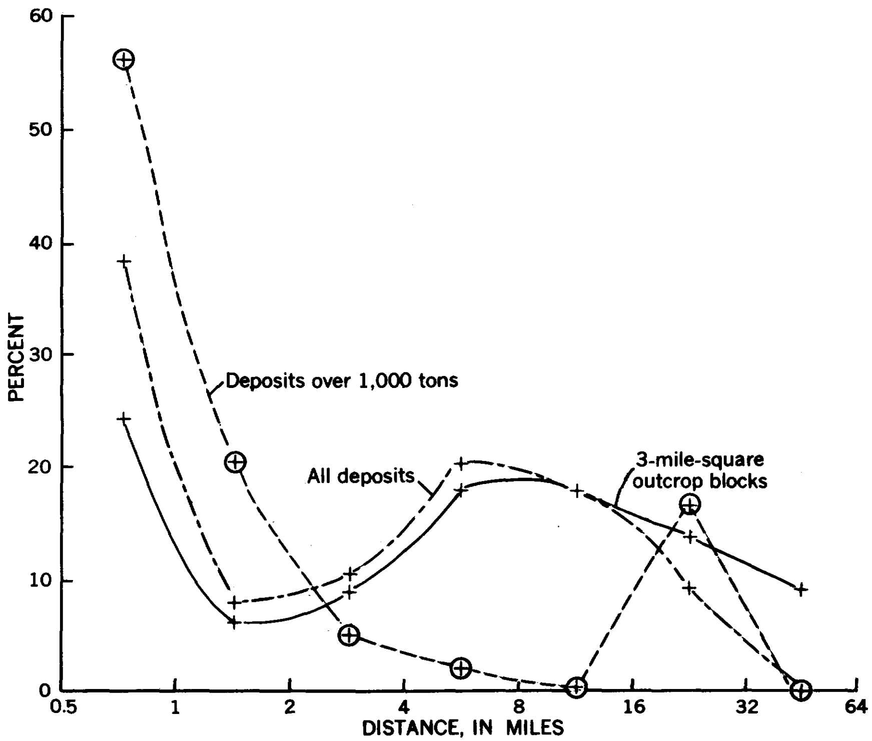


FIGURE 43.—Distribution of uranium deposits and outcrop blocks in lower sandstones of the Chinle formation as a function of distance from major fracture zones. Raw data and listing of major fracture zones used in the analysis are given in table 32.

distance from major fracture zones when only the distribution of blocks containing deposits over 1,000 tons is plotted. The frequency of all uranium deposits falling into the distance classes, as compared with the frequency of all outcrop blocks falling into the same distance classes, shows that whereas more than half of all the deposits are concentrated within 2 miles of a major fracture zone, the same distance zone contains only about one-third of the total number of outcrop blocks. The same relation is brought out even more clearly when, for each distance class, the percentage of the total number of deposits over 1,000 tons is plotted against percentage of total number of outcrop blocks. In this plot, although the proportion of outcrop blocks located less than 2 miles from a major fracture zone remains at about one-third the total, the proportion of deposits over 1,000 tons in the same distance zone increases to over three-quarters of all such deposits.

PERMEABILITY

Figure 44 shows the distribution of areas of closely spaced uranium deposits and isopleths of mean horizontal permeability of the lower Chinle sandstones. There appears to be little, if any, correlation between the permeability gradients, as outlined, and areas of uranium deposition. Although lower sandstones of the Chinle in many producing areas in southeastern Utah have a mean permeability of about 2.5 ($\log_e$ in millidarcys), significant deposits occur in east-central Utah, where the mean permeability of the lower part of the Chinle is 1.5, and in northeastern Arizona, where it is about 3.5 to 4.0.

HORIZONTAL TRANSMISSIVITY

Mean horizontal transmissivity and the distribution of major ore-producing areas in the lower sandstones of the Chinle are shown in figure 45. Most of the producing areas lie between the 1.0 and -1.0 ($\log_e$ darcy-feet) isopleths of transmissivity. The significance of this correlation, however, is questionable, owing to the small range of transmissivity (-3.0 to $+3.0$ $\log_e$ darcy-feet).

The possible correlation of a restricted range in horizontal transmissivity with areas of closely spaced ore deposits suggested that it might be instructive to outline those areas within the lower sandstones of the Chinle with a hydrologic character similar to that of the major ore-producing regions—the salt anticline region of eastern Utah, Monument Valley, the White Canyon area, and the San Rafael Swell (fig. 1.). The available measurements most likely to reflect significant differences in hydrologic character are the mean value of transmissive capacity and the standard deviations of permeability and thickness. Accordingly, an index number was derived for each of the grid points

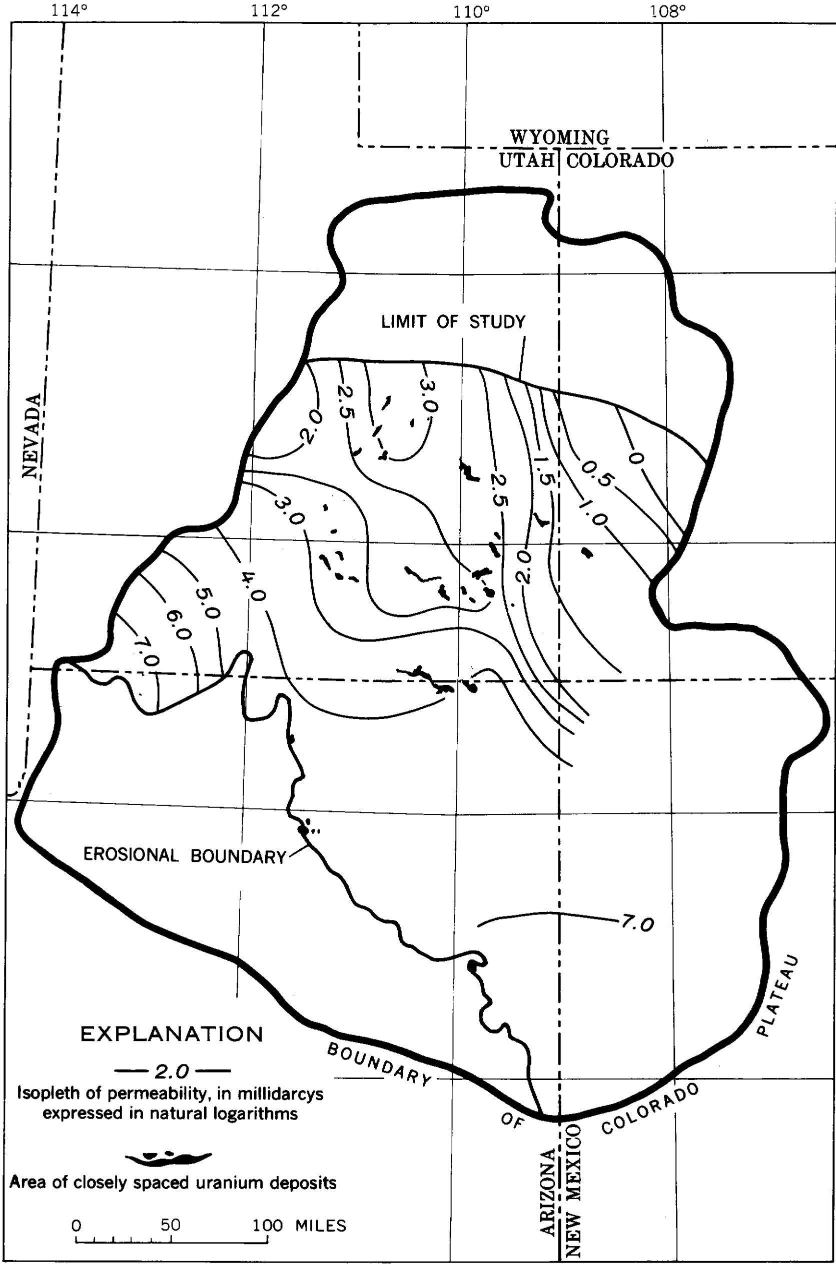


FIGURE 44.—Isopermeability map of the lower sandstones of the Chinle formation showing distribution of areas of closely spaced uranium deposits.

used in determining the isopleths of permeability and transmissivity (p. 12) by computing the difference between the mean value of these three components for the four major mining districts mentioned above and the mean value of the three components at the sample points. The

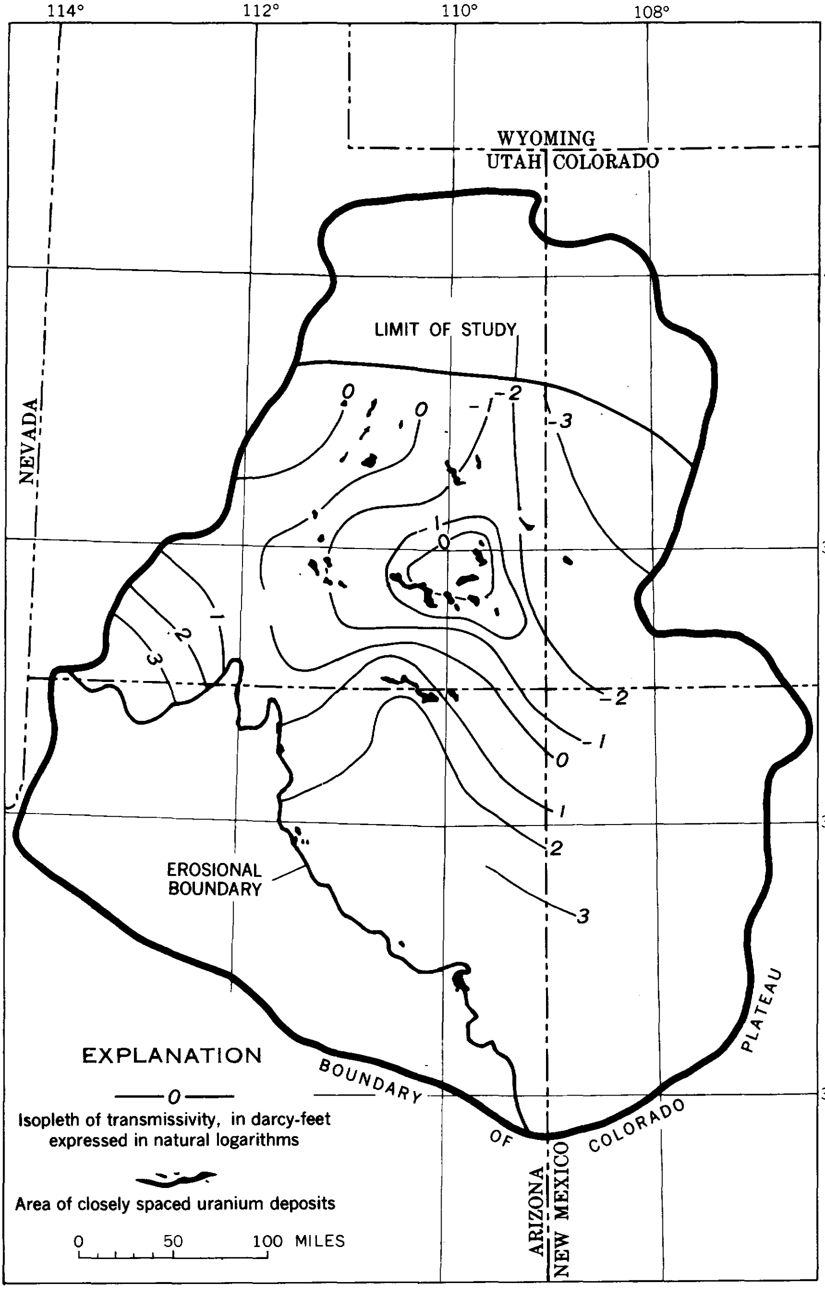


FIGURE 45.—Isotransmissivity map of lower sandstones of the Chinle formation showing distribution of areas of closely spaced uranium deposits.

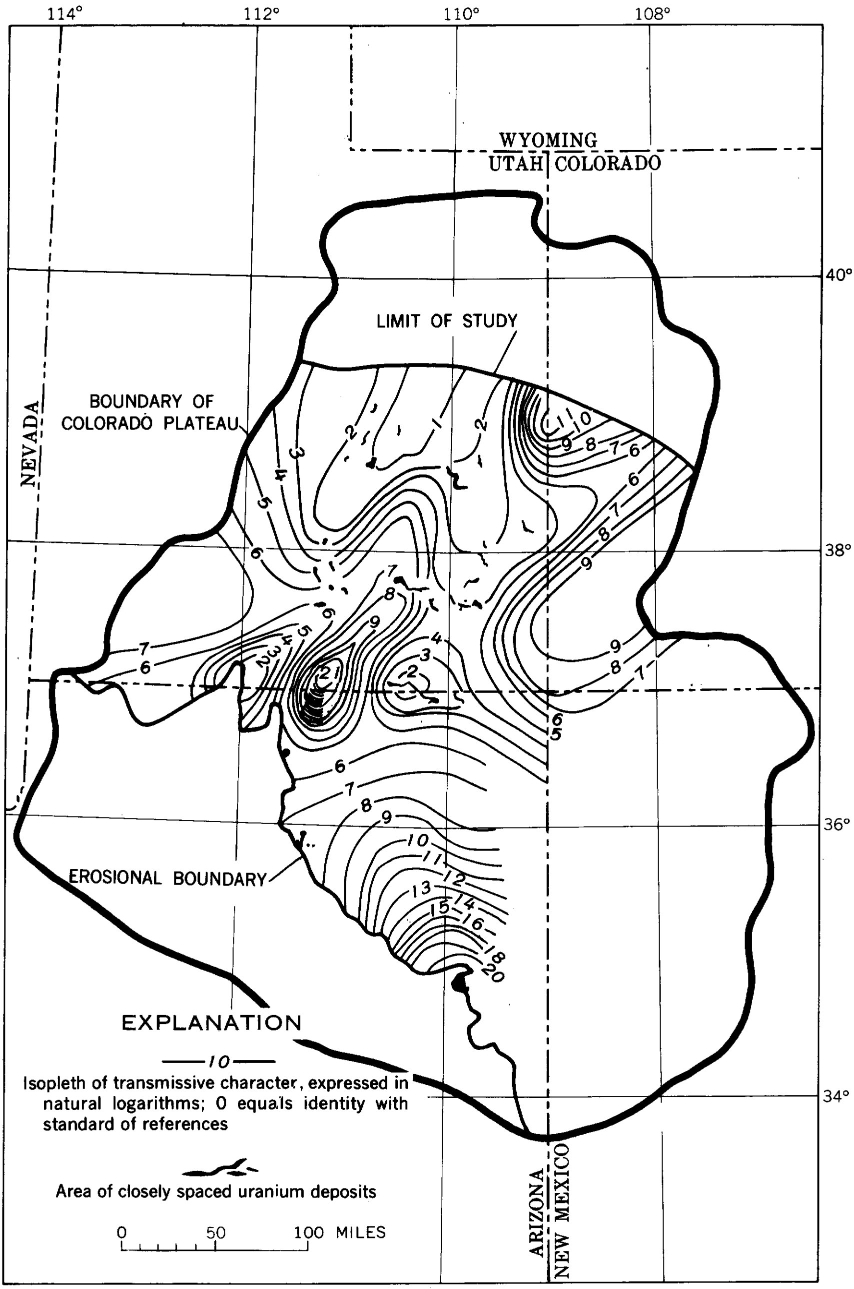


Figure 46.—Lower sandstones of the Chinle formation classified as to similarity of horizontal transmissive character to the average of the character at the most productive mining areas.

resulting values were contoured and are shown in figure 46. The theory and details of construction of such maps are discussed by Pelto (1954) and most recently by Krumbein (1955).

One of the most striking characteristics of the classifying map (fig. 46) is the small size and infrequent occurrence of areas of low index number. The significance of this is that only small scattered areas have hydrologic characteristics similar to those of areas of major ore production. A comparison of the contours with the known distribution of ore indicates that, although the major mining districts have remarkably similar hydrologic characteristics, areas with dissimilar characteristics nevertheless have had large production; the most notable examples are the White Canyon and the Cameron areas (fig. 1). A small area straddling the Arizona-Utah State line in south-central Utah has excellent hydrologic characteristics for ore deposits, as judged by comparison with the major producing areas, but, although this area has been intensively prospected recently, only a few deposits have been found.

Noteworthy in the classifying map are the rather sharp discontinuities, as evidenced by contour density, that almost universally take place short distances away from the areas of closely spaced ore deposits. Inasmuch as the mean transmissivity variation in the lower sandstones of the Chinle is known to be small, the change in the classifying function must result chiefly from variations in the standard deviations of permeability and thickness.

Figure 47 shows the logarithmic standard deviation of thickness in feet, and figure 48 the logarithmic standard deviation of permeability in millidarcys, for the lower sandstones. As might have been expected, these two factors show a sympathetic and sizable variation. Consequently, any change from the optimum value for either the standard deviation of thickness or permeability cannot be self cancelling but, rather, will result in a change in the value of the classifying function and in steep contour gradients in the classifying map.

A comparison of figures 47 and 48 shows that intermediate to high values of both standard deviation of permeability and standard deviation of thickness correlate well with the distribution of areas of closely spaced uranium deposits. The possible significance of this can best be appreciated by a brief discussion of fluid flow through an aquifer. Under constant external conditions of recharge and discharge fluid flow through an aquifer as a whole is solenoidal; that is, the amount of fluid passing through any cross section of the aquifer as a whole will be constant. As aquifers do not have either a uniform permeability or a uniform internal structure the rate of flow of an element of fluid and the path it takes will vary with its position

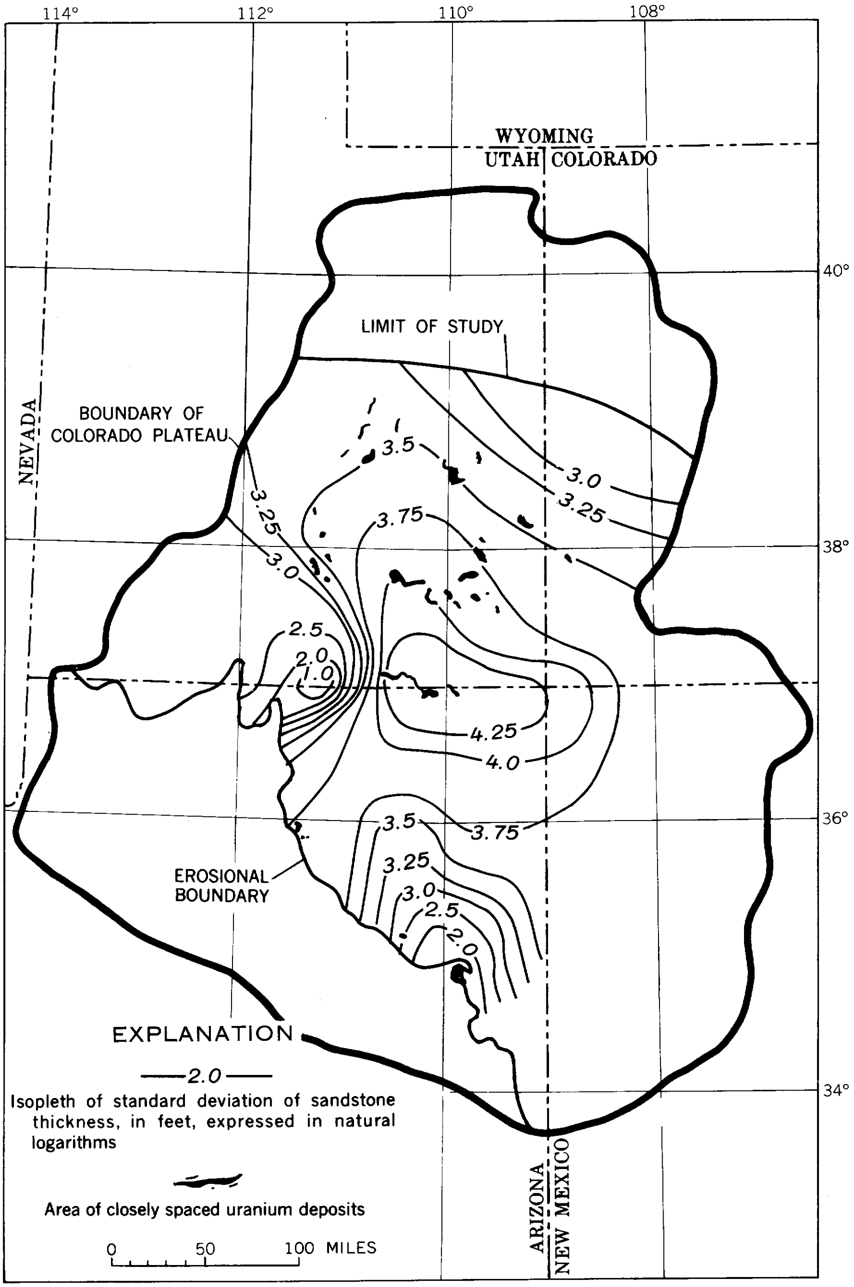


FIGURE 47.—Standard deviation of thickness of lower sandstones of the Chinle formation showing distribution of areas of closely spaced uranium deposits.

in the aquifer. The rate of flow of an element of the fluid being transmitted through the aquifer will vary inversely, and the length and complexity of its path of flow will vary directly with the degree of heterogeneity of permeability and structure of the aquifer. The

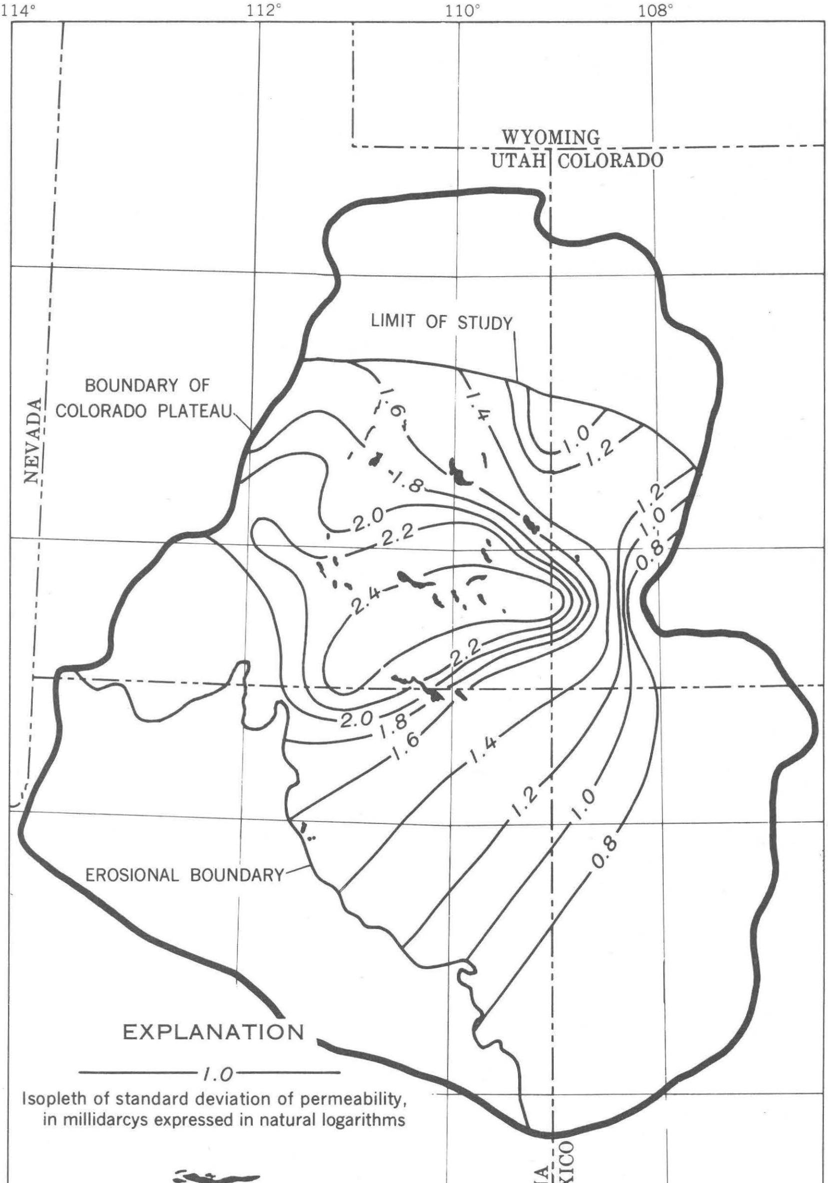


FIGURE 48.—Standard deviation of permeability of lower sandstones of the Chinle formation showing distribution of areas of closely spaced uranium deposits.

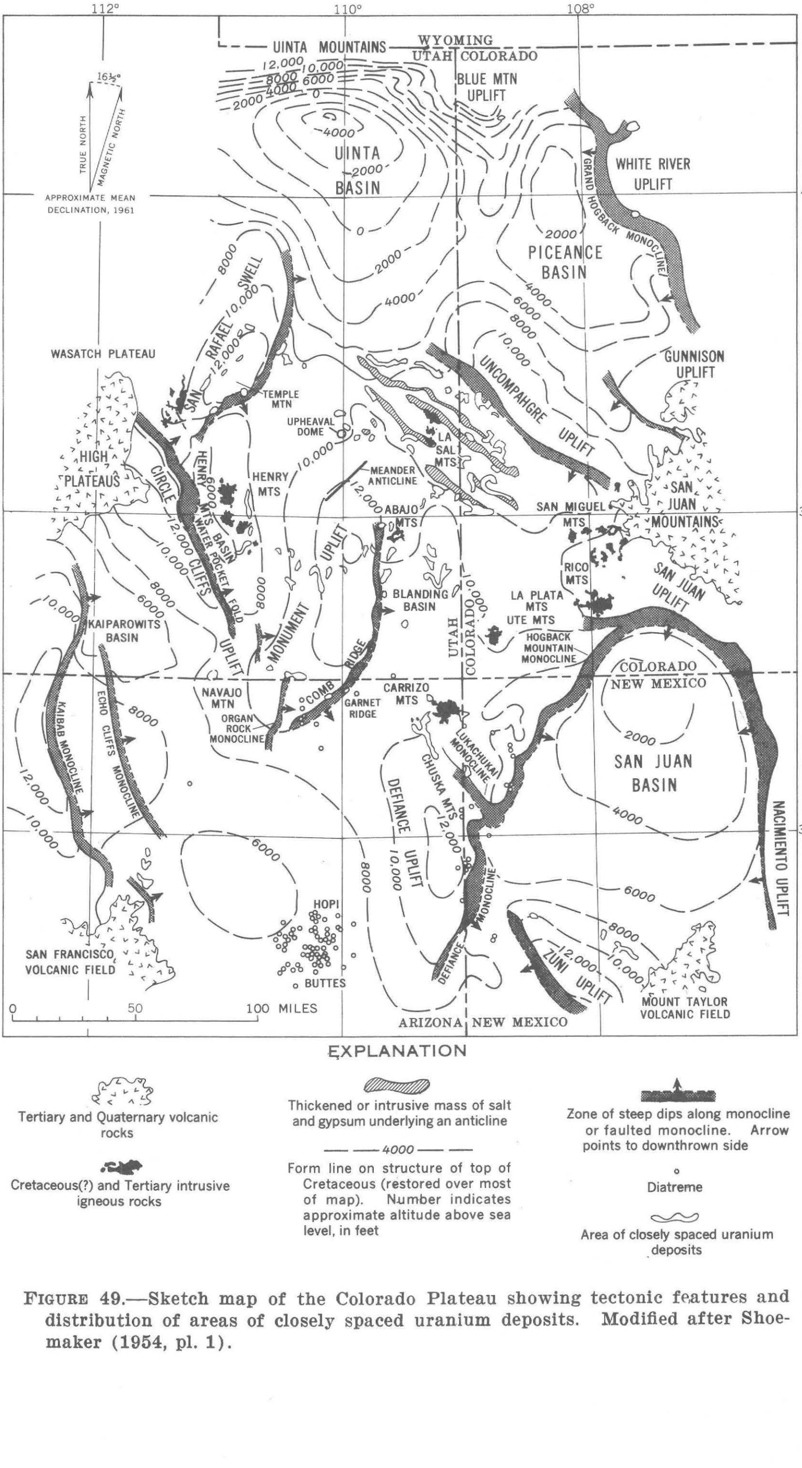


FIGURE 49.—Sketch map of the Colorado Plateau showing tectonic features and distribution of areas of closely spaced uranium deposits. Modified after Shoemaker (1954, pl. 1).

most obvious deduction that can be drawn from these facts is that, other factors being equal, uranium deposits are most numerous where the host rock would sustain the greatest diversity of velocity of flow.

VERTICAL TRANSMISSIVITY

Figure 49 shows major tectonic features; these represent zones believed to be the loci of greatest vertical transmissivity and the distribution of known areas of closely spaced ore deposits. Most areas of closely spaced ore deposits obviously are on or near major tectonic structures, although the map illustrates that not all major tectonic structures or zones of vertical transmissivity contain deposits. In most regions of the Colorado Plateau the loci of major fracture zones either coincide with or are marginal to the structurally highest parts of the local region. It could just as well be concluded that the concentration of uranium deposits is due to the effect such local uplifts had on the circulation of pore fluids rather than the enhanced vertical transmissive capacity of these same areas (McKay, 1955; and Kelley, 1955).

SANDSTONES OF THE MORRISON FORMATION

SPATIAL DISTRIBUTION OF DEPOSITS

The size distribution of a representative sample of uranium deposits in sandstones of the Morrison is shown in figure 50. These distri-

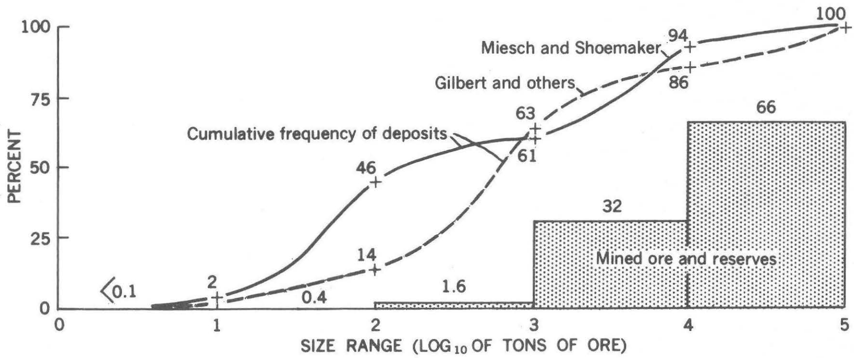


FIGURE 50.—Size distribution of uranium deposits for a representative suite of deposits in sandstones of the Morrison formation. Raw data from C. M. Gilbert and others (written communication, 1954), and A. T. Miesch and E. M. Shoemaker (written communication, 1954).

bution data do not include the large deposits found in the Jackpile and Ambrosia Lake areas, near Grants, N.Mex. (fig. 1). Addition of these deposits, although it would radically change the distribution as shown, would not change the generalizations drawn relating the size of deposits to the transmissive character of the host rock. The

631709 O—62——7

data for deposits included in figure 50 were obtained from A. T. Miesch and E. M. Shoemaker (written communication, 1954), based on data originally provided by W. I. Finch from production records and mine examinations. Similar data, although not directly comparable to those of Finch, were obtained from C. M. Gilbert and others (written communication, 1955). This information, which concerns several areas in the Uravan mineral belt that have been relatively well prospected on the outcrop and at shallow depth by drilling, provided the relative size of areas underlain by barren and uranium-bearing rock. Comparison of the cumulative-frequency curves for each set of data indicates that they are compatible with each other within the rather broad limits of accuracy of such studies.

Figure 51 shows the spatial relations between the distribution of ore deposits, outcrop blocks, and the fracture zones considered to be

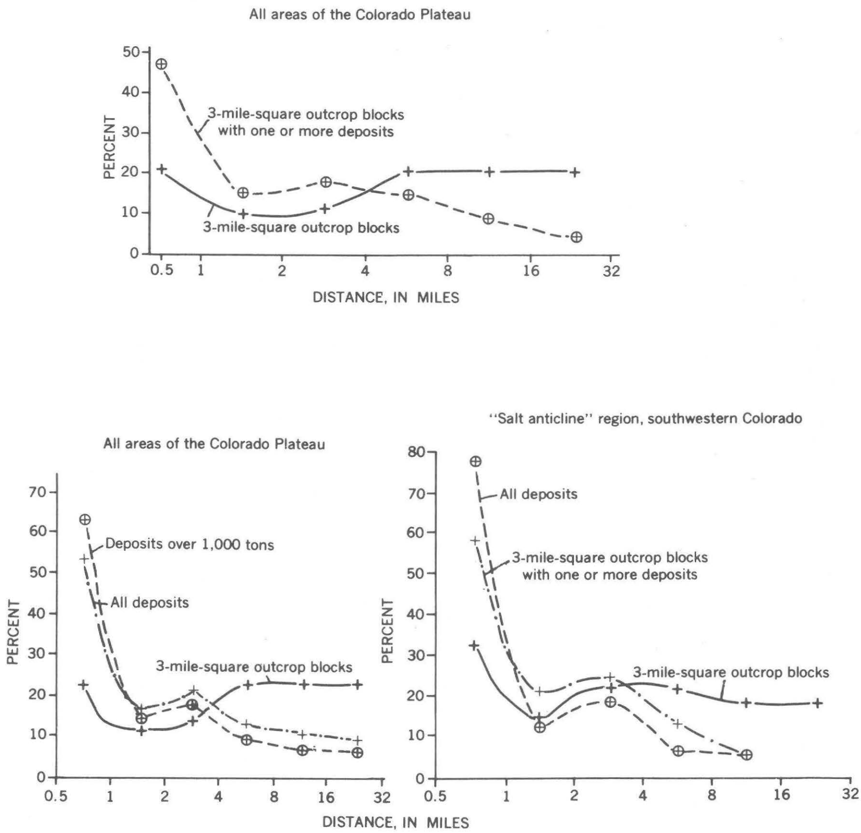


FIGURE 51.—Distribution of uranium deposits and outcrop blocks in sandstones of the Morrison formation as a function of distance from major fracture zones.

the loci of considerable horizontal transmissive capacity. In sandstones of the Morrison, as in the lower sandstones of the Chinle, there is a strong negative correlation between the frequency of outcrop blocks containing deposits with distance from the loci of appreciable vertical transmissivity. The most striking comparison—between the distribution of deposits and distribution of outcrop blocks in the salt anticline region—shows that over four-fifths of the deposits in this region are within 2 miles of the major fracture zones whereas only one-third of the total number of outcrop blocks are in the same area. A comparison of the distribution of deposits in sandstones of the Morrison formation in all areas of the Colorado Plateau with the distribution of all outcrop blocks in each distance class shows that about two-thirds of all deposits are within 2 miles of a zone of major fracturing, whereas the same distance classes only contain one-third of the total number of outcrop blocks.

PERMEABILITY

The distribution of ore deposits and isopleths of mean permeability of the Morrison sandstones are shown in figure 52. Here, as contrasted with the lower sandstones of the Chinle, most ore deposits are in areas of similar permeability; the most important deposits occur in sandstones having a mean of about 5.0 (natural logarithm of permeability, in millidarcy), and a range of from 4.5 to 5.5.

The correlation is by no means inclusive, as the deposits in northeasternmost Arizona near the Carrizo Mountains and those in northwestern New Mexico near the Mount Taylor volcanic field (fig. 49) are both in sandstones of considerably higher mean permeabilities. A contributing factor to the apparently good correlation is the rather small range of mean permeability of sandstones in the Morrison.

HORIZONTAL TRANSMISSIVITY

Figure 53 shows isopleths of transmissivity superimposed on the distribution of areas of closely spaced ore deposits. The large range in transmissive capacity associated with ore deposits is primarily due to the great range in thickness of sandstones in the Morrison of northwestern New Mexico and southwestern Colorado.

Sandstones of the Morrison were also classified as to their degree of similarity to the mean logarithmic values of transmissivity and standard deviations of permeability and thickness of the unit in three major mining districts—the Outlaw, Long Park, and Slick Rock mining districts, in the salt anticline region of southwestern Colorado (fig. 1). The sandstones were classified by the same methods used for the lower sandstones of the Chinle. Figure 54, the result of this

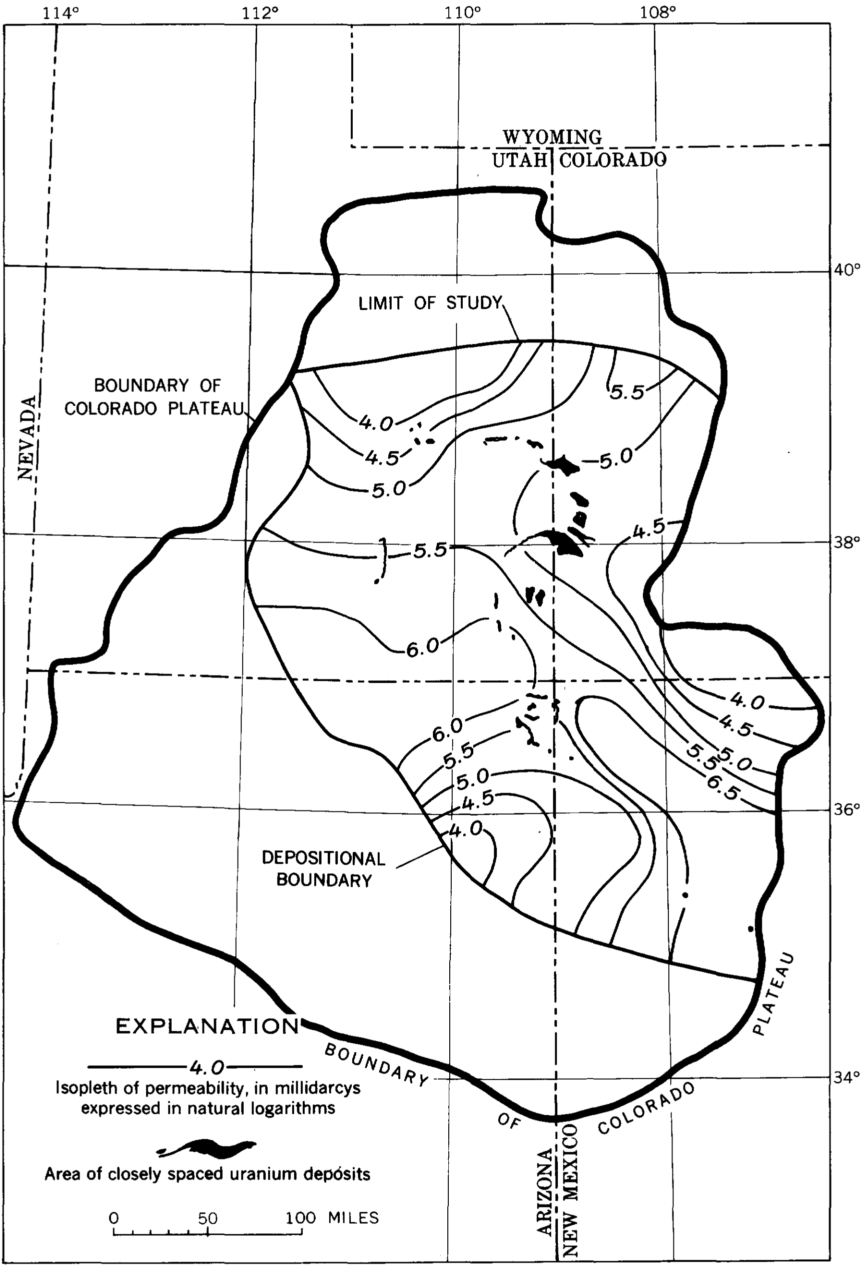


FIGURE 52.—Isopermeability of sandstones of the Morrison formation showing distribution of areas of closely spaced uranium deposits.

classification, shows that in a large area of southwestern Colorado and smaller adjacent areas of southeastern Utah, northeastern Arizona, and northwestern New Mexico the sandstones are of a nearly identical hydrologic character. Another small area, immediately

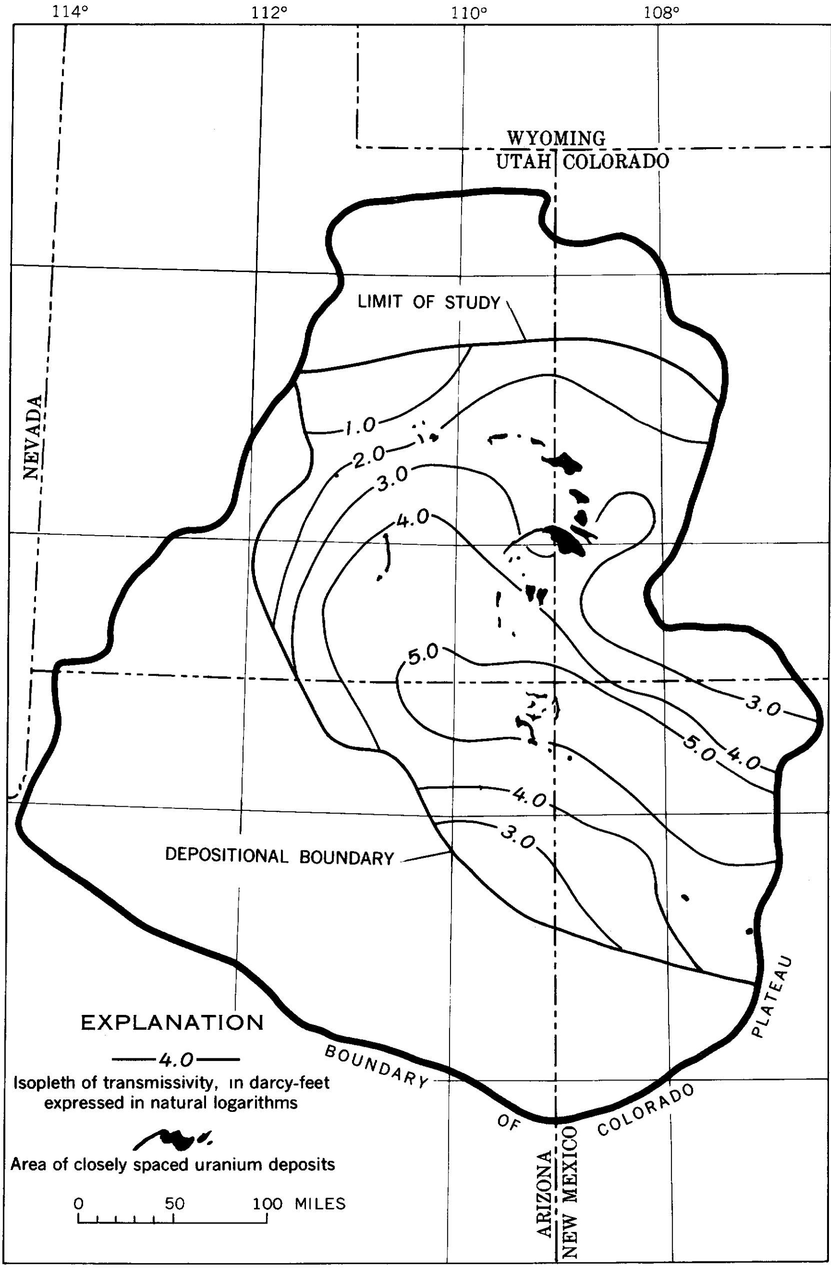


Figure 53.—Isotransmissivity of sandstones of the Morrison formation showing distribution of areas of closely spaced uranium deposits.

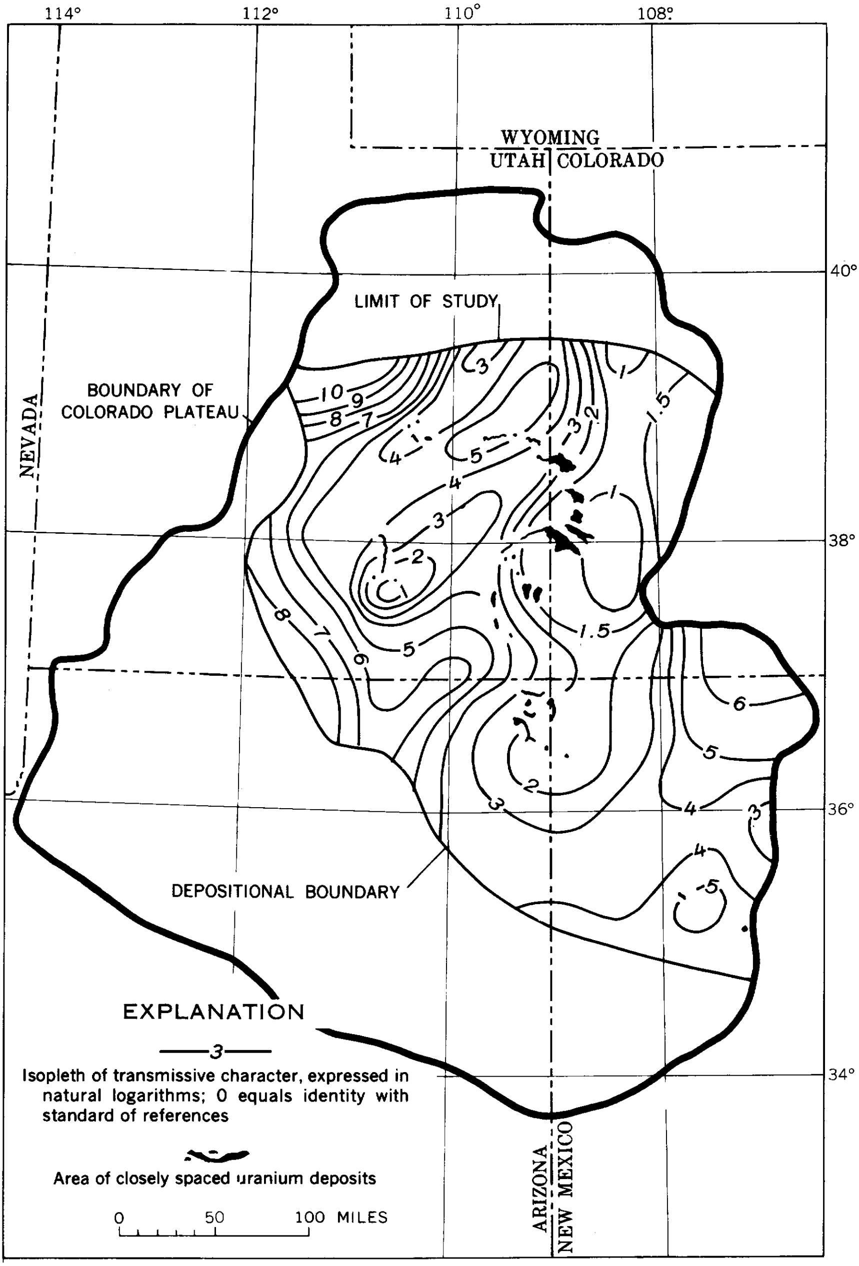


FIGURE 54.—Sandstones of the Morrison formation classified as to similarity of horizontal transmissive character to the average of the character at the most productive mining areas.

southeast of the Henry Mountains of south-central Utah, also has a low index value. This area coincides with the numerous but small deposits along the east flank of the Henry Mountains basin.

The important ore deposits in the vicinity of the Mount Taylor volcanic field of northwestern New Mexico are not in areas that have a low index value nor are the smaller and less significant deposits northeast of the San Rafael Swell, in east-central Utah. The New Mexico deposits are in sandstones of greater mean transmissivity with a lower standard deviation of permeability but a higher standard deviation of thickness than those sandstones containing most of the ore deposits (figs. 55, 56).

Isopleths of the logarithmic standard deviation of thickness (fig. 55) show a good correlation between distribution of the ore and a value of 3.0 ($\log_e$ thickness in feet), though all the ore deposits in New Mexico and Arizona are in sandstones having a larger standard deviation of thickness. The isopleth map of the logarithmic standard deviation of permeability (fig. 56) shows that a value of 1.5 seems to be characteristic of most of the areas of closely spaced ore deposits. However, the restricted range of standard deviation of permeability in the Morrison formation of the ore-producing regions is less impressive when compared with the rather limited overall range of standard deviation of permeability, 0.5 to 2.5 $\log_e$ millidarcy, for the sandstones.

VERTICAL TRANSMISSIVITY

The distribution of areas of closely spaced uranium deposits and major tectonic features—zones considered to be the loci of considerable vertical transmissivity—are shown in figure 49. The close relation of the distribution of ore deposits to the major tectonic features and highly transmissive zones is obvious except along the northeast flank of the Blanding basin. Here many small and a few large ore deposits are at a considerable distance from any visible structure or zone of vertical transmissivity; these deposits, however, do fall approximately on a line between the Ute and Abajo laccolithic mountain groups. If this line is extended northwestward it also intersects the Temple Mountain collapse structure which has tentatively been interpreted by E. M. Shoemaker (oral communication, 1955) to be a possible diatreme structure and is known to have been extensively altered by hydrothermal solutions. Temple Mountain is also the locus of large and productive mines in the lower sandstones of the Chinle.

MINOR PRODUCING HYDROLOGIC UNITS

ENTRADA SANDSTONE

The Entrada sandstone is known to contain sizable uranium deposits in only five areas: the Skull Creek deposit, on the south flank of the

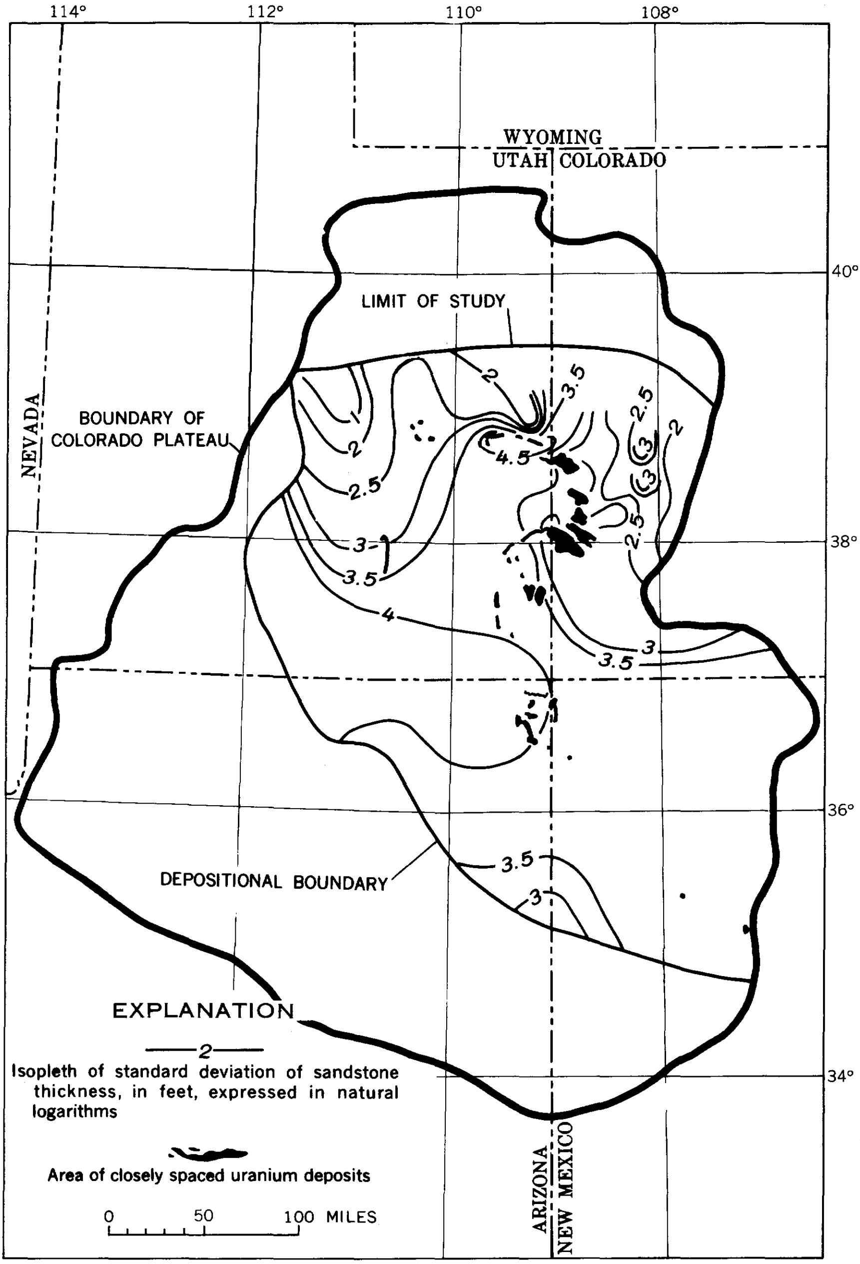


FIGURE 55.—Standard deviation of thickness of sandstones of the Morrison formation showing distribution of areas of closely spaced uranium deposits.

Blue Mountain uplift near the northern part of the Colorado-Utah State line; the Rifle and Garfield mines, along the southwest flank of the Grand Hogback bordering the White River uplift; and the Placerville, Rico, and Durango deposits located, respectively, near the flanks

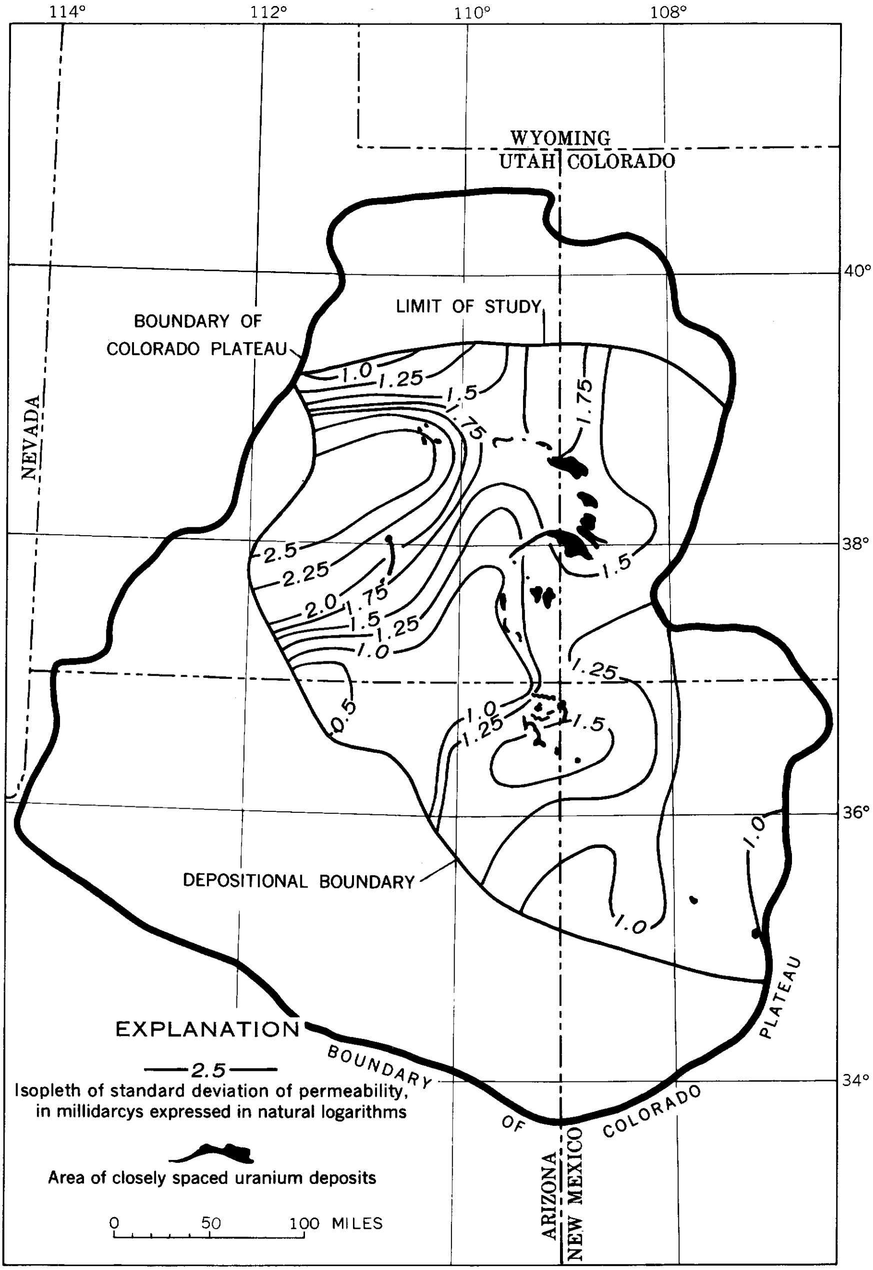


FIGURE 56.—Standard deviation of permeability of sandstones of the Morrison formation showing distribution of areas of closely spaced uranium deposits.

of the San Miguel intrusive center, and the Rico and La Plata laccolithic groups of the San Juan Mountains (fig. 49). None of these deposits exhibits primary control by sedimentary structures although the distribution of ore within the deposits is controlled to a limited extent by sedimentary features. Except for the Skull Creek deposit, the controlling factors are such as to give rise to widespread thin sheets of mineralized rock that generally incline to the bedding at a low angle and are traceable for thousands of feet (Fischer and others, 1947). The contacts between mineralized and unmineralized rock are generally diffuse but show sharp boundaries in many places, particularly where they are steeply inclined to the bedding.

The approximate size distribution of Entrada deposits is shown in figure 57, which is based on data furnished by R. P. Fischer and A. L.

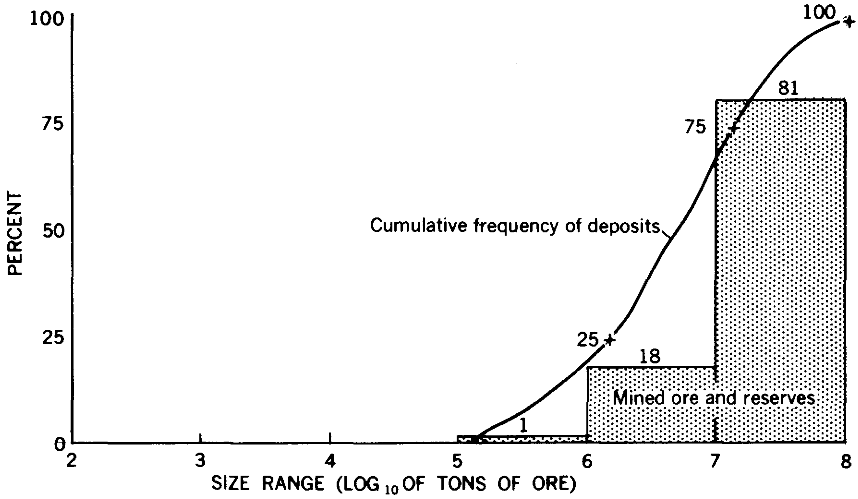


FIGURE 57.—Size distribution of uranium deposits in the Entrada sandstone. Data from R. P. Fischer and A. L. Bush (oral communication, 1954).

Bush (oral communication, 1954). It can readily be seen that there is a restricted size range and that the mean size of deposits in the Entrada sandstone is considerably larger than that of deposits in either the typical Chinle or Morrison.

At Skull Creek, where the Entrada has sedimentary structures closely similar in scale and kind to those in the productive sandstones of the Morrison, the habits of the ore are identical with those in the Morrison. A few miles to the southeast at Rifle the habit of the ore is chiefly that of an undulant layer, inclined at a low angle to the bedding, whose shape shows only very gradational and infrequent changes in keeping with the textural and structural homogeneity of the Entrada in this area.

In those areas of southwestern and west-central Colorado, where the only sizable ore deposits found are in the Entrada, the permeability and transmissive capacity of the unit are moderately low compared to the other parts of the sandstone facies. In all but one of the productive areas (Skull Creek, Colo.), the Entrada sandstone differs considerably from the major ore-producing host rocks in both hydrologic character and distribution of ore. In these areas the standard deviation of permeability in the Entrada is, on the average, much less than that of sandstones of either the lower Chinle or the Morrison. Although the Entrada thins eastward where it laps over and disappears on the remnants of Precambrian highlands (Baker and others, 1936, p. 22, 28), it has a relatively constant thickness which is in contrast to the many changes in thickness found locally in sandstones of the lower part of the Chinle and the Morrison. Taken together, the hydrologic characteristics of the Entrada are most distinct from those of the Morrison and lower sandstones of the Chinle in that the gradients of permeability and thickness, and consequently transmissivity, are much more uniform.

TODILTO LIMESTONE

The ore deposits in the Todilto limestone are almost wholly restricted to a small area on the northeast flank of the Zuni uplift where the Todilto has been deformed by much small-scale folding and is heavily jointed and faulted. The ore seems to be spatially related to the crests and troughs of small folds which resemble drag folds. The folds are jointed and sheared, and the trend of individual ore bodies is conformable to the present local structure (Ellsworth and Mirsky, 1952.). Ellsworth and Mirsky (1952) have tentatively summarized the evidence for fracture control of Todilto ore deposits as follows: rectilinear shape of the ore bodies and their tendency to follow conjugate jointing; the existence in some areas of two ore zones separated by barren beds; an apparent increase in fracture density in the Entrada outcrops beneath ore bodies in the Todilto; and localization of most ore bodies, and all the large ones, on structural noses and anticlines. The fracturing and faulting are believed to have taken place simultaneously with uplift of the Zuni Mountains which is dated as post-Dakota and pre-Miocene (T. A. Konigsmark, oral communication, 1954).

Recent detailed mapping by L. S. Hilpert (oral communication, 1955) has reaffirmed the hypothesis of localization of ore by small folds but casts some doubt as to the validity of joint control. The ore in detail follows the folds but does not, except as a secondary coating, increase in tenor in the immediate vicinity of the joints.

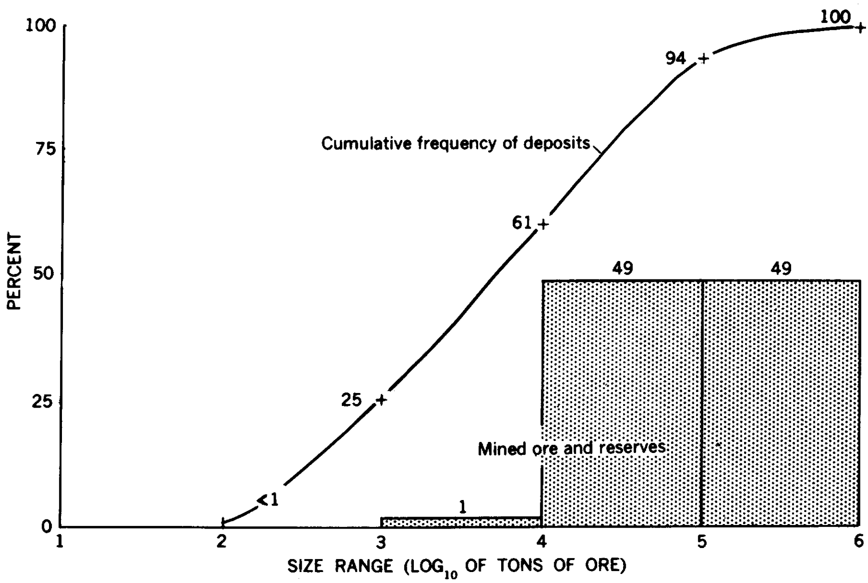


FIGURE 58.—Size distribution of uranium deposits in the Todilto limestone of the Grants district, New Mexico. Data obtained from production and reserve calculations of U.S. Atomic Energy Commission.

The approximate size distribution of ore deposits in the Todilto limestone was obtained from the production figures and reserve estimates compiled by the U.S. Atomic Energy Commission, Grand Junction, Colo. Figure 58 summarizes these data and shows that the deposits in the Todilto limestone have a somewhat more restricted size than those in sandstone of either the lower part of the Chinle or Morrison, but a less restricted range than those in the Entrada.

The structural environment of the Todilto ore deposits and the extremely low intrinsic horizontal permeability and horizontal transmissive capacity of this limestone make it probable, if this ore is of the same age as the immediately overlying ores in the Morrison, that vertical fluid movement has played a primary part in the distribution of ore in this unit.

DAKOTA SANDSTONE AND BURRO CANYON AND MESAVERDE FORMATIONS

Uranium deposits in the Cretaceous fluvial sandstones and conglomerates occur in many places on the Colorado Plateau but are mainly in northwestern New Mexico. Most of the deposits are small and have produced little commercial ore (H. S. Johnson and R. T. Chew, oral communication, 1955). Most known deposits are close to major uplifts such as those found in the northern part of the Zuni uplift

(Mirsky, 1953), and in the Lucero uplift of northwestern New Mexico (east of map boundary, fig. 49), and along the south flank of the Blue Mountain uplift in northwestern Colorado. Most of the sedimentary rocks containing the ore in these formations are shaly sandstones and mudstones that are carbonaceous. The ore is almost invariably found at the base of lenticular sandstone lenses. However, some disseminated deposits do occur in southwestern Utah at the Bulloch claims in conglomeratic sandstones, where the ore is a coating on pebbles and fractures (Beroni and others, 1953).

In none of these sandstones does the distribution of ore deposits seem to be related to any parameter of hydrologic characteristic, except proximity to areas of high vertical transmissivity.

SUMMARY AND CONCLUSIONS

On the basis of transmissive character, the exposed rocks of the Colorado Plateau may be grouped into three distinct types. One type, composed of relatively impermeable shales and mudstones, is virtually nontransmissive. Because of their abundance and position in the stratigraphic sequence, these rocks have played an important if inhibitory part in the history of circulating pore solutions. A second type is composed of marine and eolian siltstones and sandstones of relatively high mean permeability and great thickness, and this type has most of the transmissive capacity of the whole stratigraphic section. The third type is composed of fluvial sandstones and conglomeratic sandstones and makes up but a small fraction of the total thickness of transmissive rock. Rocks of the third type have steep gradients in permeability and thickness, a moderate to low transmissive capacity, and contain almost all the known uranium deposits. A comparison of the general transmissive character of these types is shown in table 6.

A comparison of relative transmissivity and uranium production between hydrologic units (table 7) shows that sandstones and conglomerates of fluvial origin which are overlain by thick relatively nontransmissive rocks have yielded more than 92 percent of recent uranium production and contain the large majority of the known ore deposits. The significant exceptions are a number of medium-sized deposits in the Todilto limestone and a few large deposits in the Entrada sandstone; together these account for only about 7 percent of the recent production of the Colorado Plateau.

A comparison of the distribution of uranium deposits with the variation in transmissive characteristics in host rocks shows that the range in size of deposits tends to vary directly with the range in magnitude of the coefficient of horizontal transmissivity. This relation seems valid for comparisons between the distribution of ore

TABLE 6.—*Comparison of transmissive character between types of transmissive sandstones exposed on the Colorado Plateau*

Sandstones of eolian or marine origin	Sandstones of fluvial origin
1. Moderate to high mean permeability.	1. Low to moderate mean permeability.
2. Small range in local permeability, vertically or horizontally.	2. Large range in local permeability, vertically and horizontally.
3. Slight, uniform gradients in regional permeability.	3. Moderate, uniform gradients in regional permeability.
4. Generally thick, chiefly one stratum.	4. Each stratum generally thin; units with several strata may attain moderate to great total thickness.
5. Generally slight, uniform gradients in local and regional thickness.	5. Large erratic gradients in local thickness; generally moderate to large, uniform gradients in regional thickness.
6. External geometry simple, commonly blanket shaped or wedge shaped.	6. External geometry complex, consists of one or more vertically and horizontally contiguous lenticular strata. Individual layers are charterized by numerous small areas of local nondeposition.
7. Internal geometry relatively simple, generally consists of large-scale, unsystematic, tangential crossbeds with few, through-going erosional planes and torrential-type crossbeds.	7. Internal geometry relatively complex, usually consists of one or more lenticular imbricated strata composed of festoon and planar-type crossbeds frequently truncating one another and separated by mudstone seams. Mudstone pellets and chert granules and pebbles frequently coat lower surface of festoon.
8. High local and regional transmissive capacity with slight, uniform local and regional gradients.	8. Low to moderate regional transmissive capacity with large nonuniform local gradients, but with slight uniform regional gradient.

deposits and coefficients of transmissivity within a single host as well as for similar comparisons between the several host rocks. A less constant relation is the apparent decrease in relative frequency of deposits with increase in magnitude and decrease in range of the mean of horizontal transmissivity. There is also a measurable although diffuse correlation of areas of closely spaced ore deposits to zones considered to be the loci of high vertical transmissivity.

In order to classify the ground that is considered the most favorable for uranium deposits in the major producing units, two classifying maps were prepared; these combine the horizontal and vertical transmissivity characteristics typically associated with the most productive mining districts of each unit.

Figures 59 and 60 show the distribution of ground in the lower sandstone units of the Chinle and in sandstones of the Morrison that are considered most favorable for ore deposits. The classification in each hydrologic unit is based on the areal distribution of ground in

TABLE 7.—*Comparison of relative transmissivity and uranium production, and distribution between types of transmissive hydrologic units*

Hydrologic unit [1]	Transmissivity relative to the mean (X)[2]	Distribution of uranium	Percent of uranium production [3]
Sandstones of the Mesaverde.	4.0*X* (0.8*X*)	Moderate number of small widely scattered deposits.	0.1
Mancos shale	None		0
Dakota and Burro Canyon.	0.5*X* (0.25*X*)	Moderate number of small, widely scattered deposits.	.1
Mudstones of the Morrison.	None		0
Sandstones of the Morrison.	0.7*X* (0.2*X*)	Large number of deposits; wide range in size and distribution.	52.0
Cow Springs, Bluff, Junction Creek, and Winsor.	1.0*X*		0
Summerville and Curtis	0.1*X*	Few small widely scattered occurrences.	0
Todilto and Pony Express.	<0.1*X*	Moderate number of medium to large deposits in one district; possibly fracture controlled.	7.7
Entrada	0.4*X*	Few small widely scattered deposits, but three very large deposits in three separate districts.	.1
Carmel	<0.1*X*		0
Navajo	7.0*X*		0
Kayenta	0.1*X*	Few widely scattered small deposits.	0
Wingate	0.5*X*	Few widely scattered small deposits; possibly fracture controlled.	.1
Mudstones of the Chinle.	None		0
Sandstones of the Chinle.	<0.1*X*	Many widely scattered small deposits; few widely scattered very large deposits.	40.0
Moenkopi	<0.1*X*	Few widely scattered small deposits.	.1
Kaibab	<0.1*X*	Few deposits in one district; possible fracture control.	0
Cutler (undivided)	0.1*X*	Moderate number of deposits, mostly small and in one district.	.1
Permian sandstones	1.0*X*		0
Hermit shale	None		0
Supai	None		0

[1] Sequence is chronological except where equivalents are treated as individual units.

[2] *X* equals the mean transmissivity of all hydrologic units on the Colorado Plateau measured in this study. Parentheses indicate relative transmissivity on a unit-stratum basis.

[3] Data adapted from Wood (1956); based on uranium oxide produced from July 1, 1953, to Jan. 1, 1955.

the unit which is similar to ground known to contain major deposits. Those areas of high vertical transmissivity that coincide with areas of moderate but highly variable horizontal transmissive capacity,

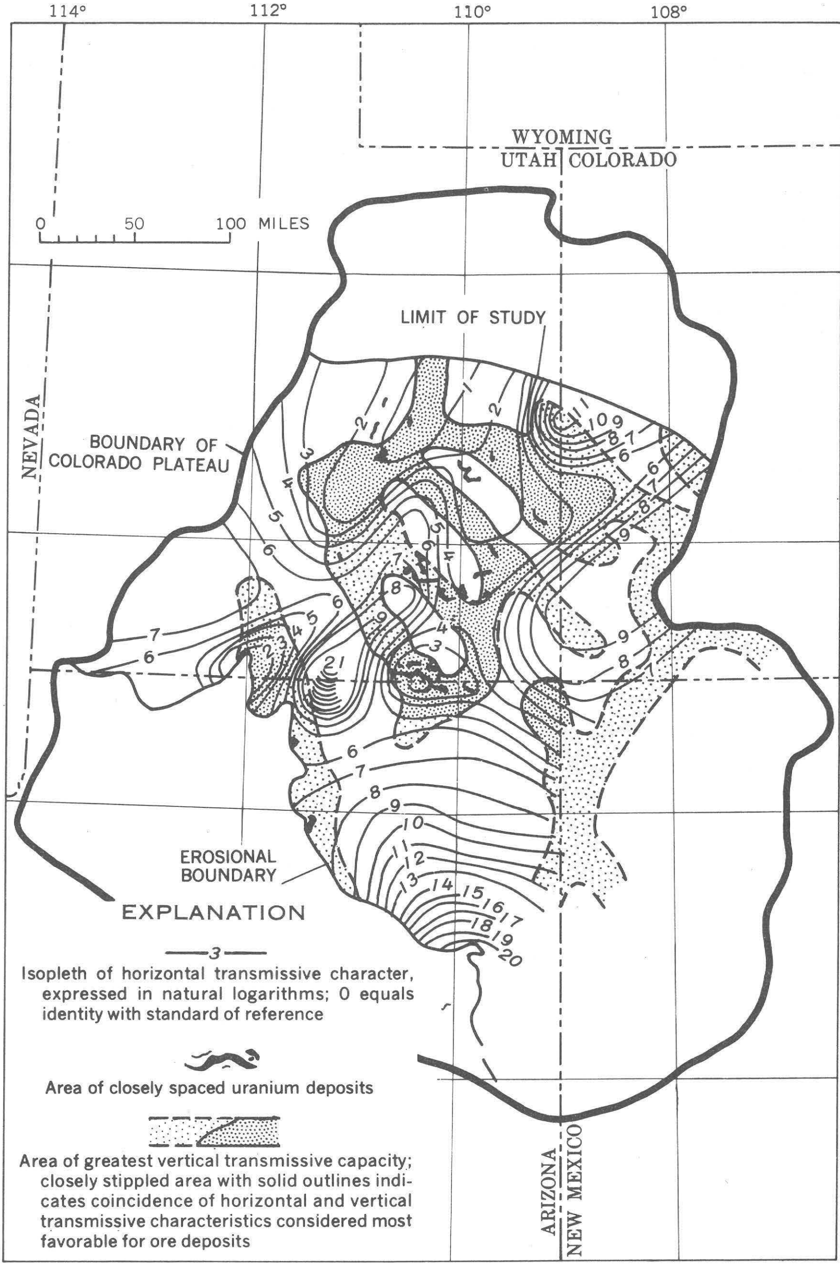


FIGURE 59.—Lower sandstones of the Chinle formation classified as to similarity of horizontal and vertical transmissive character to average transmissive character of its most productive mining areas.

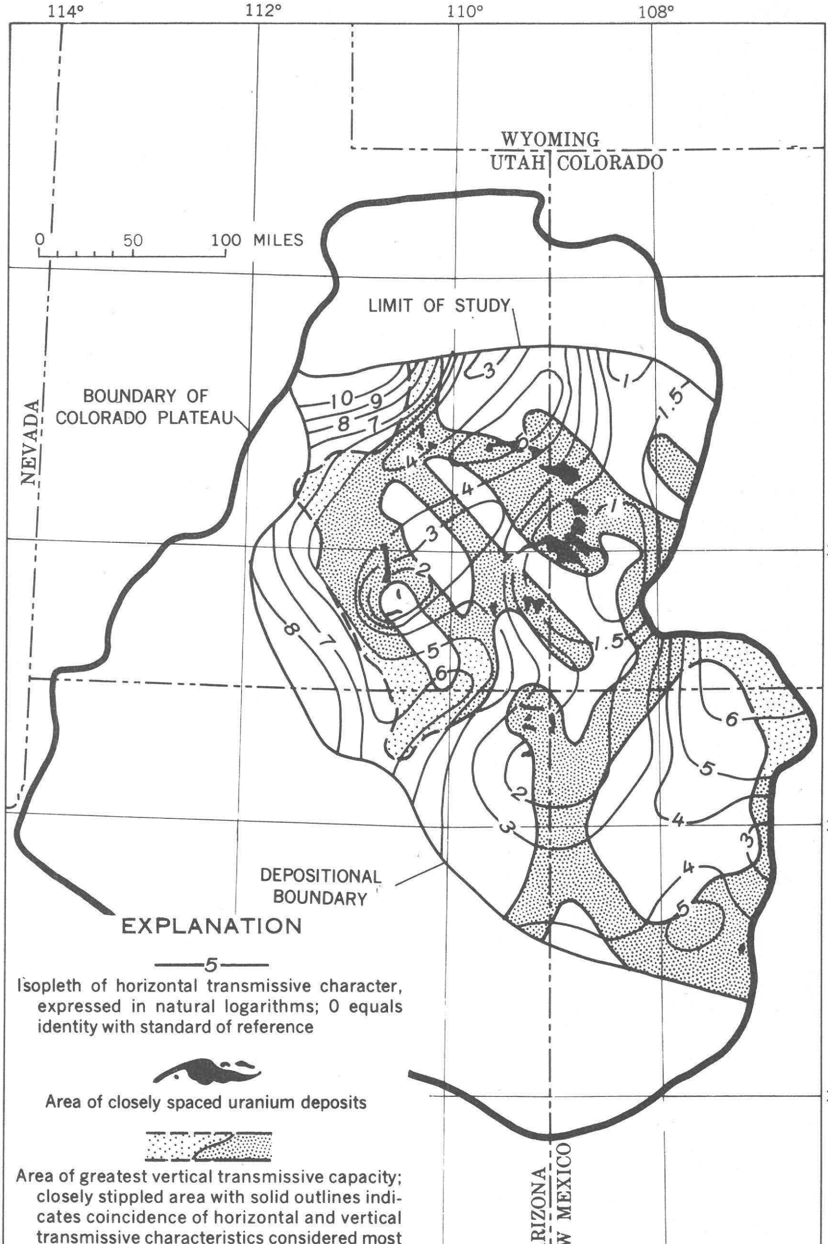


FIGURE 60.—Sandstones of the Morrison formation classified as to similarity of horizontal and vertical transmissive character to average transmissive character of its most productive mining areas.

631709 O—62——8

as delineated on the map, are considered the most likely to contain appreciable numbers of ore deposits of more than 1,000 tons.

The data summarized above suggest the following geologic conclusions: (1) the major host rocks of uranium deposits have had a moderate to low regional transmissive capacity throughout their history; (2) the selectivity both of the movement of the uranium-bearing solutions and of the places of uranium deposition was controlled to a varying degree by the horizontal and vertical transmissive character of the host rock; and (3) spatial relations between ore deposits within the stratigraphic section and relations to zones of high vertical transmissive capacity with a considerable range in horizontal transmissive character suggest a dominant control by aquicludes and regional structure which probably is of early Tertiary age.

REFERENCES CITED

American Society for Testing Materials, 1951, Control chart method of analysis and presentation of data: Spec. Tech. Pub. 15–C, pt. 3, Philadelphia, Pa.

Baker, A. A., 1946, Geology of the Green River Desert-Cataract Canyon region, Emery, Wayne, and Garfield Counties, Utah: U.S. Geol. Survey Bull. 951, 122 p.

Baker, A. A., Dane, C. H., and Reeside, J. B. Jr., 1936, Correlation of Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U.S. Geol. Survey Prof. Paper 183, 66 p.

Baker, A. A., and Reeside, J. B., Jr., 1929, Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., v. 13, no. 11, p. 1413–1448.

Bass, N. W., 1944, Correlation of basal Permian and older rocks in southwestern Colorado, northwestern New Mexico, northeastern Arizona, and southeastern Utah: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 7.

Beroni, E. P., McKeown, F. A., Stugard, F., Jr., and Gott, G. B., 1953, Uranium deposits of the Bulloch group of claims, Kane County, Utah: U.S. Geol. Survey Circ. 239.

Brown, S. C., and Halpenny, L. C., 1948, Water-supply investigation at Tuba City, Navajo Indian Reservation [Colorado–New Mexico]: U.S. Geol. Survey open file rept.

Cater, F. W., Jr., 1954, Geology of the Bull Canyon quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ–33.

Cochran, W. G., 1947, Some consequences when the assumptions for the analysis of variance are not satisfied: Biometrics, v. 3, no. 1, p. 22–38.

Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L., Mullens, T. E., and Weir, G. W., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region—A preliminary report: U.S. Geol. Survey Bull. 1009–E, p. 125–168.

Dane, C. H., 1935, Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U.S. Geol. Survey Bull. 863, 184 p.

Ellsworth, P. C., and Mirsky, A., 1952, Preliminary report on the relation of structure to uranium mineralization in the Todilto limestone, Grants district, New Mexico: U.S. Atomic Energy Comm. RME–4020, Tech. Inf. Service, Oak Ridge, Tenn.

Finch, W. I., 1955, Preliminary geologic map showing the distribution of uranium deposits and principal ore-bearing formations of the Colorado Plateau region: U.S. Geol. Survey Min. Inv. Field Studies Map MF-16.

Fischer, R. P., 1936, Peculiar hydrothermal copper-bearing veins of the northeastern Colorado Plateau: Econ. Geology, v. 31, no. 6, p. 571–599.

Fischer, R. P., Haff, J. C., and Rominger, J. F., 1947, Vanadium deposits near Placerville, San Miguel County, Colorado: Colorado Sci. Soc. Proc., v. 15, no. 3, p. 115–146.

Fisher, D. J., 1936, The Book Cliffs coal field in Emery and Grand Counties, Utah: U.S. Geol. Survey Bull. 852, 104 p.

Gregory, H. E., 1917, Geology of the Navajo country—a reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geol. Survey Prof. Paper 93, 161 p.

——— 1938, The San Juan country, a geographic and geologic reconnaissance of southeastern Utah: U.S. Geol. Survey Prof. Paper 188, 123 p.

——— 1951, The geology and geography of the Paunsaugunt region, Utah: U.S. Geol. Survey Prof. Paper 226, 116 p.

Gregory, H. E., and Moore, R. C., 1931, The Kaiparowits region, a geographic and geologic reconnaissance of parts of Utah and Arizona: U.S. Geol. Survey Prof. Paper 164, 161 p.

Harshbarger, J. W., Repenning, C. A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country: U.S. Geol. Survey Prof. Paper 291, 74 p.

Hunt, C. B., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geol. Survey Prof. Paper 228, 234 p.

——— 1956, Cenozoic geology of the Colorado Plateau: U.S. Geol. Survey Prof. Paper 279, 99 p.

Johnson, H. S., Jr., 1957, Uranium resources of the San Rafael district, Emery County, Utah—a regional synthesis: U.S. Geol. Survey Bull. 1046–D, p. 37–54.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to origin and distribution of uranium: New Mexico Univ. Pub. Geology, no. 5.

Krumbein, W. C., 1936, The application of logarithmic moments to size-frequency distributions of sediments: Jour. Sed. Petrology, v. 6, p. 35–47.

——— 1955, Composite end members in facies mapping: Jour. Sed. Petrology, v. 25, no. 2, p. 115–122.

Law, Jan, 1944. A statistical approach to the interstitial heterogeneity of sand reservoirs: Am. Inst. Mining Metall. Engineers Trans., v. 155, p. 202–221.

Luedke, R. G., and Shoemaker, E. M., 1952, Tectonic map of the Colorado Plateau: U.S. Geol. Survey open-file map.

McKay, E. J., 1955, Criteria for outlining areas favorable for uranium deposits in parts of Colorado and Utah: U.S. Geol. Survey Bull. 1009–J, p. 265–282.

McKee, E. D., 1934, An investigation of the light-colored cross-bedded sandstones of Canyon de Chelly, Arizona: Am. Jour. Sci., 5th ser., v. 8, no. 165, p. 219–233.

——— 1952, Uppermost Paleozoic stratigraphy of northwestern Arizona and southwestern Utah, *in* Utah Geol. Soc. Guidebook to the Geology of Utah no. 7, Cedar City, Utah, to Las Vegas, Nev., p. 52–55.

McKee, E. D., and Weir, G. W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, no. 4, p. 381–389.

McKelvey, V. E., Everhart, D. L., and Garrels, R. M., 1956, Summary of hypotheses of genesis of uranium deposits, *in* Page, L. R., and others, Contributions to the geology of uranium and thorium by the United States Geological

Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955: U.S. Geol. Survey Prof. Paper 300, p. 41–53.

Mirsky, A., 1953, Preliminary report on uranium mineralization in the Dakota sandstone, Zuni uplift, New Mexico: U.S. Atomic Energy Comm. RME–47, Tech. Inf. Service, Oak Ridge, Tenn.

Muskat, Morris, 1937, The flow of homogeneous fluids through porous media: New York, McGraw-Hill Book Co. Reprinted 1946 by J. W. Edwards, Inc., Ann Arbor, Mich.

Ohle, E. L., Jr., 1951, The influence of permeability on ore distribution in limestone and dolomite: Econ. Geology, v. 46, no. 7, p. 667–706; no 8, p. 871–908.

Pelto, C. R., 1954, Mapping of multicomponent systems: Jour. Geology, v. 62, p. 501–511.

Phoenix, D. A., 1956, Relation of carnotite deposits to permeable rocks in the Morrison formation, Mesa County, Colorado, *in* Page, L. R., and others, Contributions to the geology of uranium and thorium by the U.S. Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955; U.S. Geol. Survey Prof. Paper 300, p. 213–219.

Pike, W. S., Jr., 1947, Intertonguing marine and nonmarine Upper Cretaceous deposits of New Mexico, Arizona, and southwestern Colorado: Geol. Soc. America Mem. 24.

Rapaport, Irving, Hadfield, J. P., and Olson, R. H., 1952, Jurassic rocks of the Zuni Uplift, New Mexico: U.S. Atomic Energy Comm. RMO–642, Tech. Inf. Service, Oak Ridge, Tenn.

Read, C. B., 1950, Stratigraphy of the outcropping Permian rocks around the San Juan Basin *in* Guidebook of the San Juan Basin, New Mexico and Colorado: New Mexico Geol. Soc. 2d Field Conf., Guidebook, p. 62–66.

Reeside, J. B., Jr., 1924, Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin, Colorado and New Mexico: U.S. Geol. Survey Prof. Paper 134, 117 p.

Richardson, G. B., 1909, Reconnaissance of the Book Cliffs coal field between Grand River, Colorado, and Sunnyside, Utah: U.S. Geol. Survey Bull. 371, 54 p.

Sears, J. D., Hunt, C. B., and Hendricks, T. A., 1941, Transgressive and regressive Cretaceous deposits in southern San Juan Basin, New Mexico: U.S. Geol. Survey Prof. Paper 193–F, p. 110–121.

Shoemaker, E. M., 1954, Structural features of southeastern Utah and parts of Colorado, New Mexico, and Arizona, *in* Uranium deposits and general geology of southeastern Utah: Utah Geol. Soc. Guidebook to the Geology of Utah no. 9.

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

Stewart, J. H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 441–465.

Stewart, J. H., Williams, G. A., Albee, H. A., and Raup, O. B., 1959, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, *with a section on* Sedimentary petrology by R. A. Cadigan: U.S. Geol. Survey Bull. 1046–Q, p. 487–576.

Stokes, W. L., 1944, Morrison formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., v. 55, no. 8, p. 951–992.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., 16th Ann. Mtg., 1935, pt. 2, p. 519–524.

Wengerd, S. A., 1955, Geology of the Mexican Hat oil field, San Juan County, Utah *in* Geology of parts of Paradox, Black Mesa and San Juan Basins: Four Corners Geol. Soc. Guidebook, p. 150–163.

Wood, H. B., 1956, Age, environment and production of uranium host rocks on the Colorado Plateau, *in* Geology of uranium and thorium: United Nations Internat. Conf. Peaceful Uses Atomic Energy, Aug. 8–20, 1955, Proc. v. 6, p. 307–316.

STATISTICAL ANALYSIS OF METHODS AND DATA

PERMEABILITY MEASUREMENTS USING NITROGEN AND DISTILLED WATER

The object of the following analysis was to determine whether comparable results could be obtained from two methods of measuring the permeability of representative rock samples, one using distilled water as the transmitted media, the other using gaseous nitrogen. The analysis of variance, which was used to compare the two methods, yields an estimate of the population variance for each of the methods, and the ratio of these variances, the F ratio. This ratio is then compared to a table of critical values of F, with the proper degrees of freedom, for the numerator and denominator and at some predetermined level of probability; the table provides values which will rarely be exceeded if the estimated variances used to obtain the ratio are both estimates of the same population variance. In this analysis, if the F ratio is less than the critical ratio that would be exceeded only 1 time in 20 (F.05), if no difference does in fact exist between the methods, the hypothesis that there are no significant differences between methods will be accepted. If the F ratio is greater than the F.05 critical value, it will be accepted that there is a significant difference between the two methods. If the F ratio exceeds the critical value that would

TABLE 8.—*Mathematical model of the analysis of variance of permeability measured with distilled water and nitrogen*

Source of variance	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	Ratio of mean squares (F)
Methods (M)	$n-1$	$\sum_1^n(\sum_1^m x)^2/m-CT$	$\frac{SSM}{n-1}$	$\frac{MSM}{MSE}$
Samples (S)	$m-1$	$\sum_1^m(\sum_1^n x)^2/n-CT$	$\frac{SSS}{m-1}$	$\frac{MSS}{MSE}$
Residual (E)	$(n-1)(m-1)$	$\sum_1^n\sum_1^m x^2-(CT+SSM+SSS)$	$\frac{SSE}{(n-1)(m-1)}$	--------
Total (T)	$N-1$	$\sum_1^{n\,m} x^2-CT$	------------	--------

Correction term $(CT)=N=nm(\sum_1^N x^2)/N$.

x=individual determination
n=number of methods
m=number of samples
$N=nm$

be exceeded only 1 time in 100 ($F.01$), a highly significant difference will be accepted.

The F ratios obtained for methods variance in each rock unit tested are constantly much smaller than the $F.05$ ratios obtained from statistical tables. This means that no significant differences between the two methods has been proved. However, as the F ratios obtained for sample variance in each rock tested are considerably larger than the $F.01$ ratios from the tables, there is a highly significant difference between samples; one that could occur by chance for virtually identical samples less than 1 time in 100.

TABLE 9.—*Variance of permeability of representative rock samples as measured with nitrogen and water*

Sample	Water	Nitrogen	Total
Dakota sandstone and Burro Canyon formation			
334	2. 5539	2. 4941	5. 0480
1283	2. 7474	2. 6881	5. 4355
1286	2. 8395	2. 7755	5. 6150
1289	2. 8069	2. 7378	5. 5447
335	2. 0569	2. 9463	5. 0032
1284	. 9335	. 6146	1. 5481
1287	2. 9274	2. 9022	5. 8296
1290	2. 9238	2. 7697	5. 6935
336	2. 9309	3. 0406	5. 9715
1288	3. 0414	2. 9490	5. 9904
1292	2. 2095	2. 3285	4. 5380
1291	0	1. 3524	1. 3524
Total	27. 9711	29. 5988	57. 5699
Grand total			57. 5699
Correction term			138. 09555777
Sandstones of the Salt Wash member			
319	1. 6532	1. 0909	2. 7441
322	0	0	0
331	2. 9435	3. 0291	5. 9726
328	0	0	0
325	2. 6964	2. 5897	5. 2861
320	1. 0899	. 6071	1. 6970
323	0	0	0
332	3. 2989	3. 1949	6. 4938
329	0	0	0
326	0	0	0
321	1. 1367	1. 1953	2. 3320
324	0	0	0
333	3. 0170	2. 9488	5. 9658
330	0	0	0
327	1. 4487	1. 6169	3. 0656
Total	17. 2843	16. 2727	33. 5570
Grand total			33. 5570
Correction term			37. 52455680

TABLE 9.—*Variance of permeability of representative rock samples as measured with nitrogen and water*—Continued

Sample	Water	Nitrogen	Totals
Entrada sandstone			
307	1. 2355	1. 3150	2. 5505
310	. 2625	. 2408	. 5033
313	1. 8573	1. 8440	3. 7013
316	1. 5729	1. 9544	3. 5273
308	0	. 6483	. 6483
311	0	0	0
314	1. 3541	. 9371	2. 2912
317	1. 5877	1. 7532	3. 3409
309	1. 4249	1. 6340	3. 0589
312	. 2945	0	. 2945
315	1, 5237	1, 8374	3. 3611
318	1. 7582	1. 8844	3. 6426
Total	12. 8713	14. 0486	26. 9199
Grand total			26. 9199
Correction term			30. 19504233
Kayenta formation			
299	0. 3927	0	0. 3927
300	1. 7171	1. 7466	3. 4637
301	1. 2355	1. 2406	2. 4761
304	0	. 3325	. 3325
297	1. 0128	1. 2046	2. 2174
298	. 5051	. 6820	1. 1871
302	2. 0170	1. 9367	3. 9537
303	2. 5441	2. 6157	5. 1598
305	0	0	0
306	1. 6911	1. 7429	3. 4340
Total	11. 1154	11. 5016	22. 6170
Grand total			22. 6170
Correction term			25. 57643445
Wingate sandstone			
292	2. 1614	2. 1532	4. 3146
285	1. 0792	1, 3268	2. 4060
288	1. 3243	1. 3500	2, 6743
291	1. 4065	1. 2976	2. 7041
286	0	. 0248	. 0248
287	. 0294	. 6405	. 6699
289	1. 1673	1. 2917	2. 4590
290	0	0	0
293	1. 8457	2. 0170	3. 8627
294	1. 9253	1. 8600	3. 7853
295	. 9872	. 6845	1. 6717
296	. 9609	1. 0676	2. 0285
Total	12. 8872	13. 7137	26. 6009
Grand total			26. 6009
Correction term			29. 48366170

TABLE 10.—*Analysis of variance of permeability of samples measured with nitrogen and water*

Source of variance	Degrees of freedom (*DF*)	Sum of squares (*SS*)	Mean squares (*MS*)	*F*	*F* .05	*F* .01
Dakota sandstone and Burro Canyon formation						
Methods	1	0. 1103920	0. 1103920	0. 94	4. 84	9. 65
Samples	11	14. 4513542	1. 31375947	11. 22	2. 82	4. 46
Residual	11	1. 2880047	. 11709134			
Total	23	15. 8497509				
Sandstones of the Salt Wash member						
Methods	1	0. 03411115	0. 03411115	1. 75	4. 60	8. 86
Samples	14	45. 77477498	3. 26962678	167. 38	2. 48	3. 70
Residual	14	. 27347723	. 01953409			
Total	29	46. 08236336				
Entrada sandstone						
Methods	1	0. 05775147	0. 05775147	1. 42	4. 84	9. 65
Samples	11	11. 67518702	1. 061380638	26. 13	2. 82	4. 46
Residual	11	. 44674533	. 0406132118			
Total	23	12. 17968382				
Kayenta formation						
Methods	1	0. 00828613	0. 00828613	0. 40	5. 12	10. 56
Samples	8	10. 96512117	1. 37064015	66. 17	3. 18	5. 35
Residual	8	. 16571914	. 02071489			
Total	17	11. 13912644				
Wingate sandstone						
Methods	1	0. 02846254	0. 02846259	1. 15	4. 84	9. 65
Samples	11	11. 27786282	1. 02526025	41. 53	2. 82	4. 46
Residual	11	. 27156054	. 024687321			
Total	23	11. 57788590				

SPATIAL VARIATIONS IN PERMEABILITY OF REPRESENTATIVE SANDSTONES OF THE COLORADO PLATEAU

The purpose of this analysis is to determine whether samples collected several inches, several feet, and several tens of feet apart show systematic variations in permeability, and whether differently oriented subsamples, within a single sample, have significantly different permeability. As described on pages 110–111, the method of analysis of variance was used to determine the significance on the differences that were found. The same levels of significance that governed the acceptance or rejection of differences in the factors tested previously (pp. 110, 111) were used in this and all subsequent analyses.

A comparison of F ratios with the critical values of $F.05$ and $F.01$, as summarized below, shows that for all units tested, highly significant differences do occur between subsamples, oriented subsamples, and samples with a probability of less than 1 in 100 and that such differences could occur by chance if the populations tested were actually identical. It is also shown that for all formations tested there is a highly significant horizontal-vertical row interaction. The physical meaning of this is clear. Examination of the raw data given in tables 14 to 18 will show that there is a virtually random variation of permeability between horizontal row samples with respect to their position in vertical rows. In other words, the variations that occur are nonsystematic with respect to their vertical-horizontal position. The F ratios for vertical rows show that, with the given number of samples and measuring methods, no significant differences occur between the means of vertical rows of samples which are spaced about 50 feet apart. Similarly, no significant differences were proven between the mean permeability of horizontal rows in the Dakota sandstone, the Burro Canyon formation, the Kayenta formation, and the Wingate sandstone. However, the means in permeability for horizontal rows showed highly significant differences in the Salt Wash member of the Morrison formation and in the Entrada sandstone.

The meaning of this is that under the conditions of the test the Salt Wash member and Entrada sandstone, although having a fairly uniform local mean permeability, have a distinct layered effect. Although sandstones of the Dakota, Burro Canyon, Kayenta, and Wingate show no significant differences in mean permeability and do not have a layered effect, they do not all have similar permeability characteristics. The Wingate sandstone is very uniform whereas the Dakota, Burro Canyon, and Kayenta have highly variable, nonsystematic permeability variations.

TABLE 11.—*Mathematical model of the analysis of variance of permeability between horizontal and vertical rows of samples, oriented subsamples, subsamples, and replicate measurements on subsamples*

Source of variance	Degrees of freedom (*DF*)	Sum of squares (*SS*)	Mean squares (*MS*)	Ratio of mean squares (*F*)
Vertical rows (*V*)	$n-1$	$\sum_{1}^{n}\sum^{krst}(\sum x)^2/krst-CT$	$\frac{SSV}{(n-1)}$	$\frac{MSV}{MSVH}$
Horizontal rows (*H*)	$m-1$	$\sum^{m}\sum^{krst}(\sum x)^2/krst-CT$	$\frac{SSH}{(m-1)}$	$\frac{MSH}{MSVH}$
Horizontal × vertical rows (*VH*).	$(n-1)(m-1)$	$\sum^{hm}\sum^{krst}(\sum x)^2/krst-CT-SSV-SSH$	$\frac{SSVH}{(n-1)(m-1)}$	$\frac{MSVH}{\frac{SST-SSSA}{(N-1)(k-1)}}$
Samples (*SA*)	$k-1$	$\sum^{k}\sum^{rst}(\sum x)^2/rst-CT$	$\frac{SSSA}{(k-1)}$	$\frac{MSSA}{MSSB}$
Oriented subsamples (*SB*)	$k(r-1)$	$\sum^{r}\sum^{st}(\sum x)^2/st-CT-SSSA$	$\frac{SSSB}{k(r-1)}$	$\frac{MSSB}{MSSC}$
Subsamples (*SC*)	$kr(s-1)$	$\sum^{s}\sum^{t}(\sum x)^2/t-CT-SSA-SSB$	$\frac{SSSC}{kr(s-1)}$	$\frac{MSSC}{MSE}$
Error (replications) (*E*)	$krs(t-1)$	$\sum^{N}x^2-CT-SSA-SSB-SSA$	$\frac{SSE}{krs(t-1)}$	----------
Total (*T*)	$N-1$	$\sum^{N}x^2-CT$		

Correction term $(CT)=(\sum^{N}x)^2/N$.
x=value of individual measurement.
n=number of vertical rows.
m=number of horizontal rows.
k=number of samples.
r=number of oriented samples.
s=number of subsamples.
t=number of replicate measurements.
$N=krst$

TABLE 12.—*Summary of analyses of variance within samples, oriented subsamples, subsamples, and replicate measurements*

Source of variance	Degrees of freedom (*DF*)	Sum of Squares	Mean Squares	*F*	*F*.05	*F*.01	*EMS*
Dakota sandstone and Burro Canyon formation							
Between samples	11	96.909735	8.88098	68.57	2.22	3.09	0.6971
Between oriented subsamples	24	3.108293	.129512	2.44	1.82	2.35	.1128
Between subsamples	36	1.910254	.053063	5.28	1.50	1.76	.1197
Between measurements	144	1.446657	.010046				.1002
Total	215	103.374939					
Sandstones of the Salt Wash member of Morrison formation							
Between samples	14	432.7788774	30.91277695	138.94	2.04	2.74	1.3057
Between oriented subsamples	30	6.6749633	.22249878	8.74	1.71	2.14	.1812
Between subsamples	45	1.1455961	.02545769	36.65	1.45	1.69	.0909
Between measurements	180	.1250264	.00069459				.0263
Total	269	440.7244632					
Entrada sandstone							
Between samples	11	131.311657	11.93742336	27.56	2.22	3.09	0.7989
Between oriented subsamples	24	10.396720	.43319667	4.41	1.82	2.35	.2363
Between subsamples	36	3.533787	.09816075	636.83	1.50	1.76	.1807
Between measurements	144	.022197	.00015414				.0124
Total	215	145.264361					
Kayenta formation							
Between samples	8	98.300876	12.28760950	17.70	2.51	3.71	0.8025
Between oriented subsamples	18	12.497099	.69428328	5.64	2.00	2.68	.7557
Between subsamples	27	3.324737	.12313841	2414.48	1.62	1.96	.3507
Between measurements	108	.005493	.0000509				.0071
Total	161	114.128205					
Wingate sandstone							
Between samples	11	105.406599	9.582418	6.90	2.22	3.09	0.6747
Between oriented subsamples	24	33.320419	1.388351	16.56	1.82	2.35	.4662
Between subsamples	36	3.017497	.083819	1731.81	1.50	1.76	.1671
Between measurements	144	.006971	.0000484				.0069
Total	215	141.751486					

TABLE 13.—*Summary of analyses of variance of permeability within vertical and horizontal rows of samples*

Source of Variance	Degrees of freedom (*DF*)	Sum of squares	Mean squares	*F*	*F*.05	*F*.01
Dakota sandstone and Burro Canyon formation						
Vertical rows	2	5. 721974	2. 860987	0. 23	3. 98	7. 20
Horizontal rows	3	17. 822971	5. 940990	. 49	3. 59	6. 22
Horizontal-vertical interaction	6	73. 364790	12. 227465	385. 82	2. 14	2. 90
Samples (total)	11	96. 909735				
Residual	204	6. 465204	. 031692			
Total	215	103. 374939				
Sandstones of the Salt Wash member of Morrison formation						
Vertical rows	2	18. 965594	9. 4827969	1. 34	4. 46	8. 65
Horizontal rows	4	357. 233952	89. 3084880	12. 63	3. 84	7. 01
Horizontal-vertical interaction	8	56. 579332	7. 0724165	226. 98	1. 98	2. 60
Samples (total)	14	432. 7788774				
Residual	255	7. 9455858	. 0311592			
Total	269	440. 724463				
Entrada sandstone						
Vertical rows	2	4. 364062	2. 182031	3. 09	3. 98	7. 20
Horizontal rows	3	122. 709232	40. 903077	57. 90	3. 59	6. 22
Horizontal-vertical interaction	6	4. 238362	. 706394	10. 33	2. 14	2. 90
Samples (total)	11	131. 311657				
Residual	204	13. 952704	. 068396			
Total	215	145. 264361				
Kayenta formation						
Vertical rows	2	14. 539243	7. 26962150	0. 57	4. 46	8. 65
Horizontal rows	2	32. 679817	16. 339904	1. 28	4. 46	8. 65
Horizontal-vertical interaction	4	51. 081816	12. 770454	123. 45	2. 43	3. 44
Samples (total)	8	98. 300876				
Residual	153	15. 827329	. 10344659			
Total	161	114. 128205				
Wingate sandstone						
Vertical rows	2	10. 443188	5. 221594	0. 67	3. 98	7. 20
Horizontal rows	3	48. 237687	16. 079229	2. 06	3. 59	6. 22
Horizontal-vertical interaction	6	46. 725724	7. 787621	43. 71	2. 14	2. 90
Samples (total)	11	105. 406599				
Residual	204	36. 344887	. 178161			
Total	215	141. 751486				

TABLE 14.—*Raw data of analysis of variance of Dakota sandstone and Burro Canyon formation, Colorado National Monument*

	Row 1				Row 2				Row 3			
Sample	334	1283	1286	1289	335	1284	1287	1290	336	1288	1292	1291
Parallel subsamples:												
A. Run 1	2.6484	3.1644	3.0531	2.9552	3.0453	0.5211	2.9552	3.0864	2.9926	3.0513	2.5478	1.7319
Run 2	2.6253	3.0531	2.9552	2.9020	3.0453	.5172	2.9886	3.0864	3.0828	2.9886	2.5658	1.7042
Run 3	2.6484	3.0531	2.9552	2.9552	3.0453	.5132	2.9552	3.0864	2.9926	3.1644	2.5658	1.7110
Total A	7.9221	9.2706	8.9635	8.8124	9.1359	1.5515	8.8990	9.2592	9.0680	9.2043	7.6794	5.1471
B. Run 1	2.6758	2.9886	3.0212	2.8791	2.9886	1.0719	3.0212	2.8791	2.9886	3.0864	2.3674	1.6117
Run 2	2.6758	2.9552	3.0212	2.8791	3.0212	1.0253	2.9886	2.7796	3.0864	3.1644	2.3838	1.6075
Run 3	2.6758	3.0212	3.0212	2.8306	3.0864	1.0170	2.9886	2.8274	2.9294	3.0864	2.3838	1.6031
Total B	8.0274	8.9650	9.0636	8.5888	9.0962	3.1142	8.9984	8.4861	9.0044	9.3372	7.1350	4.8223
Parallel subsample total	15.9495	18.2356	18.0271	17.4012	18.2321	4.6657	17.8974	17.7453	18.0724	18.5415	14.8144	9.9694
Parallel (right angle) subsamples:												
C. Run 1	2.6484	2.8543	3.9886	2.9020	3.0492	1.3483	3.1644	2.8543	3.4594	3.0864	2.5478	1.7316
Run 2	2.6484	2.8543	3.0531	2.9020	3.2041	1.3424	3.2148	2.9020	3.2577	3.0513	2.5378	1.7251
Run 3	2.6274	2.7513	2.9886	2.8791	3.1584	1.3541	3.0864	2.9294	3.3598	3.1644	2.5198	1.7435
Total C	7.9242	8.4599	10.0303	8.6831	9.4117	4.0448	9.4656	8.6857	10.0769	9.3021	7.6054	5.2002
D. Run 1	2.9562	2.8543	2.9020	2.9020	3.1271	1.0719	3.1271	2.9886	3.0828	3.1644	2.4564	1.6484
Run 2	2.9294	2.7513	2.0920	2.9552	3.2148	1.0170	3.1644	3.0212	3.0828	3.2601	2.4265	1.5966
Run 3	2.8543	2.7796	2.9552	2.9552	3.0864	1.0086	3.0864	3.9552	2.9886	3.1271	2.4456	1.6415
Total D	8.7399	8.3852	8.7592	8.8124	9.4283	3.0975	9.3779	9.9650	9.1542	9.5516	7.3285	4.8865
Parallel (right-angle) subsamples totals	16.6641	16.8451	18.7895	17.4955	18.8400	7.1423	18.8435	18.6507	19.2311	18.8537	14.9339	10.0867
Perpendicular subsamples:												
E. Run 1	2.7796	2.6758	2.8062	2.9020	3.0531	.6232	2.8306	2.8274	3.0569	2.8306	2.5276	1.6191
Run 2	2.7308	2.6444	2.7513	2.8543	3.0212	.6232	2.8543	2.8062	2.9628	2.8306	2.5105	1.6191
Run 3	2.7308	2.6758	2.7796	2.8543	2.9886	.6180	2.8543	2.8274	3.0086	2.8306	2.5276	1.6117
Total E	8.2412	7.9960	8.3371	8.6106	9.0629	1.8644	8.5392	8.4610	9.0283	8.4918	7.5657	4.8499

F. Run 1	2.7513	2.5658	2.8543	2.8306	3.1271	.3304	3.0212	2.9020	3.1271	3.0864	2.5575	1.6191
Run 2	2.7513	2.5855	2.8306	2.9020	3.1271	.3181	2.9886	2.9020	3.0212	3.0513	2.5575	1.6561
Run 3	2.7796	2.5658	2.8543	2.8791	3.1271	.3075	2.9886	2.9020	3.2148	3.0212	2.5575	1.6191
Total F	8.2822	7.7171	8.5392	8.6117	9.3813	.9560	8.9984	8.7060	9.3631	9.1589	7.6725	4.8943
Perpendicular subsample total	16.5234	15.7131	16.8763	17.2223	18.4442	2.8204	17.5376	17.1670	18.3914	17.6507	15 2382	9.7442
Sample total	49.1370	50.7938	53.6929	52.1190	55.5163	14.6284	54.2785	53.5630	55.6949	55.0459	44.9865	29.8003
Vertical row total	----------	----------	----------	205.7427	----------	----------	----------	177.9862	----------	----------	----------	185.5276

Horizontal row totals:

1. Samples 334, 335, 336	160.348
2. Samples 1283, 1284, 1288	120.4681
3. Samples 1286, 1287, 1292	152.9579
4. Samples 1289, 1290, 1291	135.4823
Grand total	569.2565

TABLE 15.—*Raw data of analysis of variance of sandstones of the Salt Wash member, Colorado National Monument*

	Row 1					Row 2					Row 3				
Sample	319	322	331	328	325	320	323	332	329	326	321	324	333	330	327
Parallel subsamples:															
A. Run 1	1.5315	0	3.3979	0	2.8062	1.1644	0	3.3304	0	0	1.5999	0	3.1732	0	2.0170
Run 2	1.5315	0	3.2095	0	2.8307	1.1523	0	3.3304	0	0	1.6031	0	3.1004	0	2.0294
Run 3	1.5366	0	3.3045	0	2.7789	1.1553	0	3.3304	0	0	1.5966	0	3.1004	0	2.0253
Total A	4.5996	0	9.9119	0	8.4158	3.4720	0	9.9912	0	0	4.7996	0	9.3740	0	6.0717
B. Run 1	1.5682	0	3.2601	0	2.7067	1.1703	0	3.1271	0	0	1.5888	0	3.0414	0	2.0253
Run 2	1.5647	0	3.2601	0	2.6893	1.1703	0	3.1271	0	0	1.5933	0	3.0792	0	2.0253
Run 3	1.5647	0	3.2095	0	2.6893	1.1644	0	3.1271	0	0	1.5888	0	3.0414	0	2.0294
Total B	4.6976	0	9.7297	0	8.0853	3.5050	0	9.3813	0	0	4.7709	0	9.1620	0	6.0800
Parallel subsample total	9.2972	0	19.6416	0	16.5011	6.9770	0	19.3725	0	0	9.5705	0	18.5360	0	12.1517
Parallel (right-angle) subsamples:															
C. Run 1	1.6767	0	3.5635	0	2.8543	0.6149	0	3.1732	0	0	1.5198	0	3.2718	0	1.3483
Run 2	1.6637	0	3.3820	0	2.9020	.6107	0	3.1732	0	0	1.5159	0	3.2718	0	1.3483
Run 3	1.6702	0	3.3160	0	2.9294	.6107	0	3.2175	0	0	1.5159	0	3.1959	0	1.3483
Total C	5.0106	0	10.2615	0	8.6857	1.8363	0	9.5639	0	0	4.5516	0	9.7395	0	4.0449
D. Run 1	1.5315	0	3.4142	0	2.7067	0.9122	0	3.1644	0	0	1.6767	0	3.2148	0	2.0294
Run 2	1.5403	0	3.3541	0	2.6893	.9122	0	3.2148	0	0	1.6911	0	3.2148	0	2.0212
Run 3	1.5315	0	3.3541	0	2.6893	.9122	0	3.0864	0	0	1.6767	0	3.1644	0	2.0128
Total D	4.6033	0	10.1224	0	8.0853	2.7366	0	9.4656	0	0	5.0445	0	9.5940	0	6.0634

Parallel (right-angle) subsample total	9.6139	0	20.3839	0	16.7710	4.5729	0	19.0295	0	0	9.5961	0	19.3335	0	10.1083
Perpendicular subsamples:															
E. Run 1	1.2253	0	2.2380	0	2.6454	0.6848	0	3.2900	0	0	1.2279	0	3.0374	0	1.8007
Run 2	1.2253	0	2.2279	0	2.6243	.6776	0	3.3909	0	0	1.2279	0	3.0374	0	1.7938
Run 3	1.2279	0	2.2279	0	2.6454	.6848	0	3.1903	0	0	1.2279	0	3.0374	0	1.7868
Total E	3.6785	0	6.6938	0	7.9151	2.0472	0	9.8712	0	0	3.6837	0	9.1122	0	5.3813
F. Run 1	1.1732	0	2.3598	0	2.8062	0.6911	0	3.2601	0	0	1.3424	0	3.0212	0	1.8007
Run 2	1.1790	0	2.3324	0	2.7796	.6964	0	3.1644	0	0	1.3424	0	2.9552	0	1.8069
Run 3	1.1790	0	2.3502	0	2.7796	.6964	0	3.0864	0	0	1.3424	0	3.0864	0	1.8007
Total F	3.5312	0	7.0424	0	8.3654	2.0839	0	9.5109	0	0	4.0272	0	9.0628	0	5.4083
Perpendicular subsample total	7.2097	0	13.7362	0	16.2805	4.1311	0	19.3821	0	0	7.7109	0	18.1750	0	10.7896
Sample total	26.1208	0	53.7617	0	49.5526	15.6810	0	57.7841	0	0	26.8775	0	56.0445	0	33.0496
Vertical row total	----------	------	----------	------	129.4351	----------	------	----------	------	------	73.4651	------	----------	------	115.9716

Horizontal row totals:

1. Samples 319, 320, 321	68.6793
2. Samples 322, 323, 324	0
3. Samples 331, 332, 333	167.5903
4. Samples 328, 329, 330	0
5. Samples 325, 326, 327	82.6022
Grand total	318.8718

TABLE 16.—*Raw data of analysis of variance of Entrada sandstone, Colorado National Monument*

	Row 1				Row 2				Row 3			
Sample	307	310	313	316	308	311	314	317	309	312	315	318
Parallel subsamples:												
A. Run 1	1.7110	0.1732	2.0253	2.1106	1.2380	0	2.2430	2.2430	2.0569	0	2.1106	2.4014
Run 2	1.6981	.1614	2.0374	2.1303	1.2480	0	2.2253	2.2253	2.0492	0	2.1206	2.4082
Run 3	1.7042	.1523	2.0334	2.1106	1.2601	0	2.2253	2.2253	2.0569	0	2.1004	2.4014
Total A	5.1133	.4869	6.0961	6.3515	3.7461	0	6.6936	6.6936	6.1630	0	6.3316	7.2110
B. Run 1	1.7251	.0645	1.9395	2.1004	1.3345	0	2.0792	2.0792	1.9206	0	2.1399	2.2175
Run 2	1.7316	.0645	1.9263	2.1206	1.3284	0	2.0792	2.0792	1.9138	0	2.1303	2.2253
Run 3	1.7177	.0645	1.9299	2.1206	1.3345	0	2.0645	2.0645	1.9206	0	2.1303	2.2253
Total B	5.1744	.1935	5.7957	6.3416	3.9974	0	6.2229	6.2229	5.7550	0	6.4005	6.6681
Parallel subsamples total	10.2877	.6804	11.8918	12.6931	7.7435	0	12.9165	12.9165	11.9180	0	12.7321	13.8791
Parallel (right-angle) subsamples:												
C. Run 1	1.7634	1.1614	2.3096	2.3324	.6551	.1959	1.8445	1.8445	1.8555	0	2.1644	2.2672
Run 2	1.7634	1.1553	2.4564	2.3243	.6542	.1847	1.8388	1.8388	1.8445	0	2.1492	2.2529
Run 3	1.7566	1.1614	2.4456	2.3324	.6628	.1959	1.8445	1.8445	1.8445	0	2.1492	2.2672
Total C	5.2834	3.4781	7.2116	6.9891	1.9721	.5765	5.5278	5.5278	5.5445	0	6.4628	6.7873
D. Run 1	1.8500	.1523	2.4564	1.9768	1.2672	0	1.2945	2.1004	2.0212	.1523	2.1206	2.0492
Run 2	1.8555	.1959	2.4378	1.9661	1.2989	0	1.3075	2.0645	2.0212	.1335	2.1106	2.0294
Run 3	1.8555	.1732	2.4472	1.9661	1.2989	0	1.2945	2.0645	2.0128	.1430	2.1399	2.0645
Total D	5.5610	.5214	7.3414	5.9090	3.8650	0	3.8965	6.2294	6.0552	.4288	6.3711	6.1431
Parallel (right-angle) subsamples total	10.8444	3.9995	14.5530	12.8981	5.8371	.5765	9.4243	11.7572	11.5997	.4288	12.8339	12.9304

Perpendicular subsamples:												
E. Run 1	1.2480	0	1.8116	1.6981	.9031	0	1.5966	1.5966	1.7110	0	1.9450	1.3118
Run 2	1.2480	0	1.7938	1.7042	.9122	0	1.5966	1.5966	1.6839	0	1.9299	1.3032
Run 3	1.2529	0	1.8007	1.6981	.9154	0	1.5888	1.5888	1.6911	0	1.9335	1.3118
Total E	3.7489	0	5.4061	5.1004	2.7307	0	4.7820	4.7820	5.0860	0	5.8084	3.9268
F. Run 1	1.1206	.3304	1.8871	1.7316	.7412	0	1.5888	1.5888	1.6561	0	1.9206	1.5717
Run 2	1.1206	.3304	1.8814	1.7316	.7356	0	1.5999	1.5999	1.6345	0	1.9299	1.5717
Run 3	1.1239	.3304	1.8814	1.7380	.7356	0	1.5888	1.5888	1.6345	0	1.9263	1.5682
Total F	3.3651	.9912	5.6499	5.2012	2.2124	0	4.7775	4.7775	4.9251	0	5.7768	4.7116
Perpendicular subsamples total	7.1140	.9912	11.0560	10.3016	4.9431	0	9.5595	9.5595	10.0111	0	11.5852	8.6384
Sample total	28.2461	5.6711	37.5008	35.8928	18.5237	.5765	31.9003	34.2332	33.5288	.4288	37.1512	35.4479
Vertical row total				107.3108				85.2337				106.5567

Horizontal row total:	
1. Samples 307, 308, 309	80.2986
2. Samples 310, 311, 312	6.6764
3. Samples 313, 314, 315	106.5523
4. Samples 316, 317, 318	105.5739
Grand total	299.1012

TABLE 17.—*Raw data of analysis of variance of Kayenta formation, Colorado National Monument*

	Row 1			Row 2			Row 3		
Sample	297	300	304	298	301	305	299	302	306
Parallel subsamples:									
A. Run 1	1.6031	1.9818	0.2529	1.0128	1.9201	0	0.1614	2.2601	2.0128
Run 2	1.5999	1.9818	.2529	1.0086	1.9143	0	.1430	2.2601	2.0170
Run 3	1.5999	1.9818	.2529	1.0128	1.9196	0	.1523	2.2718	2.0170
Total A	4.8029	5.9454	.7587	3.0342	5.7540	0	.4567	6.7920	6.0468
B. Run 1	1.6075	2.0000	1.1399	1.0414	1.8254	0	.1959	2.2175	2.0128
Run 2	1.6075	2.0086	1.1399	1.0414	1.8254	0	.1847	2.2253	2.0170
Run 3	1.6031	2.0000	1.1399	1.0414	1.8325	0	.1847	2.2253	2.0170
Total B	4.8181	6.0086	3.4197	3.1242	5.4833	0	.5653	6.6681	6.0468
Parallel subsamples total	9.6210	11.9540	4.1784	6.1584	11.2373	0	1.0220	13,4601	12.0936
Parallel (right-angle) subsamples:									
C. Run 1	1.5682	1.9974	.7135	1.3304	1.1399	0	0	2.1106	2.0086
Run 2	1.5611	1.9921	.7024	1.3304	1.1614	0	0	2.1206	2.0128
Run 3	1.5717	1.9969	.7135	1.3345	1.1492	0	0	2.1303	2.0128
Total C	4.7010	5.9864	2.1294	3.9953	3.4505	0	0	6.3615	6.0342
D. Run 1	1.2480	2.0294	0	1.0569	1.8808	0	.2430	2.2430	1.9552
Run 2	1.2405	2.0645	0	1.0719	1.8555	0	.2330	2.2355	1.9450
Run 3	1.2430	2.0492	.0531	1.0569	1.8500	0	.2455	2.2529	1.9450
Total D	3.7315	6.1431	.0531	3.1857	5.5863	0	.7215	6.7314	5.8452
Parallel (right-angle) subsamples total	8.4325	12.1295	2.1825	7.1810	9.0368	0	.7215	13.0929	11.8794

Perpendicular subsamples:									
E. Run 1	1. 2480	1. 9504	. 4378	. 7882	. 0334	0	0	2. 1303	1. 8651
Run 2	1. 2405	1. 9504	. 4378	. 7882	. 0334	0	0	2. 1399	1. 8692
Run 3	1. 2430	1. 9390	. 4314	. 7882	. 0334	0	0	2. 1492	1. 8751
Total E	3. 7315	5. 8398	1. 3070	2. 3646	. 1002	0	0	6. 4194	5. 6094
F. Run 1	1. 2742	1. 9335	. 0414	. 8531	. 1173	0	0	2. 0969	1. 9020
Run 2	1. 2672	1. 9299	. 0334	. 8488	. 1173	0	0	2. 1106	1. 9085
Run 3	1. 2788	1. 9450	. 0334	. 8531	. 1173	0	0	2. 1106	1. 9138
Total F	3. 8202	5. 8084	. 1082	2. 5550	. 3519	0	0	6. 3181	5. 7243
Perpendicular subsamples total	7. 5517	11. 6482	1. 4152	4. 9196	. 4521	0	0	12. 7375	11. 3337
Sample total	25. 6052	35. 7317	7. 7761	18. 2590	20. 7262	0	1. 7435	39. 2905	35. 3067
Vertical row total			69. 1130			38. 9852			76. 3407

Horizontal row totals:	
1. Samples 297, 298, 299	45. 6077
2. Samples 300, 301, 302	95. 7484
3. Samples 304, 305, 306	43. 0828
Grand total	814. 4389

TABLE 18.—*Raw data of analysis of variance of Wingate sandstone, Colorado National Monument*

	Row 1				Row 2				Row 3			
Sample	285	288	291	294	286	289	292	295	287	290	293	296
Parallel subsamples:												
A. Run 1	1.7170	1.9823	1.4099	2.1931	0.4742	1.2355	2.4472	1.3201	1.4487	0	2.3598	1.6561
Run 2	1.6911	1.9777	1.4048	2.2014	.4742	1.2253	2.4654	1.3010	1.4456	0	2.3424	1.6637
Run 3	1.6911	1.9777	1.4048	2.2175	.4742	1.2227	2.4742	1.3010	1.4409	0	2.3598	1.6561
Total A	5.0992	5.9377	4.2195	6.6120	1.4226	3.6835	7.3868	3.9221	4.3352	0	7.0620	4.9759
B. Run 1	1.9450	1.7380	1.9768	2.2014	.2810	2.0128	2.2967	1.2068	1.3522	.0531	2.3502	1.5682
Run 2	1.9450	1.7380	1.9713	2.2014	.2810	2.0086	2.3243	1.1987	1.3464	.0531	2.3598	1.5682
Run 3	1.9395	1.7380	1.9768	2.2095	.2672	2.0043	2.3054	1.1987	1.3560	.0531	2.3598	1.5717
Total B	5.8295	5.2140	5.9249	6.6123	.8292	6.0257	6.9264	3.6042	4.0546	.1593	7.0698	4.7081
Total parallel subsamples	10.9287	11.1517	10.1444	13.2243	2.2518	9.7092	14.3132	7.5263	8.3898	.1593	14.1318	9.6840
Parallel (right-angle) subsamples:												
C. Run 1	1.3820	1.9661	1.4786	2.1847	.0969	1.7505	2.6656	.9159	1.1239	0	2.2355	1.3598
Run 2	1.3711	1.9661	1.4742	2.1847	.0969	1.7251	2.6551	.9159	1.1303	0	2.2529	1.3541
Run 3	1.3711	1.9605	1.4742	2.1703	.0969	1.7380	2.6444	.9122	1.1303	0	2.2430	1.3655
Total C	4.1242	5.8927	4.4270	6.5397	.2907	5.2136	7.9651	2.7440	3.3845	0	6.7314	4.0794
D. Run 1	1.6637	1.8692	1.3139	2.1790	.5551	1.2945	2.5763	1.2788	.8768	0	2.0934	1.4955
Run 2	1.6637	1.8751	1.2672	2.1790	.5478	1.3075	2.5658	1.2788	.8768	0	2.0899	1.5159
Run 3	1.6561	1.8692	1.2810	2.2014	.5478	1.3201	2.5465	1.2810	.8727	0	2.0934	1.4955
Total D	4.9835	5.6135	3.8621	6.5594	1.6507	3.9221	7.6886	3.8386	2.6263	0	6.2767	4.5069
Parallel (right-angle) subsamples total	9.1077	11.5062	8.2891	13.0991	1.9414	9.1357	15.6537	6.5826	6.0108	0	13.0081	8.5863

Perpendicular subsamples:												
E. Run 1	0	1.1399	1.4409	1.8215	0	.8176	2.0212	.3711	.4502	0	2.0645	.0969
Run 2	0	1.1399	1.4409	1.8338	0	.8176	2.0212	.3711	.4502	0	2.0569	.0969
Run 3	0	1.1461	1.4409	1.8215	0	.8176	2.0170	.3747	.4502	0	2.0492	.0969
Total E	0	3.4259	4.3227	5.4768	0	2.4528	6.0594	1.1169	1.3506	0	6.1706	.2907
F. Run 1	0	.9894	1.2601	1.8651	0	.8859	2.0934	.2672	.3243	0	2.1004	.0755
Run 2	0	.9841	1.2553	1.8751	0	.8859	2.0934	.2529	.3243	0	2.1004	.0755
Run 3	0	.9894	1.2553	1.8808	0	.8820	2.0969	.2529	.3181	0	2.1106	.0755
Total F	0	2.9629	3.7707	5.6210	0	2.6538	6.2837	.7730	.9667	0	6.3114	.2265
Total perpendicular subsamples	0	6.3888	8.0934	11.0978	0	5.1066	12.3431	1.8899	2.3173	0	12.4820	.5172
Total samples	20.0364	29.0467	26.5269	37.4212	4.1932	23.9515	42.3100	15.9988	16.7179	.1593	39.6219	18.7875
Vertical row total				113.0312				86.4535				75.2866

Horizontal row totals:	
1. Samples 285, 286, 287	40.9475
2. Samples 288, 289, 290	53.1575
3. Samples 291, 292, 293	108.4588
4. Samples 294, 295, 296	72.2075
Grand total	274.7713

PRECISION, OPERATOR-SAMPLE INTERACTION, AND OPERATOR EFFECTS IN ROUTINE PERMEABILITY MEASUREMENTS

The purpose of this analysis is to determine whether operators differ significantly in measuring permeability, and if significant differences do occur, to determine their nature and evaluate their effect on the precision of routine permeability measurements.

Comparisons of the mean-square values and F ratios obtained in the analysis with the $F.05$ and $F.01$ critical ratios from the statistical tables allow several conclusions to be drawn: First, the mean squares for "duplicate measurements" and "operators × samples" are small and of the same magnitude. Further, the $F.05$ and F ratios for "operators × samples" show that no interaction is proven. The significance of this is that the differences that occur between "operators" and "samples" are nearly constant. This can be verified by comparing the readings for each sample by each operator in the table. It will be seen that there is a small but consistent bias between operators: operator A reads consistently higher than operator B. It follows from this that the proper F ratio to test differences between operators would include both the variance about "duplicate measurements" and the "method × operator" interaction variance. The resulting analysis shows that although both sample and operator differences are highly

TABLE 19.—*Mathematical model of analysis of variance of operator performance*

Source of variance	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	Ratio (F)
Operators (O)	$n-1$	$\sum_{1}^{n} (\sum^{mkr} x)^2/mkr - CT$	$\frac{SSO}{n-1}$	$\frac{MSO}{MSF+MSO\times S}$
Samples (S)	$m-1$	$\sum_{1}^{m} (\sum^{nkr} x)^2/nkr - CT$	$\frac{SSS}{m-1}$	$\frac{MSS}{MSF+MSO\times S}$
Operator-samples interaction ($O\times S$).	$(n-1)(m-1)$	$\sum^{nm} (\sum^{kr} x)^2/kr - CT - SSO - SSS$	$\frac{SSO\times S}{(n-1)(m-1)}$	$\frac{MSO\times S}{MSF}$
Experiments (E)	$k-1$	$\sum_{1}^{k} (\sum^{r} x)^2/r - CT$		
Duplicate measurements (F)	$k(r-1)$	$\sum_{1}^{r} x^2 - CT - SSE$	$\frac{SSF}{k(r-1)}$	
Total	$N-1$	$\sum_{1}^{N} x^2 - CT$		

Correction term $(CT) = (\sum^{N} x)^2/N$.
x = individual determination
n = number of operators
m = number of samples
k = number of experiments
r = number of replications
$N = kr$

significant the operator variance is so small when compared to the sample variance that differences in samples will not be obscured if the variance from different operators is pooled with the precision error.

TABLE 20.—*Raw data of variance of operator performance*

Sample	Operator A			Operator B			Total
	Run 1	Run 2	Total	Run 1	Run 2	Total	
286	0.5431	0.5478	1.0909	0.5551	0.5478	1.1029	2.1938
289	1.3202	1.3075	2.6277	1.2945	1.3202	2.6147	5.2424
290	0	0	0	0	0	0	0
291	1.3304	1.3222	2.6526	1.2810	1.3139	2.5949	5.2475
296	1.5105	1.5237	3.0342	1.4955	1.5159	3.0114	6.0456
298	1.0828	1.0934	2.1762	1.0569	1.0719	2.1288	4.3050
300	2.0645	2.0792	4.1437	2.0645	2.0492	4.1137	8.2574
301	1.8692	1.8814	3.7506	1.8808	1.8555	3.7363	7.4869
302	2.2430	2.2430	4.4860	2.2430	2.2529	4.4959	8.9819
304	.0969	.1072	.2041	.0531	.0969	.1500	.3541
306	1.9552	1.9552	3.9104	1.9552	1.9450	3.9002	7.8106
307	1.8609	1.8692	3.7301	1.8500	1.8555	3.7055	7.4356
308	1.2945	1.2945	2.5890	1.2989	1.2672	2.5661	5.1551
309	2.0294	2.0294	4.0588	2.0212	2.0212	4.0424	8.1012
310	.2148	.2253	.4401	.1959	.1732	.3691	.8092
311	0	0	0	0	0	0	0
313	2.4378	2.4378	4.8756	2.4564	2.4378	4.8942	9.7698
314	1.2878	1.2878	2.5756	1.2945	1.3075	2.6020	5.1776
315	2.1004	2.1399	4.2403	2.1206	2.1106	4.2312	8.4715
316	1.9974	1.9872	3.9846	1.9768	1.9661	3.9429	7.9275
317	2.1004	2.1004	4.2008	2.1004	2.0645	4.1649	8.3657
319	1.5563	1.5563	3.1126	1.5315	1.5403	3.0718	6.1844
320	.9274	.9274	1.8548	.9122	.9122	1.8244	3.6792
321	1.6911	1.7042	3.3953	1.6767	1.6911	3.3678	6.7631
328	0	0	0	0	0	0	0
330	0	0	0	0	0	0	0
Total			67.1340			66.6311	133.7651

Σ Runs² = 66.33352091
Σ Samples² = 66.32736652
Σ Operators² = 40.00243150
Σ Total² = 172.04905750
Σ (A+B)² = 66.32122145

TABLE 21.—*Analysis of variance of operator performance*

Source of variance	Degrees of freedom (*DF*)	Sum of squares	Mean squares	*F*	*F*.05	*F*.01
Operators	1	0.0024315	0.0024315	18.97	4.03	7.15
Samples	25	66.32122145	2.65284886	20,699.51	1.73	2.16
Operators × samples	25	.00371357	.00014854	1.26	1.73	2.16
Experiments	51	66.32736652				
Duplicate measurements	52	.00615439	.00011835	Pooled error =	*SS* 0.00986796	*MS* 0.00012816
Total	103	66.33352091				

$EMS = \sqrt{0.00011835} = 0.0108$

$$\text{Operator}\Sigma = \frac{\sqrt{0.0024315 - 0.00012816}}{26} = 0.0094$$

LOCAL AND REGIONAL VARIATIONS IN PERMEABILITY

This analysis was designed to see if the mean regional permeabilities of representative formations differ, and whether local and regional differences in mean permeability are apparent within distances as far as 50 miles apart along the strike of the basin of deposition.

A comparison of the F ratios obtained for each unit tested shows that, except between sites about 5 miles apart in the Entrada sandstone, no significant regional or local differences are apparent. The

TABLE 22.—*Mathematical model of the analysis of variance of mean permeability between formations and at localities within formations, separated by distances of 5 to 10 and 50 miles*

Source of variance	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	Ratio of mean squares (F)
Areas (A)	$n-1$	$\sum_{1}^{n}\left(\sum_{1}^{mk}x\right)^2/mk-CT$	$\frac{SSA}{n-1}$	$\frac{MSA}{MSL}$
Locations (L)	$n(m-1)$	$\sum_{1}^{m}\left(\sum_{1}^{nk}x\right)^2/nk-CT$	$\frac{SSL}{n(m-1)}$	$\frac{MSL}{MSE}$
Error (E)	$nm(k-1)$	$\sum_{1}^{N}x^2-CT-SSA-SSL$	$\frac{SSE}{nm(k-1)}$	--------
Total (T)	$N-1$	$\sum_{1}^{N}x^2-CT$	----------	--------

Correction term $(CT)=N=nmk\left(\sum_{1}^{N}x\right)^2/N$.

x=individual determination
n=number of samples
m=number of subsamples
k=number of replications
N=nmk
CV=coefficient of variation in percent= $\frac{100\sqrt{\text{Error mean square}}}{\text{Grand mean}}$.

TABLE 23.—*Mathematical model of the analysis of variance of mean permeability between hydrologic units*

Source of variance	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	Ratio of mean squares (F)
Hydrologic units (H)	$n-1$	$\sum_{1}^{n}\left(\sum_{1}^{mk}x\right)^2/mk-CT$	$\frac{SSF}{n-1}$	$\frac{MSH}{MSA}$
Areas (A)	$n(m-1)$	$\sum_{1}^{m}\left(\sum_{1}^{nk}x\right)^2nk-CT$	$\frac{SSA}{n(m-1)}$	$\frac{MSA}{MSE}$
Error (E)	$nm(k-1)$	$\sum_{1}^{N}x^2-CT-SSH-SSA$	$\frac{SSE}{nm(k-1)}$	--------
Total (T)	$N-1$	$\sum_{1}^{N}x^2-CT$	----------	--------

Correction term (CT)=N=nmk $\left(\sum_{1}^{N}x\right)^2/N$.

x=individual determination
n=number of formations
m=number of areas
k=number of replications
$N=nmk$

meaning of this seems clear: the differences on a sample-to-sample scale (3 to 5 miles) are so large, and regional (50 miles) variations so

TABLE 24—*Variance of permeability of representative formations between sites (5 to 10 miles apart) and areas (50 miles apart)*

Sample	Colorado National Monument area		Uravan area	
	Site 1	Site 2	Site 1	Site 2
Dakota sandstone and Burro Canyon formation				
1	2. 7634	1. 7324	3. 0645	2. 8156
2	3. 6493	1. 6385	2. 9782	2. 4814
3	3. 1673	2. 6739	2. 4669	2. 1761
4	2. 8597	2. 4871	3. 0453	1. 2201
5	. 9455	2. 0569	2. 6990	2. 5145
6	2. 9370	2. 4502	3. 1139	1. 9395
7	3. 0294	1. 2355	2. 8646	2. 9479
8	3. 0719	2. 5551	0	3. 2672
9	2. 8971	2. 4548	1. 2148	1. 8376
10	2. 9309	2. 3802	0	2. 8842
11	1. 6493	2. 1461	1. 1430	2. 6848
12	2. 5038	2. 3032	2. 8306	2. 5717
Site totals	32. 4046	26. 1139	25. 4208	29. 3406
Area totals	58. 5185		54. 7614	
Grand total				113. 2799
Correction term				267. 3403279
Sandstones of the Salt Wash member				
1	2. 6405	1. 5428	1. 2122	1. 6314
2	2. 9284	. 9943	2. 6170	2. 5575
3	3. 1399	1. 5119	1. 5944	2. 4314
4	2. 3711	0	2. 4713	2. 0969
5	2. 9112	0	2. 2148	2. 4728
6	2. 4669	0	1. 6021	2. 1335
7	2. 4166	2. 7752	1. 8814	1. 6021
8	1. 0969	1. 9085	2. 3766	2. 1139
9	. 1139	0	. 9777	2. 4728
10	1. 5911	0	. 8513	. 7243
11	1. 3365	0	. 7243	1. 0792
12	2. 2175	3. 2279	1. 8603	. 9243
13	0	3. 2601	2. 1818	1. 9952
14	0	3. 1367	1. 7745	2. 2742
Site total	25. 2305	18. 3574	24. 3397	26. 5095
Area total	43. 5879		50. 8492	
Grand total				94. 4371
Correction term				159. 2565331

TABLE 24—*Variance of permeability of representative formations between sites (5 to 10 miles apart) and areas (50 miles apart)*—Continued

Sample	Colorado National Monument area		Uravan area	
	Site 1	Site 2	Site 1	Site 2
Entrada sandstone				
1	1. 6085	0. 9647	1. 9415	0. 4771
2	1. 0607	2. 4409	1. 7782	. 5315
3	1. 8669	2. 5038	. 1038	1. 8293
4	. 7559	2. 0086	0	3. 0414
5	0	2. 6345	2. 3243	2. 5328
6	0	2. 2833	1. 7135	2. 6128
7	2. 0828	1. 2122	1. 4698	2. 0492
8	1. 3655	2. 3284	2. 1206	2. 3160
9	2. 0864	2. 5944	2. 1790	3. 0719
10	2. 1173	2. 3201	. 5185	2. 2648
11	2. 0128	2. 2553	2. 3345	2. 1584
12	1. 9590	2. 4997	1. 4346	2. 0170
Site totals	16. 9158	26. 0459	17. 9183	24. 9022
Area totals	42.9617		42.8205	
Grand total				85. 7822
Correction term				153. 3038716
Kayenta formation				
1	1. 0969	2. 5575	1. 2577	1. 2742
2	. 0212	. 3222	. 9345	. 9956
3	1. 9685	. 1461	. 3424	1. 1614
4	1. 5465	0	. 6021	1. 4393
5	2. 1584	2. 3874	. 6721	. 2304
6	2. 7709	1. 5441	0	1. 2253
7	. 6902	2. 6395	0	1. 9934
8	0	2. 3010	0	1. 3617
9	1. 9557	1. 0828	1. 2068	. 9445
Site total	12. 2083	12. 9806	5. 0156	10. 6258
Area total	25. 1889		15. 6414	
Grand total				40. 8303
Correction term				46. 30870550

TABLE 24—*Variance of permeability of representative formations between sites (5 to 10 miles apart) and areas (50 miles apart)*—Continued

Sample	Colorado National Monument area		Uravan area	
	Site 1	Site 2	Site 1	Site 2
Wingate sandstone				
1	1. 6075	2. 6684	0	0
2	. 0086	2. 5999	1. 5587	. 7404
3	1. 2380	2. 5478	1. 1523	2. 1222
4	1. 7292	2. 4548	. 3222	2. 0000
5	1. 6866	2. 6609	1. 5966	2. 1461
6	0	. 6532	2. 1004	1. 0212
7	1. 6128	1. 2900	1. 8195	1. 3324
8	2. 2967	1. 8663	2. 2201	1. 6021
9	2. 2253	2. 1173	1. 6812	1. 6767
10	2. 1271	0	1. 2041	2. 3802
11	1. 4786	0	1. 6532	1. 7993
12	1. 3838	2. 0374	2. 0453	. 8573
Site total	17. 3942	20. 8960	17. 3536	17. 6779
Area total	38. 2902		35. 0315	
Grand total			73. 3217	
Correction term			112. 0014935	

small that, in sampling to detect regional variations, only a few sites need be sampled but at each site many samples must be collected.

A comparison of the F ratio obtained for differences between formations indicates that these differences are highly significant.

TABLE 25.—*Analysis of variance of permeability of representative formations between sites and areas*

Source of variance	Degrees of freedom (*DF*)	Sum of squares (*SS*)	Mean squares (*MS*)	*F*	*F*.05	*F*.01
Dakota sandstone and Burro Canyon formation						
Areas	1	0. 0037431	0. 0037431	0. 01	4. 06	7. 24
Sites	2	2. 2890724	1. 1445362	1. 83	3. 21	5. 12
Residual	44	27. 4260611	. 6233195			
Total	47	29. 7188766				
Sandstones of the Salt Wash member						
Areas	1	0. 9415442	0. 9415442	0. 96	4. 03	7. 17
Sites	2	1. 8552692	. 9276346	. 97	4. 18	5. 06
Residual	52	49. 9392718	. 9603706			
Total	55	52. 7360852				
Entrada sandstone						
Areas	1	0. 0004153	0. 0004153		4. 06	7. 24
Sites	2	5. 5055661	2. 75278304	4. 80	3. 21	5. 12
Residual	44	25. 2396901	. 57362932			
Total	47	30. 7456715				
Kayenta formation						
Areas	1	2. 53207656	2. 53207656	3. 89	4. 15	7. 50
Sites	2	1. 78171064	. 89085532	1. 37	3. 30	5. 34
Residual	32	20. 82200247	. 65068758			
Total	35	25. 13578967				
Wingate sandstone						
Areas	1	0. 22123180	0. 2212318	0. 35	4. 06	7. 24
Sites	2	. 51532390	. 2576620	. 40	3. 21	5. 12
Residual	44	28. 09812099	. 63859366			
Total	47	28. 83467679				

TABLE 26.—*Variance of mean permeability between hydrologic units*

Hydrologic units	Colorado National Monument area (sites 1 and 2)	Uravan area (sites 1 and 2)	Total
Burro Canyon formation	2. 7004	2. 1184	
	2. 1762	2. 4451	
	4. 8766	4. 5635	9. 4401
Sandstones of the Salt Wash member	1. 3112	1. 7386	
	1. 8022	1. 8935	
	3. 1134	3. 6321	6. 7455
Entrada sandstone	1. 4097	2. 0752	
	2. 1705	1. 4936	
	3. 5802	3. 5688	7. 1490
Kayenta formation	1. 3654	1. 1806	
	1. 5264	. 5573	
	2. 8918	1. 7379	4. 6297
Wingate sandstone	1. 4495	1. 4461	
	1. 7413	1. 4807	
	3. 1908	2. 9268	6. 1176
Grand total			34. 0819
Correction term			58. 07879538

TABLE 27.—*Analysis of variance of mean permeability between hydrologic units*

Source of variance	Degrees of freedom (DF)	Sum of squares	Mean squares	*F*	*F*.05	*F*.01
Hydrologic units	4	3. 0673574	0. 7668393	7. 43	3. 48	5. 99
Areas	5	. 4420981	. 0884196	. 86	3. 33	5. 64
Error	10	1. 0322185	. 1032219			
Total	19	4. 5416740				

DIFFERENCES BETWEEN MEASURED AND COMPUTED PERMEABILITY

This analysis was designed to see if significant differences occur between permeability values determined by use of a permeameter and those computed from a limited range of parameters of grain-size analysis. A preliminary analysis has shown that the empirical formula which yielded the best fit between the two sets of values was reliable for only 97 percent of the available data—those in which the kurtosis was <20 phi units and the standard deviation >1.0 phi units.[2]

[2] Modal diameter (*Md*), kurtosis (*K*), and standard deviation (σ) are in phi units determined by the method of moment measures as applied to sediment analysis by W. C. Krumbein (1936). Percent solubles is that portion of the sample which, after being dissolved in 400 ml of 20-percent strength boiling citric acid, cooled to room temperature, and acidified with 20 to 50 ml of concentrated hydrochloric acid, is removed by 4 to 6 washings of distilled water.

It was the permeability values derived by use of this formula, as given below, which were tested in this analysis.

The F ratios obtained in all analyses of hydrologic units except those for the Kayenta formation are well under the critical $F.05$ ratios, indicating that with these data no significant differences between the methods of computing permeability have been proven. The F ratio for the analysis of the Kayenta is less than the critical ratio, although only slightly less; thus the two methods have a probability of slightly more than 1 in 20 of yielding indistinguishable results.

$$P=\frac{Md\,K^2}{G^3}(20-S)$$

where

P = Permeability, in millidarcy
Md = Modal diameter
K = Kurtosis
G = Standard deviation
S = Percent solubles

TABLE 28.—*Mathematical model of the analysis of variance of permeability measured with nitrogen and computed from grain-size analysis parameters*

Source of variance	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	Ratio of mean squares (F)
Methods (M)	$n-1$	$\sum_1^n\sum_1^m(\Sigma x)^2/m-CT$	$\frac{SSM}{n-1}$	$\frac{MSM}{MSE}$
Samples (S)	$m-1$	$\sum_1^m\sum_1^n(\Sigma x)^2/n-CT$	$\frac{SSS}{n-1}$	$\frac{MSS}{MSE}$
Residual	$(n-1)(m-1)$	$\sum^{n}\sum^{m}x^2-CT-SSM-SSS$	$\frac{SSE}{(n-1)(m-1)}$	
Total (T)	$N-1$	$\sum_1^{n}\sum^{m}x^2-CT$		

Correction term $(CT)=N=nm(\sum_1^N x^2)/N$

NOTE.—x = individual determination
n = number of methods
m = number of samples
$N=nm$

TABLE 29.—*Raw data of variance of computed and measured permeability of representative formations*

Sample	Computed	Measured	Total
Dakota sandstone and Burro Canyon formation			
1	2. 2878	2. 1173	4. 4051
2	0	0	0
3	. 6021	0	. 6021
4	0	0	0
5	. 6021	. 4771	1. 0792
6	. 7781	1. 9085	2. 6866
7	1. 4786	1. 4771	2. 9557
8	1. 6628	1. 7709	3. 4337
9	1. 0792	1. 1761	2. 2553
10	2. 8597	2. 1703	5. 0300
Total	11. 3504	11. 0973	22. 4477

CT	25. 19496176
Σ Samples ²	15. 42755451
Σ Methods ²	0. 00320299
Σ Total ²	14. 33686769
Σ Error	1. 08748383

631709 O—62——10

TABLE 29.—*Raw data of variance of computed and measured permeability of representative formations*—Continued

Sample	Computed	Measured	Total
Sandstones of the Salt Wash member			
1	1. 1461	0. 7782	1. 9243
2	. 4771	. 6021	1. 0792
3	0	0	0
4	1. 7924	1. 8261	3. 6185
5	. 3010	. 3010	. 6020
6	0	0	0
7	. 9031	1. 3222	2. 2253
8	. 8451	1. 7634	2. 6085
9	1. 5911	1. 8692	3. 4603
10	1. 5441	. 9031	2. 4472
11	1. 3010	. 3010	1. 6020
12	. 3010	0	. 3010
13	. 8451	1. 4150	2. 2601
14	1. 6021	1. 3979	3. 0000
15	2. 1106	1. 9590	4. 0696
16	1. 0792	1. 0414	2. 1206
17	1. 8976	1. 6021	3. 4997
18	1. 0414	. 6990	1. 7404
19	. 6021	. 3010	. 9031
20	. 7782	. 6021	1. 3803
21	0	0	0
22	0	0	0
23	0	0	0
24	1. 8633	1. 7853	3. 6486
25	0	0	0
26	0	. 9542	. 9542
27	0	0	0
28	0	0	0
29	0	0	0
30	2. 2967	2. 2624	4. 5591
Total	24. 3183	23. 6857	48. 0040

CT	38. 40640026
ΣSamples ²	33. 22185452
ΣMethods ²	0. 00666972
ΣTotal ²	31. 02964671
ΣError	2. 18553809

TABLE 29.—*Raw data of variance of computed and measured permeability of representative formations*—Continued

Sample	Computed	Measured	Total
Entrada sandstone			
1	0. 4771	0. 8541	1. 3312
2	0	0	0
3	. 6021	. 6021	1. 2042
4	1. 3802	1. 0000	2. 3802
5	. 7782	. 6990	1. 4772
6	1. 6990	1. 8865	3. 5855
7	1. 0000	1. 3617	2. 3617
8	. 4771	. 4771	. 9542
9	2. 2430	2. 0253	4. 2683
10	0	0	0
11	. 6021	. 6990	1. 3011
12	. 6021	. 3010	. 9031
13	. 6990	. 9031	1. 6021
14	. 3010	. 3010	. 6020
15	0	0	0
16	. 3010	0	. 3010
17	. 9031	1. 1139	2. 0170
18	. 6021	. 4771	1. 0792
19	1. 3010	1. 1139	2. 4149
20	. 6990	1. 1461	1. 8451
21	. 9031	1. 0414	1. 9445
22	1. 1761	1. 0000	2. 1761
Total	16. 7463	17. 0023	33. 7486
CT			25. 88563640
Σ Samples [2]			13. 22911124
Σ Methods [2]			0. 00149460
Σ Total [2]			12. 68723959
Σ Error			0. 54037705
Kayenta formation			
1	0	0	0
2	1. 7634	1. 4314	3. 1948
3	2. 4150	1. 5798	3. 9948
4	1. 7924	. 3010	2. 0934
5	0	. 3010	. 3010
6	. 7782	. 6021	1. 3803
7	. 7782	. 3010	1. 0792
8	. 3010	0	. 3010
9	1. 6128	1. 0000	2. 6128
10	1. 5441	. 6990	2. 2431
11	2. 3075	1. 2041	3. 5116
12	1. 1139	1. 7634	2. 8773
13	0	. 3010	. 3010
14	0	0	0
15	1. 0792	1. 0000	2. 0792
Total	15. 4857	10. 4838	25. 9695
CT			22. 4804977
ΣSamples [2]			12. 8598450
ΣMethods [2]			0. 8339668
ΣTotal [2]			19. 2287859
ΣError			5. 5341741

TABLE 29.—*Raw data of variance of computed and measured permeability of representative formations*—Continued

Sample	Computed	Measured	Total
Wingate sandstone			
1	0	0	0
2	. 6021	. 4771	1. 0792
3	1. 0000	. 8541	1. 8541
4	1. 2041	1. 4624	2. 6665
5	0	0	0
6	0	. 4771	. 4771
7	. 3010	. 6990	1. 0000
8	. 8541	0	. 8541
9	. 7782	. 4771	1. 2553
10	1. 3010	1. 7404	3. 0414
11	. 6690	. 8451	1. 5141
12	. 4771	0	. 4771
13	. 9542	1. 3222	2. 2764
14	. 4771	1. 2553	1. 7324
15	. 4771	. 6021	1. 0792
16	. 6021	. 6021	1. 2042
Total	9. 6971	10. 8140	20. 5111

CT	13. 14703822
ΣSamples²	7. 01888405
ΣMethods²	0. 03898330
ΣTotal²	4. 48330438
ΣError	2. 53557967

TABLE 30.—*Analysis of variance of computed and measured permeability of representative formations*

Source of variance	Degrees of freedoom (*DF*)	Sum of squares (*SS*)	Mean squares (*MS*)	*F*	*F*.05	*F*.01
Dakota sandstone and Burro Canyon formation						
Methods	1	0. 00320299		0. 05	4. 45	8. 40
Samples	1	14. 33686769		224. 12	4. 45	8. 40
Error	17	1. 08748383	0. 06396964			
Total	19	15. 42755451				
Sandstones of the Salt Wash member						
Methods	1	0. 00666972	0. 00666972	0. 17	4. 01	7. 10
Samples	1	31. 02964671	31. 02964671	926. 98	4. 01	7. 10
Error	57	2. 18553809	. 03834277			
Total	59	33. 22185452				
Entrada sandstone						
Methods	1	0. 00149460	0. 0014946	0. 11	4. 08	7. 21
Samples	1	12. 68723959	12. 68723959	962. 62	4. 08	7. 21
Error	41	. 54037705	. 013179928			
Total	43	13. 22911124				
Kayenta formation						
Methods	1	0. 8339668	0. 8339668	4. 07	4. 21	7. 60
Samples	1	12. 8598450	12. 8598450	62. 70	4. 21	7. 60
Error	27	5. 5349741	. 2050987			
Total	29	19. 2287859				
Wingate sandstone						
Methods	1	0. 03898330	0. 03898330	0. 45	4. 18	7. 60
Samples	1	4. 48330438	4. 48330438	52. 08	4. 18	7. 60
Error	29	2. 49649637	. 08608608			
Total	31	7. 01878405				

PERMEABILITY OF SAMPLES

The number of samples, the mean permeability, and the standard deviation of permeability (in millidarcys) of the sample profiles are shown in table 31, grouped by hydrologic units. The profile numbers are keyed to the listed figures.

TABLE 31.—*Permeability of samples*

Profile	Location	Number of samples	Mean (log_{10})	Standard deviation (log_{10})
Mesaverde formation (fig. 35)				
1	Mesa Verde National Park, Colo	26	2. 21	0. 38
2	Seco, Utah	17	2. 64	. 74
3	Soldiers Canyon, Utah	15	2. 05	. 84
4	Salina Canyon, Utah	12	2. 82	. 66
5	Canyon of Dirty Devil River, San Rafael Swell, Utah.	17	2. 38	. 61
6	Straight Cliffs, west of Escalante, Utah	15	3. 16	. 48
7	Rough Rock trading post, Navajo Reservation, Ariz.	21	3. 75	1. 27
8	Toadlena coal mine, Navajo Reservation, N. Mex.	6	3. 35	. 96
9	East of Toadlena, Navajo Reservation, N. Mex.	6	2. 34	. 96
10	Mariana Pass, Navajo Reservation, N. Mex	4	2. 83	. 07
11	Crown Point trading post, Navajo Reservation, N. Mex.	4	2. 41	. 48
12	Smiths Lake trading post, Navajo Reservation, N. Mex.	11	2. 83	. 36
Cedar Mountain formation, Dakota sandstone, and Burro Canyon formation (fig. 34)				
1	Colorado National Monument, west entrance	------	------	------
2	Colorado National Monument, east entrance	12	2. 35	0. 13
3	Atkinson Mesa, Uravan, Colo	11	3. 32	1. 23
4	Spring Creek Mesa, Uravan, Colo	12	2. 75	. 57
5	McElmo Canyon, southwest of Cortez, Colo	4	2. 27	. 34
6	Comb Ridge, west of Blanding, Utah	4	2. 91	. 43
7	Seven-mile Canyon, north of Moab, Utah	11	2. 51	. 78
8	Northeastern part of San Rafael Swell, Utah	9	2. 50	. 78
9	Southeast of mouth of Canyon of Dirty Devil River, San Rafael Swell, Utah.	2	1. 59	------
10	Southwest of Escalante, Utah	6	2. 29	. 26
11	Marsh Pass, west of Kayenta, Ariz	3	2. 58	. 28
12	Lupton, Ariz	5	2. 62	. 04
13	Southeast of Toadlena, Navajo Reservation, N. Mex.	8	2. 68	. 40
14	Kit Carsons Cave, Navajo Reservation, N. Mex.	12	2. 69	. 48
15	New Laguna, east of Grants, N. Mex	6	2. 33	. 44
16	Circle Cliffs, south of Fruita, Utah	3	2. 80	. 48
Morrison formation (fig. 32)				
1	Colorado National Momument, west entrance	15	2. 78	1. 35
2	Colorado National Momument, east entrance	15	2. 93	1. 12
3	Atkinson Mesa, Uravan, Colo	26	2. 43	. 84
4	Atkinson Mesa, Uravan, Colo. (Brushy Basin member).	6	2. 93	. 49
5	Spring Creek Mesa, Uravan, Colo	20	2. 18	. 55
6	McElmo Canyon, southwest of Cortez, Colo. (Salt Wash member).	10	2. 42	1. 04
7	McElmo Canyon, southwest of Cortez, Colo. (Westwater Canyon member).	7	2. 77	. 85

TABLE 31.—*Permeability of samples*—Continued

Profile	Location	Number of samples	Mean (log_{10})	Standard deviation (log_{10})
Morrison formation (fig. 32)—Continued				
8	Bridger Jack group of mines, southeast of Moab, Utah.	18	2.46	0.77
9	Northeast of Seven-mile Canyon, south of Thompsons, Utah.	2	2.69	.33
10	Northeastern part of San Rafael Swell, Utah	21	3.47	.26
11	Eastern flank of Henry Mountains basin, northwest of Hite, Utah.	14	2.71	.92
12	North of Burr Trail into Circle Cliffs, Utah	5	3.65	1.23
13	Escalante, Utah	13	2.86	.95
14	Comb Ridge, northwest of Blanding, Utah	10	2.91	.99
15	East of Marsh Pass, west of Kayenta, Ariz. (Salt Wash member).	4	2.73	.92
16	Marsh Pass, west of Kayenta, Ariz. (Westwater Canyon member).	6	2.92	.39
17	Cove Mesa, Ariz., in Four Corners area (Salt Wash and Westwater Canyon undivided).	16	2.54	.69
18	Kit Carsons Cave, northeast of Gallup, N. Mex. (Westwater Canyon).	6	2.39	.21
19	do	4	2.75	.24
20	Kit Carsons Cave, northeast of Gallup, N. Mex. (Recapture).	8	1.89	.73
21	Poison Springs Canyon area, northwest of Grants, N. Mex. (Brushy Basin).	15	2.93	.65
22	Poison Springs Canyon area, northwest of Grants, N. Mex. (Westwater Canyon).	9	3.36	.97
23	Poison Springs Canyon area, northwest of Grants, N. Mex. (Recapture member).	8	2.58	.59
24	North of New Laguna, east of Grants, N. Mex. (Brushy Basin).	10	3.01	.62
25	North of New Laguna, east of Grants, N. Mex. (Westwater Canyon).	7	2.71	.65
Cow Springs, Bluff, and Junction Creek sandstones and Winsor formation (fig. 27)				
1	McElmo Canyon, southwest of Cortez, Colo	4	3.51	1.41
2	Bluff, Utah	11	3.04	.68
3	South of Escalante, Utah	7	2.63	.47
4	Marsh Pass area, west of Kayenta, Ariz	8	2.78	.46
5	Cove Mesa, Ariz., in Four Corners area	5	2.75	.34
6	Red Lake trading post area, Navajo Reservation, Ariz.	9	2.38	.50
7	Lupton, Ariz	10	2.55	.54
8	Kit Carsons Cave area, northeast of Gallup, N. Mex.	10	2.21	.64
9	U.S. Highway 66, east of Grants, N. Mex	7	2.41	.80

TABLE 31.—*Permeability of samples*—Continued

Profile	Location	Number of samples	Mean (log_{10})	Standard deviation (log_{10})
	Entrada sandstone (fig. 23)			
1	Colorado National Monument, west entrance	12	2.00	0.79
2	Colorado National Monument, east entrance	12	2.46	.54
3	Atkinson Mesa, Uravan, Colo	12	2.26	.78
4	Spring Creek Mesa, Uravan, Colo	12	2.71	.83
5	Bear Creek, southwest of Placerville, Colo	10	1.92	.62
6	McElmo Canyon, southwest of Cortez, Colo	9	3.16	1.03
7	East of Bowknot group of mines, northwest of Moab, Utah.	3	1.77	.19
8	Northeastern part of San Rafael Swell, Utah	3	1.60	.31
9	West flank of Henry Mountains opposite Burr Trail into Circle Cliffs, Utah.	8	2.49	.62
10	Escalante area, Utah	4	2.30	.29
11	Comb Ridge, west of Blanding, Utah	10	2.14	1.06
12	Comb Ridge, west of Bluff, Utah	5	1.42	.31
13	North of Red Lake trading post, Navajo Reservation, Ariz.	6	2.19	.36
14	Rough Rock trading post, Navajo Reservation, Ariz.	4	1.93	.67
15	Southwest of Lupton, Ariz	13	3.29	.29
16	Kit Carsons Cave, northeast of Gallup, N. Mex.	10	2.85	.21
17	Poison Springs Canyon, northwest of Grants, N. Mex.	7	2.58	.25
18	New Laguna, east of Grants, N. Mex	5	2.38	.45
19	Cove Mesa, Ariz., in Four Corners area	10	2.30	.97
	Navajo sandstone (fig. 20)			
1	Spring Creek Mesa, Uravan, Colo	7	2.56	0.84
2	McElmo Canyon, southwest of Cortez, Colo	8	2.25	.96
3	Comb Ridge, west of Bluff, Utah	13	2.60	.39
4	Comb Ridge, west of Blanding, Utah	5	2.72	.45
5	East of Bowknot group of mines, northwest of Moab, Utah.	5	2.37	.62
6	Dirty Devil River Canyon, San Rafael Swell, Utah.	10	2.91	.61
7	Halls Creek, Circle Cliffs, Utah	14	2.78	.22
8	East of Escalante, Utah	10	3.05	.16
9	West of Kayenta, Ariz	6	2.53	.23
	Kayenta formation (fig. 17)			
1	Colorado National Monument, west entrance	15	2.34	0.85
2	Colorado National Monument, east entrance	15	2.45	.99
3	Blue Mesa, Uravan, Colo	10	1.79	.48
4	Atkinson Mesa, Uravan, Colo	10	.78	.48
5	Southeast of Bowknot group of mines, northwest of Moab, Utah.	8	1.81	.79
6	North of mouth of Dirty Devil River Canyon, San Rafael Swell, Utah.	9	1.99	.94
7	Halls Creek, Circle Cliffs, Utah	3	2.10	.66
8	Comb Ridge, northwest of Blanding, Utah	9	2.14	.71
9	Comb Ridge, west of Bluff, Utah	6	2.45	.97
10	West of Kayenta, Ariz	9	2.47	1.40
11	Northwest of Lupton, Ariz	5	0.	0.

TABLE 31.—*Permeability of samples*—Continued

Profile	Location	Number of samples	Mean (log_{10})	Standard deviation (log_{10})
Wingate sandstone (fig. 14)				
1	Colorado National Monument, west entrance	12	2.18	0.81
2	Colorado National Monument, east entrance	12	2.66	1.01
3	Blue Mesa, Uravan, Colo	12	1.98	.71
4	Atkinson Mesa, Uravan, Colo	12	1.91	.68
5	Comb Ridge west of Bluff, Utah	5	1.80	.34
6	Comb Ridge west of Blanding, Utah	6	2.06	.47
7	East of Bowknot group of mines, northwest of Moab, Utah.	7	2.34	.75
8	Northwest of mouth of Dirty Devil River Canyon, San Rafael Swell, Utah.	3	1.83	.43
9	Burr Trail into Circle Cliffs, Utah	3	2.10	.60
10	Northwest of Kayenta, Ariz	5	2.46	.15
11	Cove Mesa area, Ariz., in Four Corners area	10	2.53	.23
12	Lupton, Ariz	5	1.75	.35
Lower sandstones of the Chinle (fig. 10)				
1	Paradox Valley, west of Uravan, Colo	5	0.02	0.05
2	Dolores River Canyon southwest of Uravan, Colo.	8	.34	.45
3	Dolores River Canyon northeast of Cortez, Colo.	5	0.	0.
4	Big Indian Wash, northeast of Monticello, Utah.	6	.74	.58
5	Bowknot group of mines, northwest of Moab, Utah.	11	.80	.57
6	do	3	2.15	.61
7	Dirty Devil River Canyon, San Rafael Swell, Utah.	3	1.32	.22
8	Capitol Reef National Monument, Utah	10	2.45	.77
9	Deer Flat, east of Hite, Utah (Moss Back member).	7	2.95	.63
10	Deer Flat, east of Hite, Utah (Shinarump member).	10	2.45	1.35
11	Shinarump Cliffs, Ariz., southeast of Kanab, Utah.	8	3.02	.46
12	The Gap, north of Cameron, Ariz	7	2.05	1.04
13	Monument Valley, north of Kayenta, Ariz	10	2.98	.57
14	U.S. Highway 66, west of Lupton, Ariz	10	3.01	1.07
15	Indian Creek Canyon near junction of Green and Colorado Rivers, Utah.	6	1.61	.64
Permian sandstones (fig. 6)				
1	Paradox Valley, west of Uravan, Colo	4	0.25	0.05
2	Dolores River Canyon, northeast of Cortez, Colo.	3	1.75	1.33
3	Big Indian Wash, northeast of Monticello, Utah.	6	2.52	1.37
4	Indian Creek Canyon, near junction of the Green and Colorado Rivers, Utah.	4	1.13	.98
5	Shafer Trail, west of Moab, Utah	7	2.22	1.04

TABLE 31.—*Permeability of samples*—Continued

Profile	Location	Number of samples	Mean (log_{10})	Standard deviation (log_{10})
Permian sandstones—Continued				
6	Labyrinth Canyon, Green River, northeast of Moab, Utah.	6	2. 94	0. 56
7	White Canyon, east of Hite, Utah	5	2. 29	. 87
8	Hite, Utah	13	2. 37	1. 01
9	North Wash, northeast of Hite, Utah	16	2. 50	. 33
10	Northeastern part, San Rafael Swell, Utah	8	3. 06	. 93
11	Northeastern part, San Rafael Swell, Utah (Kaibab limestone).	3	0	0
12	Hacks Canyon, Ariz., south of Kanab, Utah	9	2. 00	. 39
13	Monument Valley, northwest of Kayenta, Ariz.	5	2. 84	. 22
14	Canyon De Chelly, east of Chinle, Ariz	12	2. 70	. 39
15	Fort Defiance, north of Lupton, Ariz	12	1. 78	. 61
16	Black Canyon, north of Lupton, Ariz	10	1. 39	. 78
17	Zuni Canyon, south of Grants, N. Mex. (San Andres limestone).	4	2. 40	. 30
18	Zuni Canyon, south of Grants, N. Mex. (Glorieta sandstone.)	8	2. 25	. 71
19	Zuni Canyon, south of Grants, N. Mex. (Meseta Blanca member).	7	1. 68	. 87
Miscellaneous units (not shown on maps)				
	San Rafael Swell, Utah (Carmel formation)	2	0. 0	0. 0
	San Rafael Swell, Utah (Curtis formation)	2	2. 33	. 60
	East of Bowknot group of mines, northwest of Moab, Utah (Carmel formation).	4	0	0
	East of Bowknot group of mines, northwest of Moab, Utah (Chinle formation).	2	0	0
	McElmo Canyon, southwest of Cortez, Colo. (Brushy Basin member).	2	1. 0	------
	McElmo Canyon, southwest of Cortez, Colo. (Carmel formation).	2	0	0
	Atkinson Mesa, Uravan, Colo. (Carmel formation).	1	0	0
	Paradox Valley, west of Uravan, Colo. (Chinle formation).	5	. 02	. 06
	Monument Valley, northwest of Kayenta, Ariz.	1	0	0
	Comb Ridge, west of Blanding, Utah (Carmel formation).	2	1. 33	------
	Comb Ridge, west of Bluff, Utah (Chinle formation).	3	. 04	------
	White Canyon, east of Hite, Utah (Carmel formation).	4	1. 73	1. 11

DISTRIBUTION OF URANIUM DEPOSITS AND OUTCROP BLOCKS

In table 32 uranium deposits and outcrop blocks are classed as a function of distance from major fracture zones in the sandstones of the Chinle and Morrison formations.

TABLE 32.—*Distribution of uranium deposits and outcrop blocks from major fracture zones*

Type of deposit or outcrop block	Distance from major fracture zones (miles)						
	0–1	1–2	2–4	4–8	8–16	16–32	32–64
Lower unit of the Chinle							
All 3-mile-square outcrop blocks	127	33	42	101	100	82	61
Percent of total	24	6	8	18	18	15	11
All 3-mile-square outcrop blocks with one or more deposits	33	12	14	32	20	11	0
Percent of total	27	10	11	27	16	9	0
All deposits	122	24	28	66	57	26	0
Percent of total	38	7	9	20	18	8	0
All deposits greater than 1,000 tons	23	8	2	1	0	7	0
Percent of total	56	20	5	2	0	17	0
Sandstones of the Morrison (entire Colorado Plateau)							
All 3-mile-square outcrop blocks	139	63	79	145	143	140	3
Percent of total	20	9	11	20	20	20	<1
All 3-mile-square outcrop blocks with one or more deposits	119	33	43	38	18	10	0
Percent of total	45	13	16	15	7	4	0
All deposits	1, 047	281	327	231	128	39	0
Percent of total	51	14	16	11	6	2	0
All deposits greater than 1,000 tons	156	32	48	18	5	2	0
Percent of total	60	13	17	7	2	1	0
Sandstones of the Morrison (western Colorado and salt anticline region)							
All 3-mile-square outcrop blocks	93	33	61	55	41	41	0
Percent of total	29	10	18	17	13	13	0
All 3-mile-square outcrop blocks with one or more deposits	60	14	22	9	0	0	0
Percent of total	57	13	21	9	0	0	0
All deposits	688	75	152	8	0	0	0
Percent of total	75	8	16	1	0	0	0

The major fault and fracture zones considered to be the loci of considerable vertical transmissive capacity and used in the foregoing analysis are listed below:

Major monoclinal axis.—Grand Hogback, Hogback Mountain monocline, Comb Ridge, Waterpocket fold, and Kaibab, Echo Cliffs, Organ Rock, and Lukachukai monoclines.

Fault and fracture zones associated with intrusives.—San Miguel intrusive center and the Rico, La Plata, Ute, Abajo, La Sal, Henry Mountains, Navajo Mountain, and Carrizo laccoliths.

Axial trace of steep limb of major uplifts and associated fault and fracture zones.—Blue Mountain, Gunnison, Uncompahgre, Circle Cliffs, Monument, Defiance, Zuni, and Nacimiento uplifts, and San Rafael Swell.

Faults and fracture zones associated with extrusives.—Mount Taylor volcanic field, Hopi Buttes volcanic field and many diatremes scattered over northern Arizona and northwestern New Mexico.

Salt anticlines.—Bordering fault traces where anticline is breached, and axial trace where unbreached.

INDEX

U. S. GOVERNMENT PRINTING OFFICE : 1962 O - 631709