Distribution of Elements in Sedimentary Rocks of the Colorado Plateau— A Preliminary Report

GEOLOGICAL SURVEY BULLETIN 1107-F

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By WILLIAM L. NEWMAN

CONTRIBUTIONS TO THE GEOLOGY OF URANIUM

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DISTRIBUTION OF ELEMENTS IN SEDIMENTARY ROCKS OF THE COLORADO PLATEAU—A PRELIMINARY REPORT

By William L. Newman

ABSTRACT

Study of the distribution, volume, and lithologies of sedimentary rocks of the Colorado Plateau, together with the distribution of elements contained within these rocks, was undertaken to provide background data that might further the understanding of the genesis of uranium deposits. The study of the sedimentary rocks was made in conjunction with related studies of uranium deposits and igneous rocks of the Colorado Plateau.

The gross chemical compositions of sandstone, mudstone, and limestone from many of the formations of the Colorado Plateau were determined chiefly by spectrographic analysis; selected suites of samples were analyzed by chemical methods. Spectrographic and chemical analyses were treated by conventional mathematical methods for grouped data.

The average chemical compositions of sandstone from the principal host rocks of the Colorado Plateau—the Shinarump and Moss Back members of the Chinle formation of Late Triassic age and the Salt Wash member of the Morrison formation of Late Jurassic age—differ only moderately from the average chemical compositions of sandstones from formations of Paleozoic and Mesozoic age on the Colorado Plateau. Sandstones of the Shinarump and Moss Back members contain more aluminum, iron, titanium, zirconium, vanadium, chromium, and copper than average sandstone of the Colorado Plateau, and less magnesium and calcium. Sandstones of the Salt Wash member contain more calcium and copper than the average sandstone of the plateau, and less boron, nickel, and cobalt. Sandstones of the Shinarump contain more titanium, zirconium, copper, chromium, cobalt, nickel, vanadium, than sandstones of the Salt Wash, and more than two times as much aluminum and iron.

Most of the uranium deposits of the Morrison formation occur in uppermost sandstone strata of the Salt Wash member. No significant chemical difference was found among the uppermost strata and the intervening and basal strata, except that the uppermost strata contain less potassium and calcium.

The distribution of copper and vanadium in unmineralized sandstone of the Salt Wash member corresponds favorably to the area comprising the Uravan mineral belt. There is a good possibility of defining similar large areas of potential uranium-bearing rock on the basis of variations in concentration of these two elements in unmineralized sandstone.

The distribution of elements commonly associated with igneous or crystalline rocks indicate three possible crystalline rock source areas for detrital minerals in sandstone of the Salt Wash member. These areas are the Meeker-Craig area of Colorado, an area just south of the so-called Four Corners in Arizona and New Mexico, and the San Rafael Swell area in east-central Utah.

The distribution of chromium, titanium, zirconium, boron, ytterbium, vanadium, uranium, and copper in unmineralized sandstones of the Shinarump and Moss Back members shows two areas that contain abnormally high concentrations of these elements and may reflect possible source areas for detritus in these members. One area is located in east-central Utah. The concentrations of elements in sandstone of this area may be the result of accumulation of material derived directly from the exposed Precambrian core of igneous and metamorphic rocks of the Uncompahgre highland.

The second area is located in southeastern Utah and forms an indistinct belt of ground extending northwestward from the Four Corners area. The source of the material containing these elements may have been the Cutler formation that was exposed over a large area adjacent to the western edge of the Uncompahgre highland during the beginning of Late Triassic time.

Studies of the variations in chemical composition of sandstone from many formations of the Colorado Plateau with regard to the occurrence of uranium deposits show that sandstones containing about half a percent of potassium or less are more favorable than sandstones containing more than half a percent of potassium. Favorable host rocks, as judged by potassium content, include (1) sandstones of the Dakota sandstone, the Cedar Mountain formation including the Buckhorn conglomerate member of Stokes (1952); and (2) the Burro Canyon formation, all of Cretaceous age; (3) the Salt Wash, Westwater Canyon, and Brushy Basin members of the Morrison formation of Jurassic age; (4) the Shinarump and Moss Back members of the Chinle formation of Triassic age; and (5) the Coconino sandstone of Permian age.

"Bleached" mudstone of the Moenkopi at, or close to, the contact between the Moenkopi and Chinle contains as much as 160 ppm uranium and more gallium, lanthanum, yttrium, ytterbium, scandium, niobium, and cerium than normal reddish-brown mudstone of the Moenkopi or Chinle formation. The accumulation of these elements may indicate the presence of a fossil soil that developed on the Moenkopi surface during the middle Triassic hiatus.

No chemical feature serves to distinguish bentonitic mudstone from nonbentonitic mudstone of the Brushy Basin member of the Morrison formation in the Yellow Cat area of Utah, or at Spring Creek Mesa, near Uravan, Colo. Likewise, except for calcium, no chemical feature serves to distinguish red mudstone from green mudstone of the Salt Wash member of the Morrison formation in the Jo Dandy area, Colorado.

Carbonate rocks of Precambrian and Paleozoic age exposed in the Grand Canyon, Ariz., show a progressive increase in magnesium content and a progressive decrease in calcium content in successively older rocks. The greatest change in magnesium content apparently occurs in the lower part of the Redwall limestone of Mississippian age where the magnesium content drops from more than 10 percent to about 0.07 percent. In addition to being lean in magnesium, the Redwall contains relatively little silicon, aluminum, iron, sodium, potassium, titanium, zirconium, barium, boron, scandium, cobalt, nickel, gallium, yttrium, and ytterbium. Concentrations of vanadium and chromium seem to be consistent in carbonate rocks of Precambrian and Paleozoic ages.

INTRODUCTION

Sandstone-type uranium deposits have a wide and scattered distribution on the Colorado Plateau. In spite of the wide areal distribution of uranium deposits, and even though deposits are known in host rocks of greatly different ages, most uranium ore has been mined from sandstone strata of Late Triassic and Late Jurassic ages. To provide information on the geochemical environment of the uranium deposits, a regional study of the distribution of elements in the rocks and ores of the Colorado Plateau was begun in 1951. The study of the distribution of elements in sedimentary rocks is part of a general study that includes the distribution of elements in sandstone-type uranium deposits and in the igneous rocks of the Colorado Plateau.

The work has been divided into two parts. The first part is a study of the physical features of the sedimentary rocks of the Colorado Plateau to establish a stratigraphic sequence for sampling and to provide data concerning the thicknesses, geographic distributions, and lithologies of systems, formations, and members.

The second part is a study of the chemical features of the sedimentary rocks of the Colorado Plateau to determine the average concentrations of elements for each rock unit investigated, to determine regional and stratigraphic variations in element content of some of the rock units, and to provide data from which to determine possible geochemical relationships between uranium deposits and host rocks.

The descriptions of physical features of the sedimentary rocks were compiled largely from data contained in published literature referred to in the text, the U.S. Geological Survey geological map of the United States (1932), the State geological maps of Colorado (Burbank and others, 1935), eastern and southern Utah (Andrews and Hunt, 1948), Arizona (Darton and others, 1924), and New Mexico (Darton, 1928).

Thanks are due to many members of the U.S. Geological Survey who have worked on one or more phases of this study, including analytical work and sample collection. The names of these Survey members are given in the text where the contribution of each is noted.

This paper was prepared as part of a program that is being conducted by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

PHYSICAL FEATURES OF SEDIMENTARY ROCKS

The Colorado Plateau covers an area of about 130,000 square miles in western Colorado, southeastern Utah, northern Arizona, and northwestern New Mexico. The exposed rocks range in age from Precambrian to Recent. Except for the Silurian, every geologic period is represented.

Some of the physical features of the sedimentary rocks of the Colorado Plateau are shown in a series of maps (figs. 42–68). These features include outcrop pattern, areal extent, thickness, volume of sediments, and lithologic composition of rock units, ranging from systems in the Paleozoic era to series, formations, and members in the Mesozoic era. Rocks of the Tertiary system are only briefly described.

TABLE 1.—*Original volumes of sediments of some of the principal rock units on the Colorado Plateau*

Rock unit	Volume of sedimentary rock (cubic miles)	Percent of—			Volume, in cubic miles		
		Limestone	Mudstone	Sandstone	Limestone	Mudstone	Sandstone
Cretaceous system:							
Upper Cretaceous series including Dakota sandstone	81,000	5	65	30	4,000	53,000	24,000
Dakota sandstone only	1,400	<1	30	70	0	400	1,000
Lower Cretaceous series	800	5	75	20	40	600	160
Jurassic system:							
Morrison formation	8,000	<1	60	40	0	4,770	3,230
Brushy Basin member	3,200	1	88	11	30	2,820	350
Westwater Canyon member	1,000	<1	20	80	0	200	800
Recapture member	1,300	1	50	49	10	650	640
Salt Wash member	2,500	1	41	58	30	1,020	1,450
Bluff sandstone	300	<1	2	98	0	10	290
Cow Springs sandstone	2,500	<1	2	98	0	50	2,450
Summerville formation	1,500	1	34	65	20	510	970
Todilto limestone	200	95	5	0	190	10	0
Curtis formation	700	10	10	80	70	70	560
Entrada sandstone	3,800	<1	2	98	0	100	3,700
Carmel formation	2,800	15	25	60	400	700	1,700
Navajo sandstone	11,000	<1	<1	100	0	0	11,000
Kayenta formation	1,100	<1	10	90	0	100	1,000
Triassic system:							
Wingate sandstone	3,000	<1	<1	100	0	0	3,000
Chinle formation, less basal sandstone units	16,000	5	55	40	800	8,800	6,400
Basal sandstone units of the Chinle formation, chiefly the Shinarump and Moss Back member	1,000	<1	10	90	0	100	900
Moenkopi formation	10,000	20	30	50	2,000	3,000	5,000
Permian system including Cutler formation	39,000	10	25	65	4,000	10,000	25,000
Cutler formation only	6,000	<1	30	70	0	1,800	4,200
Pennsylvanian system	30,000	65	10	25	19,500	3,000	7,500
Mississippian system	8,500	90	5	5	7,700	400	400
Devonian system	5,800	80	10	10	4,600	600	600
Cambrian system	16,000	20	50	30	3,200	8,000	4,800

The lithologic components of sediments on the Colorado Plateau have been grouped into three broad categories: (1) sandstone, including quartzite and conglomerate; (2) mudstone, including siltstone, claystone, and carbonaceous material; and (3) limestone, including gypsum and dolomite. The proportions of sandstone, mudstone, and limestone of each rock unit described are shown on a ternary diagram accompanying each map. These proportions have been estimated from published geologic sections and from other data of the U.S. Geological Survey. An effort was made to obtain at least 10 stratigraphic sections per reported unit upon which to base the proportionate amounts of the 3 rock types. Volumes of sediments were calculated from planimetric measurements of isopachs of each rock unit. As a check on the validity of the calculations, the volumes of formations and systems in the Paleozoic and Mesozoic eras were totaled for each era and compared with volumes calculated from isopach maps of each era (McKee, 1951). Comparison of the 2 sets of data showed differences of less than 5 percent. Volumes of sediments and proportions of sandstone, mudstone, and limestone of each rock unit described are summarized in table 1.

PRECAMBRIAN SEDIMENTARY ROCKS

Unmetamorphosed Precambrian sedimentary rocks crop out on the north and south margins of the Colorado Plateau, but within the plateau, exposures are limited to the Uinta Mountains area, Utah (Childs, 1950; Crittenden, 1950; Forrester, 1937; Kinney, 1955; and Weeks, F. B., 1907), the Grand Canyon area (Noble, 1914; Van Grundy, 1951; and Gregory, 1917), and the Defiance uplift (Allen and Balk, 1954) of Arizona. (See fig. 42.) Precambrian sedimentary rocks consist of arkose and quartzite in the Uinta Mountains, quartzite in the Defiance uplift, and limestone, shale, and quartzite in the Grand Canyon. In areas adjacent to the Colorado Plateau, Precambrian sedimentary rocks crop out in the San Juan Mountains of Colorado (Cross and others, 1905), in the Wasatch Mountains of Utah (Eardley and Hatch, 1940; Calkins and Butler, 1943), and in the Sierra Ancha region of central Arizona (Darton, 1932). (See fig. 42.) Precambrian metamorphic rocks, including metasedimentary and metaigneous rocks, are exposed on the Uncompahgre Plateau, Colo., in the Black Canyon of the Gunnison River, Colo. (Hunter, 1925), the Zuni Mountains region, New Mexico, and the Grand Canyon, Ariz. This report does not include results of studies of the metamorphic rocks, however.

At all exposures the Precambrian rocks are overlain unconformably by younger rocks, and the unconformity is marked by a beveled surface. Rocks of Cambrian age overlie the Precambrian in the Uinta Mountains and in the Grand Canyon, whereas rocks of Permian age rest upon the Precambrian on the Defiance uplift.

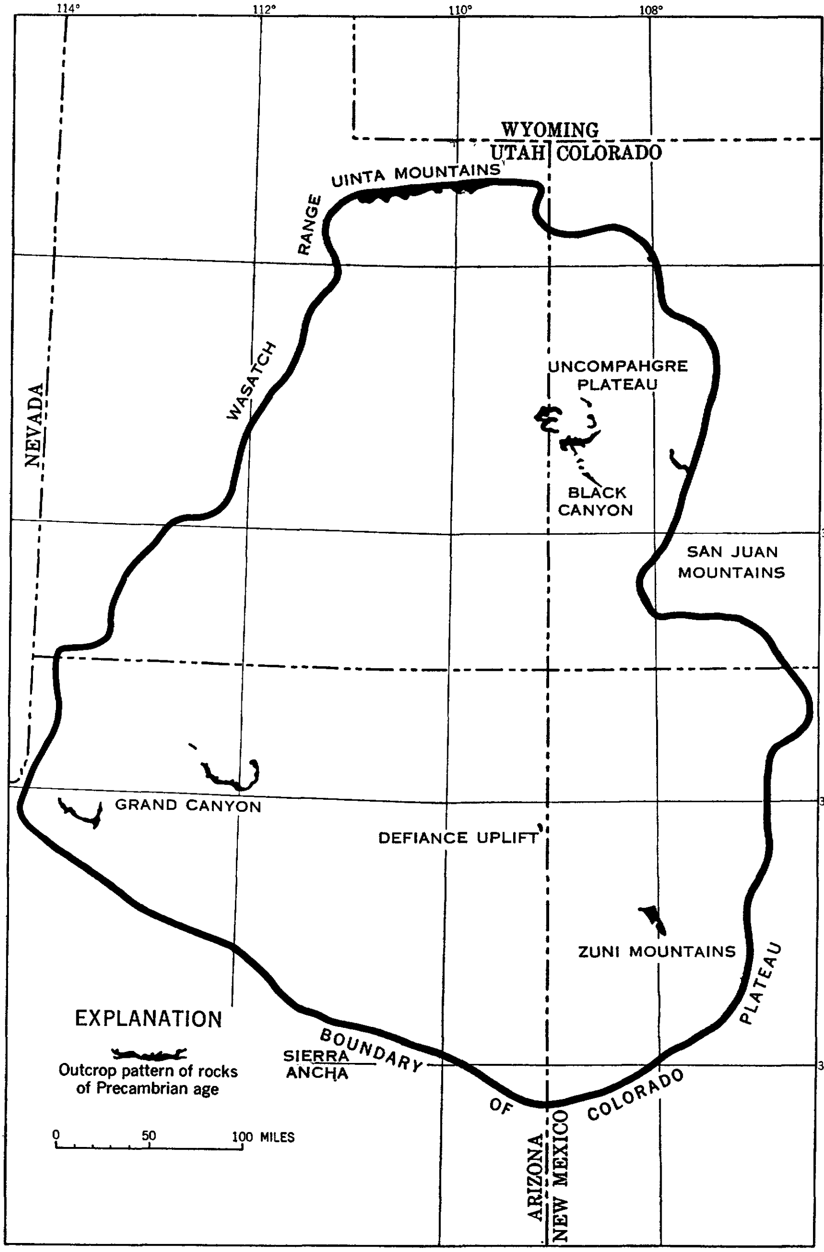
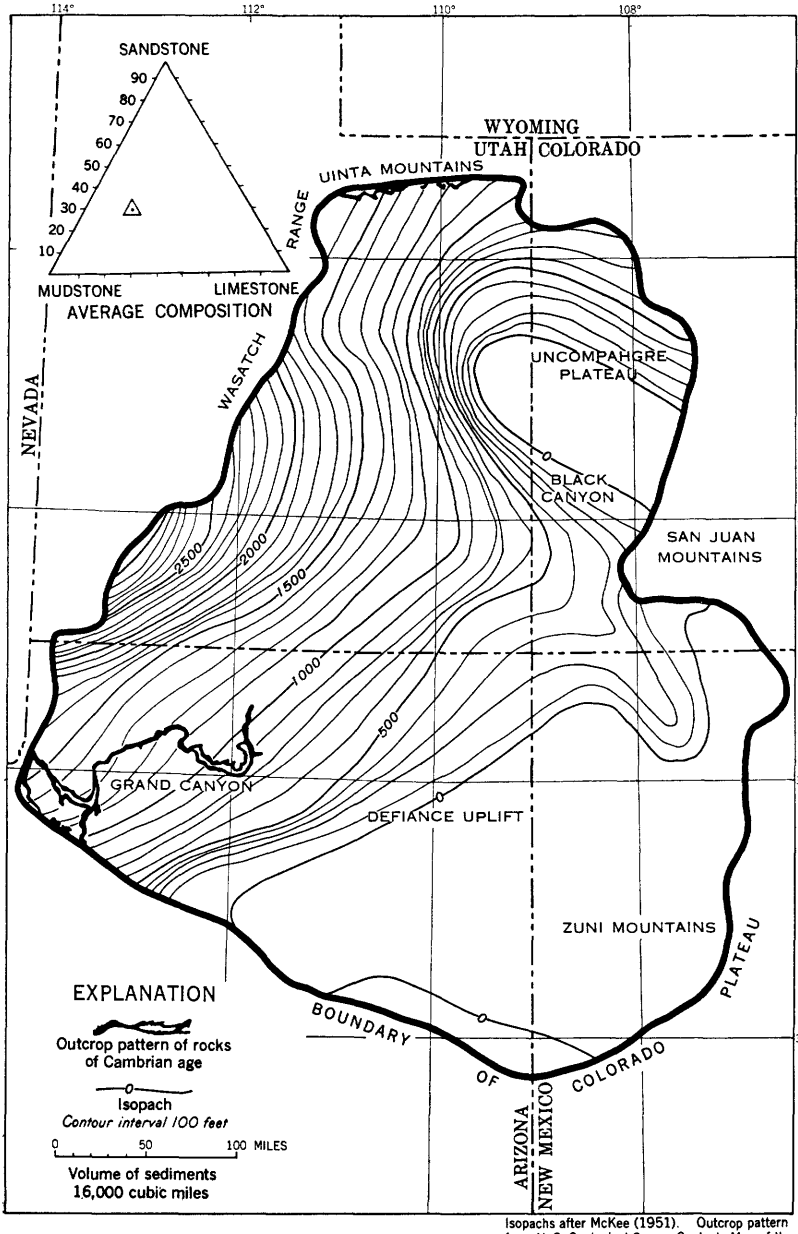


FIGURE 42.—Map of the Colorado Plateau showing outcrop pattern of rocks of Precambrian age.

CAMBRIAN SYSTEM

Rocks of known Cambrian age underlie about 89,000 square miles of the Colorado Plateau area and are exposed at two widely separated localities (fig. 43): (1) within the Grand Canyon of northwestern



Isopachs after McKee (1951). Outcrop pattern from U. S. Geological Survey Geologic Map of the United States, 1932

FIGURE 43.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Cambrian system.

Arizona (Bass, 1944, 1950; Howell and others, 1944; McKee, 1945; McKee, 1951; and Noble, 1914) and (2) along the flanks of the Uinta Mountains (Atwood, 1909; Baker and others, 1949; Crittenden, 1950;

and Weeks, F. B., 1907). Rocks of Cambrian age are also exposed adjacent to the Colorado Plateau in the San Juan Mountains region of southwestern Colorado (Cross and Larsen, 1935) and in the Wasatch Mountains of Utah (Howell and others, 1944; Atwood, 1909). Rocks of Cambrian age consist of quartzite in the San Juan Mountains region; conglomerate, sandstone, siltstone, mudstone, and limestone in the Grand Canyon; and varicolored sandy shales in the Uinta Mountains.

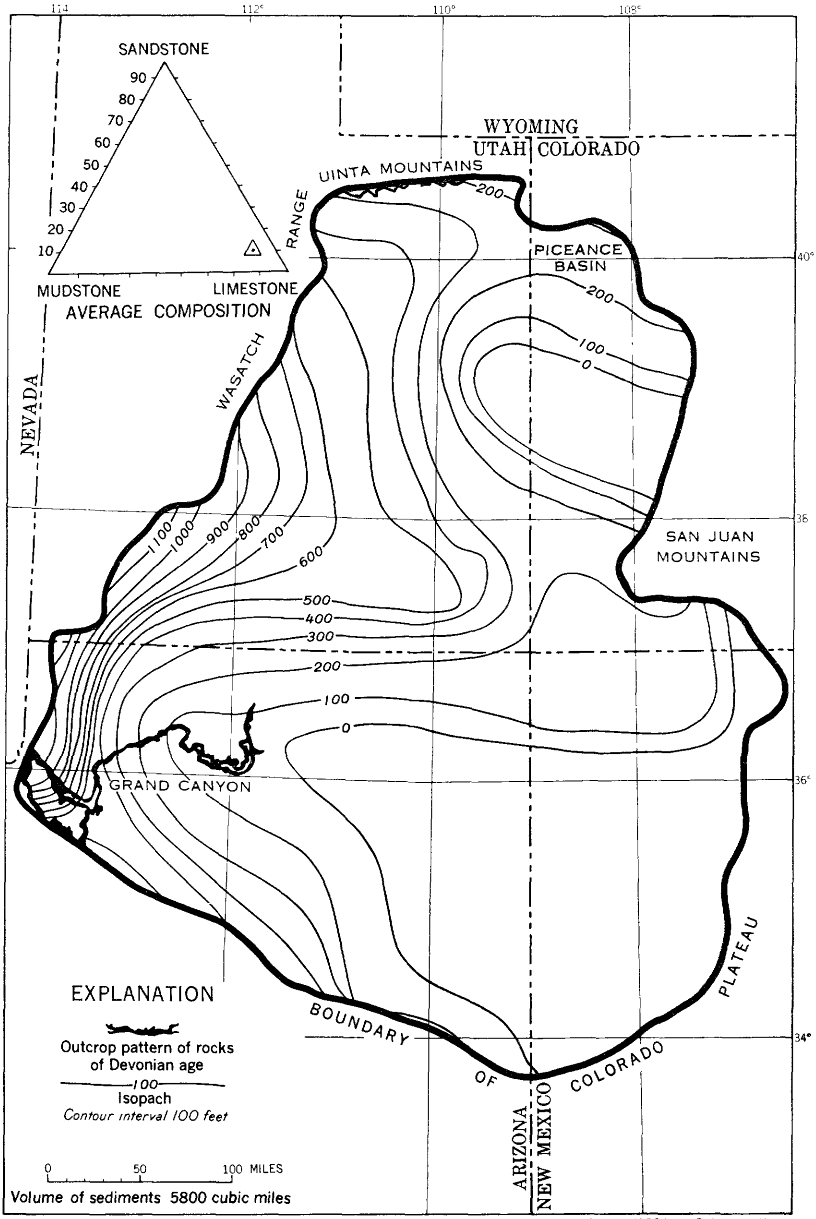
The volume of sediments of Cambrian age is about 16,000 cubic miles, of which about 50 percent is composed of mudstone, 30 percent of sandstone, and 20 percent of limestone (table 1). These figures are estimated from published stratigraphic sections of rocks of Cambrian age measured in the Uinta Mountains, the Grand Canyon, and the San Juan Mountains region.

ORDOVICIAN SYSTEM

Rocks of Ordovician age have been tentatively recognized in deep drill holes and in exposures along the northeast margin of the Colorado Plateau and in Glenwood Canyon, Colo. These rocks, for the most part, consist of thin beds of limestone pebble conglomerate, limy shale, and thin-bedded brown siliceous dolomite. Formations of Ordovician age on the Colorado Plateau are thin, and they are included with the Cambrian system in figure 43.

DEVONIAN SYSTEM

Rocks of Devonian age (Cooper and others, 1942) underlie about 91,000 square miles of the Colorado Plateau area and crop out in the Grand Canyon (Noble, 1914; Darton, 1910; and McKee, 1951), along the south flank of the Uinta Mountains (Baker and others, 1949; Weeks, 1907), and in the Piceance basin of northwestern Colorado (Bass and Northrop, 1955). (See fig. 44.) Rocks of Devonian are also exposed just east of the Colorado Plateau in the San Juan Mountains (Cross and Larsen, 1935) of southwestern Colorado and in the Wasatch Mountains of Utah, west of the Colorado Plateau. Rocks of Devonian age consist chiefly of limestone interbedded with minor amounts of shale and quartzite. The volume of sediments of Devonian age on the Colorado Plateau totals about 5,800 cubic miles. Of this total, 80 percent consists of limestone, 10 percent of mudstone, and 10 percent of sandstone (table 1). These figures are estimated from published stratigraphic sections of rocks of Devonian age measured in the Uinta Mountains, the Grand Canyon, and the San Juan Mountains region.



Isopachs after McKee (1951) Outcrop pattern from U. S Geological Survey Geologic Map of the United States, 1932

FIGURE 44.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Devonian system.

MISSISSIPPIAN SYSTEM

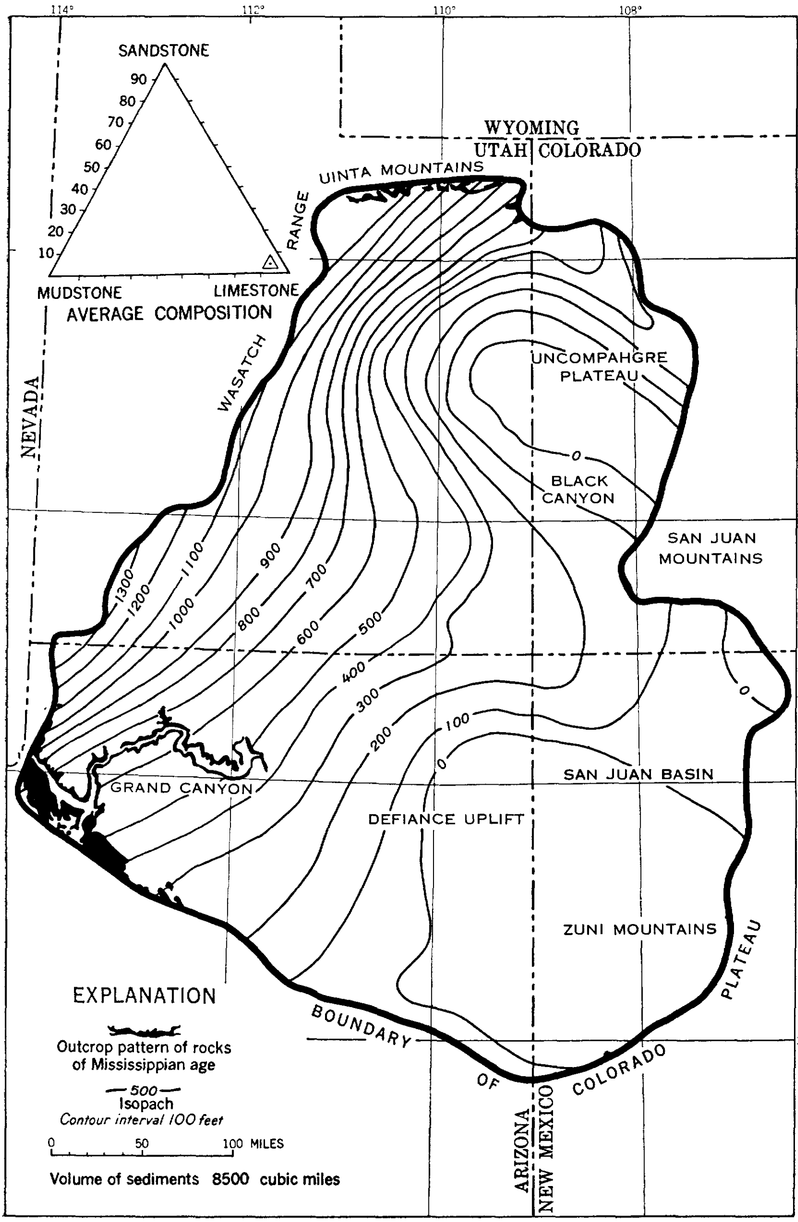
Rocks of Mississippian age (Weller and others, 1942) underlie about 99,000 square miles of the Colorado Plateau area and consist almost entirely of limestone and minor amounts of sandstone and shale. The rocks include the Redwall limestone of the Grand Canyon (Noble, 1914; McKee, 1951; and Darton, 1910), the Madison limestone, the Deseret limestone, Humbug formation, an unnamed black shale, and possibly part of the Morgan formation [now considered to be of Pennsylvanian age] in the Uinta Mountains (Baker and others, 1949; Bissel, 1950; and Weeks, F. B., 1907) and Wasatch Mountains. Rocks of Mississippian age in the San Juan Mountains region (Cross and Larsen, 1935) consist of limestones of the Leadville limestone (also locally known as the Macho limestone in the subsurface of the San Juan basin, see Di Giambattista, 1952). Exposures of positively indentified rocks of Mississippian age on the Colorado Plateau are found only in the Grand Canyon region and along the south flank of the Uinta Mountains. (See fig. 45.) In this study none of the Morgan formation has been included with rocks of Mississippian age.

The volume of preserved sediments before Tertiary erosion totals about 8,500 cubic miles, of which 90 percent is limestone, 5 percent is mudstone, and 5 percent is sandstone (table 1). These figures are estimated from published stratigraphic sections of rocks of Mississippian age measured in the Grand Canyon, the Uinta Mountains, and the San Juan Mountains region.

PENNSYLVANIAN SYSTEM

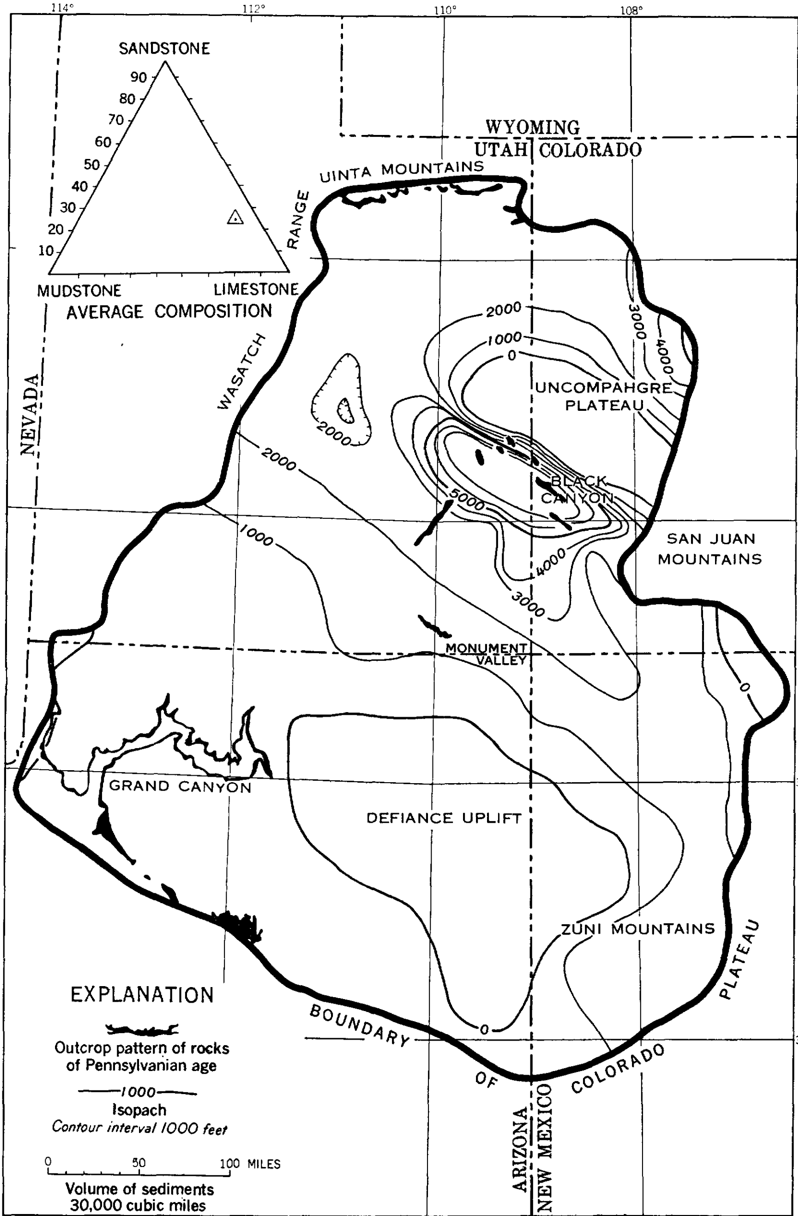
Rocks of Pennsylvanian age (Moore, and others, 1944) underlie about 105,000 square miles of the Colorado Plateau area and are exposed in the Grand Canyon of Arizona (Noble, 1914; Darton, 1910; and McKee, 1951), along the flanks of the Uinta Mountains (Baker and others, 1949; Bissell, 1950; Schultz, 1918; and Weeks, 1907), in the San Juan Mountains region of Colorado (Cross and Larsen, 1935), in anticlinal structures in Colorado and eastern Utah (Baker and others, 1933; Bass, 1944), and in southeastern Utah in Monument Valley (Baker, 1936; Gregory, 1938). (See fig. 46.)

Rock types range from sandstone, shale, and limestone of the lower part of the Supai formation in the Grand Canyon; sandstone, limestone, black shale, and evaporites of the Hermosa formation exposed in the anticlinal structures; to quartzite and calcareous sandstones of the Weber and Morgan formations in the Uinta Mountains area. Rocks of Pennsylvanian age in the San Juan Mountains region consist of red friable sandstone and limestone lenses of the Molas formation; a series of alternating limestone, shale, and sandstone of the Hermosa formation; and a series of red shale and sandstone beds of the Rico



Isopachs after McKee (1951). Outcrop pattern after U. S. Geological Survey Geologic Map of the United States, 1932

FIGURE 45.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Mississippian system.



Isopachs after McKee (1951). Outcrop pattern from U. S. Geological Survey Geologic Map of the United States, 1932

FIGURE 46.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Pennsylvanian system.

formation (Henbest, 1948). Exposures of the Rico of Pennsylvanian and Permian age along the San Juan River in southeastern Utah consist chiefly of limestone and red mudstone. Equivalents of the Manning Canyon shale of Mississippian and Pennsylvanian age and the Oquirrh formation of Pennsylvanian and Permian age of the Wasatch Mountains, Utah (Baker and others, 1949), and of the Maroon formation of Pennsylvanian and Permian age and the Gothic formation of Langenheim (1952) of northwestern Colorado (Bass, 1944; Wood, G. H., and others, 1946) probably are represented in the subsurface on the Colorado Plateau.

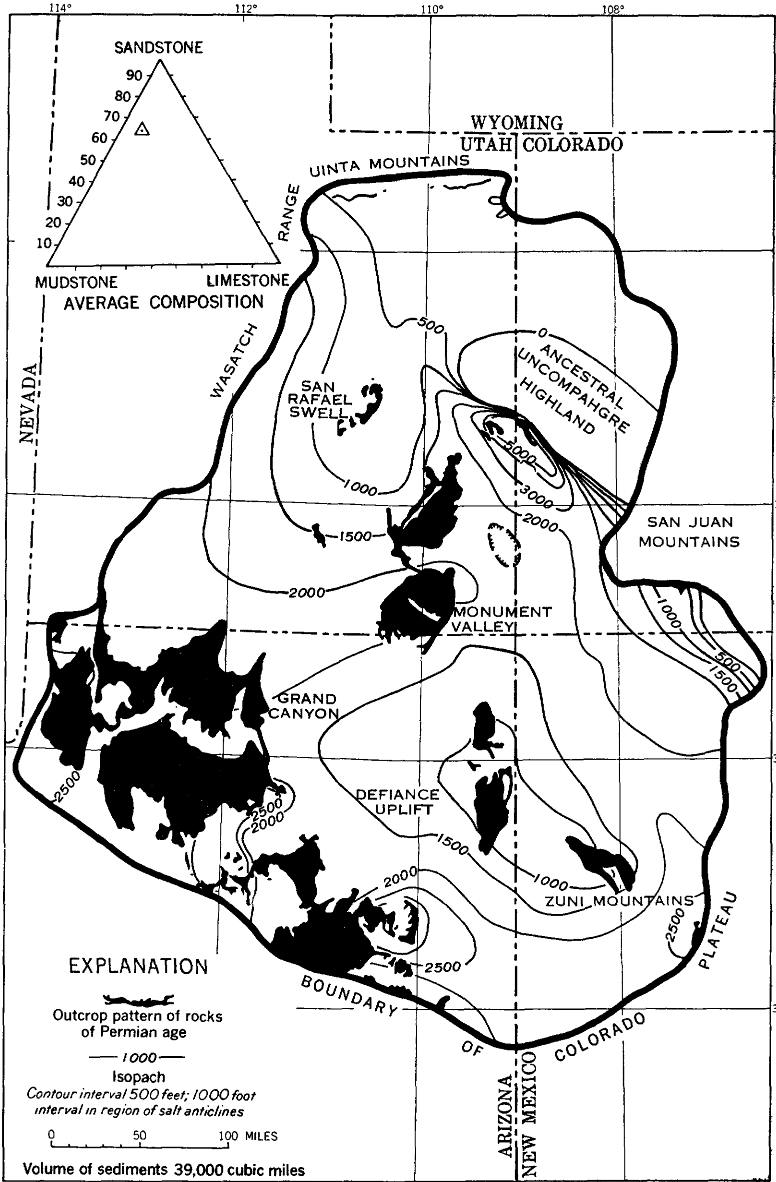
The volume of sediments of Pennsylvanian age deposited on the Colorado Plateau totaled about 30,000 cubic miles. Limestone is estimated to constitute about 65 percent of this volume, sandstone about 25 percent, and mudstone about 10 percent (table 1). These figures are estimated from published stratigraphic sections of rocks of Pennsylvanian age measured in the Grand Canyon, the Uinta Mountains, the San Juan Mountains, and Monument Valley regions of southern Utah and the region of salt anticlines in western Colorado and eastern Utah.

PERMIAN SYSTEM

Rocks of Permian age originally covered about 120,000 square miles of the Colorado Plateau area (fig. 47) and are exposed chiefly in the Grand Canyon region (Noble, 1914; McKee, 1938) the Defiance uplift (Baker and Reeside, 1929); and the southern margin of the Colorado Plateau in Arizona (Darton, 1910); the Zuni Mountains, N. Mex. (Bass, 1944; Read, 1950), Monument Valley (Baker, 1936; Gregory, 1938), San Rafael Swell (Gilluly and Reeside, 1928), and the Uinta Mountains, Utah (Baker and others, 1949; Bissell, 1950, 1952; Thomas and Krueger, 1946; Schultz, 1918); and in the salt anticlinal structures of western Colorado and eastern Utah (Baker, 1933, 1935).

Rocks of the Permian system are generally sandstone, grit, and conglomerate, but they include some red shale and sandy limestone. Permian rocks contrast strongly with rocks of early Paleozoic time. Sediments of early Paleozoic age consist dominantly of carbonates and fine clastics, whereas sediments of Permian age include great thicknesses of conglomerate, arkose, and sandstone and only minor amounts of limestone.

The Permian in the Uinta Mountains area is characterized by red shales, sandstones, clays, and argillaceous limestones. The rocks of Permian age in the Grand Canyon include sandstone and siltstone of the upper part of the Supai formation, shales of the Hermit shale, sandstone of the Coconino sandstone, and shales and limestones of the Toroweap and Kaibab formations. Exposures of rocks of Permian



Isopachs after McKee (1951). Outcrop pattern from U. S. Geological Survey Geologic Map of the United States, 1932, and Andrews and Hunt (1948)

Figure 47.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Permian system.

age in the Monument Valley region of Utah consist of great thicknesses of sandstones of the Cutler formation, parts of which are equivalents of the Coconino sandstone (Baker and Reeside, 1929). In the San Juan Mountains region (Cross and Larsen, 1935), east of the Colorado Plateau, the rocks of Permian age are chiefly reddish sandstone, arkose, and conglomerate, but they include some sandy shale and sandy limestones of the Cutler formation. In the Zuni Mountains the rocks of Permian age consist chiefly of quartzose and arkosic sandstone, fine-grained sandstone, and siltstone, and some limestone beds of the Abo, Yeso, and San Andres formations.

The volume of sediments deposited during Permian time totals about 39,000 cubic miles. About 65 percent of this volume is estimated to be sandstone, 10 percent limestone, and 25 percent mudstone (table 1). These figures are estimated in part from an average of published stratigraphic sections of formations of Permian age measured in the Grand Canyon, the Defiance uplift, the Zuni Mountains, Monument Valley, San Rafael Swell, Uinta Mountains, and the region of salt anticlines in western Colorado and eastern Utah and in part from sections measured by members of the U.S. Geological Survey at Monument Valley, Clay Hills, Poncho House, Monitor Butte, Comb Wash, and the area between the Green and Colorado Rivers, Utah, and Owl Rock, Ariz. (figs. 73, 76).

For this report, estimates of the volume and lithologic features of the Cutler formation were prepared separately. The Cutler formation of Baker (1936) in southern Utah and northern Arizona consists of the following units, in ascending order: The Halgaito tongue, Cedar Mesa sandstone member, Organ Rock tongue, De Chelly sandstone member, and Hoskinnini tongue.[1] In part of eastern Utah and southwestern Colorado, the Cutler formation is a thick wedge of coarse arkosic debris derived from and surrounding the Precambrian core of the ancestral Uncompahgre highland.

Although a separate outcrop and isopach map of the Cutler formation is not included, the following data are a summary of the thickness, areal extent, and lithology compiled from 13 measured sections from localities selected to represent the Cutler formation on the Colorado Plateau (table 1):

Cutler formation

Areal extent ---------- square miles --	23, 000
Volume ---------- cubic miles --	6, 000
Amount of sandstone ---------- percent --	70
Amount of mudstone ---------- do ----	30

[1] Recent work by Stewart (1959) shows that the Hoskinnini tongue is in part equivalent to lower beds of the Moenkopi formation. For statistical treatment in this report, however, rocks of the Hoskinnini tongue have been considered to be part of the Cutler formation.

TRIASSIC SYSTEM

The Triassic system of the Colorado Plateau consists of three formations; in ascending order, they are the Moenkopi, the Chinle, and the Wingate sandstone. On the northwestern margin of the Colorado Plateau the equivalent of the Moenkopi formation includes three formations—the Woodside, Thaynes, and Ankareh; the equivalent of the Chinle formation locally is called the Stanaker formation of Thomas and Krueger (1946). A sandstone at the base of the Chinle formation in the Uinta Mountains, locally known as the Gartra grit member of the Stanaker formation of Thomas and Krueger (1946), may possibly be the equivalent of the Shinarump member or the Moss Back member, which are sandstone beds in the lower part of the Chinle of the central part of the Colorado Plateau. Similarly, the Agua Zarca sandstone member of the Chinle of northwestern New Mexico (Wood, S. A., and others, 1946) is possibly equivalent to beds in the lower part of the Chinle of Arizona. The volume of sediments of Triassic age deposited on the Colorado Plateau totals about 30,000 cubic miles.

MOENKOPI FORMATION

The Moenkopi formation originally covered about 85,000 square miles in the western part of the Colorado Plateau (Gilluly and Reeside, 1928; Gregory, 1938, 1950; McKee, 1951; Shoemaker and Newman, 1959). It is exposed in a rather narrow southeastward-trending belt across northeastern Arizona and as narrow belts and patches in southeastern Utah and western Colorado (fig. 48). The equivalent Ankareh, Thaynes, and Woodside formations are exposed along the south flank of the Uinta Mountains (Forrester, 1937; Stokes, 1950; Thomas and Krueger, 1946; Williams, 1945) and are included in the outcrop pattern of the Moenkopi formation.

The Moenkopi formation is a wedgelike unit that thins from more than 2,000 feet in western Utah and southern Nevada to a featheredge that coincides approximately with the Arizona-New Mexico and Utah-Colorado boundaries (McKee, 1954). The formation is partly marine and partly continental in origin in the western section and is interpreted by McKee as mainly continental in origin in the eastern section.

In western Colorado and eastern Utah the deposition of the Moenkopi formation was influenced by the presence of northwest-trending anticlines with evaporite cores. Accumulations of arkose, micaceous sands, silts, and muds from the Uncompahgre highland were deposited in deep local basins that surrounded the salt anticlines (Shoemaker and Newman, 1959). Rocks of the Moenkopi formation in places wedge out against the flanks of the anticlines as a result of erosion before deposition of the overlying Chinle formation.

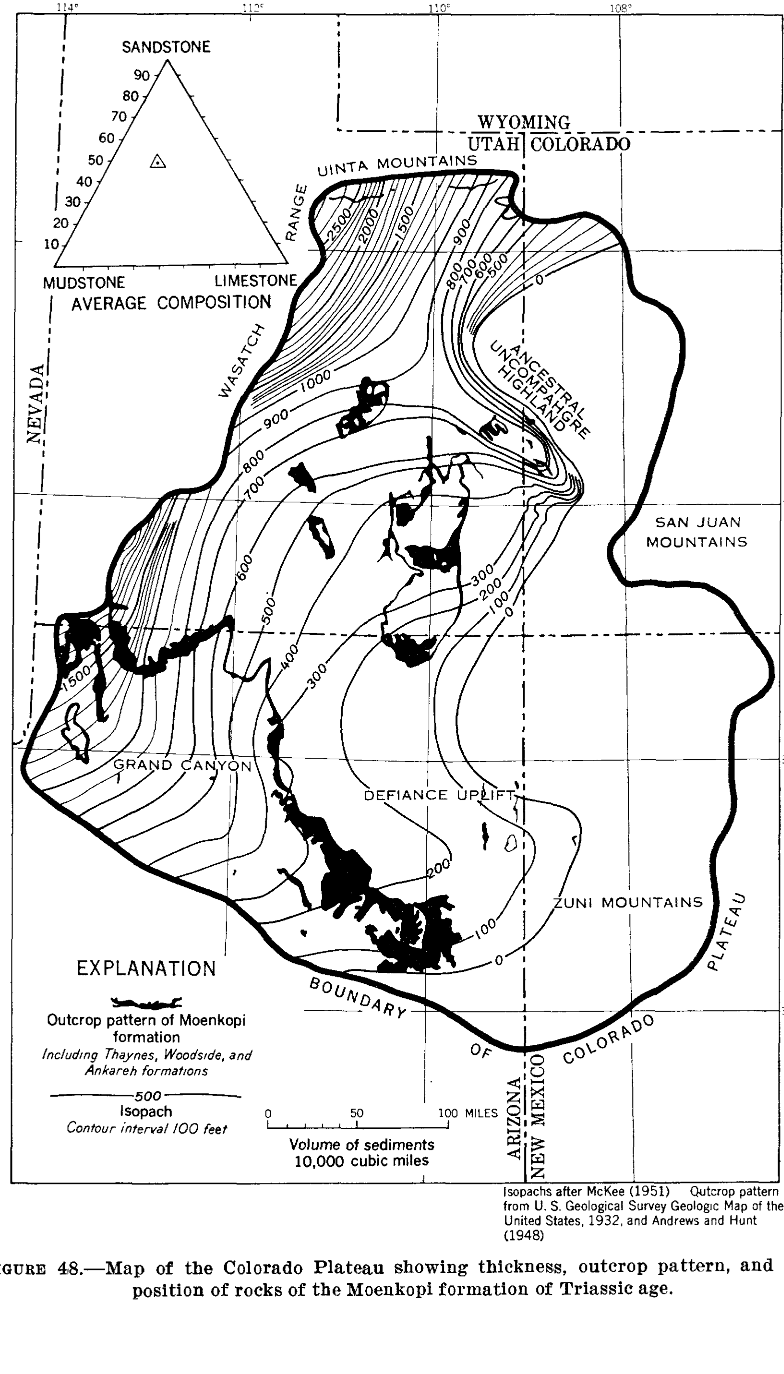


FIGURE 48.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Moenkopi formation of Triassic age.

The volume of sediments of the Moenkopi deposited on the Colorado Plateau totals about 10,000 cubic miles. Limestone makes up about 20 percent of this volume, mudstone about 30 percent, and sandstone about 50 percent (table 1). These figures are in part estimated from published stratigraphic sections of the Moenkopi and equivalent formations measured in the Uinta Mountains, the Park City district, the San Rafael Swell, and the San Juan region, Utah, and the Little Colorado River Valley in Arizona and in part from sections measured by members of the U.S. Geological Survey in the San Rafael Swell, and at Poncho House, Monitor Butte, North Six-shooter Peak, Comb Wash, and in the area between the Green and Colorado Rivers, Utah, and Owl Rock, Ariz. (figs. 73, 76).

CHINLE FORMATION

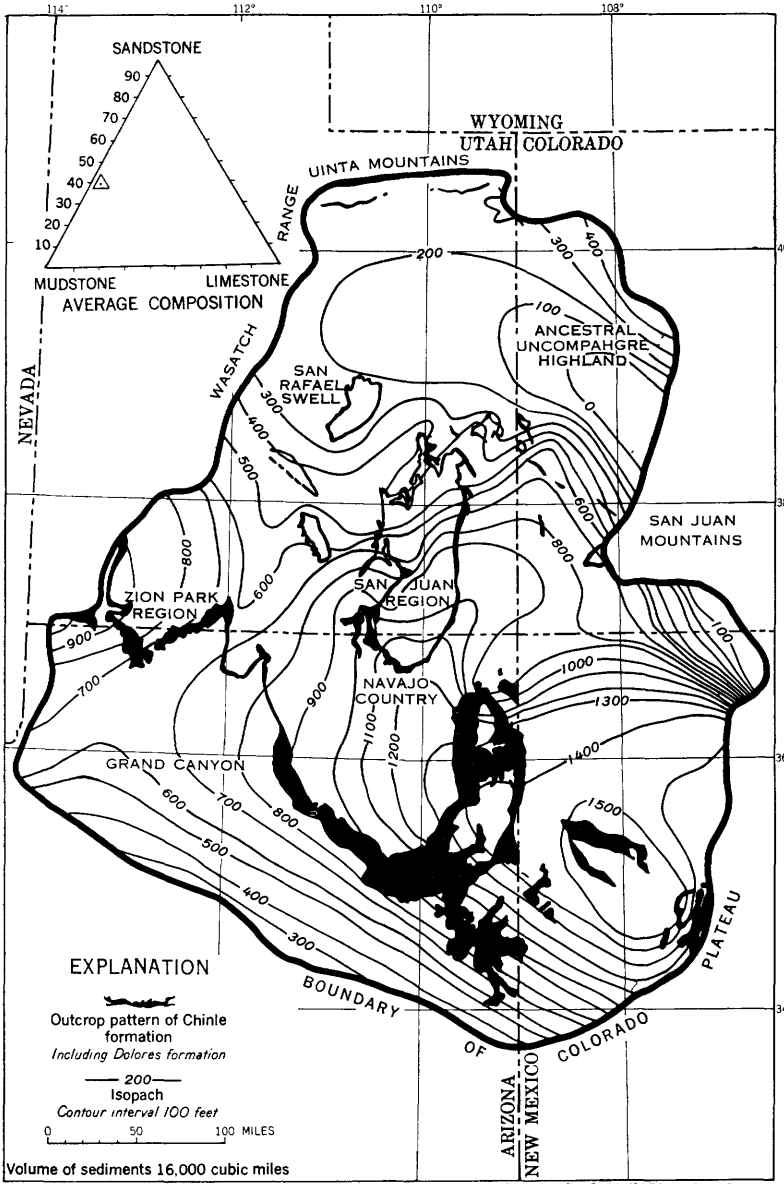
Rocks of the Chinle formation and its equivalents extend far beyond the eastward limit of Lower Triassic rocks and originally covered about 110,000 square miles of the Colorado Plateau area (fig. 49). The Chinle crops out along the southern flanks of the Uinta Mountains of Utah (Stokes, 9150; Thomas and Krueger, 1946), along valley walls of the collapsed salt anticlines in southwestern Colorado and eastern Utah (Cater, 1955a, b), and along major structures in the center of the Colorado Plateau (Gilluly and Reeside, 1928); extensive exposures are found in northern Arizona and northeastern New Mexico (McKee, 1951; Gregory, 1917, 1938, 1950; Harshbarger and others, 1957).

The Dolores formation of western Colorado (Cross and Larsen, 1935) and the Stanaker formation (restricted) of the Uinta Mountains described by Thomas and Krueger (1946) are considered to be equivalents of the Chinle formation.

Rocks of the Chinle formation are of continental origin and consist chiefly of variegated claystone, mudstone, siltstone, and sandstone and minor amounts of fresh-water limestone.

A sequence of rocks, chiefly sandstone, of Triassic(?) age extends throughout most of the western part of the Navajo Country, Ariz., where it overlies the Chinle formation and underlies the Kayenta formation. This sequence has been named the Moenave formation and has been assigned to the Glen Canyon group (Harshbarger and others, 1957); however, these rocks were previously mapped partly as Wingate sandstone and partly as Chinle. For this report these rocks now assigned to the Moenave formation have been included with rocks of the Chinle formation after Gregory (1950).

As a result of recent stratigraphic studies of the Chinle formation on the Colorado Plateau, the lowermost Upper Triassic rocks of the Chinle are divided into three members; in ascending order they are



Isopachs after Smith (1951, fig. 1). Outcrop pattern compiled from U. S. Geological Survey Geologic Map of the United States, 1932; Andrews and Hunt (1948), and Darton, Lausen, and Wilson (1924)

FIGURE 49.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Chinle formation of Triassic age.

the Shinarump, the Monitor Butte, and the Moss Back (Stewart, 1957).

The volume of sediments of the Chinle formation originally deposited—less the Shinarump and Moss Back members—totals about 16,000 cubic miles. Limestone constitutes about 5 percent of this volume, mudstone 55 percent, and sandstone 40 percent (table 1). These figures are estimated in part from published stratigraphic sections of the Chinle and equivalent formations measured in the Uinta Mountains, San Rafael Swell, the Navajo Country, and the San Juan, Zion Park, and San Juan Mountains regions, and in part from sections measured by members of the U.S. Geological Survey at Poncho House, Monitor Butte, Comb Wash, San Rafael Swell, Lockhart Canyon, and in the area between the Green and Colorado Rivers, Utah, and Owl Rock, Ariz. (figs. 73, 76).

BASAL SANDSTONE UNITS OF THE CHINLE FORMATION

Basal sandstone units of the Chinle formation, as used in this report, include rocks of the Shinarump and Moss Back members as defined by Stewart (1957), the Poleo sandstone lentil, the Agua Zarca sandstone member, the Gartra grit member of the Stanaker formation of Thomas and Krueger (1946), and several unnamed sandstone units.

Rocks of the Shinarump member of the Chinle formation extend throughout much of northern Arizona and southern Utah, but the member thins and reaches an irregular northern limit about 60 miles north of the Utah-Arizona State line. The southern limit of known Shinarump is marked by a belt of exposures extending from the Virgin River near Hurricane in southeastern Utah, following roughly the north side of the Little Colorado River (Finch, 1955; Gregory, 1917, 1938, 1950). The extent of the Shinarump member in northwestern New Mexico and western Colorado is not well known. Although the area underlain by the Shinarump on the Colorado Plateau is probably large, the member rarely exceeds 100 feet in thickness.

The Moss Back member of the Chinle formation was formerly included with the Shinarump conglomerate of Gregory (1938), Gilluly and Reeside (1928), Baker (1946), and Hunt (1953). The Moss Back forms a northwest-trending lens, about 50 miles wide and 155 miles long that extends from southwestern Colorado to central Utah (Stewart, 1957). Mapping and stratigraphic study have shown that it is a discrete sandstone separated from the Shinarump by as much as 250 feet of interbedded claystone and sandstone. The southern limit of the Moss Back roughly coincides with the northern limit of the Shinarump. The Moss Back may be equivalent to the Poleo sandstone lentil of the Chinle formation in New Mexico (Wood, G. H., and others, 1946) and to the Santa Rosa sandstone that crops out in central and eastern New Mexico.

The Gartra grit member of Thomas and Krueger (1946), found along the southern flank of the Uinta Mountains, may be equivalent to either the Moss Back or the Shinarump member of the Chinle. Kinney (1955, p. 63) retains the name Shinarump conglomerate for beds formerly called Gartra grit (Thomas and Krueger, 1946, p. 270) in the eastern Uinta Mountains area.

The lithology of the basal units is not uniform, but they are composed mainly of arkosic sandstone and conglomerate with abundant tuffaceous material. Large areas do not contain conglomerate lenses, but where conglomerate is conspicuous, lenses of shale, siltstone, and lime pellets are generally present. Fossil wood and bone are common. The major sedimentary structures are channels cut into underlying shales.

In estimating the volume and lithologic characteristics of these basal sandstone units, they have been treated as a single unit. The outcrop pattern of this composite unit is shown in figure 50.

The volume of the basal sandstone units is estimated to be about 1,000 cubic miles; it was calculated by assuming that the average thickness of these beds is 40 feet throughout the Colorado Plateau. Isopach lines were not drawn on the outcrop map because of the difficulty experienced in showing all the members as a single unit, and because of erratic local variations in thickness of each member. Sandstone is estimated to constitute about 90 percent of this volume and mudstone the remaining 10 percent; limestone probably makes up less than 1 percent (table 1).

WINGATE SANDSTONE

The Wingate sandstone (Baker and others, 1936, 1947) is the basal formation of the Glen Canyon group. It underlies the central part of the Colorado Plateau, and had an original areal extent of about 81,000 square miles within the plateau (fig. 51). The thickest sections of Wingate sandstone are in southeastern Utah, northeastern Arizona, and northwestern New Mexico (Gregory, 1938; Harshbarger and others, 1951; Harshbarger and others, 1957) where the formation is more than 400 feet thick. In the Navajo Country the Wingate sandstone consists of two mappable units: a lower Rock Point member and an upper Lukachukai member (Harshbarger and others, 1957). The Rock Point member of the Wingate correlates with an upper member of the Chinle formation, the Church Rock member, in southeastern Utah. The Rock Point member of the Wingate sandstone is here included as part of the Chinle formation.

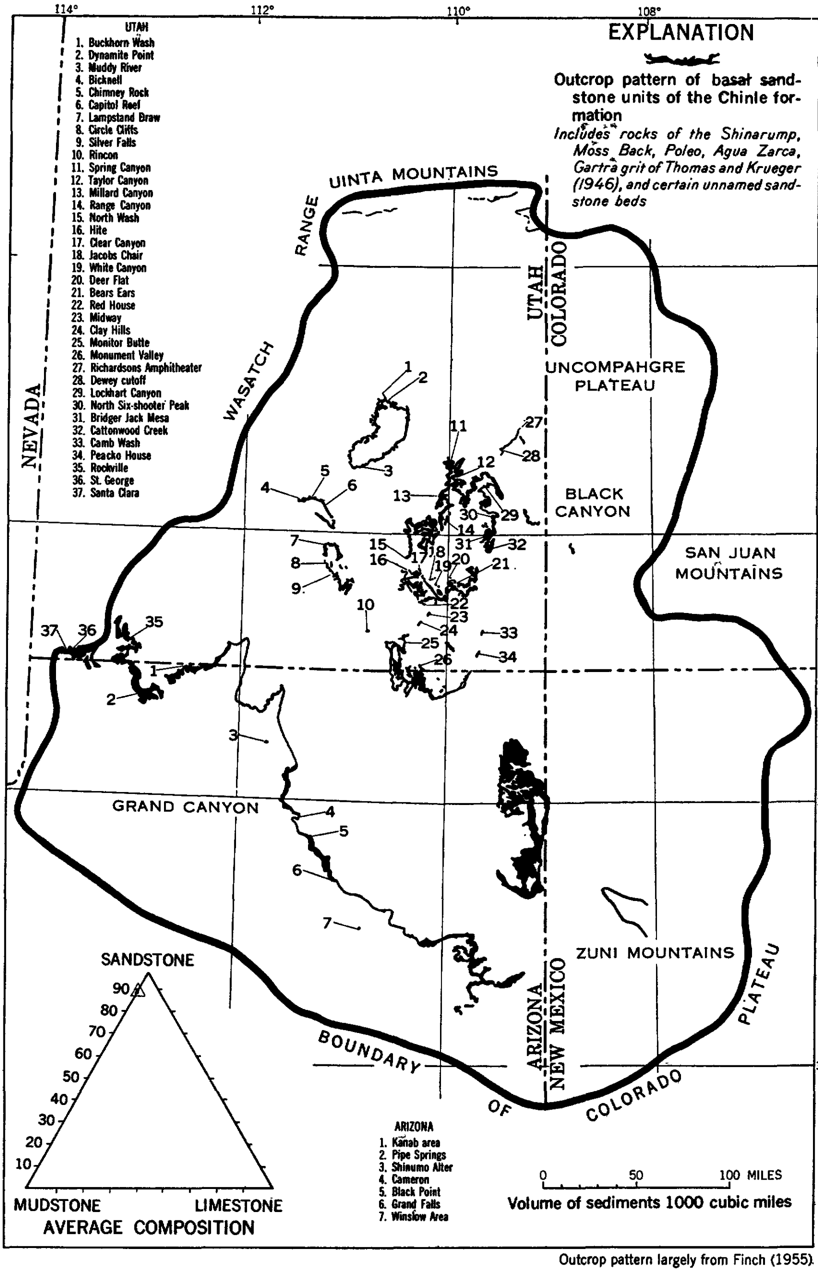
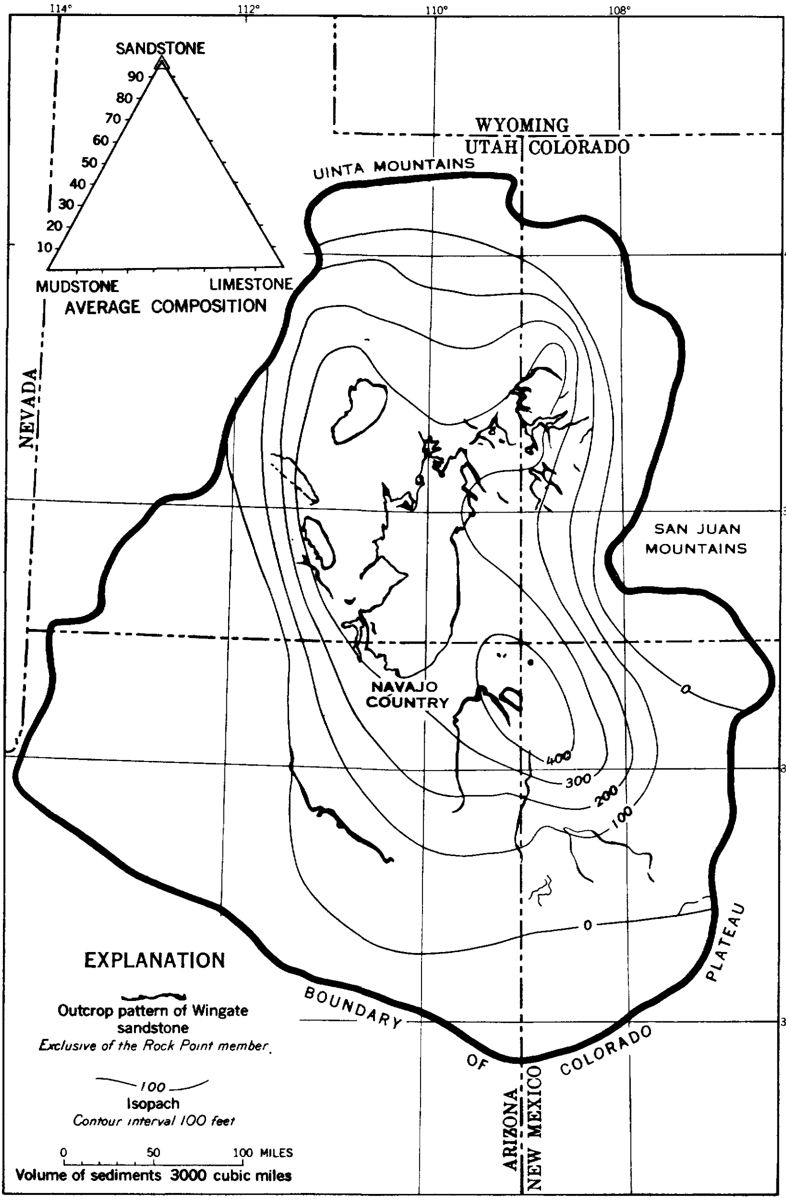


FIGURE 50.—Map of the Colorado Plateau showing location of sampling sites, outcrop pattern, and composition of rocks of basal sandstone units of the Chinle formation of Triassic age.



Isopachs after Baker, Dane, and Reeside (1936). Outcrop pattern compiled from U. S. Geological Survey Geologic Map of the United States, 1932; Andrews and Hunt (1948); and Darton, Lausen, and Wilson (1924)

FIGURE 51.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Wingate sandstone of Triassic age.

The Wingate consists chiefly of reddish-brown fine-grained sandstone; it is cross stratified on a large scale, and commonly forms nearly vertical massive cliffs. The cliff-forming characteristic of the Wingate sandstone is reflected in its outcrop pattern; exposures form sinuous very narrow bands that are found flanking major structures and along the trace of incised stream channels.

The volume of Wingate sandstone deposited on the Colorado Plateau is estimated to total about 3,000 cubic miles (table 1). Although the Wingate contains some fine-grained material, the percent of mudstone contained is considered negligible for this report.

JURASSIC SYSTEM

The Jurassic system of the Colorado Plateau includes part of the Glen Canyon group, the San Rafael group, and the Morrison formation. Formations of Jurassic age represented in the Glen Canyon group include, in ascending order, the Kayenta formation of Jurassic(?) age and the Navajo sandstone of Jurassic and Jurassic(?) age. The San Rafael group includes, in ascending order, the Carmel formation, the Entrada sandstone, and the Curtis and Summerville formations. Formations of limited extent which are equivalent to parts of the San Rafael group are the Cow Springs sandstone, the Bluff sandstone, and the Todilto limestone. The Morrison formation is the youngest Jurassic formation on the Colorado Plateau. The original volume of sediments of Jurassic age on the plateau total about 32,000 cubic miles (table 1).

KAYENTA FORMATION

Rocks of the Kayenta formation (Baker and others, 1936, 1947; Imlay, 1952) of Jurassic(?) age originally covered about 48,000 square miles in the central part of the Colorado Plateau (Harshbarger and others, 1951). The Kayenta is more restricted in its distribution than the Wingate sandstone (fig. 52).

The thickest part of the Kayenta formation lies in southeastern Utah (Gregory, 1938, 1950), and the formation thins rather uniformly in all directions. The formation, commonly a bench-forming unit, is composed chiefly of irregularly bedded sandstone of different grain sizes but includes subordinate lenses of shale, mudstone, and locally, thin beds of impure limestone.

The volume of sediments of the Kayenta formation deposited within the boundary of the Colorado Plateau totals about 1,100 cubic miles. Sandstone makes up about 90 percent of this volume and mudstone the remaining 10 percent; limestone probably comprises less than 1 percent (table 1). These figures are in part estimated from published stratigraphic sections of the Kayenta formation measured in the San Juan region and in part from sections measured by members

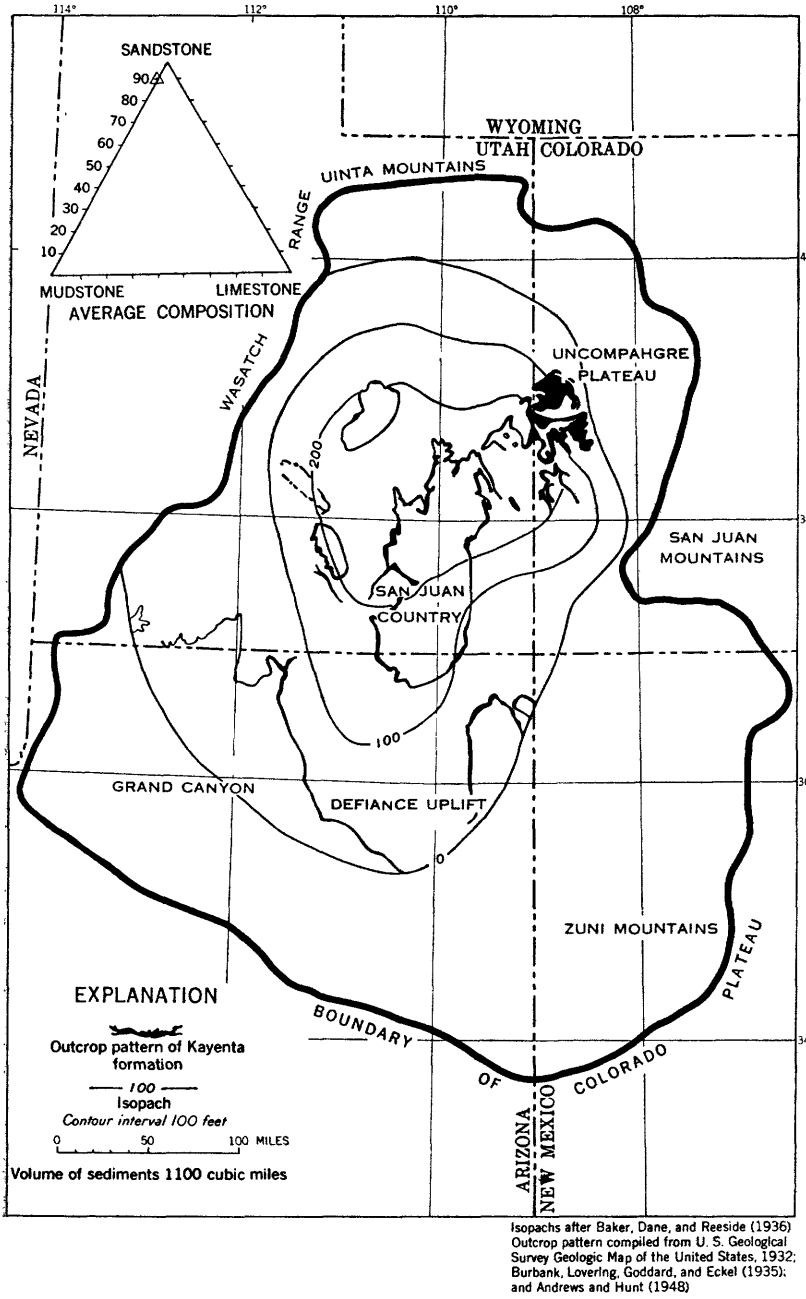


FIGURE 52.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Kayenta formation of Jurassic(?) age.

of the U.S. Geological Survey at the Dolores River and Dry Creek anticline, Colorado; at Black Dragon Canyon, San Rafael Swell, and Indian Creek, Utah; and at Beclabito dome, New Mexico (figs. 73, 76).

NAVAJO SANDSTONE

The Navajo sandstone (Baker and others, 1936, 1947; Imlay, 1952) originally covered about 77,000 square miles in the western half of the Colorado Plateau (fig. 53). Exposures occur chiefly in southern Utah and northern Arizona (Gregory, 1938). The Nugget sandstone of the Uinta Mountains area (Schultz, 1918; Sears, 1924) is considered to be equivalent to the Navajo sandstone.

The Navajo sandstone forms a wedge-shaped unit that thins eastward from more than 2,000 feet in thickness in the Zion National Park area of southwestern Utah (Gregory, 1950, 1951) to a vanishing edge in western Colorado and northeastern Arizona (Harshbarger and others, 1951; Gregory, 1938). The sandstone is commonly buff to grayish white but at places is red. A characteristic feature of the Navajo sandstone is large-scale crossbeds that become very conspicuous on weathering. Single crossbeds may extend for more than 100 feet.

The volume of sediments of Navajo age deposited on the Colorado Plateau is estimated to total about 11,000 cubic miles. Although some thin beds of shale and siltstone and thin discontinous lenses of limestone occur locally, sedimentary rocks of Navajo age are considered to be composed entirely of sandstone (table 1).

CARMEL FORMATION

The Carmel formation originally covered about 71,000 square miles in the western two-thirds of the Colorado Plateau (fig. 54). The Carmel is exposed chiefly in southeastern Utah and northeastern Arizona. The Twin Creek limestone (Spieker, 1946; Kinney and Rominger, 1947; Imlay, 1952) of the Uinta Mountains and Wasatch Mountains areas is considered to be equivalent to the Carmel formation.

The Carmel formation reaches a maximum thickness of more than 650 feet in the northwestern part of the Colorado Plateau. From there it thins to the east and south. West of the Wasatch plateau the Carmel formation may constitute the basal portion or more of the Arapien shale (Spieker, 1946), a thick sequence of shale and fine-grained sandstone.

The lithology of the Carmel formation is variable. In the San Rafael Swell (Gilluly and Reeside, 1928) the Carmel is composed chiefly of limestone, limy shales, and shales with abundant gypsum. Eastward and southeastward from the San Rafael Swell the Carmel becomes a series of sandy shales and sandstones. In the Monument

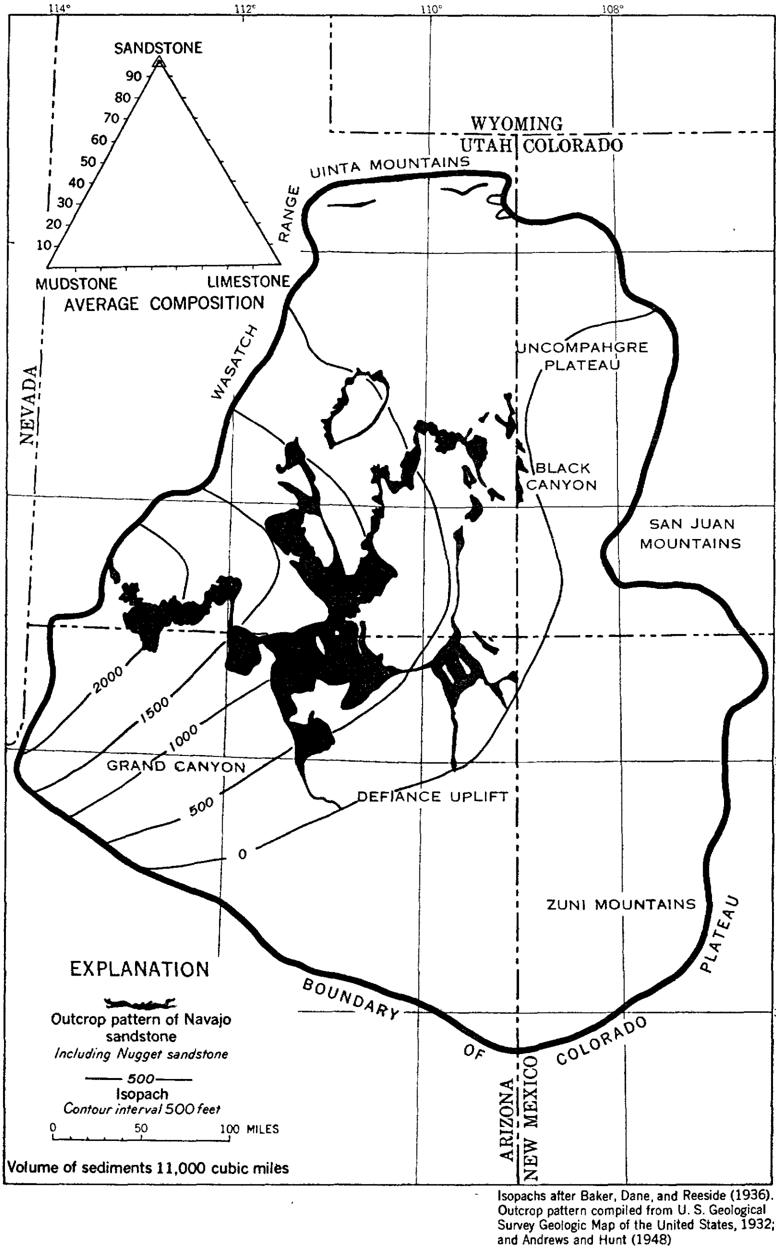
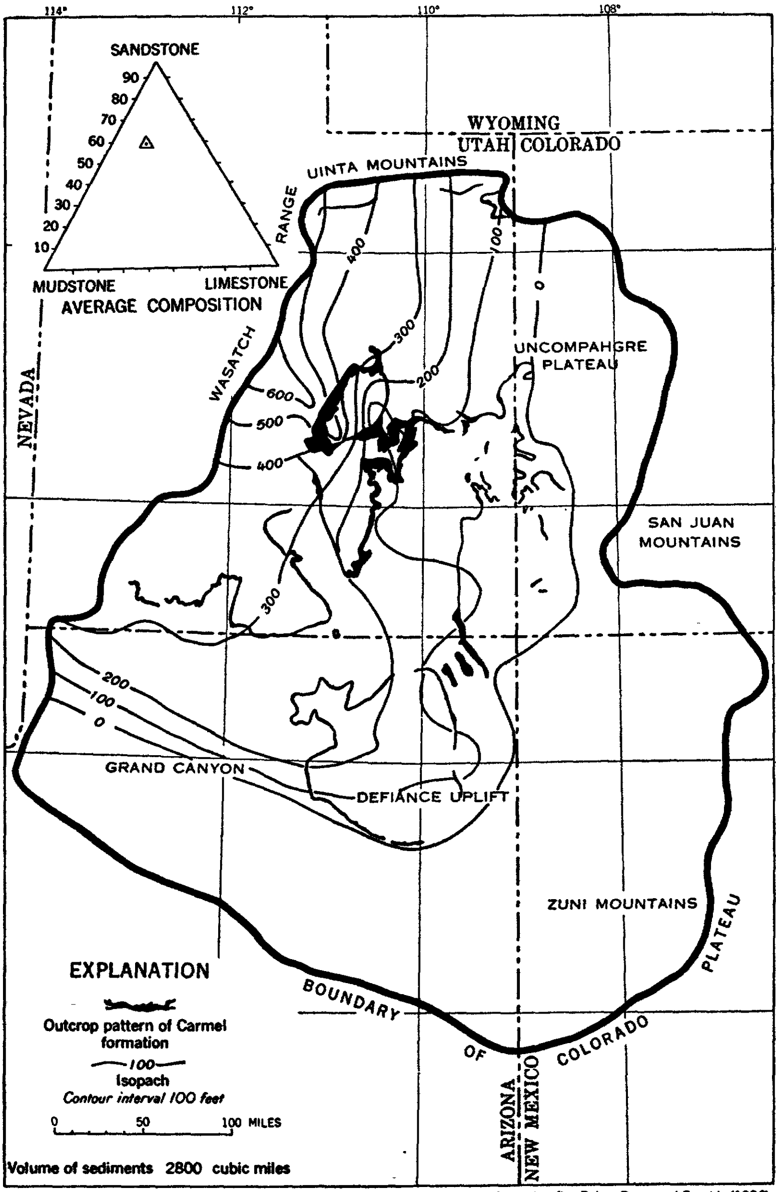


FIGURE 53.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Navajo sandstone of Jurassic and Jurassic(?) age.



Isopachs after Baker, Dane, and Reeside (1936). Outcrop pattern compiled from U. S. Geological Survey Geologic Map of the United States, 1932; Burbank, Lovering, Goddard, and Eckel (1935); and Andrews and Hunt (1948)

FIGURE 54.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Carmel formation of Jurassic age

Valley area (Baker, 1936; Baker and others, 1936) of southeastern Utah and northeastern Arizona, the Carmel consists of sandstone, shale, and mudstone; but in southwestern Utah (Gregory and Moore, 1931; Gregory, 1938, 1950, 1951) it is composed chiefly of fossiliferous limestone.

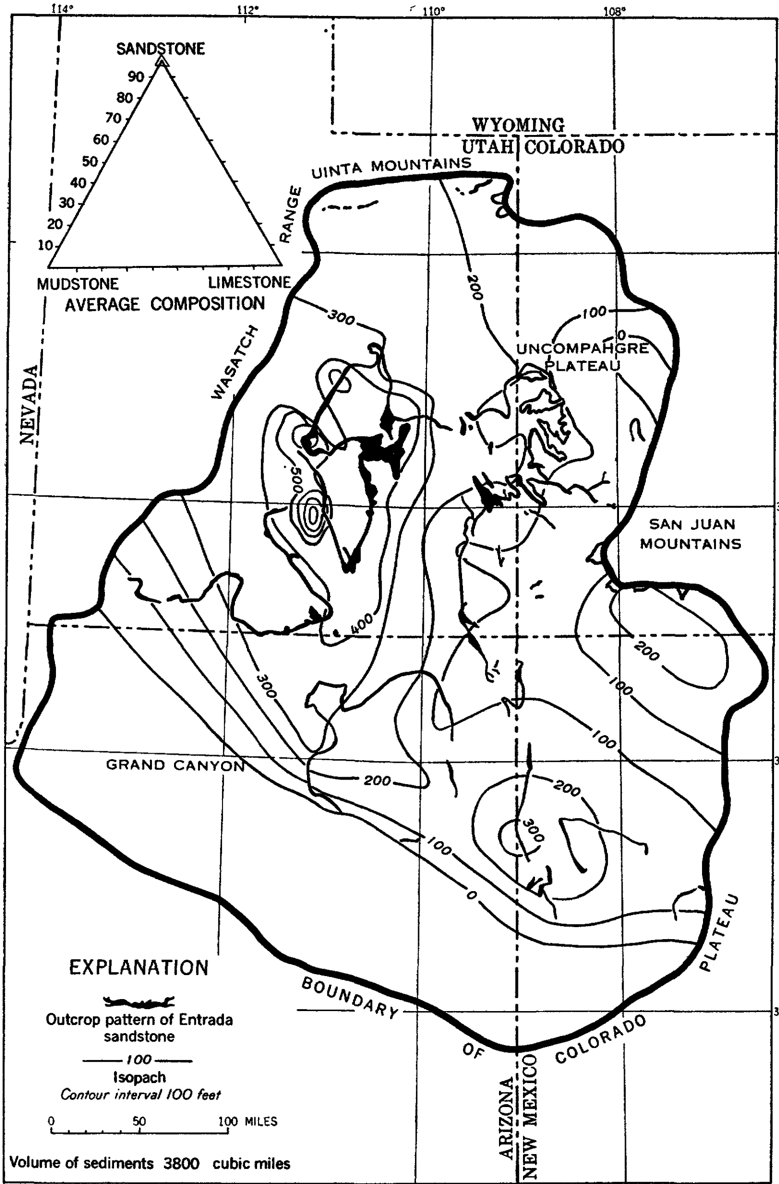
Sediments of the Carmel formation deposited on the Colorado Plateau are estimated to have totaled about 2,800 cubic miles. Sandstone comprises about 60 percent of this volume, mudstone about 25 percent, and limestone about 15 percent (table 1). These figures are in part estimated from published stratigraphic sections of the Carmel formation measured in the San Rafael Swell, Monument Valley, and the Kaiparowits, San Juan, Zion Park, and Paunsaugunt regions of Utah, and in part from sections measured by members of the U.S. Geological Survey at the Dolores River and McElmo Canyon, Colo.; at La Sal Creek, Montezuma Canyon, San Rafael Swell, and Circle Cliffs, Utah; and at Oak Creek, N. Mex. (figs. 73, 76).

ENTRADA SANDSTONE

The Entrada sandstone (Imlay, 1952; Baker, 1936) originally covered about 99,000 square miles and is present throughout most of the Colorado Plateau except in the southern part where the formation has been removed by pre-Dakota erosion (fig. 55).

The Entrada in central and southwestern Utah (Gregory and Moore, 1931; Gregory, 1938, 1950, and 1951; and Gilluly and Reeside, 1928) consists of an earthy sandstone and siltstone facies which becomes a clean fine-grained sandstone in Colorado, eastern Utah, northeastern Arizona, and northern New Mexico (Craig and others, 1955). In the vicinity of Moab, Utah, a thick sandstone unit that overlies the Entrada sandstone is known as the Moab tongue of the Entrada (Baker, 1933). The thickness of the Moab tongue is included in the thickness of the Entrada sandstone.

The rocks of the Entrada on the Colorado Plateau are estimated to have totaled about 3,800 cubic miles. Sandstone constitutes about 98 percent of this volume and mudstone the remaining 2 percent (table 1). These figures are estimated from published stratigraphic sections of the Entrada sandstone measured in the Kaiparowits, San Juan, Zion Park, and Paunsaugunt regions, the San Rafael Swell, and the Moab Valley region, Utah, and in part from sections measured by members of the U.S. Geological Survey at the Dolores River and McElmo Canyon, Colo.; at Last Chance, San Rafael Swell, La Sal Creek, Mancos Jim Butte, and Montezuma Canyon, Utah; and at Oak Creek, N. Mex. (figs. 73, 76).



Isopachs from unpublished data on file in U. S. Geological Survey. Outcrop pattern after U. S. Geological Survey Geologic Map of the United States, 1932

FIGURE 55.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Entrada sandstone of Jurassic age.

CURTIS FORMATION

The Curtis formation (Baker and others, 1936; Imlay, 1952) originally covered about 24,000 square miles in the northwestern third of the Colorado Plateau (fig. 56), and is exposed chiefly along the south-

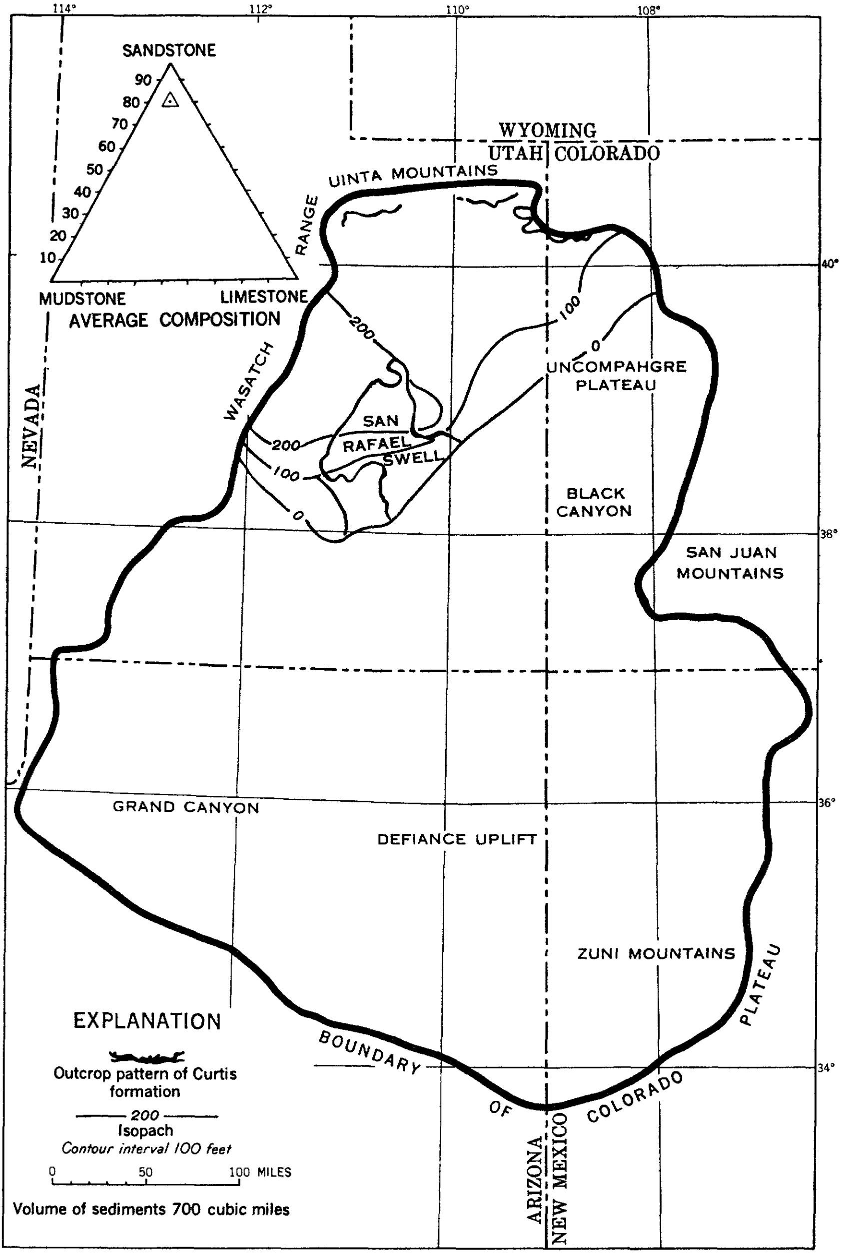


FIGURE 56.--Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Curtis formation of Jurassic age.

ern flank of the Uinta Mountains (Thomas and Krueger, 1946) and in the San Rafael Swell area (Gilluly and Reeside, 1928).

Rocks of the Curtis formation are composed principally of fine-grained sandstone with shales and some bedded gypsum. In the eastern Uinta Mountains area the Curtis consists of sandy limestone, sandstone, and shale. In the San Rafael Swell the formation is composed principally of sandstone and minor amounts of green shales and gypsum.

Sediments of the Curtis formation deposited on the Colorado Plateau total about 700 cubic miles. Limestone comprises about 10 percent of this volume—although this figure may be too conservative; mudstone makes up about 10 percent, and sandstone makes up the remaining 80 percent (table 1). These figures are in part estimated from published stratigraphic sections of the Curtis formation measured in the Uinta Mountains and the San Rafael Swell, Utah, and in part from sections measured by members of the U.S. Geological Survey in the Circle Cliffs area, San Rafael Swell, and Tidwell ranch, Utah (figs. 73, 76).

TODILTO LIMESTONE

The Todilto limestone (Gregory, 1917; Baker and others, 1947) originally covered about 18,000 square miles in the southeastern part of the Colorado Plateau (fig. 57). The Todilto limestone (Harshbarger and others, 1957) and the Pony Express limestone member of the Wanakah formation (Burbank, 1930; Goldman and Spencer, 1941) of southwestern Colorado are considered to be correlative. The Todilto in the vicinity of Todilto Park, N. Mex., is composed chiefly of mudstone and some thin beds of limestone. The limestone is locally aphanitic and has a fetid odor. The limestone unit thickens eastward, and in the vicinity of Haystack Butte, N. Mex., the formation includes a thick section of gypsum.

The Pony Express limestone member and Todilto limestone are important host rocks for ore deposits on, and at the edge of, the Colorado Plateau. In the Ouray mining district of southwestern Colorado the Pony Express limestone member is one of the host rocks for base and precious metal ores (Burbank, 1930); in the Grants area of New Mexico the Todilto limestone is an important host rock for uranium deposits (Hilpert and Corey, 1955, p. 117).

The volume of combined sediments of the Todilto limestone and Pony Express limestone member of the Wanakah on the Colorado Plateau totals about 200 cubic miles. Limestone (including gypsum) constitutes about 95 percent of this volume and mudstone about 5 percent (table 1). These figures are in part estimated from published stratigraphic sections of the Todilto limestone and Pony Express limestone member of the Wanakah formation measured in the Navajo Country and the San Juan Mountains region, Colorado, and in part from sections measured at Beclabito dome, New Mexico, and Placerville, Colo., by members of the U.S. Geological Survey (fig. 76).

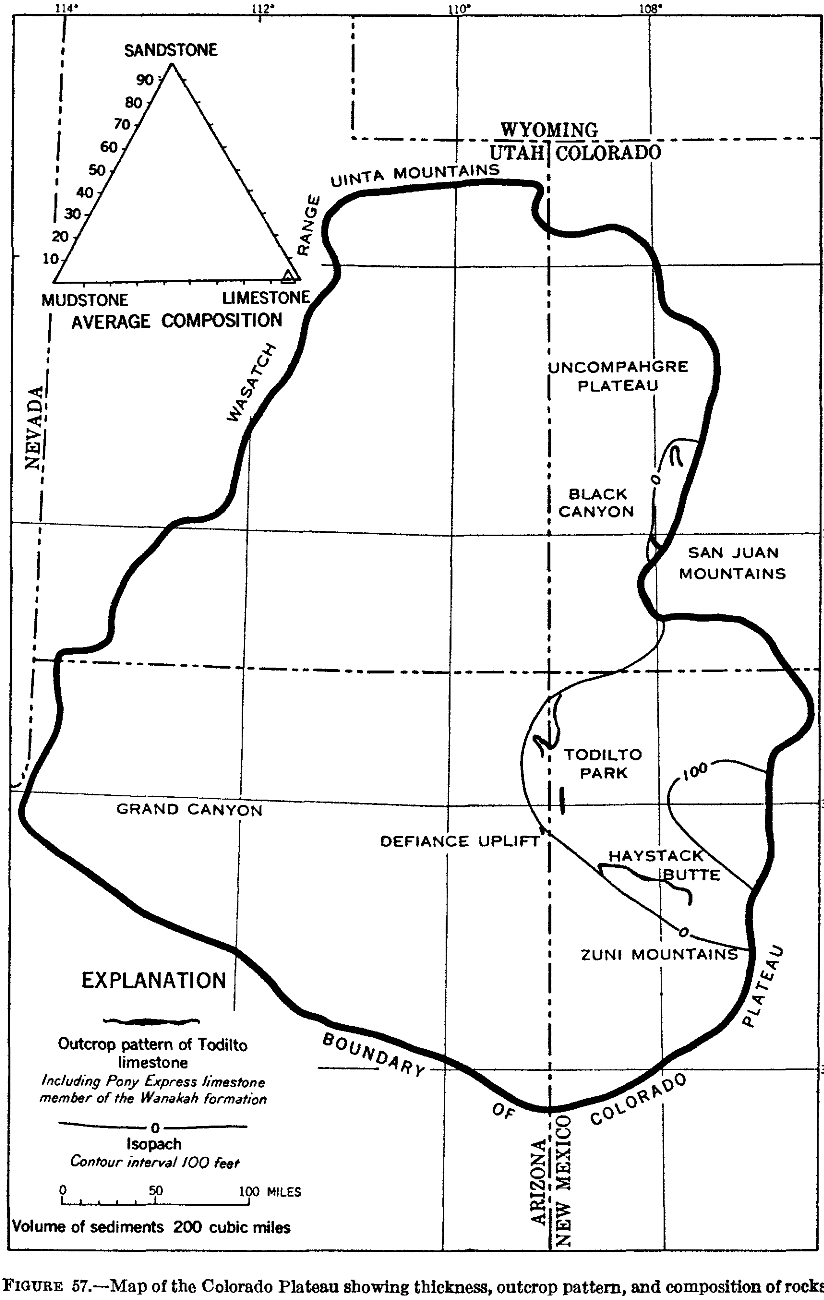


FIGURE 57.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Todilto limestone and the Pony Express limestone member of the Wanakah formation of Jurassic age.

SUMMERVILLE FORMATION

Rocks of the Summerville formation (Gilluly and Reeside, 1928; Imlay, 1952; and Craig and Holmes, 1951) originally covered an area of about 61,000 square miles in a broad northwestward-trending belt across the center of the Colorado Plateau (fig. 58). The marl and Bilk Creek sandstone members of the Wanakah formation (Goldman and Spencer, 1941; Stokes, 1944) are considered to be equivalent to, and are included with, the Summerville formation.

The northern limit of the Summerville formation lies beneath the Uinta Basin and is not exposed; at its southern limit it grades into the lower part of the Cow Springs sandstone (Harshbarger and others, 1951; Harshbarger and others, 1957).

In order to compute the volume of the Summerville formation the southern limit of the formation is shown as a pinchout in spite of the fact that this line actually marks the approximate line where the Summerville becomes indistinguishable from the Cow Springs sandstone. Some detail may be lost by use of this convention, but the resulting inaccuracies in computing volumes of intertonguing formations are slight.

The Summerville formation consists chiefly of red sandstone, siltstone, and shale and becomes more sandy to the south.

The original volume of sediments of the Summerville totals about 1,500 cubic miles. Sandstone makes up about 65 percent of this volume, mudstone about 34 percent, and limestone about 1 percent (table 1). These figures are in part estimated from published stratigraphic sections measured in the San Rafael Swell, the Navajo Country, and southwestern Colorado, and in part from sections measured by members of the U.S. Geological Survey at the Dolores River and McElmo Canyon, Colo.; at La Sal Creek, Mancos Jim Butte, Montezuma Canyon, and San Rafael Swell, Utah; and at Oak Creek, N. Mex. (figs. 73, 76).

COW SPRINGS SANDSTONE

Rocks of the Cow Springs sandstone (Harshbarger and others, 1951; Harshbarger and others, 1957) originally covered an area of about 47,000 square miles in an elongate northwestward-trending belt in the southern part of the Colorado Plateau (fig. 59). The Winsor formation (Gregory, 1950; 1951) of the Zion National Park area, Utah, is here considered to be equivalent to the Cow Springs and is included with the Cow Springs in figure 59.

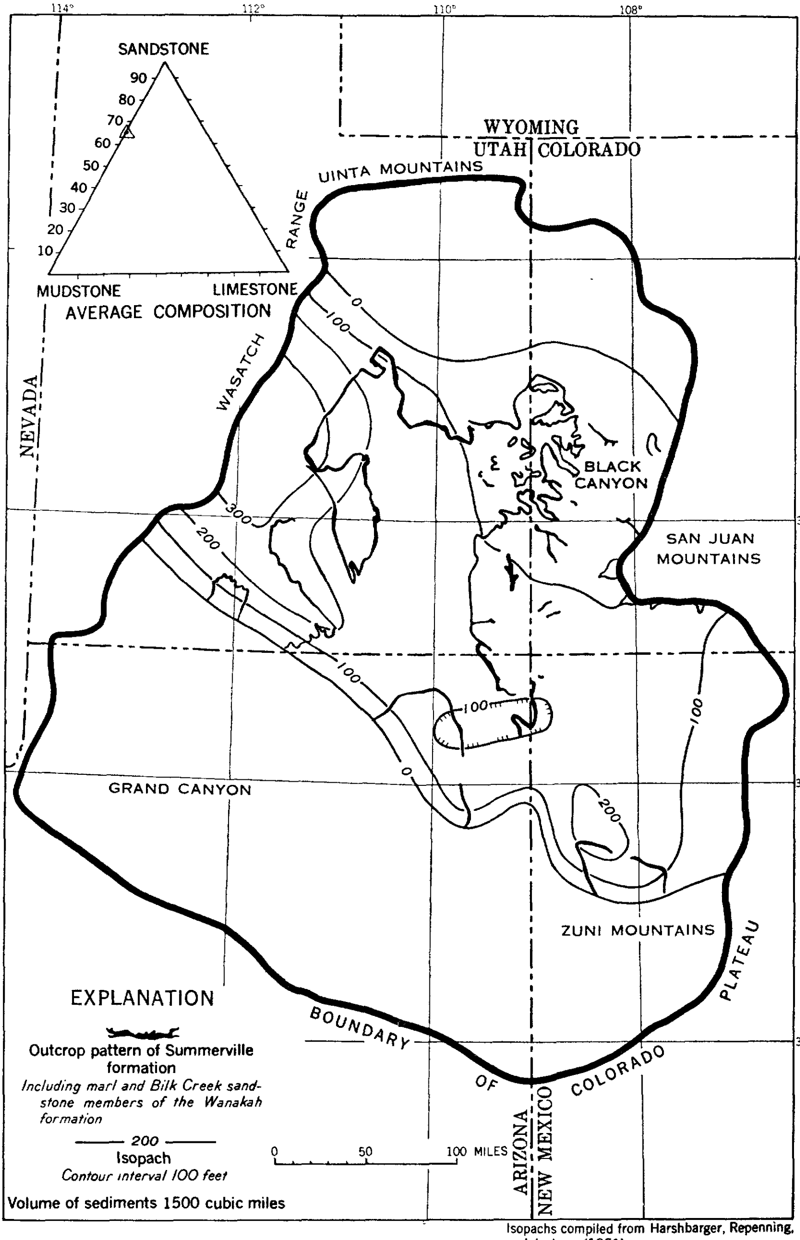


FIGURE 58.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Summerville formation of Jurassic age.

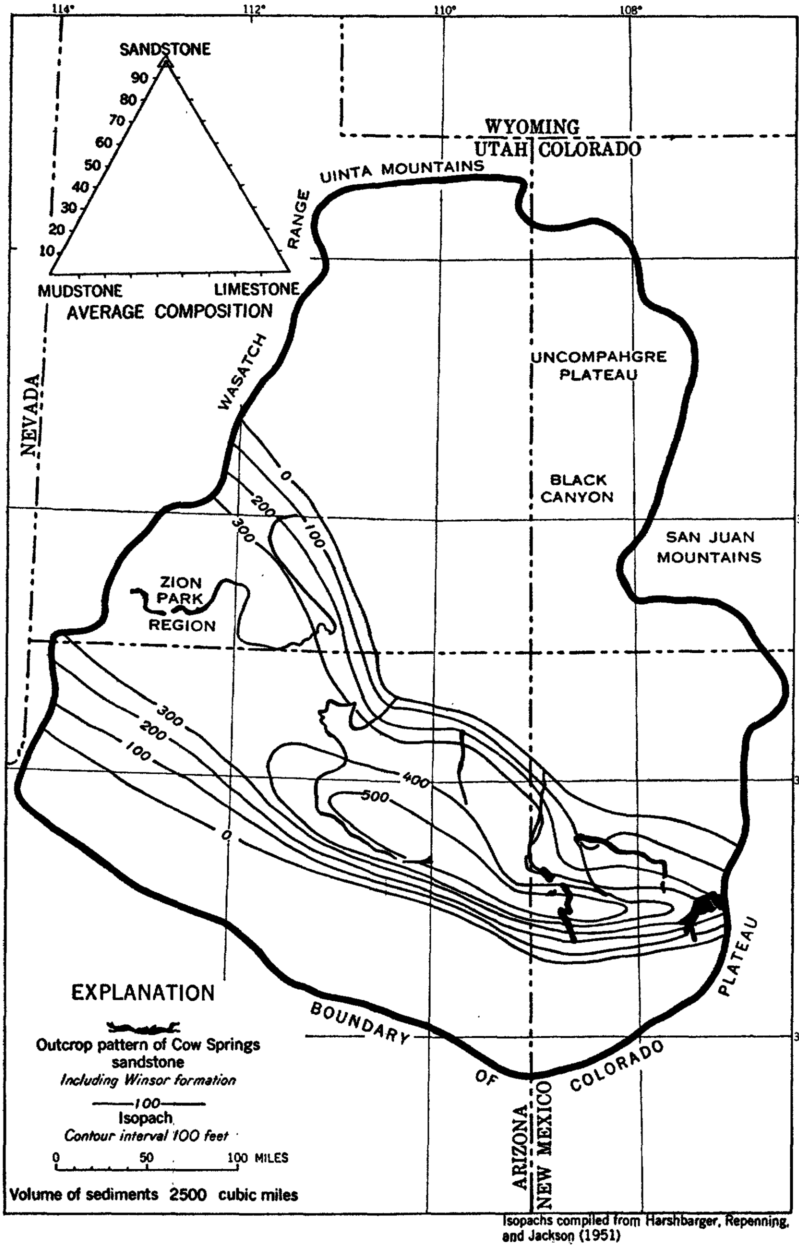


FIGURE 59.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Cow Springs sandstone of Jurassic age.

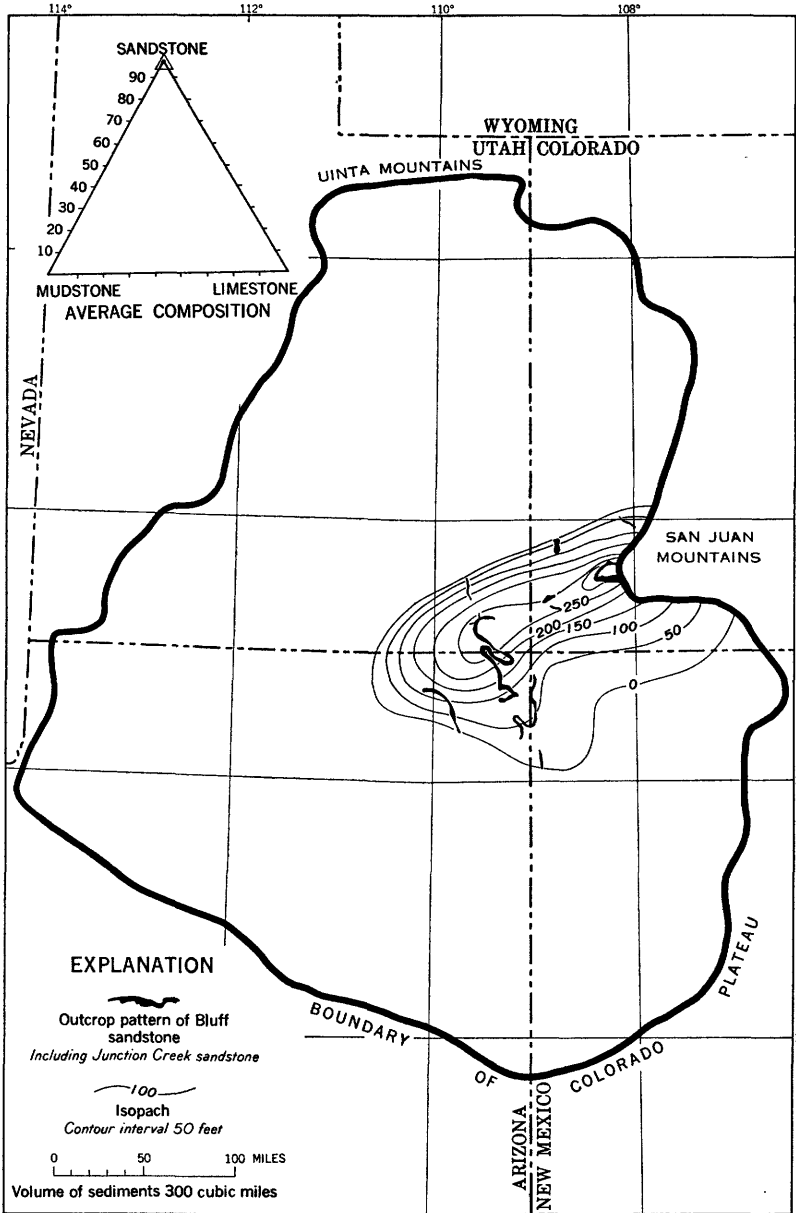
The Cow Springs sandstone apparently occupies a considerable interval in the Jurassic stratigraphic section (Harshbarger and others, 1951; and Harshbarger and others, 1957). The Summerville formation grades into the lower part of the Cow Springs; in the southernmost part of the Navajo Reservation the Entrada cannot be easily separated from the Cow Springs, and lower units of the Morrison formation grade into the upper part of the Cow Springs. To the south the formation has been truncated by a pre-Dakota erosion surface. Rocks of the Cow Springs sandstone resemble the rocks of the Navajo sandstone and consist of gray fine-grained sandstone; large-scale crossbeds are typical. The Cow Springs commonly weathers into smooth rounded slopes, or it forms vertical cliffs where overlain and protected by the Dakota sandstone.

The original volume of sediments of the Cow Springs totals about 2,500 cubic miles. Sandstone is estimated to constitute about 98 percent of this volume and mudstone the remaining 2 percent (table 1).

BLUFF SANDSTONE

Rocks of the Bluff sandstone (Gregory, 1938; Craig and Holmes, 1951; Harshbarger and others, 1951; Harshbarger and others, 1957) originally covered an area of about 15,000 square miles in the east-central part of the Colorado Plateau (fig. 60). The Junction Creek sandstone (Goldman and Spencer, 1941; Craig and others, 1955) is considered to be equivalent to the Bluff sandstone, and rocks of the Junction Creek have been included with those of the Bluff. In places, the Bluff sandstone intertongues with the underlying Summerville formation and also intertongues with the overlying Morrison formation. Harshbarger, Repenning, and Irwin (1957) believe that the Bluff sandstone is a tongue of the Cow Springs sandstone, extending northward from the main mass of the Cow Springs.

The Bluff is typically a white well-sorted crossbedded eolian sandstone which forms a massive cliff; it contains short thin lenses of red mudstone. In an area just northeast of so-called Four Corners (the point common to Colorado, Utah, Arizona, and New Mexico) the Bluff is more than 300 feet thick, but it thins rapidly in all directions. The original volume of Bluff sediments totals about 300 cubic miles. Sandstone comprises about 98 percent of this volume and mudstone the remaining 2 percent (table 1). These figures are estimated from stratigraphic sections measured by members of the U.S. Geological Survey at McElmo Canyon, Colo.; Collette Creek, Utah; and Oak Creek, N. Mex. (fig. 73).



Map compiled from material on file in offices of U. S. Geological Survey

FIGURE 60.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Bluff sandstone of Jurassic age.

MORRISON FORMATION

The Morrison formation (Cross, 1894, p. 2) of Jurassic age originally covered an area of about 81,000 square miles within the Colorado Plateau (fig. 61). The Morrison can be separated into a lower part and an upper part, each of which has two members (Craig and others, 1955, p. 134). The lower part of the Morrison consists of the Salt Wash and Recapture members. These members interfinger and grade into each other over a broad area in the vicinity of the Four Corners. The upper part of the Morrison consists of the Westwater Canyon and Brushy Basin members. The Brushy Basin member is present over most of the Colorado Plateau, but the Westwater Canyon is restricted to an area in the central-southeastern part of the Colorado Plateau.

The volume of sediments of the Morrison formation deposited on the Colorado Plateau is about 8,000 cubic miles. Mudstone is estimated to constitute about 60 percent of this volume and sandstone about 40 percent. Limestone, although present, probably accounts for less than 1 percent of the total volume (table 1).

SALT WASH MEMBER

The Salt Wash member (Craig and others, 1955, p. 135; Lupton; 1914, p. 127; Gilluly and Reeside, 1928, p. 82) forms the lower part of the Morrison over a large fan-shaped area of about 77,000 square miles in the central and northern part of the Colorado Plateau (fig. 62). The Salt Wash is composed dominantly of interstratified units of sandstone and claystone. The sandstone forms either a stratum composed of a single lenticular bed 1 to 20 feet thick or strata composed of many lenticular beds which may have a total thickness of 80 feet or more. Typically, the Salt Wash member includes a basal sandstone unit, one or more intermediate sandstone units, and a top sandstone unit. Strata between the sandstone units consist of dominantly grayish and reddish mudstones and claystones with minor sand lenses. In areas where the Recapture and Westwater Canyon members are missing, the Salt Wash directly underlies variegated shales and mudstones of the Brushy Basin member.

The volume of Salt Wash sediments deposited on the Colorado Plateau totals about 2,500 cubic miles. Sandstone comprises about 58 percent of this volume, mudstone, 41 percent, and limestone about 1 percent (table 1). These figures are estimated from stratigraphic sections measured by members of the U.S. Geological Survey at the Dolores River and Lower McElmo Canyon, Colo.; at Last Chance, La Sal Creek, Montezuma Canyon, and San Rafael Swell, Utah; and at Oak Creek, N. Mex. (fig. 73).

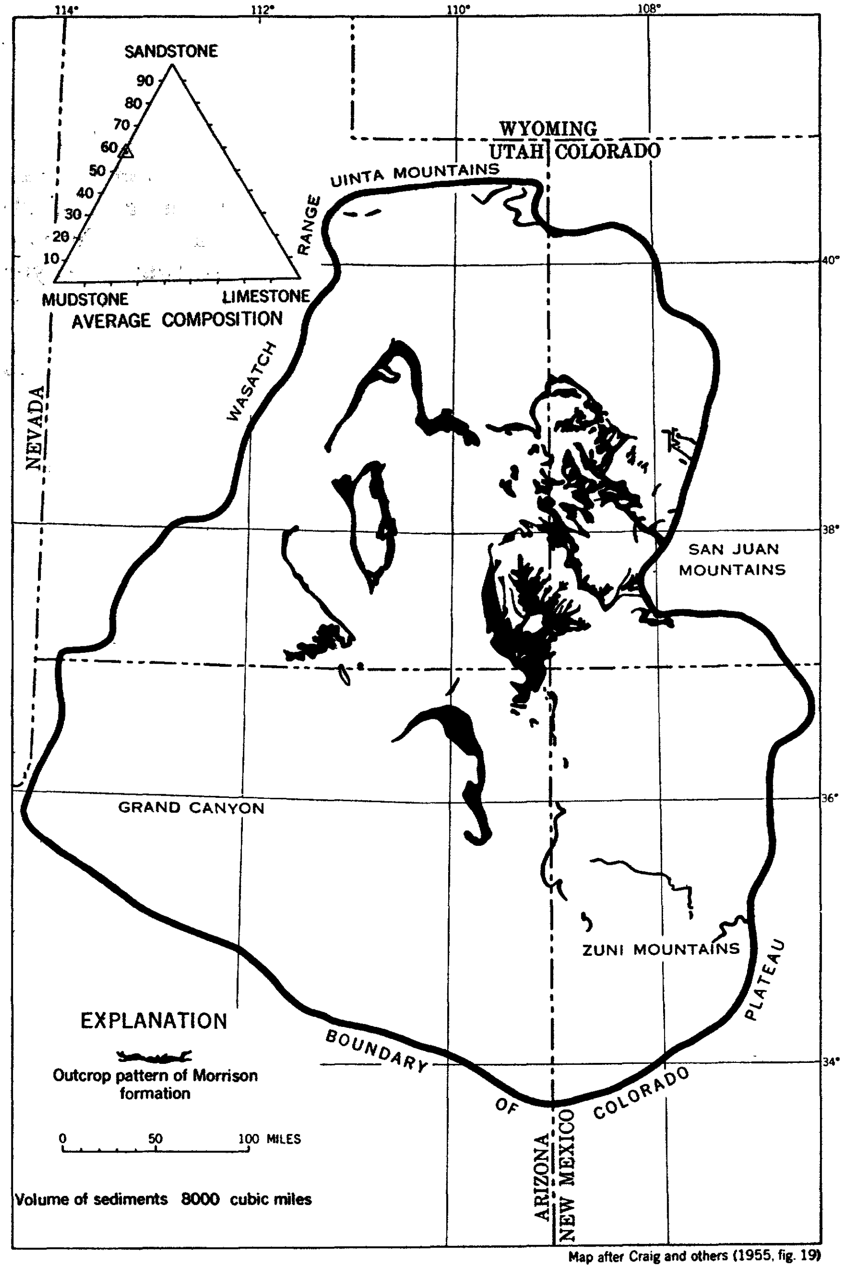
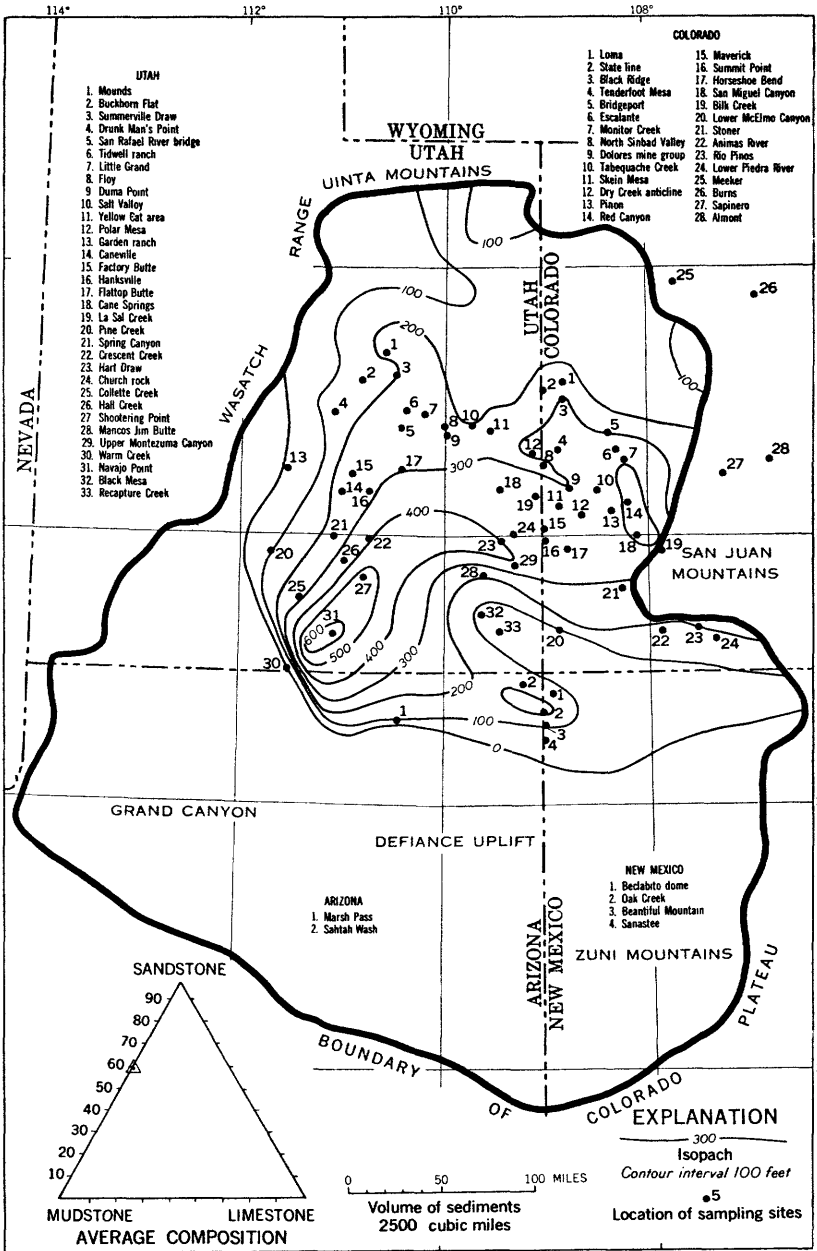


FIGURE 61.—Map of the Colorado Plateau showing outcrop pattern and composition of rocks of the Morrison formation of Jurassic age.



Map after Craig and others (1955, fig. 21)

FIGURE 62.—Map of the Colorado Plateau showing location of sampling sites, thickness, and composition of rocks of the Salt Wash member of the Morrison formation.

RECAPTURE MEMBER

Rocks of the Recapture member (Gregory, 1938, p. 58; Craig and others, 1955, p. 137) extend over an area of about 30,000 square miles in northeastern Arizona and northwestern New Mexico (fig. 63). To the north this member intertongues with, and grades into, the Salt Wash member. To the southwest it tongues with, and grades into, the Cow Springs sandstone. The eastward extent of the Recapture in north-central New Mexico is not known.

The Recapture member is composed chiefly of interstratified claystone and sandstone, but a conglomeratic sandstone facies occupies a narrow lobate area north of Gallup, N. Mex.

The volume of sediments of the Recapture member deposited on the Colorado Plateau totals about 1,300 cubic miles. Sandstone makes up about 49 percent of this volume, mudstone about 50 percent, and limestone about 1 percent (table 1). These figures are estimated from stratigraphic sections measured by members of the U.S. Geological Survey at McElmo Canyon, Colo.; Recapture Creek, Utah; and Oak Creek, N. Mex. (fig. 73).

WESTWATER CANYON MEMBER

The Westwater Canyon member (Gregory, 1938, p. 59; Craig and others, 1955, p. 153) is present over part of northeastern Arizona, southeastern Utah, northwestern New Mexico, and southwestern Colorado (fig. 64). Its original areal extent of about 31,000 square miles closely approximates that of the Recapture member. In the Ute Mountains area of southwestern Colorado and southeastern Utah, the Recapture grades into the Salt Wash member and the separation of the Westwater Canyon member from the underlying Salt Wash member is difficult. At least part of the Westwater Canyon intertongues with, and grades into, the lower part of the Brushy Basin member. Southward, the Westwater Canyon wedges out mostly as a result of post-Morrison erosion. The eastward extent of the Westwater Canyon in north-central New Mexico is not known.

The Westwater Canyon member is composed of interstratified sandstone and minor amounts of claystone; a conglomerate facies occupies a wide lobate area north of Gallup, N. Mex.

The volume of sediments of the Westwater Canyon member deposited upon the Colorado Plateau totaled about 1,000 cubic miles. Sandstone constitutes about 79 percent of this volume, mudstone about 20 percent, and limestone about 1 percent (table 1). These figures are estimated from stratigraphic sections measured by members of the U.S. Geological Survey at McElmo Canyon, Colo.; Recapture Creek, Utah; and Oak Creek, N. Mex. (fig. 73).

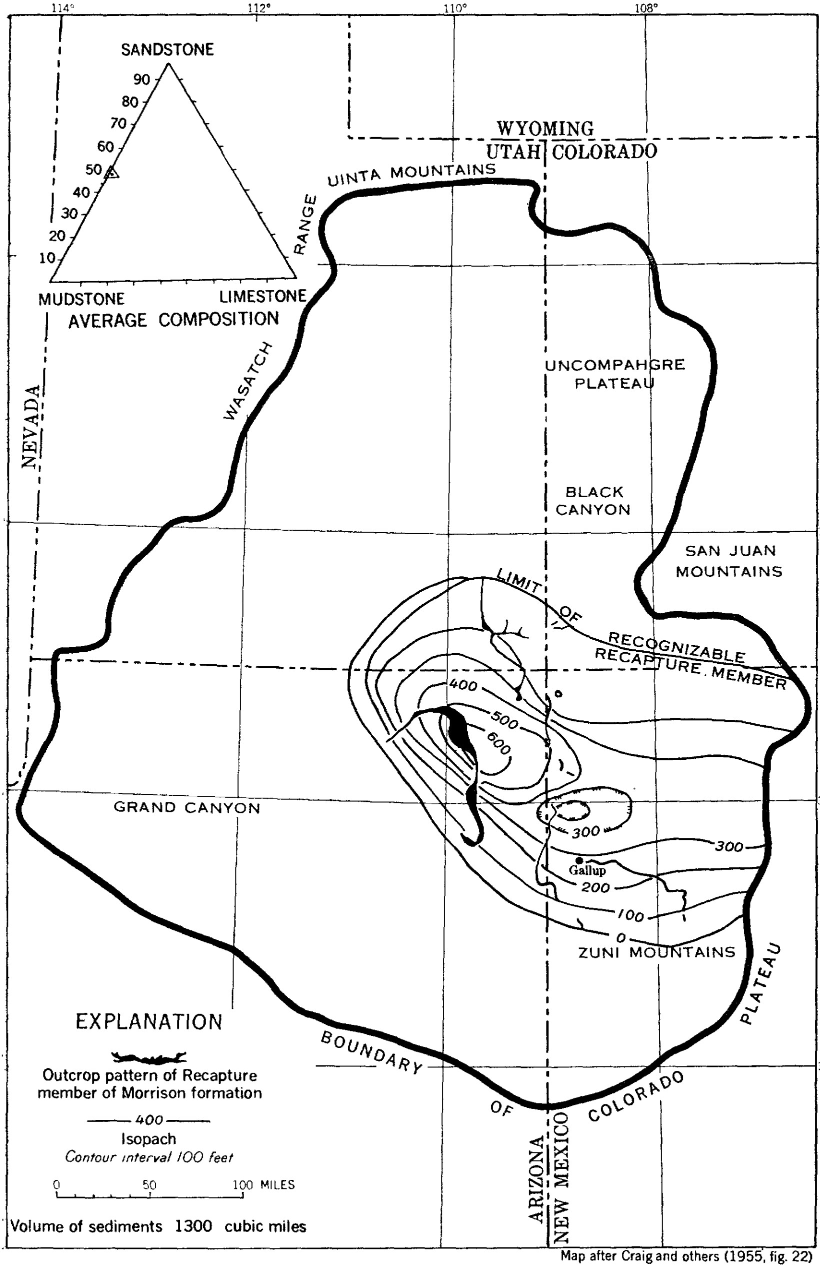


FIGURE 63.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Recapture member of the Morrison formation.

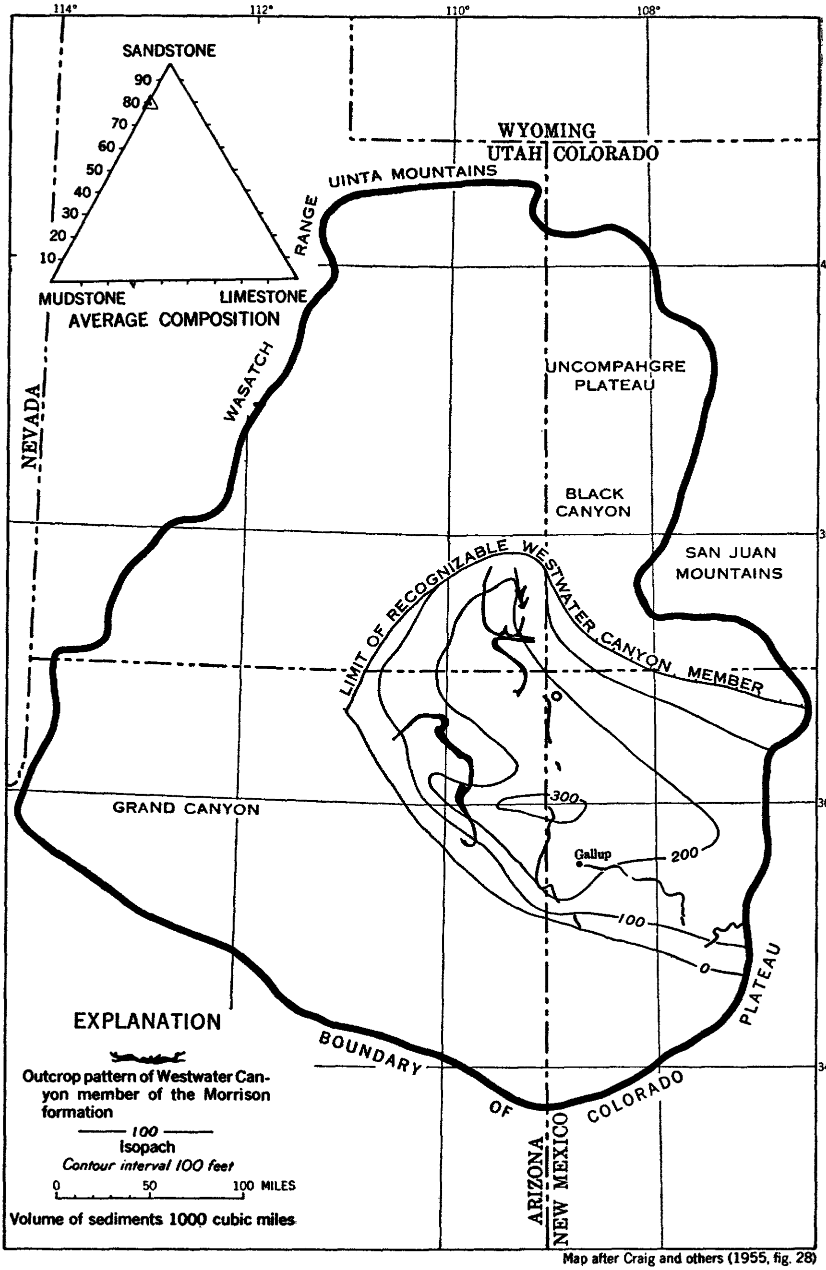


FIGURE 64.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Westwater Canyon member of the Morrison formation.

BRUSHY BASIN MEMBER

The Brushy Basin member (Gregory, 1938, p. 59; Craig and others, 1955, p. 155) is present in western Colorado, eastern Utah, northern New Mexico, and part of northeastern Arizona and extends over an area of about 69,500 square miles. The distribution of sedimentary rocks of the Brushy Basin member is shown by isopachs in figure 65. South of the zero isopach, the Brushy Basin member has been removed by erosion.

The Brushy Basin member is composed chiefly of variegated claystone and subordinate amounts of siltstone and sandstone. Lenses of conglomeratic sandstone containing pebbles of red, green, white, and black chert are common. Much of the claystone is bentonitic, and was derived by devitrification of volcanic debris.

The original volume of sediments of the Brushy Basin member on the Colorado Plateau totals about 3,200 cubic miles. Sandstone constitutes about 11 percent of this volume, mudstone about 88 percent, and limestone the remaining 1 percent (table 1). These figures are estimated from stratigraphic sections measured by members of the U.S. Geological Survey at the Dolores River and McElmo Canyon, Colo.; at La Sal Creek, Montezuma Canyon, and San Rafael Swell, Utah; and at Oak Creek, N. Mex. (figs. 73, 76).

LOWER CRETACEOUS SERIES

Rocks of Early Cretaceous age (Cobban and Reeside, 1952) originally covered about 40,000 square miles in the northern part of the Colorado Plateau (fig. 66). The formations that comprise the Lower Cretaceous series on the plateau include the Cedar Mountain formation with the Buckhorn conglomerate member of Stokes (1952) at its base and the Burro Canyon formation (Stokes, 1944; Stokes and Phoenix, 1948).

Lower Cretaceous rocks were probably removed by pre-Dakota erosion along the zero isopach line marking the southern limit of these beds in figure 66. However, in places these beds pass laterally into clays that cannot be distinguished from the Brushy Basin member of the Morrison, and therefore, in a few places beds of Early Cretaceous age may be included with the Morrison south of the zero isopach.

The Cedar Mountain formation consists of variegated shale and numerous elongate sandstone lenses. It is overlain by the Dakota sandstone and contains a lenticular conglomerate at its base—the Buckhorn conglomerate member of Stokes (1952). His Buckhorn conglomerate member is conspicuous in the northern part of the San Rafael Swell, and consists of sandstone, claystone, minor limestone, and conglomerate composed mostly of black chert pebbles and minor sandy lentils.

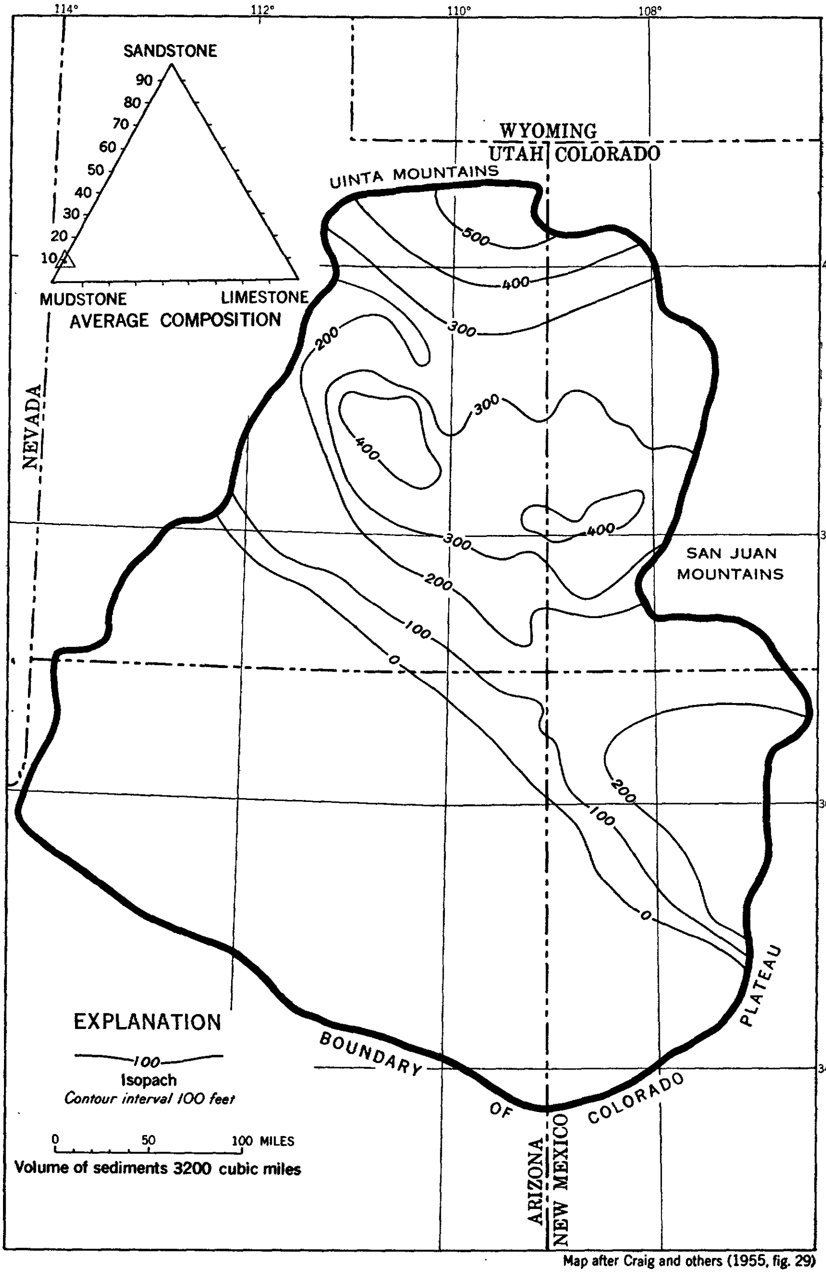


FIGURE 65.—Map of the Colorado Plateau showing thickness and composition of rocks of the Brushy Basin member of the Morrison formation.

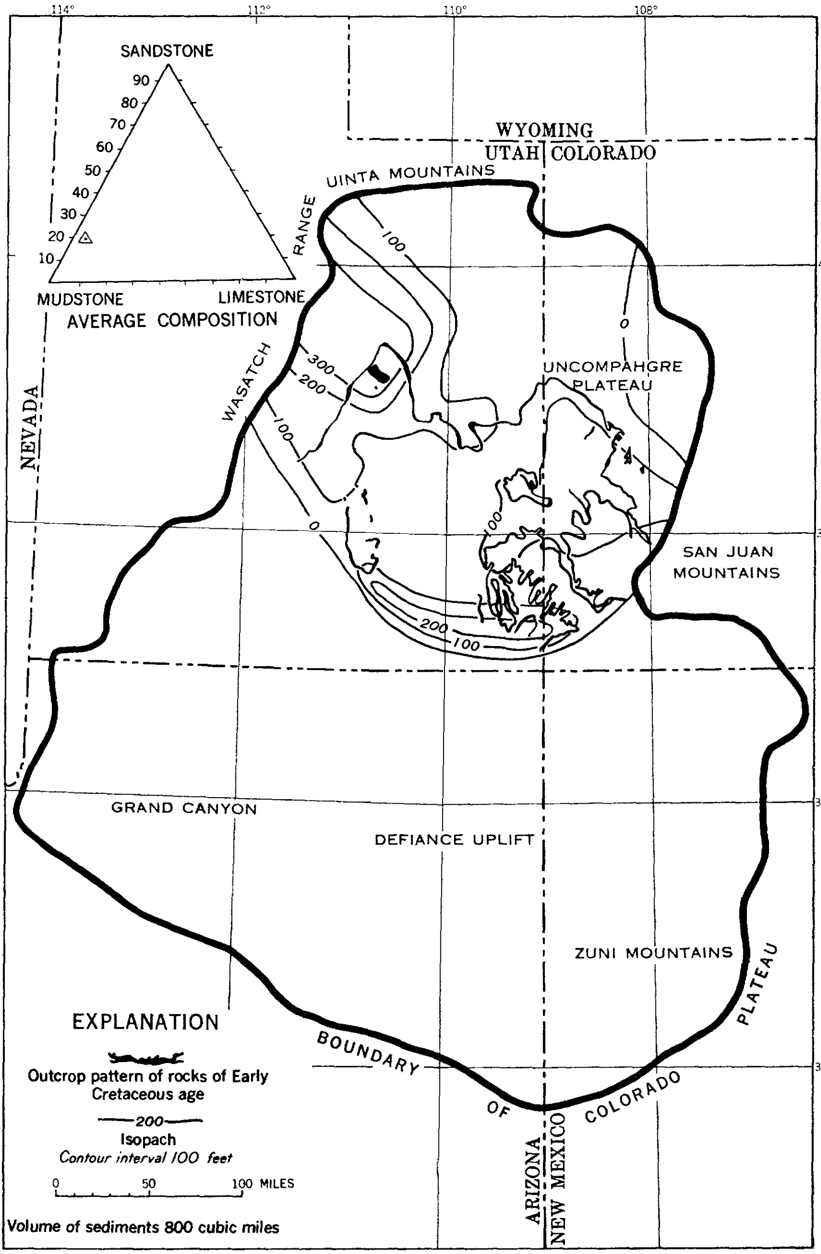


FIGURE 66.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Lower Cretaceous series.

The Burro Canyon formation consists of alternating conglomerate, sandstone, shale, limestone, and chert and grades laterally into the Cedar Mountain formation.

The volume of Lower Cretaceous sediments deposited on the Colorado Plateau totals about 800 cubic miles. Of this volume, sandstone constitutes about 20 percent, mudstone about 75 percent, and limestone about 5 percent (table 1). These figures are estimated from stratigraphic sections measured by members of the U.S. Geological Survey at the Dolores River and McElmo Canyon, Colo.; at La Sal Creek, Montezuma Canyon, and San Rafael Swell, Utah; and at Oak Creek, N. Mex. (fig. 73).

UPPER CRETACEOUS SERIES

Sediments of Late Cretaceous age (Cobban and Reeside, 1952; Fisher, D. J., 1936) on the Colorado Plataeu comprise the thickest sections of any series where full sections are exposed. They are thousands of feet thick. These rocks probably covered most of the Colorado Plateau, but they have been extensively reduced by erosion (fig. 67). The original thicknesses of the rocks are now confined chiefly to the basin areas of the plateau (McKee, 1951): the Uinta Basin and Piceance basin (Fisher, D. J., 1936; Walton, 1944; Kinney, 1955) in the northern and northeastern part of the Colorado Plateau, the San Juan basin (Reeside, 1924; Sears, 1934; Sears and others, 1941; Silver, 1951) in the southeastern part, and the Black Mesa basin (Gregory, 1917) in the southwestern part. Upper Cretaceous rocks are also exposed in the high plateaus of Utah (Spieker, 1931, 1946) that border the Colorado Plateau on the northwest and in the Zion and Bryce Canyon National Parks regions of southwestern Utah (Gregory and Moore, 1931; Gregory, 1950).

The volume of sediments of the Upper Cretaceous deposited on the Colorado Plateau is estimated to have been about 81,000 cubic miles. Sandstone makes up about 30 percent of this volume, mudstone about 65 percent, and limestone about 5 percent (table 1). These figures are estimated in part from published stratigraphic sections of the Upper Cretaceous formations measured in the Uinta Basin, Piceance, San Juan, and Black Mesa basins, the high plateaus of Utah, and Zion and Bryce Canyon National Parks region and in part from sections, chiefly those of the Dakota sandstone, measured by members of the U.S. Geological Survey.

For this report, estimates of the volume and lithologic characteristics of the Dakota sandstone were necessary. Although a separate outcrop and isopach map of the Dakota sandstone is not shown, the

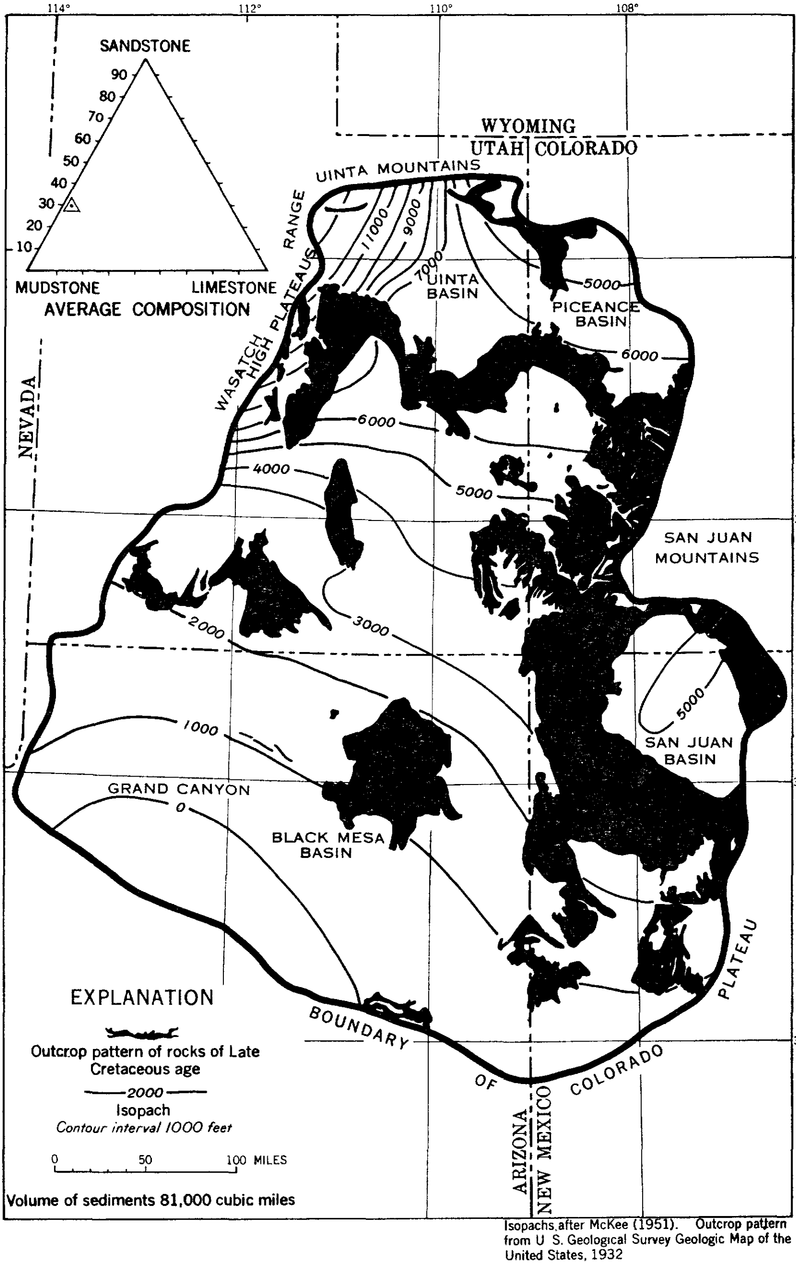


FIGURE 67.—Map of the Colorado Plateau showing thickness, outcrop pattern, and composition of rocks of the Upper Cretaceous series.

following data represent a summary of thickness, areal extent, and lithologic variations (table 1).

Dakota sandstone

Original areal extent	square miles	130,000
Average thickness	feet	70
Volume of sediments deposited	cubic miles	1,400
Amount of sandstone	percent	70
Amount of mudstone	do	30

TERTIARY SYSTEM

Sedimentary rocks of Tertiary age on the Colorado Plateau (fig. 68) are exposed chiefly in the Uinta Basin, Piceance basin (Bradley, 1931, 1936; Wood, H. E., and others, 1941), San Juan basin (Simpson, 1950), and Zion and Bryce Canyon National Parks region (Gregory, 1950).

Rocks of Tertiary age have been extensively eroded, and the original thicknesses of the formations cannot be determined in many areas of the Colorado Plateau. Insufficient data on the distribution, thickness, and lithology of rocks of Tertiary age prevent the compilation of isopach maps or estimates of lithologic composition.

SUMMARY OF THE PHYSICAL FEATURES OF SEDIMENTARY ROCKS

During the span of geologic time beginning with the Cambrian period and extending to the close of the Cretaceous, more than 240,000 cubic miles of sediments were deposited upon the Colorado Plateau. These sediments, if evenly distributed throughout the area of the Colorado Plateau, would form a blanket of rock nearly 2 miles thick. This mantle is composed chiefly of sandstone, which constitutes 42 percent of the volume; mudstone makes up 39 percent and limestone 19 percent. Table 2 shows volumes of each of the three main rock types according to periods and eras.

More than 65 percent of the rocks of the combined Permian, Triassic, and Jurassic systems of the Colorado Plateau are sandstone, and more than 99 percent of the uranium produced in the plateau has come from deposits in these rocks. However, examination of the rock types in each formation of these three systems indicates that sandstone alone cannot be the essential factor in the localization or genesis of uranium deposits. Units consisting principally of sandstone, such as the Wingate, Navajo, Cow Springs, and the Bluff sandstones, have not produced significant amounts of uranium. Where deposits have been reported in these host rocks, the uranium commonly occurs in fractured or faulted areas where relations of the deposits to the host rocks are obscure.

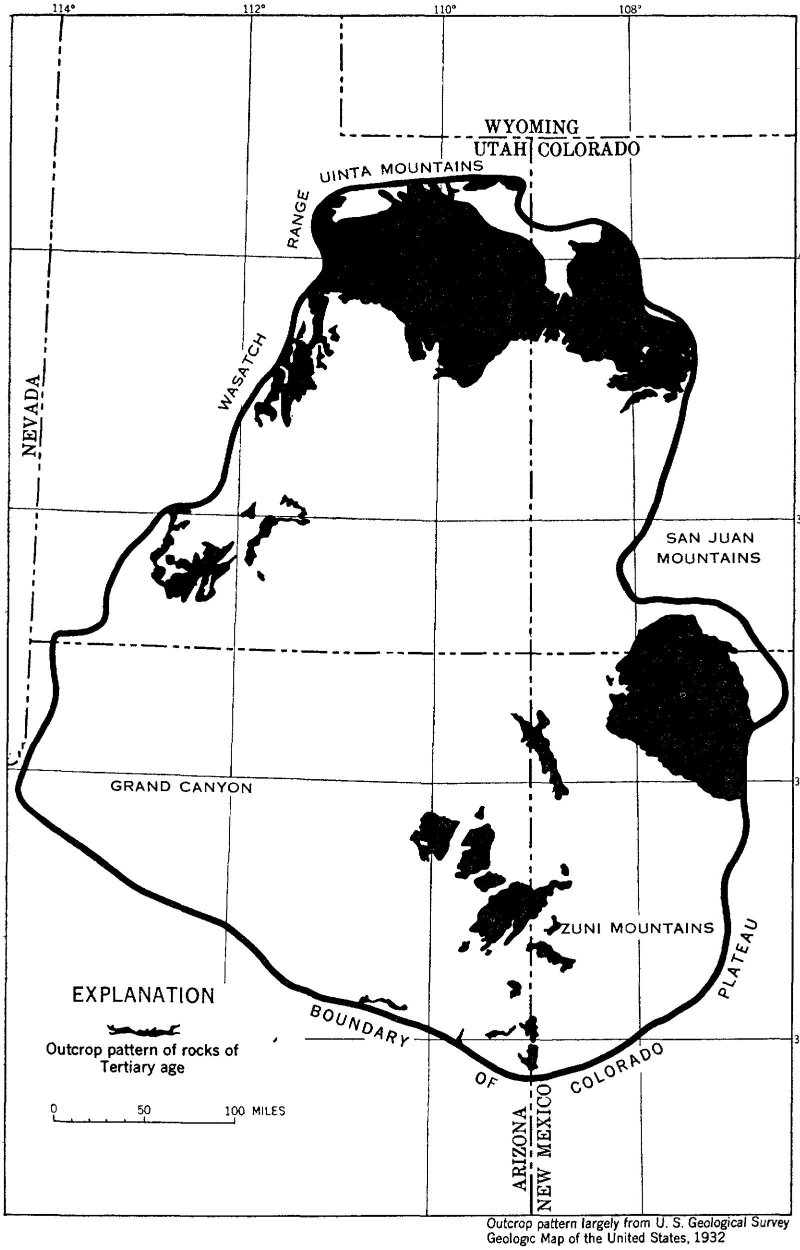


FIGURE 68.—Map of the Colorado Plateau showing outcrop pattern of sedimentary rocks of the Tertiary system.

TABLE 2.—*Volume of limestone, mudstone, and sandstone of the Paleozoic and Mesozoic systems of the Colorado Plateau*

System	Volume, in cubic miles			
	Sedimentary rocks	Limestone	Mudstone	Sandstone
Cretaceous	81,800	4,040	53,600	24,160
Jurassic	31,900	760	6,240	24,900
Triassic	30,000	2,800	11,900	15,300
Total volume of sedimentary rocks of Mesozoic age	143,700	7,600 (5 percent)	71,740 (50 percent)	64,360 (45 percent)
Permian	39,000	4,000	10,000	25,000
Pennsylvanian	30,000	19,500	3,000	7,500
Mississippian	8,500	7,700	400	400
Devonian	5,800	4,600	600	600
Cambrian	16,000	3,200	8,000	4,800
Total volume of sedimentary rocks of Paleozoic age	99,300	39,000 (39 percent)	22,000 (22 percent)	38,300 (39 percent)
Total volume of rocks of Paleozoic and Mesozoic ages	243,000	46,600 (19 percent)	93,740 (39 percent)	102,660 (42 percent)

CHEMICAL FEATURES OF SEDIMENTARY ROCKS

APPROACH TO THE STUDY OF CHEMICAL FEATURES

The Colorado Plateau is a vanadium and uranium province, and constitutes the most productive source of uranium in this country (McKelvey, 1955). It is also a region that contains a large amount of continental-type sediments. As shown in the preceding section, nearly half the sediments deposited during Paleozoic and Mesozoic time consist of sandstone, and about 65 percent of the material deposited during the combined Triassic and Jurassic periods consists of sandstone. Sandstones of Triassic and Jurassic ages are, furthermore, the major host rocks for uranium deposits, and more than 85 percent of the known uranium deposits are in basal sandstone and conglomeratic sandstone strata of the Chinle formation of Late Triassic age and in sandstone strata of the Morrison formation of Late Jurassic age. The apparent preference of uranium for certain sandstone beds suggests that the chemistry of these particular host rocks may be unique in some respect, and that chemical as well as sedimentary features of certain sandstone strata may have controlled the deposition of uranium.

Mudstone (including shale, siltstone, claystone, and carbonaceous material, after Twenhofel, 1937, p. 81–104) constitutes a large part of the sedimentary rocks of the Colorado Plateau. In the preceding section it was shown that 39 percent of the sedimentary material deposited during Paleozoic and Mesozoic time consists of mudstone (table 2). Even more important than volume, however, is the probable influence of mudstone in the localization and precipitation of uranium, vanadium, and associated elements to form ore deposits. The most favorable host rocks for uranium-vanadium deposits of the Colorado Plateau seem to be sandstone strata that contain from 25 to 60 percent mudstone in the form of interbedded layers, as seams and pellets, and as intergranular material.

The physical properties of mudstone, particularly its low permeability, makes it important as a trap and guide for ore-bearing solutions. Chemical properties of mudstones may be equally important in the formation of uranium-vanadium deposits, but the chemical influence of mudstone is not readily understood.

Discoveries of deposits of uranium in the Todilto limestone of Late Jurassic age in New Mexico indicate that, although limestone (including gypsum) constitutes only 19 percent of the sedimentary rocks of the Colorado Plateau, it may be an important host rock. How the chemical properties of limestone affect the deposition of uranium and the distribution of ore deposits is not clearly understood.

A description of the methods and the results of investigations made to determine some of the chemical characteristics of the various types of sedimentary host rocks of the Colorado Plateau are given in the following sections.

METHODS OF SAMPLING AND SAMPLE PREPARATION

A large suite of samples of sedimentary rocks was collected from outcrops during detailed stratigraphic and petrologic investigations of rocks of the Colorado Plateau by L. C. Craig, R. A. Cadigan, V. L. Freeman, T. E. Mullens, G. W. Weir, L. G. Schultz, J. H. Stewart, and the writer, all of the Geological Survey. Splits of most of these samples, selected to provide geographic as well as stratigraphic representation of the formations, were supplied to the writer by R. A. Cadigan.

The samples are mostly grab samples of outcrop material selected as representative of individual strata or parts of strata. The samples consist of 2 to 5 pounds of the freshest available rock, from which about 250 grams of material were quartered out. All samples were ground to −80 mesh in a disk grinder with ceramic plates (Barnett and others, 1955) before analysis. Samples were taken without regard to proximity of known uranium deposits, but no samples that were visibly mineralized or found to have radioactivity greater than 0.005 percent eU were used in the study of unmineralized sandstone.

DEFINITION OF UNMINERALIZED SANDSTONE

The empirical definition of unmineralized sandstone used in this report is based on the observed frequency distribution of measurements of radioactivity in the samples. In general, this frequency distribution, plotted graphically with concentration as the abscissa and frequency as the ordinate, is expressed by a curve or histogram characterized by one large peak or mode and low tails extending away from the peak towards lower and higher concentrations.

A point on the curve, representing an equivalent uranium content (eU) of 0.005 percent, was selected to differentiate between unmineralized and mineralized sandstone. Using this point as a reference, unmineralized sandstone comprised 98 percent of the total number of samples; the remaining 2 percent of the samples with more than 0.005 percent equivalent uranium content was considered mineralized.

No implication is intended in these definitions that either the mineralized or unmineralized sandstone has or has not been affected by geologic processes related to the formation of the uranium ore deposits, nor are the definitions related to grade cutoffs used by the Geological Survey to classify drill holes or to calculate ore reserves.

The distinction between unmineralized and mineralized sandstone is based upon content of eU rather than chemical uranium because the eU content of a sample can be simply and rapidly measured, whereas chemical determinations for uranium in trace amounts are time consuming and therefore inconvenient for preliminary selection of samples for study.

ANALYTICAL METHODS

Most of the analyses were done by a rapid semiquantitative spectrographic method under the supervision of A. T. Myers, of the U.S. Geological Survey. In this procedure a weighed amount of the sample mixture is burned in a controlled direct-current arc and the spectrum recorded on a photographic plate. Selected lines on the resulting plate are visually compared with those of standard spectra prepared in a manner similar to that for the unknowns. The standard spectra were prepared from mixtures of materials containing 68 elements in the following concentrations, expressed in percent: 10, 4.6, 2.2, 1.0, 0.46, etc. These values were chosen so that the concentrations of the elements decrease from 10 percent to about 0.0001 percent by a factor of the reciprocal of the cube root of 10. This factor provides a geometric concentration series which has three members for each order of magnitude and which is consistent with the relation between the blackness of the spectral line and the amount of an element present. By means of a comparator showing enlarged adjacent images of the sample spectra and the standard spectra, visual estimates are made of concentrations of the elements in the sample which are then reported as being between two standards in the following manner: x indicating the middle portion (2–5) of an order of magnitude, x^+ the higher portion (5–10), and x^- the lower (1–2) (table 3).

TABLE 3.—*Notation used in reporting semiquantitative spectrographic analyses*

Concentrations as reported by laboratory	Theoretical class interval (percent)		Theoretical class midpoint (percent)
	From—	To—	
xx	10. 0	100. 0	
x.+	4. 6	10. 0	6. 8
x	2. 2	4. 6	3. 2
x.—	1. 0	2. 2	1. 5
.x+	. 46	1. 0	. 68
.x	. 22	. 46	. 32
.x—	. 10	. 22	. 15
.0x+	. 046	. 10	. 068
.0x	. 022	. 046	. 032
.0x—	. 010	. 022	. 015
.00x+	. 0046	. 010	. 0068
.00x	. 0022	. 0046	. 0032
.00x—	. 0010	. 0022	. 0015
.000x+	. 00046	. 0010	. 00068
.000x	. 00022	. 00046	. 00032
.000x—	. 00010	. 00022	. 00015

( ), values estimated near threshold amount of element based on special study.
Tr., trace, near threshold of spectrographic method (below limit of sensitivity).
0, looked for, but not detected.
— not looked for.

The above method of reporting is used because the inherent limitations of this particular method of spectrographic analysis make the precision of the determinations less than the precision attained in preparing the standards. Major sources of error are (1) chemical and physical differences between the samples and the standards, (2) the omission of complete quantitative procedures for sample preparation and plate calibration, and (3) lack of duplicate determinations. Experimental work has shown that about 60 percent of the reported results fall within the proper portion of an order of magnitude.

About 60 elements are detectable with 1 exposure by this method. Certain elements, such as sulfur and selenium, are too volatile to be detected by the spectrographic method in the ranges of concentration in which they are present in the rocks studied. About 30 elements are commonly present in unmineralized sandstone above or near the spectrographic limits of sensitivity, and about 30 elements commonly looked for were not detected.

The limits of sensitivity for each element are in general those listed by Myers (1954, p. 195) and shown in table 4. As the analytical work has extended over a period of 3 years and some changes were made in the details of the technique during this time, and as the individual analysts followed slightly different practices in reporting elements near the limit of sensitivity, the limit of sensitivity actually achieved or reported for each element has varied slightly.

TABLE 4.—*Standard sensitivities for elements determined by the semiquantitative spectrographic method and special sensitivities attained in this investigation*

[Figures in parentheses are the sensitivities attained for this investigation by special study by R. G. Havens. Precision below standard sensitivities is less than precision above standard sensitivities]

Element	Sensitivity (percent)	Element	Sensitivity (percent)	Element	Sensitivity (percent)
Ag	0.0001 (0.00001)	Hg	1.0	Sb	0.05
Al	.001	In	.001	Sc	.001 (0.0002)
As	.1 (0.05)	Ir	.005	Si	.001
Au	.005	K	1.0 (0.2)	Sm	.01
B	.005 (0.001)	La	.005 (0.002)	Sn	.001 (0.005)
Ba	.0001	Li	.01	Sr	.0001
Be	.0001	Mg	.005	Ta	.05
Bi	.001	Mo	.001 (0.0002)	Te	.5
Ca	.001	Mn	.0005 (0.0001)	Th	.05
Cd	.005 (0.002)	Na	.05 (0.01)	Ti	.001
Ce	.05 (0.01)	Nb	.001	Tl	.05
Co	.0005 (0.0001)	Nd	.01 (0.005)	U	.05
Cr	.0005 (0.0001)	Ni	.0005 (0.0001)	V	.001 (0.0005)
Cu	.0001	Os	.005	W	.01
Dy	.05	P	.5	Y	.001 (0.0005)
Er	.005	Pb	.001 (0.0002)	Yb	.0005
Fe	.001	Pd	.0005	Zn	.05 (0.01)
Ga	.001 (0.0005)	Pt	.005	Zr	.001
Gd	.05	Re	.005		
Ge	.0005	Rh	.005		
Hf	.1	Ru	.005		

Spectrographic data on zinc, copper, lead, cobalt, nickel, selenium, antimony, and arsenic have been supplemented by colorimetric analyses. These elements are generally present in sandstone in concentrations below the spectrographic limit of sensitivity. Fluorimetric analyses were made for trace amounts of uranium.

STATISTICAL TREATMENT OF ANALYSES

The concentrations of the elements, as determined by semiquantitative spectrographic analysis, are reported in a series of 15 equal logarithmic classes that span the range from 0.0001 to 10 percent (table 3). Concentrations greater than 10 percent or less than 0.0001 percent are generally beyond the range of sensitivity of the spectrographic method employed and are noted but not classified. The theoretical class interval is equal to 0.33 in $\log_{10}$ values, and the class limits form a geometric series that is generated by integral powers of the cube root of 10 (2.15). After log transformation the analytical data may be treated with conventional mathematical methods for grouped data described in texts on statistical methods (see, for examples, Waugh, 1943, p. 81–154, 372–430; Snedecor, 1946, p. 31–74, 137–168; and Hoel, 1947, p. 3–20, 78–92, 128–166). The formulae used are as follows:

$$\bar{x}=\frac{1}{n}\sum f_i x_i \tag{1}$$

where $\bar{x}$=mean log
n=total number of samples
x_i=class midpoint of the ith class in logs
f_i=frequency of ith class.

$$s=\left[\frac{\sum f_i(\bar{x}-x_i)^2}{n-1}\right]^{1/2}=\left[\frac{1}{n-1}\left(\sum f_i x_i^2-\frac{[\sum f_i x_i]^2}{n}\right)\right]^{1/2} \tag{2}$$

where s=log standard deviation.

$$r=\frac{n\sum f_i x_i y_i-(\sum f_i x_i)\ (\sum f_i y_i)}{n\sum f_i x_i^2-(\sum f_i x_i)^2]^{1/2}\ [n\sum f_i y_i^2-(\sum f_i y_i)^2]^{1/2}} \tag{3}$$

where r=linear correlation coefficient between x and y, which are the logs of the concentration of two elements.

The number of significant figures that may be retained for $\bar{x}$ and s is a function of the number of samples and the magnitude of s up to a limit determined by the precision with which the standards used in the analysis were prepared. No assumptions or judgments on the precision or accuracy of the analyses or on the frequency distribution of the analytical results are involved in the statistical theory of the formulae employed. The computed value of $\bar{x}$ and s may be assigned some probability determined by the precision and accuracy of the analyses.

Statistical comparison of some of the semiquantitative spectrographic determinations with chemical analyses of the same material indicates that the absolute error of the spectrographic analysis is proportional to the concentration over the range of sensitivity, and analysis of replicate determinations shows that deviations from the geometric mean are approximately lognormally distributed. The frequency distribution of most elements that lie above the spectrographic limit of sensitivity in the various groups of samples studied have been found by the chi-square test to be approximately lognormal in unmineralized sandstone. Thus, the statistical theory for normal or Gaussian distribution may be applied to the spectrographic data with the least bias after log transformation. The transformation is based on the results obtained from the samples and is not concerned with the underlying causes of the form of the distribution.

The simplest and generally most useful measure of central tendency that may be computed from the spectrographic analyses is the arithmetic mean of the logs, the antilog of which is the geometric mean.

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For a lognormal distribution the geometric mean is an estimate of the population median, or true median. The most efficient estimate (Fisher, R. A., 1921, p. 309–310) of the true or population arithmetic mean may also be obtained from the geometric mean by methods given by Sichel (1952, p. 265–285). For purposes of comparison the geometric mean is generally the most satisfactory measure of central tendency for lognormal or approximately lognormal distributions, because the logarithmic variance of geometric means of small sets of samples drawn from a lognormally distributed population is less than the logarithmic variance of the arithmetic means (the geometric mean is a more efficient or more stable statistic).

SANDSTONE

SANDSTONE OF THE SALT WASH MEMBER OF THE MORRISON FORMATION

Most of the ore produced to date (1955) from the Morrison formation has come from lenticular beds of the uppermost sandstone unit of the Salt Wash member (McKay, 1955, p. 269). The ore deposits are generally tabular masses that appear to be localized in the thicker parts of sandstone lenses. Within a mineralized layer, high-grade concentrations of uranium and vanadium minerals occur in masses or pods commonly associated with carbonaceous material.

Because of economic importance, the geologic features of the Salt Wash member have been investigated by many workers, and considerable information concerning the stratigraphy, depositional environment, lithology, and mineralogy of the Salt Wash has been compiled. This study is intended to supplement these data and to provide a basis for study of the distribution of elements within the uranium deposits themselves.

AVERAGE CHEMICAL COMPOSITION

The geometric-mean composition and the estimated arithmetic-mean composition of 96 samples of sandstone from the Salt Wash member of the Morrison formation are given in table 5. For all elements whose means are above the spectrographic limit of sensitivity, arithmetic means were estimated from the mean log and log variance by use of tables prepared by Sichel (1952, p. 265–285). For some elements whose means lie close to or below the spectrographic limit of sensitivity, such as cobalt ,nickel, silver, yttrium, ytterbium, and boron, estimates of the geometric mean were derived by the use of area tables for the normal curve. To obtain an estimate of the the mean log, a logarithmic variance for each of these elements was assumed to be equal to the average log variance for all the other elements. An estimated arithmetic mean was obtained by inserting the estimated mean log and the assumed log variance in the equation for the maximum likelihood estimate of the arithmetic mean. The arithmetic mean given for uranium is based on fluorimetric analyses of 93 samples and is the sum of the analyses divided by the number of samples.

TABLE 5.—*Geometric-mean composition and estimated arithmetic-mean composition of unmineralized sandstone of the Salt Wash member of the Morrison formation*

[Composition, in percent]

Element	Range of geometric mean		Geometric deviation (GD) [2]	Arithmetic mean [3]
	Geometric mean (GM)	Confidence interval [1] × or ÷		
Al	1. 2	1. 2	1. 8	1. 5
Fe	. 24	1. 2	1. 9	. 30
Mn	. 022	1. 3	2. 9	. 038
Ca	2. 9	1. 4	3. 6	7. 2
Mg	. 24	1. 3	2. 6	. 40
Ti	. 053	1. 2	2. 1	. 064
K	≈. 5	----------	----------	----------
Na	≈. 09	----------	----------	----------
Ba	. 032	1. 3	2. 9	. 063
Sr	. 0057	1. 2	2. 1	. 0070
Zr	. 0089	1. 3	2. 4	. 015
Cr	. 00086	1. 3	2. 9	. 00090
B	≈. 001	----------	----------	----------
V	. 0012	1. 3	2. 3	. 0018
Ni	≈. 00008	----------	----------	----------
Co	≈. 00005	----------	----------	----------
Cu	. 0017	1. 3	2. 4	. 0020
Pb	≈. 00007	----------	----------	----------
Zn	<. 0020	----------	----------	----------
U	. 00018	1. 2	1. 9	. 00024

[1] The 99 percent confidence interval for the geometric mean. The limits of the confidence interval are determined from Student's $\bar{t}$ distribution (Fisher and Yates, 1953, p. 1, 40). For a lognormal distribution:

$$\text{confidence interval of the geometric mean} = \text{antilog } \underline{t}\left[\frac{\text{log geometric deviation}}{\sqrt{n-1}}\right];$$

where $\underline{t}$ is the deviation (or range of the population mean) in units of estimated standard error, and n is the number of samp les

[2] Antilog of the log standard deviation.

[3] The most efficient estimate of the arithmetic mean of a lognormal population may be obtained from the following equation if n is large:

Log_{10} estimated arithmetic mean $= \text{Log}_{10}\,\text{GM} + 1.1513\,(\text{Log}_{10}\,\text{GD})^2$.

Estimates for the composition of sandstones given by Rankama and Sahama (1950) have been selected for purposes of comparison because they represent a relatively recent compilation. The mean concentrations of some of the major elements in sandstone given by Rankama and Sahama are derived from an analysis of a composite sample of 253 sandstones prepared in 1895 by G. K. Gilbert and G. W. Stose and analyzed by H. N. Stokes (Clarke, 1924, p. 547).

Sandstone of the Salt Wash contains about half as much aluminum, iron, magnesium, and potassium as average sandstone prepared by Gilbert and Stose, and twice as much calcium. This difference reflects the fact that sandstones of the Salt Wash are well sorted or relatively clean quartose sandstones cemented by calcite as compared with the composite of Gilbert (Clarke, 1924), which evidently contained many graywackes. This inference is supported by a comparison (table 6) of mineral components of sandstone of the Salt Wash with those of average sandstone described by Clarke (1924, p. 33).

Sources of data for the average concentration of minor elements in sandstones given by Rankama and Sahama (1950) are diverse. The mean concentrations of strontium, chromium, cobalt, nickel, yttrium, and boron are those for quartzite from southern Lapland by Sahama (1945), and the means for barium and vanadium are by Von Englehardt and Jost, respectively, as quoted by Rankama and Sahama (1950, p. 482 and 601, respectively). Barium and strontium seem to be especially abundant in sandstone of the Salt Wash member compared with means of Rankama and Sahama.

TABLE 6.—*Mineral components, in percent, of sandstone of the Salt Wash member of the Morrison formation and average sandstone*

	Sandstone of the Salt Wash member [1]	*Average sandstone* [2]
Silica	79.0	66.8
Feldspar	5.5	11.5
Carbonate	13.0	11.1
Clay	[3] 2.5	6.6
Limonite and other minerals	.0	4.0
Total	100.0	100.0

[1] Craig and others (1955. p. 147–148).
[2] Clarke (1924, p. 33).
[3] Average based on 35 randomly selected sandstone samples of the Salt Wash member.

The published mean for silver is derived from three analyses by L. Wagoner (quoted by Clarke, 1924, p. 657) and agrees very closely with the estimate of the concentration of silver in sandstone of the Salt Wash. No estimate for copper in sandstone is given by Rankama and Sahama (1950), but the concentration of 20 ppm (parts per million) for sandstone of the Salt Wash compares well with 34 ppm found in silt from the Mississippi River (Clarke, 1924, p. 509).

The mean for uranium in average sandstone is based on 10 radiometric analyses of assorted samples reported by Evans and Goodman (1941, table 9), only 2 of which are actually sandstones, and 1 of these is from the Colorado Plateau. The estimated mean concentrations of vanadium and uranium in sandstones of the Salt Wash member are very similar to the averages of Jost (Rankama and Sahama, 1950, p. 601) and of Evans and Goodman (1941), respectively. This close agreement probably is partly fortuitous, but it suggests that sandstones of the Salt Wash do not contain exceptional quantities of these two ore elements, nor can the sandstones of the Salt Wash be considered as exceptionally rich in other elements found in unusual abundance in the uranium deposits. In fact, unmineralized sandstones of the Salt Wash show, if anything, a slight deficiency in several of the trace elements.

DISTRIBUTION OF ELEMENTS IN MECHANICAL FRACTIONS OF SANDSTONE

Five samples, taken from widely scattered localities and representing the uppermost, basal, and intermediate strata of the Salt Wash member, were mechanically disaggregated and sieved to provide a coarse fraction (>44 microns) and a fine fraction (<44 microns). The fine fraction contains particles ranging from coarse silt to clay in size. Heavy minerals were separated from the coarse fraction by tetrabromethane (sp gr 2.90) suspension. Heavy minerals were not separated from the fine fraction. Semiquantitative spectrographic analyses were made on the fine fraction and on both the heavy and light portions of the coarse fractions of each of the five samples (table 7). Microscopic examination was made of the coarse portions of each sample.

Sandstone of the Salt Wash member, according to Craig and others (1955, p. 147), may be classified as fine-grained quartzitic sandstone that contains only a small suite of light and heavy minerals. An average of the 5 samples shows that the coarse fraction constitutes 96.2 percent of the sandstone whereas the fine fraction constitutes 3.8 percent. The coarse fraction contains about 99.8 percent light minerals (sp gr <2.90). The light minerals consist of about 82 percent quartz, 9 percent chert, and 9 percent potassic and sodic feldspar. Detrital grains of zircon, tourmaline, barite, garnet, rutile, staurolite, and anatase comprise the bulk of the heavy minerals. These percentages and mineral suites correspond closely to the figures given by Craig and others (1955, p. 147–148) on the basis of 202 samples.

TABLE 7.—*Semiquantitative spectrographic analyses of total rock and rock fractions of five selected samples of unmineralized sandstone of the Salt Wash member of the Morrison formation*

[Analyst: R. G. Havens. See table 3 for explanation of notation used in reporting analytical data]

Sample No.	Location	Elements										
		Si	Al	Fe	Mg	Ca	Na	K	Ti	Zr	Mn	Ba
COARSE FRACTION, >44 MICRONS **Light portion, sp gr <2.90**												
L-45	North Sinbad Valley, Colo	xx.	0.x+	0.x	0.x−	x.−	0.0x+	0	0.0x	0.00x+	0.0x−	0.0x−
321	Marsh Pass, Ariz	xx.	.x+	.x	.x−	.x	.x−	.x+	.0x	.00x+	.00x	.0x
377	Oak Creek, N. Mex	xx.	x.−	.x	.x	x.−	.x	.x+	.0x	.00x	.00x+	.0x
499	Polar Mesa, Utah	xx.	.x+	.x	.x−	.x+	0	0	.0x	.00x+	.00x+	.0x+
825	Navajo Point, Utah	xx.	.x+	.x−	.0x+	.x	.0x+	.x+	.0x	.00x	.0x−	.0x−
Heavy portion, sp gr >2.90												
L-45	North Sinbad Valley, Colo	x.+	x.	xx.	0.x+	0.x+	0.x−	0	x.+	x.	0.x−	x.+
321	Marsh Pass, Ariz	x.−	x.−	xx.	.x	.x+	.x−	Trace	x.−	.x+	.x−	.0x+
377	Oak Creek, N. Mex	x.+	x.	xx.	.x+	x.−	.x−	0	x.+	x.	.x	.x−
499	Polar Mesa, Utah	x.−	.x+	x.+	.x−	.x	0	0	.x+	.0x+	.x−	xx.
825	Navajo Point, Utah	x.+	x.	x.	.x+	x.−	.x−	0	x.+	x.+	.x−	x.
FINE FRACTION, <44 MICRONS **Light and heavy portions**												
L-45	North Sinbad Valley, Colo	xx.	x.	0.x+	0.x+	x.+	0.x	x.−	0.x−	0.0x−	0.0x	0.x−
321	Marsh Pass, Ariz	xx.	x.	x.−	.x+	x.−	.x	x.−	.x	.0x	.0x−	.0x+
377	Oak Creek, N. Mex	xx.	x.	.x+	.x+	x.	.x+	x.−	.x−	.0x+	.0x	.0x+
499	Polar Mesa, Utah	xx.	x.+	x.−	.x+	x.−	.0x+	x.−	.x−	.0x−	.0x+	x.−
825	Navajo Point, Utah	x.+	x.	.x+	.x	xx.	.x−	x.−	.x	.0x	.0x+	.0x+
TOTAL ROCK ANALYSES **[From table 28]**												
L-45	North Sinbad Valley, Colo	xx.	x.−	0.x	0.x	x.	0.0x+	0	0.0x	0.0x−	0.0x−	0.0x
321	Marsh Pass, Ariz	xx.	x.−	.x	.0x+	.x−	.x	x.−	.0x	.00x+	.00x	.0x
377	Oak Creek, N. Mex	xx.	x.−	.x	.x	x.	.x	.x+	.0x	.0x	.0x−	.0x
499	Polar Mesa, Utah	xx.	x.−	.x	.x	.x+	0	0	.0x	.0x−	.0x	.x
825	Navajo Point, Utah	xx.	x.−	.x	.x−	x.+	.0x+	.x+	.0x+	.0x−	.0x−	.0x

Sample No.	Location	Elements									
		Sr	Li	B	P	Sc	V	Cr	Co	Ni	Cu
COARSE FRACTION, >44 MICRONS Light portion, sp gr <2.90											
L-45	North Sinbad Valley, Colo	0.00x−	0	0	0	0	0.00x	0.000x+	0.000x+	0	0.00x−
321	Marsh Pass, Ariz	.00x−	0	0	0	0	Tr.	.000x+	0	0	.000x+
377	Oak Creek, N. Mex	.00x+	0	0	0	0	.00x	.000x+	0	0	.00x−
499	Polar Mesa, Utah	.00x−	0	0	0	0	Tr.	.000x+	0	0	.00x−
825	Navajo Point, Utah	.00x−	0	0	0	0	.00x−	.000x	0	0	.000x+
Heavy portion, sp gr >2.90											
L-45	North Sinbad Valley, Colo	0.0x+	0	0.x	0	0.00x	0.0x+	0.x−	0.00x	—	0.0x
321	Marsh Pass, Ariz	.00x+	0	.x−	0	.00x−	.00x+	.0x	.00x−	—	.0x−
377	Oak Creek, N. Mex	.0x−	0	.x	0.x+	.00x	.0x+	.x−	.00x	—	.0x
499	Polar Mesa, Utah	x.−	0	.00x	0	.000x+	.0x−	.0x−	.00x−	—	.0x−
825	Navajo Point, Utah	.x−	0	.x+	x.−	.00x	.0x+	.x	.00x	—	.0x
FINE FRACTION, <44 MICRONS Light and heavy portions											
L-45	North Sinbad Valley, Colo	0.0x−	0.0x+	0.00x−	0	Tr.	0.0x−	0.00x	0.000x	0.000x+	0.0x−
321	Marsh Pass, Ariz	.0x−	0	.00x	0	Tr.	.00x	.00x	.000x	.000x+	.00x+
377	Oak Creek, N. Mex	.0x−	0	.00x	0	0	.00x+	.00x	.000x	0	.00x+
499	Polar Mesa, Utah	.0x	0.0x	.00x−	0	Tr.	.00x+	.00x	.000x+	.000x+	.0x−
825	Navajo Point, Utah	.0x−	0	.00x−	0	Tr.	.00x+	.00x	.000x	.000x+	.00x+
TOTAL ROCK ANALYSES [From table 28]											
L-45	North Sinbad Valley, Colo	0.00x−	0	0.00x	0	0	0.00x	0.000x+	0	0.000x−	0.00x−
321	Marsh Pass, Ariz	.00x	0	.00x	0	0	.000x+	.000x	0	0	.000x+
377	Oak Creek, N. Mex	.00x+	0	.00x−	0	0	.00x−	.00x−	0	0	.00x−
499	Polar Mesa, Utah	.00x	0	.00x−	0	0	.000x+	.000x+	0	.000x−	.00x
825	Navajo Point, Utah	.00x	0	.00x−	0	0	.00x−	.000x+	0	0	.00x−

TABLE 7.—*Semiquantitative spectrographic analyses of total rock and rock fractions of five selected samples of unmineralized sandstone of the Salt Wash member of the Morrison formation*—Continued

Sample No.	Location	Elements										
		Ga	Y	Nb	Nd	Mo	Sn	La	Hf	Ce	Yb	Pb
COARSE FRACTION, >44 MICRONS **Light portion, sp gr <2.90**												
L-45	North Sinbad Valley, Colo	0	0	0	0	0	0	0	0	0	0	0
321	Marsh Pass, Ariz	0	0	0	0	.00x−	0	0	0	0	0	0
377	Oak Creek, N. Mex	0	0	0	0	0	0	0	0	0	0	0
499	Polar Mesa, Utah	0	0	0	0	0	0	0	0	0	0	0
825	Navajo Point, Utah	0	0	0	0	0	0	0	0	0	0	0
Heavy portion, sp gr >2.90												
L-45	North Sinbad Valley, Colo	0.000x+	0.0x	0.00x	0.0x	0.00x−	0.00x	0.0x−	0.0x	0.0x−	0.00x+	0.0x−
321	Marsh Pass, Ariz	.000x+	.0x−	.00x−	0	.0x	0	.00x+	.0x	0	.00x	.0x−
377	Oak Creek, N. Mex	.000x+	.0x	.00x+	.0x	Tr.	.00x	.0x−	.0x	.0x−	.00x	.00x+
499	Polar Mesa, Utah	Tr.	.00x	Tr.	.0x−	0	0	.0x−	0	.0x−	.000x	.00x+
825	Navajo Point, Utah	.000x+	.0x+	.00x+	.0x	0	.00x+	.0x−	.0x+	.0x−	.00x+	.0x−
FINE FRACTION, <44 MICRONS **Light and heavy portions**												
L-45	North Sinbad Valley, Colo	0.000x+	0.00x−	0	0	0	0	0	0	0	0.000x−	0.00x−
321	Marsh Pass, Ariz	Tr.	.00x−	0	0	.00x	0	0	0	0	.000x−	.00x−
377	Oak Creek, N. Mex	Tr.	.000x+	0	0	0	0	0	0	0	.000x−	.00x−
499	Polar Mesa, Utah	.000x+	.00x−	0	0	0	0	0	0	0	.000x−	.00x−
825	Navajo Point, Utah	Tr.	.00x−	0	0	0	0	0	0	0	.000x−	Tr.
TOTAL ROCK ANALYSES **[From table 28]**												
L-45	North Sinbad Valley, Colo	0	0	0	0	0	0	0	0	0	0	0
321	Marsh Pass, Ariz	0	0	0	0	.00x−	0	0	0	0	0	0
377	Oak Creek, N. Mex	0	0	0	0	0	0	0	0	0	0	.000x−
499	Polar Mesa, Utah	0	.000x	0	0	0	0	0	0	0	0	0
825	Navajo Point, Utah	0	0	0	0	0	0	0	0	0	0	0

The average concentrations of elements in the various fractions of sandstone are shown in table 8. Elements found to be more abundant in the heavy portion of the coarse fraction than in the light include iron, barium, strontium, titanium, zirconium, chromium, boron, vanadium, copper, cobalt, lead, tin, molybdenum, gallium, scandium, ytterbium, lanthanum, yttrium, phosphorus, cerium, hafnium, niobium, and neodymium. Strontium, titanium, zirconium, vanadium, copper, and lead are also more abundant in the fine fraction than in the coarse light fraction.

Elements that are most abundant in the fine fraction include aluminum, potassium, sodium, calcium, magnesium, and lithium. The light portion of the coarse fraction contains some calcium, aluminum, alkali metals, iron, and magnesium.

TABLE 8.—*Average concentrations of elements in coarse and fine fractions of sandstone of the Salt Wash member of the Morrison formation*

[Composition, in geometric-mean percent. All entries are the average of the 5 samples given in table 7]

Element	*A* Total rock	*B* Fine fraction (3.8 percent of total rock)	*C* Coarse fraction (96.2 percent of total rock)	
			Light portion (96 percent of total rock)	Heavy portion (0.2 percent of total rock)
Si	>10.0	>10.0	>10.0	5
Al	1	4	.8	2
K	~0.5	1	.4	[1] BT
Na	.1	.2	.09	.1
Fe	.3	.9	.3	>10.0
Mn	.01	.04	.008	.2
Ca	2	4	1	.8
Mg	.2	.6	.2	.4
Ba	.04	.2	.03	1
Sr	.003	.02	.002	.07
Ti	.05	.2	.03	3
Zr	.02	.03	.005	1
Cr	.0009	.003	.0006	.08
B	.002	.002	BT	.1
V	.001	.007	.001	.02
Cu	.001	.009	.001	.02
Ni	BT	.0006	BT	[2] —
Co	BT	.0004	BT	.002
Pb	BT	.001	BT	.01
Sn	BT	BT	BT	.002
Ga	BT	.0004	BT	.0006
Sc	BT	BT	BT	.002
Yb	BT	.0002	BT	.003
La	BT	BT	BT	.01
Y	BT	.001	BT	.02
Ce	BT	BT	BT	.01
Hf	BT	BT	BT	.03
Nb	BT	BT	BT	.003
Nd	BT	BT	BT	.02

[1] BT, below the threshold value of the spectrographic analysis for this material. See table 4, for list of threshold values.
[2] —, not looked for.

Although the heavy minerals contain the highest concentration of some elements, the greatest quantity of each element is contained in the light coarse fraction of the sandstone studied. Microscopic examination of the light fraction shows that a carbonate crust coats many, if not all, of the detrital grains. Mechanical separation failed to dislodge mineral fragments that adhered to this crust as tiny satellites to grains of silica. It is believed that this crust plus the tiny grains of both light and heavy minerals contain the bulk of the less abundant metallic elements.

STRATIGRAPHIC VARIATIONS OF ELEMENTS

The Salt Wash member of the Morrison formation in many places consists of 2 or more major sandstone beds ranging in thickness from about 20 feet to about 80 feet with intervening beds consisting of mudstone, siltstone, and thin sandstone lenses. Most of the uranium deposits of the Morrison formation occur in the Salt Wash member, and in many mining districts of the Colorado Plateau the deposits are found in one sandstone stratum within the Salt Wash (Weir, 1952). In southwestern Colorado and part of eastern Utah this stratum is near the top of the member.

To determine if the average composition of the sandstones of the Salt Wash member varied with the stratigraphic position of the sandstone in any measurable respect, the 96 sandstone samples were separated into 3 categories: (1) samples from uppermost sandstone strata, (2) samples from basal sandstone strata, and (3) samples from sandstone strata in intermediate stratigraphic positions.

The concentrations of elements in sandstones from each of the three categories were averaged and compared to detect differences in chemical composition. The average compositions of sandstones from the three categories are given in table 9 on page 403.

With the possible exception of the potassium and calcium content, no significant difference in composition among the three categories of sandstone was found. Calcium shows a progressive decrease in concentration in samples from the basal sandstone category to samples from the uppermost sandstone category. The amount of calcium in sandstone may be an indirect measure of the permeability and transmissivity of the strata. Much calcium in sandstone indicates the presence of carbonate and sulfate cements that would reduce the permeability of the strata. The uppermost strata of sandstone appears to contain less potassium than the basal and intervening strata.

TABLE 9.—*Average chemical composition of major sandstone strata of the Salt Wash member of the Morrison formation*

[Geometric-mean percent]

Element	Samples from— Basal sandstone strata (29 samples): Range of geometric mean: Geometric mean	Basal: Confidence interval [2]	Basal: Geometric deviation [3]	Intermediate sandstone strata (42 samples) [1]: Range of geometric mean: Geometric mean	Intermediate: Confidence interval [2]	Intermediate: Geometric deviation [3]	Uppermost sandstone strata (25 samples): Range of geometric mean: Geometric mean	Uppermost: Confidence interval [2]	Uppermost: Geometric deviation [3]
Al	1.2	1.4	1.9	1.2	1.3	1.8	1.3	1.5	2.0
Fe	.25	1.5	2.1	.22	1.3	1.8	.25	1.4	1.0
Mg	.23	1.6	2.6	.23	1.6	3.2	.23	1.8	2.7
Ca	4.3	1.7	2.7	3.7	1.7	3.6	2.1	2.2	3.9
Na	.1	1.3	1.5	.1	1.5	2.6	.1	1.9	2.9
K	.4	1.6	2.3	.6	1.5	2.5	.2	1.6	2.3
Ti	.05	1.4	1.9	.05	1.3	2.0	.06	1.5	2.0
Zr	.01	1.6	2.4	.01	1.5	2.5	.01	1.7	2.4
Mn	.02	1.6	2.4	.02	1.6	3.3	.02	1.9	3.0
Ba	.03	1.7	2.8	.04	1.6	3.2	.03	1.9	3.0
Sr	.005	1.5	2.1	.005	1.5	2.6	.004	1.8	2.7
V	.001	1.6	2.5	.001	1.6	3.2	.0008	1.7	2.5
Cr	.0007	1.4	1.9	.0007	1.5	2.5	.0006	1.6	2.4
Cu	.002	1.6	2.5	.001	1.4	2.1	.001	1.5	2.1
U	.0002	1.4	1.9	.0002	1.4	1.9	.0002	1.4	2.1

[1] Uranium based on 29 samples; 13 samples not analyzed.
[2] The 99 percent confidence interval for the geometric mean (see footnote 1, table 5).
[3] Antilog of the log standard deviation.

REGIONAL DISTRIBUTION OF ELEMENTS

The Salt Wash member of the Morrison formation is described by Craig and others (1955) as formed on a broad fan-shaped alluvial plain and deposited by an aggrading stream system. Its major source area probably lay in west-central Arizona near the apex of the fan, and its secondary source areas were scattered along the margins of the fan.

Some of the elements in sandstone of the Salt Wash member show a relatively systematic regional distribution. Titanium, zirconium, boron, chromium, ytterbium, and yttrium occur in above-average concentrations in three widely separated areas, two of which are near the lateral margins of the Salt Wash fan (fig. 69). These areas probably contain more than average amounts of heavy minerals. The southern area, in the vicinity of the Four Corners area, reflects mixing of materials of the Recapture member into the Salt Wash member (Robert A. Cadigan, oral communication, 1955). In contrast to the Salt Wash member, the Recapture contains materials definitely derived from crystalline rocks, probably from a source area in west-central New Mexico; the concentration of titanium, zirconium, boron, chromium, ytterbium, and yttrium in this area may be accounted for by the addition to the Salt Wash of heavy minerals derived from the source area of the Recapture. The explanation of the other two areas of concentration is less certain. The area in central Utah may reflect the local addition of volcanic materials.

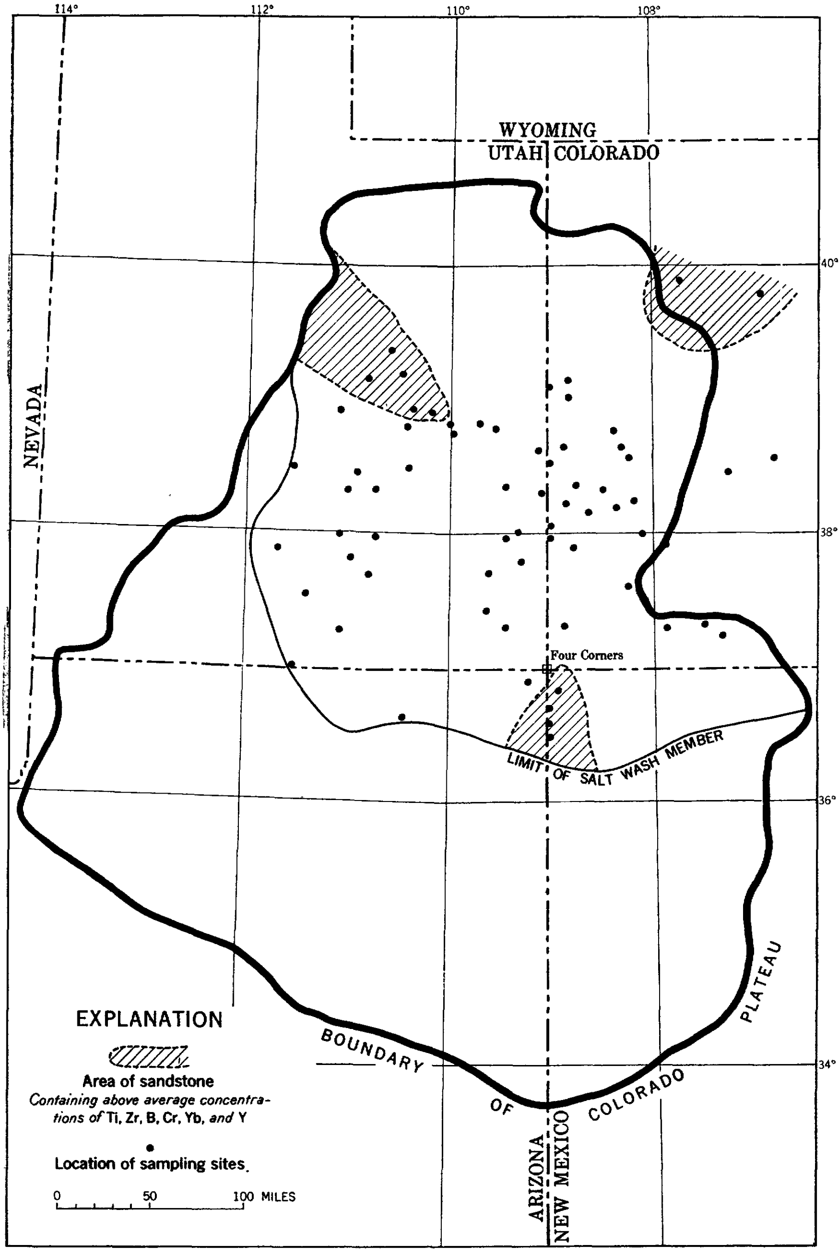

FIGURE 69.—Map of the Salt Wash member of the Morrison formation showing areas of high concentrations of elements that may be contained in minerals derived from crystalline rocks or volcanic sources.

Vanadium has a distribution that reflects the distribution of uranium-vanadium deposits. Most of the high concentrations of vanadium occur within a restricted area that includes the Uravan mineral belt (Fischer and Hilpert, 1952) and within an area just south of Four Corners (fig. 70). A few isolated highs are scattered throughout southeastern Utah and southwestern Colorado.

The distribution of high concentrations of copper (fig. 71) seems to be less systematic than the distribution of high concentrations of vanadium. The Uravan mineral belt is not so clearly defined on the basis of copper content, and there are distinct areas of low copper concentrations. A particularly distinct area of low copper content lies just north of Four Corners. The regional variation of copper in sandstone corresponds roughly to the regional variation of the copper content in the uranium-vanadium deposits. (Shoemaker and others, 1959). Deposits that contain impressive amounts of copper occur in host rocks that contain somewhat more than average amounts of copper.

BASAL SANDSTONE UNITS OF THE CHINLE FORMATION

Most of the uranium ores in Triassic rocks of the Colorado Plateau are in sandstone units in the lower part of the Chinle formation (Page and others, 1956, p. 9). Rocks of these units consist chiefly of fluvial conglomerates, sandstones, and interbedded mudstones in which plant debris is abundant. In many respects the uranium deposits in these rocks are similar in appearance to uranium deposits in the Salt Wash member of the Morrison formation. The deposits appear to be localized in the thicker parts of sandstone lenses, and many of the deposits are characterized by "roll" ore bodies; green or gray mudstone seems to be at least spatially related to the deposits. However, certain mineralogic differences serve to distinguish some uranium ore found in Chinle rocks from uranium ore found in the Morrison formation. Copper, copper-uranium, and high uranium-low vanadium ores are typical of the ores mined from Triassic rocks, whereas high vanadium-low uranium ores form the bulk of the ore from the Morrison formation. In addition, studies of the trace-element content of these two groups of ore (Shoemaker and others, 1959) show that ores from the Chinle are characterized by relatively higher average concentrations of arsenic, zinc, nickel, cobalt, chromium, and iron.

The principal host rocks of the Chinle formation are sandstone strata of the Shinarump and Moss Back members. A total of 97 samples of these 2 members were selected from a collection of samples made by J. H. Stewart and R. A. Cadigan for stratigraphic and mineralogic investigation. Six of these samples were taken from basal sandstone beds which may or may not be equivalent to the Shinarump

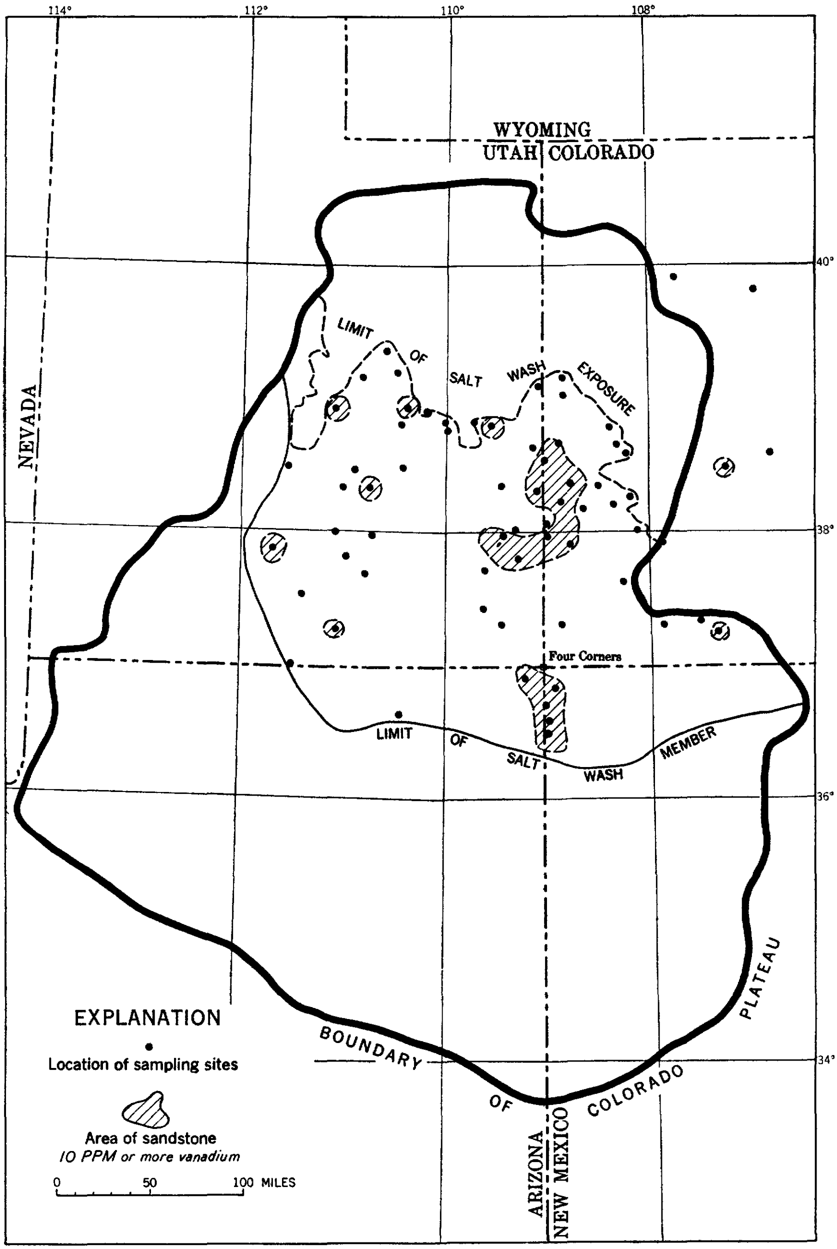

FIGURE 70.—Map of the Salt Wash member of the Morrison formation showing areas of sandstone containing at least 10 ppm vanadium.

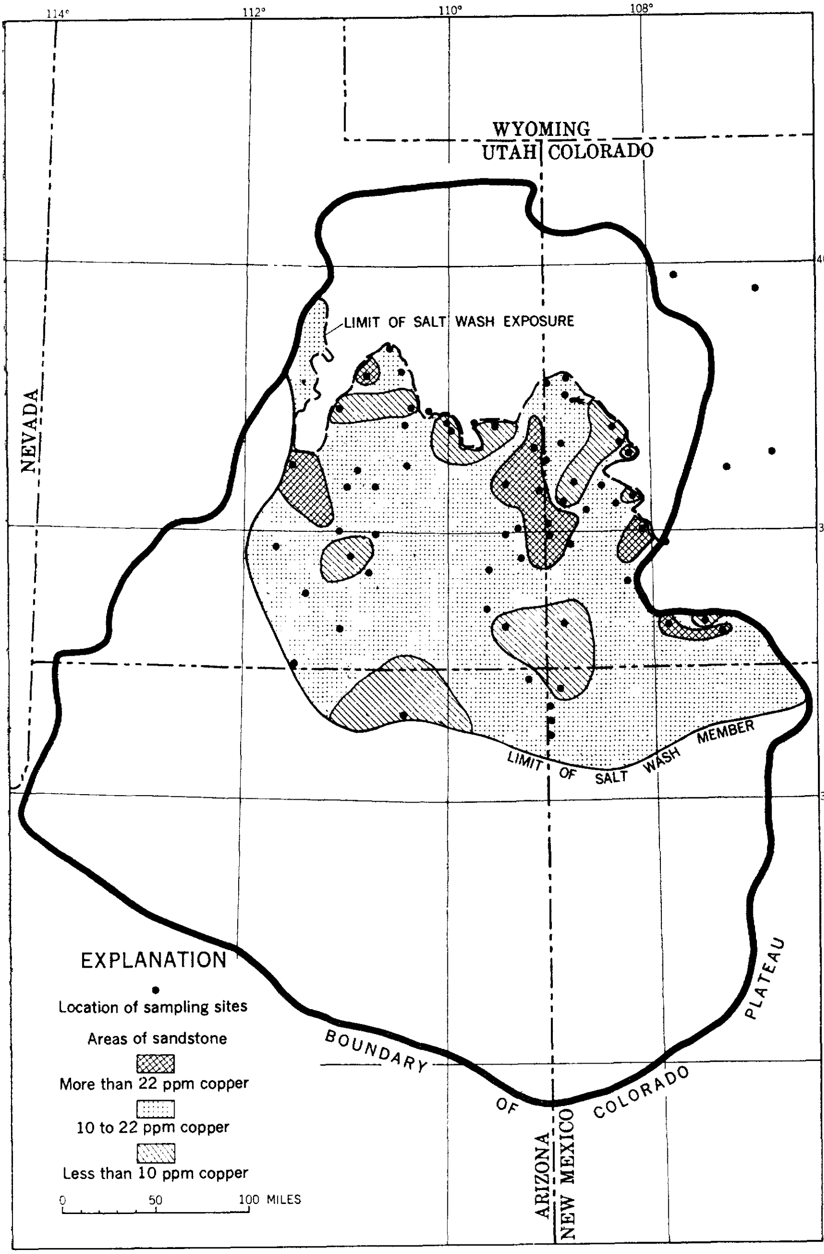

FIGURE 71.—Map of the Salt Wash member of the Morrison formation showing distribution of copper in sandstone.

or Moss Back. The 97 samples are from 44 localities in Utah and Arizona and were selected to achieve as uniform a sampling pattern as possible. Locations of these sampling sites are shown in figure 50. Analyses of these samples are shown in table 23.

AVERAGE CHEMICAL COMPOSITION

The estimated geometric-mean composition and the estimated arithmetic-mean composition of sandstone of the Shinarump and Moss Back members are given in table 10. The arithmetic means were estimated by the same methods described on pages 394 and 395.

TABLE 10.—*Geometric-mean composition and estimated arithmetic-mean composition of unmineralized sandstone of the Shinarump and Moss Back members of the Chinle formation*

[Number of samples used in the determinations: U, fluorimetric analyses, 93; Zn, colorimetric analyses, 79; As, colorimetric analyses, 88; all others, semiquantitative spectrographic analyses, 97]

[Composition, in percent]

Element	Range of geometric mean		Geometric deviation [2]	Arithmetic mean [3]
	Geometric mean	Confidence interval [1] × or ÷		
Al	3.2	1.3	2.3	4.5
Fe	.65	1.3	2.4	.97
Mn	.017	1.6	6.1	.095
Ca	.68	1.7	7.2	4.5
Mg	.18	1.4	3.4	.37
Ti	.092	1.3	2.4	.13
K	≈.5	----------	----------	----------
Na	[4]≈.08	----------	----------	----------
Ba	.044	1.4	3.3	.092
Sr	.0082	1.5	4.1	.022
Zr	.012	1.3	2.9	.022
Cr	.0013	1.3	2.7	.0021
B	[4]≈.001	----------	----------	----------
V	.0022	1.3	3.0	.0040
Ni	[4]≈.0003	----------	----------	----------
Co	[4]≈.0002	----------	----------	----------
Cu	.0020	1.4	3.5	.0043
Pb	[4]≈.0001	----------	----------	----------
Zn	.0014	1.5	3.7	.0033
As	.0012	1.2	1.9	.0017
U	.00024	1.2	2.0	.00030

[1] The 99 percent confidence interval for the geometric mean (see footnote 1, table 5).
[2] Antilog of the log standard deviation.
[3] Estimated arithmetic mean (see footnote 3, table 5).
[4] Estimated geometric mean. Estimated by assuming the part of the frequency distribution below the limit of sensitivity conforms to part of a lognormal distribution and by assuming for the element in question an average log-standard deviation computed for elements in Triassic host sandstone. The average log-standard deviation is 0.536 (GD=3.4).

Sandstone of the Shinarump and Moss Back members contains more than twice as much aluminum and iron and more potassium, titanium, strontium, zirconium, and vanadium, but less calcium and magnesium than does sandstone of the Salt Wash member of the

Morrison formation. These differences in chemical composition reflect differences in the lithologies of sandstone of these two members. The Salt Wash consists of well-sorted relatively clean quartzose sandstone cemented by calcite, whereas the lithology of sandstone of the Shinarump and Moss Back is not uniform. Rocks of the Shinarump and Moss Back members are chiefly arkosic sandstone and conglomerate with abundant tuffaceous material.

Concentrations of sodium, boron, and uranium in sandstone of the Shinarump and Moss Back members are similar to concentrations of these elements in sandstone of the Salt Wash.

Vanadium, iron, copper, cobalt, and nickel, and perhaps chromium, are among those elements that are commonly associated with uranium in the sandstone-type deposits of the Colorado Plateau. Comparisons of mean compositions of uranium deposits (Shoemaker and others, 1959) show that deposits in upper Triassic host rocks contain more vanadium, iron, copper, cobalt, nickel, and chromium than deposits in the Morrison formation. Although the differences in the average content of these elements in the two principal host rocks are not large, they do suggest that the host rocks contributed certain amounts of these elements during formation of the uranium deposits; thus, host rocks that contained greater amounts of these elements may have provided greater quantities of these elements.

REGIONAL DISTRIBUTION OF ELEMENTS

The origin of thin but widespread conglomerates in the basal part of the Chinle formation has been the subject of debate among geologists for many years (Gregory, 1913, p. 424–438; Stokes, 1950). Stratigraphic and cross-stratification studies, pebble assemblage studies, and mineralogic studies now underway by the U.S. Geological Survey may lead to conclusions concerning the mode of origin and sources of material found in these beds. The distribution of elements may also provide clues as to the origin of these strata that are so unusual in character.

If variations in concentration of a single element are plotted with respect to sample locations, the distribution pattern that results is indefinite. However, if a suite of elements is plotted, the pattern becomes strengthened and more definitive. Figure 72 shows two areas that contain above-average concentrations of chromium, titanium, zirconium, boron, ytterbium, yttrium, vanadium, uranium, and copper: a northern area in east-central Utah and a southern area in southeast Utah. The distribution of these elements may reflect possible source areas for part of the basal strata of the Chinle.

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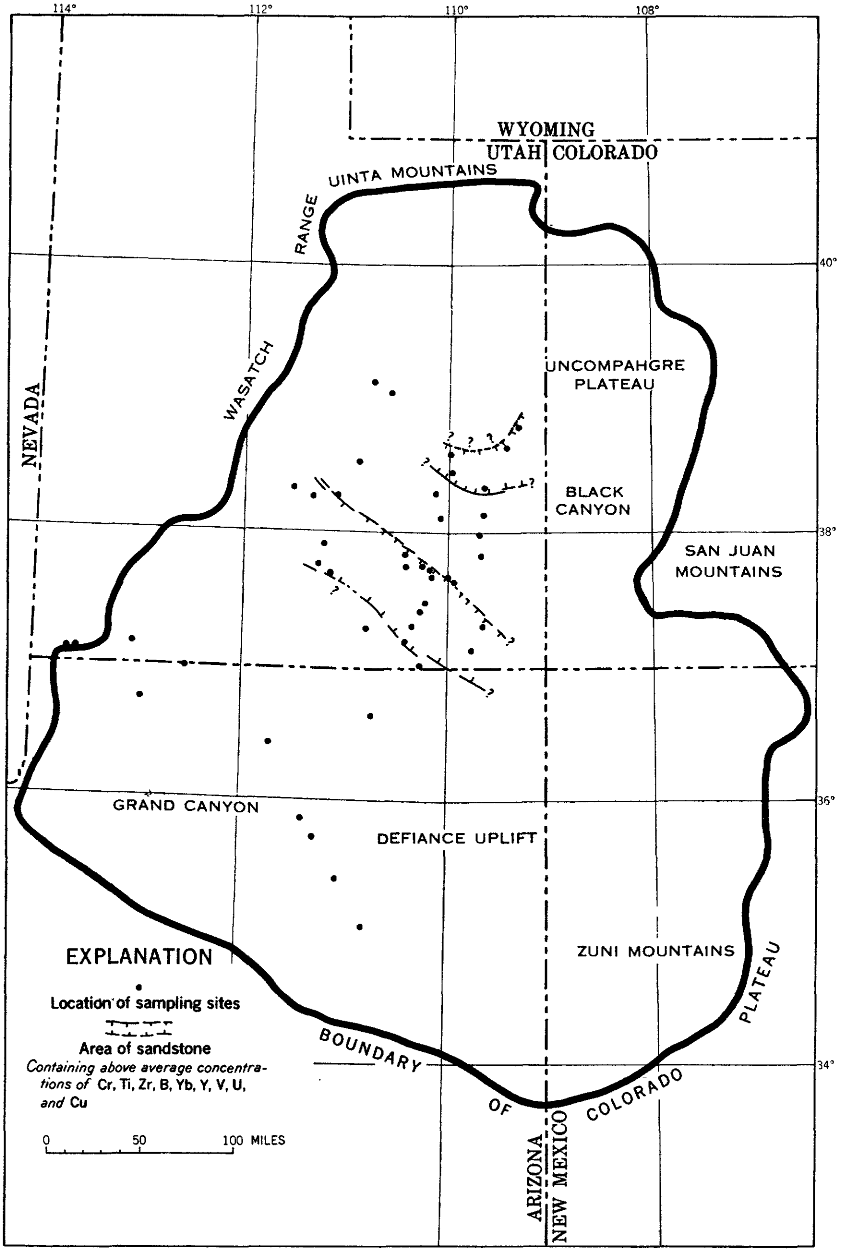

FIGURE 72.—Map of the Colorado Plateau showing areas of sandstone of the Shinarump member of the Chinle formation containing above-average amounts of elements commonly found in heavy minerals.

The northern area may reflect the addition of material derived directly from the Precambrian core of the ancestral Uncompahgre highland which was exposed at the beginning of Late Triassic time. The southern area containing above-average concentrations of these elements is more difficult to interpret, but it may be indirectly related to Precambrian rocks of the ancestral Uncompahgre highland. The Precambrian core contributed large quantities of debris to the Cutler formation of Permian age; and in northeastern Arizona in the vicinity of the Defiance uplift, the Shinarump member of the Chinle formation rests directly upon sandstone, in part arkosic, of the Cutler formation. The source of the elements concentrated in sandstone of the Shinarump in the southern area may have been the Cutler formation, which was also exposed over a large area adjacent to the west edge of the ancestral Uncompahgre highland during Late Triassic time.

STRATIGRAPHIC DISTRIBUTION OF ELEMENTS IN SANDSTONES OF PRE-TERTIARY AGE

MEAN COMPOSITION OF SANDSTONES

A total of 353 samples of sandstone from 21 formations of Precambrian, Paleozoic, and Mesozoic ages was selected from a large suite of samples of sedimentary rocks collected chiefly by R. A. Cadigan. The original suite was collected primarily for mineralogic studies and grain-size analyses. The source areas of samples selected for this study are shown in figure 73. Analyses of these samples are shown in tables 20–31.

The average chemical compositions of sandstones from each of the formations studied are shown in table 11. The chemical composition of each of the rock units is expressed as the geometric mean; the mean concentration for each element is based on the number of samples indicated in table 11.

The mean composition of sandstone of the Colorado Plateau (table 12) was determined by calculating the geometric mean of each element from the means shown on table 11. The calculated geometric-mean compositions of basal sandstone beds of the Chinle formation, chiefly those of the Shinarump and Moss Back members, and those of the Salt Wash member of the Morrison formation, are repeated in table 12 for ease of comparison.

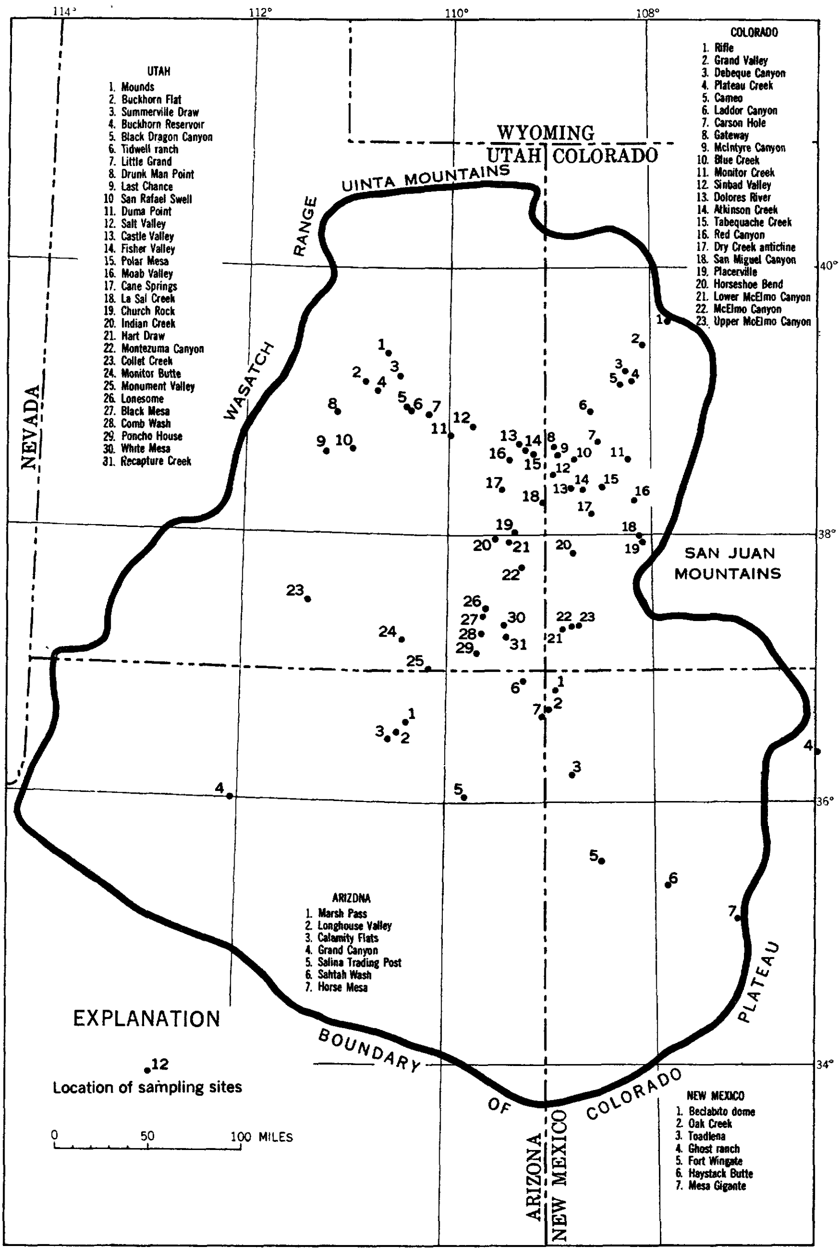

FIGURE 73.—Index map of the Colorado Plateau showing sources of samples of sandstone from some of the principal formations.

TABLE 11.—*Average chemical composition of sandstones from some of the principal sedimentary formations of the Colorado Plateau*

[Composition, in geometric-mean percent]

System	Formation	Number of samples	Elements																
			Al	Fe	Mg	Ca	Na	K	Ti	Zr	Mn	Ba	Sr	B	V	Cr	Co	Ni	Cu
Cretaceous: Upper Cretaceous	Mesa Verde formation	4	3.0	0.6	0.6	1.0	0.8	1.0	0.2	0.02	0.02	0.06	0.01	0.002	0.003	0.001	<0.0001	0.0005	0.002
	Dakota sandstone	7	.8	.3	.04	0.08	.03	<.2	.05	.005	.001	.008	.0004	<.001	.0005	.0003	<.0001	<.0001	.0005
Cretaceous: Lower Cretaceous	Cedar Mountain formation	3	0.4	0.3	0.2	5.0	0.04	<0.2	0.02	0.003	0.1	0.005	0.007	<0.001	0.001	0.0004	<0.0001	0.0001	0.0007
	Buckhorn Conglomerate member of stokes (1952)	5	.4	.2	.2	.8	.04	<.2	.03	.005	.009	.03	.003	.002	.001	.0006	<.0001	<.0001	.0009
	Burro Canyon formation	9	.5	.2	.07	.5	.02	<.2	.04	.01	.004	.02	.002	.002	.0004	.0004	<.0001	<.0001	.0007
Jurassic	Morrison formation:																		
	Brushy Basin member	12	0.8	0.3	0.2	4.0	0.1	0.1	0.04	0.006	0.05	0.07	0.007	0.001	0.0007	0.0003	<0.0001	0.0003	0.0008
	Westwater Canyon member	3	.5	.2	.09	.3	.09	.2	.04	.005	.007	.02	.002	.001	.0005	.0002	<.0001	<.0001	.0005
	Recapture member	5	.7	.2	.1	.7	.2	.5	.04	.007	.01	.03	.005	.001	.0009	.0002	<.0001	<.0001	.0003
	Salt Wash member	96	1.0	.2	.2	3.0	.09	.5	.05	.009	.02	.03	.006	.001	.001	.0009	<.0001	<.0001	.002
	Bluff sandstone	5	1.0	.3	.2	1.0	.08	.7	.05	.007	.02	.03	.004	.002	.001	.0004	<.0001	<.0001	.001
	Cow Springs sandstone	7	1.0	.4	.2	.9	.2	.8	.05	.006	.008	.03	.004	.001	.001	.0004	<.0001	<.0001	.0006
	Summerville formation	16	.9	.3	.4	2.0	.08	.7	.03	.006	.02	.04	.007	.001	.002	.0005	<.0001	.0003	.001
	Curtis formation	2	2.0	.5	.5	3.0	.5	2.0	.07	.01	.01	.07	.007	.002	.002	.002	<.0001	.0003	.0005
	Entrada sandstone	12	.8	.3	.4	.7	.1	.8	.04	.01	.008	.03	.006	.002	.001	.0006	.0002	.0002	.0008
	Carmel formation	4	2.0	1.0	.7	2.0	.2	1.0	.1	.02	.02	.03	.007	.004	.002	.001	.0002	.0005	.001
Jurassic and Jurassic(?)	Navajo sandstone	5	1.0	0.2	0.08	0.3	0.1	0.7	0.04	0.008	0.008	0.03	0.003	0.002	0.0008	0.0006	<0.0001	<0.0001	0.0006
Jurassic(?)	Kayenta formation	3	1.0	0.4	0.7	1.0	0.3	1.0	0.06	0.01	0.03	0.04	0.01	0.001	0.0008	0.001	0.0001	0.0003	0.0008
Triassic	Wingate sandstone	12	1.0	0.3	0.2	0.4	0.2	1.0	0.07	0.01	0.008	0.02	0.005	0.003	0.0008	0.0007	<0.0001	<0.0001	0.0009
	Chinle formation	7	1.0	.9	1.0	3.0	.3	.5	.1	.02	.04	.03	.009	.003	.001	.002	.0002	.0008	.001
	Basal sandstone beds, chiefly the Shinarump and Moss Back members	97	3.0	.7	.2	.7	.08	.5	.09	.01	.02	.04	.008	.001	.002	.001	.0002	.0003	.002
	Moenkopi formation	16	2.0	.9	1.0	4.0	.4	2.0	.1	.01	.08	.07	.02	.002	.004	.002	.0003	.0005	.002
Permian	Cutler formation	14	2.0	0.6	0.6	2.0	0.5	1.0	0.09	0.01	0.01	0.06	0.02	0.002	0.003	0.002	0.0001	0.0004	0.001
	Toroweap formation	1	1.0	.7	.7	3.0	.3	.7	.1	.01	.01	.01	.003	.003	.001	.003	.0003	.0007	.0003
	Coconino sandstone	3	.5	.2	.09	.3	< .01	<.1	.04	.007	.002	.01	.0009	.001	.0005	.0007	.0002	.001	.0009
Permian and Pennsylvanian	Supai formation	2	0.7	0.1	0.2	3.0	< .03	<0.2	0.03	0.005	0.007	0.01	0.001	0.001	<0.0003	0.0005	0.0001	<0.0002	0.0007
Precambrian	Shinumo quartzite	3	0.9	0.7	0.04	0.01	<0.01	0.2	0.007	0.009	0.002	0.002	0.001	<0.001	<0.0003	0.0003	<0.0001	0.0001	0.0009

TABLE 12.—*Average chemical composition, in parts per million, of sandstone of the Colorado Plateau and sandstones from the principal uranium-bearing strata*

Element	Unmineralized sandstones from—		
	Colorado Plateau [1]	Basal units of Chinle formation	Salt Wash Member of the Morrison formation
Al	12, 000	32, 000	12, 000
Fe	4, 200	6, 500	2, 400
Mg	3, 400	1, 800	2, 400
Ca	16, 000	6, 800	29, 000
Na	~1, 800	~800	~900
K	~6, 000	~5, 000	~5, 000
Ti	610	920	530
Zr	91	120	89
Mn	210	170	220
Ba	320	440	320
Sr	61	82	57
B	~17	~10	~10
V	12	22	12
Cr	9	13	9
Co	~1	~2	~. 5
Ni	~3	~3	~. 8
Cu	9	20	17
U	----------	2	2

[1] Geometric mean of the geometric-mean composition of sandstones in each of 26 rock units ranging in age from Precambrian through Cretaceous (353 samples averaged by rock units shown in table 11).

Sandstone of the Salt Wash member compares closely with average sandstone of the Colorado Plateau. Although the Salt Wash is somewhat lower in iron, it contains distinctly more calcium which is present largely as a carbonate cement. The estimated concentrations of cobalt and nickel in sandstone of the Salt Wash member, which seem to be significantly lower than average, are subject to some uncertainty, for the concentrations in most of the samples are below the limits of sensitivity of the spectroscopic method used, and some variation exists in the sensitivities actually attained. However, concentrations of these two elements seem to be significantly lower in the Salt Wash than in average sandstone of the Colorado Plateau.

Basal sandstones of the Chinle formation contain almost three times as much aluminum as average sandstone of the Colorado Plateau. The aluminum is contained partly in interstitial clay and partly in detrital feldspar. These sandstones are also characterized by a high copper content, and concentrations of iron, titanium, zirconium, vanadium, and chromium are greater than in average sandstone of the Colorado Plateau. These elements are commonly associated with the clay content of a sandstone, and as the clay content increases, a corresponding increase in the concentrations of these elements is to be expected. But part of the observed high concentrations of these elements is due to the arkosic and tuffaceous material in basal sandstones of the Chinle formation.

In summary, sandstone of the Salt Wash member is closely comparable in composition to the average sandstone of the Colorado Plateau. The basal sandstones of the Chinle formation differ in composition from average sandstone of the Colorado Plateau to an extent that might be explained by a high clay content and the presence of considerable arkosic and tuffaceous material.

RELATION BETWEEN COMPOSITION OF SANDSTONE AND THE DISTRIBUTION OF URANIUM DEPOSITS

Certain sandstone strata on the Colorado Plateau are consistently more favorable for uranium deposits than others. Although the total favorableness of any sandstone unit is undoubtedly determined by a combination of geologic features, one of these features may be chemical composition of the sandstone.

Variations in average composition of the sandstone can be noted throughout the geologic column (table 11), but variations that may be related to the occurrence of uranium deposits are difficult to detect by inspection. Therefore, a statistical technique was used to study the relation between the composition of sandstone and the stratigraphic distribution of uranium deposits. The average concentration of each element was plotted as a function of the number of known deposits per 1,000 cubic miles of sandstone contained in each sandstone unit studied (table 13). Scatter diagrams were prepared for each element. Each of 18 rock units studied is a point on each scatter diagram. From data shown on each scatter diagram the linear correlation coefficient of the logs of the two variables was calculated.

TABLE 13.—*List of rock units showing number of known ore deposits as of 1955 and volume of sandstone*

Rock unit	Number of known ore deposits	Volume of sandstone (cubic miles)
Dakota sandstone	17	1, 000
Lower Cretaceous series	9	160
Morrison formation:		
Brushy Basin member	30	350
Westwater Canyon member	20	800
Recapture member	6	640
Salt Wash member	1, 900	1, 450
Bluff sandstone	[1] <1 (0. 5)	290
Cow Springs sandstone	[1] <1 (0. 5)	2, 450
Summerville formation	7	970
Entrada sandstone	29	3, 700
Carmel formation	[1] <1 (0. 5)	1, 700
Navajo sandstone	2	11, 000
Kayenta formation	7	1, 000
Wingate sandstone	7	3, 000
Chinle formation (less deposits in Shinarump and Moss Back members)	165	6, 400
Shinarump and Moss Back members	423	900
Moenkopi formation	4	5, 000
Cutler formation	49	4, 200

[1] A value of 0.5 was arbitrarily assigned.

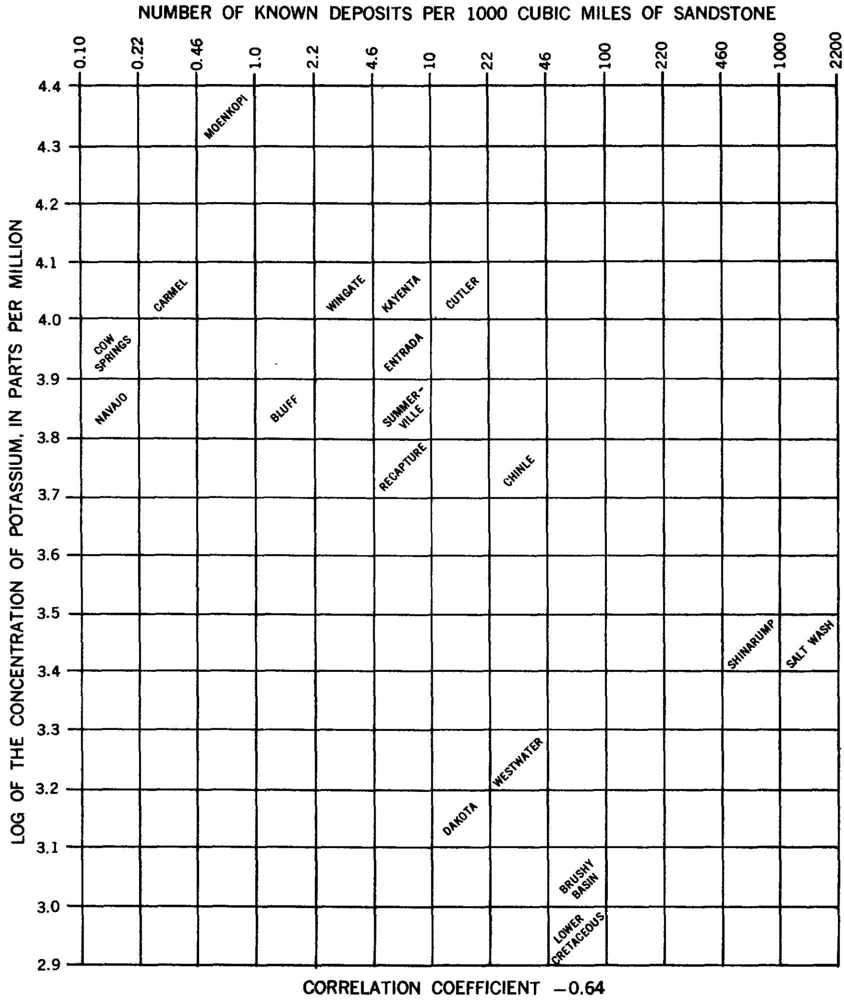

FIGURE 74.—Scatter diagram showing the correlation between the number of known uranium deposits per 1,000 cubic miles of sandstone and the estimated geometric mean concentration of potassium in late Paleozoic and Mesozoic sandstones of the Colorado Plateau.

Of the 17 elements listed in table 11, potassium is the only element found to have a significant[2] correlation with the number of known deposits per 1,000 cubic miles of sandstone (fig. 74). The calculated coefficient, −0.64, suggests that low concentrations of potassium are favorable for the occurrence of uranium deposits. The scatter diagram of vanadium (fig. 75) shows a random scatter of points and is typical of the diagrams for the other elements. Diagrams of these

[2] Lowest significant value for linear correlation coefficients based on 18 pairs of numbers is 0.58 at 99 percent confidence.

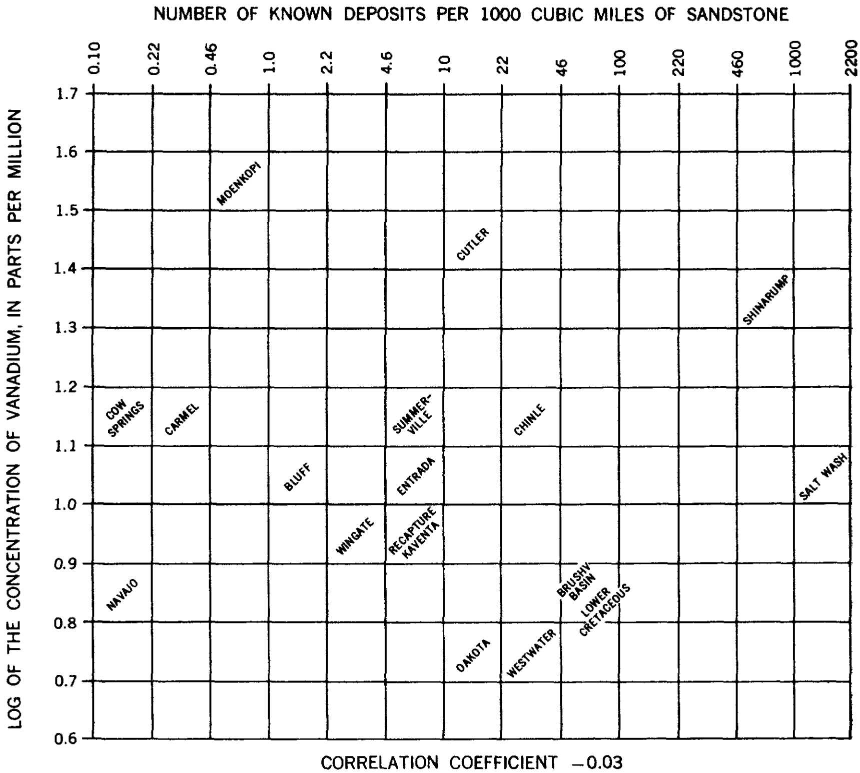

FIGURE 75.—Scatter diagram showing the correlation between the number of known uranium deposits per 1,000 cubic miles of sandstone and the estimated geometric-mean concentration of vanadium in late Paleozoic and Mesozoic sandstones of the Colorado Plateau.

other elements are not shown because their calculated coefficients were all below the level of significance as stated above.

The reason for this relationship between potassium and favorable sandstone is not known at present.

Favorable host rocks, as judged by potassium content, include sandstones of the Dakota sandstone, Cedar Mountain formation including the Buckhorn conglomerate member of Stokes (1952); the Burro Canyon, Morrison, and Chinle formations; and the Coconino sandstone. If the concentration of potassium is diagnostic of favorable sandstones, the possibility should not be overlooked that sandstone units classed generally as unfavorable may, in local areas, contain low concentrations of potassium, and therefore, be favorable locally for the occurrence of uranium deposits.

MUDSTONE

Several features of mudstone have been observed to show some relation to the occurrence of uranium-vanadium deposits. One of these features is color. The color of mudstones most commonly grades from red to brown, but some mudstones grade from gray to green. Black mudstones as well as white mudstones are present on the Colorado Plateau, but are not common. In this report, mudstones that range in color from dark brown to red are classed as "red" mudstones, and mudstones that range in color from dark gray to green are classed as "green" mudstones.

Color is of particular interest because of the observed relation between green mudstone and the occurrence of uranium-vanadium deposits. Mudstone within or adjacent to ore-bearing sandstone beds is preponderantly green. Red mudstone, on the other hand, is seldom present directly adjacent to or within the ore-bearing sandstone beds. However, beds of green mudstone occur throughout large areas on the Colorado Plateau that do not have adjacent uranium deposits. The color of mudstone, nevertheless, serves as an empirical indicator of favorable ground in the Salt Wash member (Weir, 1952, p. 20; McKay, 1955, p. 269–272).

Another characteristic of mudstone that may be related to uranium-vanadium deposits is the type of clay minerals that are contained in mudstone. Volcanic debris in the Brushy Basin member of the Morrison formation and in the Chinle formation, now mostly altered to clay minerals (chiefly minerals of the montmorillonite group) suggests that there may be a relation between the uranium-vanadium deposits in underlying sandstone beds and the devitrification of the volcanic debris (Waters and Granger, 1953). Love (1952) suggests that the source of the uranium now concentrated in deposits in sandstone beds of the Wasatch formation in the Pumpkin Buttes area, Wyoming, was tuff beds in the overlying White River formation.

CHEMICAL COMPOSITION OF SOME MUDSTONES OF THE MORRISON FORMATION

RED AND GREEN MUDSTONE

Extensive diamond drilling plus geologic mapping from 1948 to 1954 in Paradox Valley, Colorado (fig. 76) by the U.S. Geological Survey permitted detailed correlations of mudstone and sandstone layers to be made and referenced to known uranium-vanadium deposits (Newman and Elston, 1959). Samples of mudstone, selected from drill core, were analyzed to determine if variations in chemical composition could be related to differences in color. The average compositions of red and green sandstone are shown in table 14.

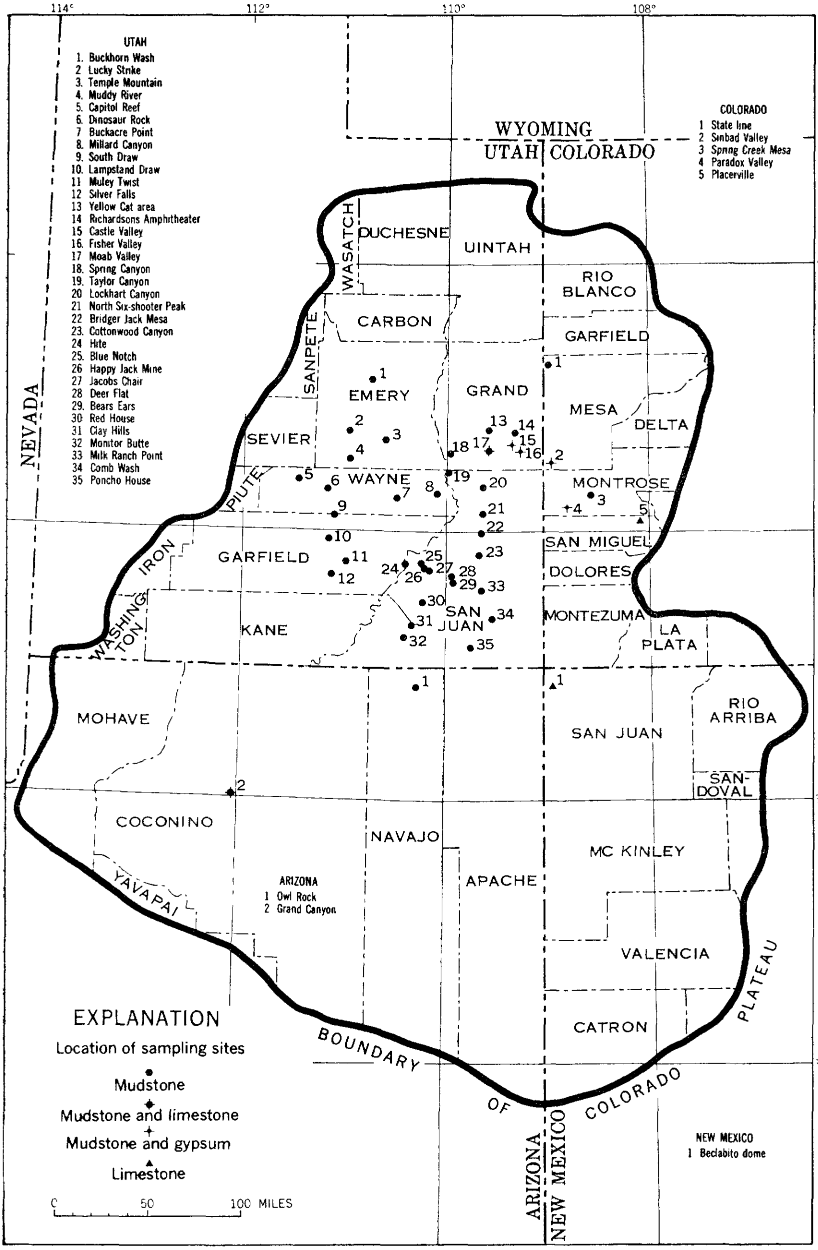

FIGURE 76.—Index map of the Colorado Plateau showing sources of samples of mudstone, limestone, and gypsum.

TABLE 14.—*Average chemical composition, in percent, of red and green mudstone from the Salt Wash member of the Morrison formation, Jo Dandy area, Paradox Valley, Colorado* [1]

Element	Red mudstone (13 samples)			Green mudstone (19 samples)		
	Range of geometric mean		Geometric deviation [3]	Range of geometric mean		Geometric deviation [3]
	Geometric mean	Confidence interval [2] ×or÷		Geometric mean	Confidence interval [2] ×or÷	
Al	3.0	1.5	1.6	4.0	1.4	1.7
Fe	1.5	1.5	1.7	1.4	1.3	1.4
Mg	2.0	1.4	1.5	1.7	1.4	1.7
Ca	2.0	1.5	1.6	.9	1.7	2.3
Na	.18	1.3	1.4	.19	1.3	1.4
K	2.2	1.4	1.5	2.4	1.3	1.5
Ti	.10	1.6	1.7	.14	1.4	1.7
Zr	.007	1.7	1.8	.009	1.9	1.8
Mn	.03	1.5	1.6	.016	1.6	2.0
Ba	.014	1.2	1.2	.017	1.3	1.5
Sr	.013	1.4	1.5	.015	----------	<1.2
B	.004	1.7	1.9	.004	1.4	1.7
Sc	.0010	1.4	1.5	.0011	1.3	1.5
V	.006	1.9	2.0	.008	1.6	2.0
Cr	.003	1.4	1.5	.003	1.2	1.3
Co	.0006	1.3	1.4	.0005	1.5	2.1
Ni	.0010	1.4	1.5	.0011	1.3	1.5
Cu	.002	1.7	1.8	.0025	1.3	1.4
Y	.002	1.3	1.3	.0015	1.4	1.6
Yb	.00016	1.4	1.5	.00016	1.7	2.3
Pb	.0010	2.5	2.9	.0009	1.6	2.0

[1] Table, slightly revised, from Newman and Elston, 1959, p. 135.
[2] The 99 percent confidence interval for the geometric mean (see footnote 1, table 5).
[3] Antilog of the log standard deviation.

The chemical composition of green mudstone differs only slightly, and probably not significantly, from the composition of red mudstone with the confidence limits set for this study. In fact, comparison of the two color varieties of mudstone shows a remarkable similarity in amounts of chemical constituents. The concentrations of calcium may indicate the only significant difference; red mudstone seems to contain about twice as much calcium as does green mudstone. However, there is no evidence apparent in the data to establish a chemical relationship between the color of mudstone and the occurrence of mineralized rock. This conclusion is supported in part by the recent work of W. D. Keller in the mineralogy of clay minerals in red and green mudstone. Keller (1959, p. 117) states:

> No significant difference was found between the clay minerals in stratigraphically equivalent red and green counterparts of mudstones collected from the Rico, Cutler, Moenkopi, and Chinle formations, and the Salt Wash and Brushy Basin members of the Morrison formation, or within clay mineral groups including the kaolin group, the hydrous micas, the montmorillonites, and probably chlorite.

If mineralizing solutions, which formed the uranium-vanadium deposits, effected a chemical difference in adjacent layers of clays, the difference is too subtle to be detected by sampling methods used in this study.

Although comparison of chemical compositions of red and green mudstone fail to show significant differences that would explain color variations, it is generally believed that the red color is due to a pervasive "paint" of ferric iron in the form of hematite and other oxides and possibly hydroxides of iron. This is in accord with the findings of Van Houten (1948, p. 2090) who states in part, "By X-ray analysis, anhydrous ferric oxide, hematite, has been determined to be the principal coloring agent in red soils and sedimentary rocks." According to MacCarthy (1926), the hydrated ferric oxides produce the yellow and brown colors in sedimentary rocks, whereas red colors are produced by anhydrous ferric oxides.

The intrinsic colors of many of the clay minerals contained in mudstone of the Colorado Plateau may be shades of green to white, or, if carbon is present, shades of dark gray to gray. If no impurities are present, the mudstone could possess any one of these colors. The green color may be due to iron ions held in the crystal structure through ionic substitution (Ross and Hendricks, 1945, p. 29; Grim, 1953, p. 58, 65, 72). If part of the green color is due to an exotic pigmenting agent which merely coats the mudstone, however, the pigment must be quite stable under the natural oxidizing conditions of surface exposure.

BENTONITIC AND NONBENTONITIC MUDSTONE

Samples of both bentonitic and nonbentonitic mudstone of the Brushy Basin member of the Morrison formation were collected from outcrops in the Yellow Cat area, Thompsons district, Utah, near the Cactus Rat mine (fig. 76). Additional samples from the Brushy Basin member were selected from diamond-drill core from a drill hole on Spring Creek Mesa, near Uravan, Colo.

Field tests were used to classify mudstone samples into bentonitic and nonbentonitic types. Samples that turned bright blue with benzidine solution (a qualitative color test for the montmorillonite type of clay minerals, Hendricks and Alexander, 1940), and that also showed visible swelling when treated with water were classed as bentonitic. Samples that gave a weak or no reaction to benzidene and that showed no visible signs of swelling with water were classed as nonbentonitic. During the testing of the samples, it was found that most of the samples which showed visible signs of swelling were green or shades of gray to green. However, sufficient numbers of "red" mudstones possessed swelling characteristics to prevent a classification of clay types based partly on color.

Comparisons of average amounts of chemical constituents in both bentonitic and nonbentonitic mudstone from the Yellow Cat area and Spring Creek Mesa (table 15) show that no chemical features were found which clearly distinguish the two types of mudstone. A few differences in composition between bentonites and nonbentonites in a particular location can be seen, but these local differences do not persist to other localities. For instance, samples of bentonitic mudstone from the Yellow Cat area contain about 3.0 percent magnesium, whereas samples of nonbentonitic mudstone contain about half as much magnesium. But the average magnesium content of samples of bentonitic and nonbentonitic mudstone from Spring Creek Mesa is identical. Thus, a high magnesium content is not a consistent charateristic of bentonitic mudstone. The small differences shown for other elements are not statistically significant.

TABLE 15.—*Chemical composition, in geometric-mean percent, of bentonitic and nonbentonitic mudstone of the Brushy Basin member of the Morrison formation*

Element	Mudstone from—			
	Thompsons district, Utah		Spring Creek Mesa, Colo.	
	Bentonitic (4 samples)	Nonbentonitic (4 samples)	Bentonitic (10 samples)	Nonbentonitic (10 samples)
Al	10. 0	10. 0	6. 0	6. 0
Fe	3. 0	2. 0	1. 4	1. 7
Mg	3. 0	1. 5	1. 2	1. 2
Ca	. 5	. 4	. 4	1. 3
Na	. 8	. 4	. 4	. 6
K	1. 5	1. 5	2. 0	2. 0
Ti	. 3	. 3	. 2	. 3
Zr	. 015	. 015	. 015	. 017
Mn	. 01	. 03	. 02	. 03
Ba	. 015	. 01	. 02	. 04
Sr	. 02	. 02	. 03	. 03
Be	~. 0002	<. 0001	~. 0001	~. 0001
B	. 004	. 006	. 003	. 002
Sc	. 0015	. 001	. 0009	. 0009
V	. 005	. 006	. 005	. 006
Cr	. 002	. 004	. 002	. 002
Co	. 0008	. 0008	. 0005	. 0005
Ni	. 0015	. 001	. 0007	. 001
Cu	. 002	. 003	. 003	. 003
Ga	. 002	. 0015	. 001	. 001
Y	. 007	. 002	. 003	. 003
Yb	. 0004	. 0002	. 0003	. 0003
Pb	. 001	. 0007	. 0013	. 0011

CHEMICAL COMPOSITION OF MUDSTONE OF TRIASSIC AGE

Samples were selected to represent the rocks that characterize the upper part of the Moenkopi (the top 25 feet) and the lower part of the Chinle formation at 32 localities (fig. 76). The samples were collected either by L. G. Schultz for detailed studies of clay minerals or by the writer.

The average chemical compositions of mudstone from the Moenkopi and Chinle formations are shown in table 16.

TABLE 16.—*Average chemical composition, in percent, of mudstone of Triassic age*

	Unmineralized mudstone from—								
	Moenkopi formation (34 samples)			Shinarump and Moss Back members of the Chinle formation (15 samples)			Chinle formation (41 samples)		
Element[1]	Range of geometric mean		Geometric deviation[3]	Range of geometric mean		Geometric deviation[3]	Range of geometric mean		Geometric deviation[3]
	Geometric mean	Confidence interval × or ÷[2]		Geometric mean	Confidence interval × or ÷[2]		Geometric mean	Confidence interval × or ÷[2]	
Al	8.9	1.2	1.6	8.8	1.3	1.5	8.2	1.3	1.7
Fe	2.1	1.3	1.7	1.7	1.8	2.3	1.8	1.2	1.6
Mg	1.6	1.3	1.8	.72	1.8	2.4	.64	1.5	2.7
Ca	.38	2.6	7.4	.17	3.4	5.9	.12	2.1	5.9
Na	.58	1.4	2.0	.43	2.2	3.1	.36	1.9	4.4
K	5.2	1 2	1.5	2.7	1.7	2.2	2.5	1.5	2.5
Ti	.26	1.2	1.5	.32	1.1	<1.2	.29	1.1	1.3
Zr	.013	1.2	1.6	.015	1.1	<1.2	.018	1.2	1.5
Mn	.029	1.7	3.2	.012	2.0	2.8	.0081	1.8	3.7
Ba	.032	1.2	1.6	.015	2.0	2.6	.0084	1.6	2.8
Sr	.016	1.4	1.9	.011	1.5	1.9	.0087	1.4	2.2
Be	.00018	1.4	2.2	.00016	1.3	1.5	.00013	1.3	1.7
B	.0047	1.2	1.5	.0048	1.5	1.8	.0048	1.2	1.5
Sc	.0020	1.3	1.6	.0017	1.4	1.6	.0017	1.2	1.6
V	.0075	1.2	1.4	.0083	2.2	3.0	.0064	1.2	1.5
Cr	.0057	1.2	1.5	.0058	1.2	1 3	.0051	1.2	1.5
Co	.0010	1.5	2.2	.0011	1.6	1.9	.00067	1.5	2.5
Ni	.0025	1.5	2.4	.002	1.4	1.7	.0015	1.3	1.9
Cu	.0051	1.6	2.6	.0032	2.1	2.9	.0032	1.4	2.0
Ga	.0010	1.4	1.9	.0013	1.7	2.1	.0010	1.4	2.1
Y	.0028	1.4	2.1	.0026	1.3	1.4	.0024	1.2	1.7
Yb	.00031	1.4	2.0	.0003	1.1	<1.2	.00030	1.2	1.6
Pb	.0009	1.5	2.4	.001	2.1	3.0	.0006	1.5	2.7
Zn[4]	.007	----------	----------	.0058	----------	----------	.0031	----------	----------
As[4]	.0011	----------	----------	.0015	----------	----------	.0009	----------	----------
U[5]	.0006	----------	----------	.0006	----------	----------	.0004	----------	----------

[1] Average based on semiquantitative spectrographic analyses, except where noted.
[2] The 99 percent confidence interval for the geometric mean (see footnote 1, table 5).
[3] Antilog of the log standard deviation.
[4] Averages based on colorimetric analyses.
[5] Averages based on fluorimetric analyses.

Comparisons of average chemical compositions show that mudstones of the Moenkopi formation appear to contain significantly more calcium, magnesium, manganese, barium and potassium, and possibly more copper and iron than mudstones of the Chinle. Part of the sample suite of the Moenkopi consisted of "bleached" mudstone taken at, or very close to, the top of the formation. These samples are indicated by footnote reference in table 33. Comparisons of the "bleached" mudstone (material which may range in color from purple to various shades of gray and green) with unbleached mudstone shows that manganese has been leached out of the "bleached" mudstone, whereas uranium appears to have been redistributed in, or added to, the bleached material. Histograms comparing the uranium and manganese contents of the mudstones are shown in figure 77. In addition, gallium, lanthanum, yttrium, and to a lesser degree scandium, ytterbium, niobium and cerium tend to be concentrated in the "bleached" mudstone. Perhaps these elements were

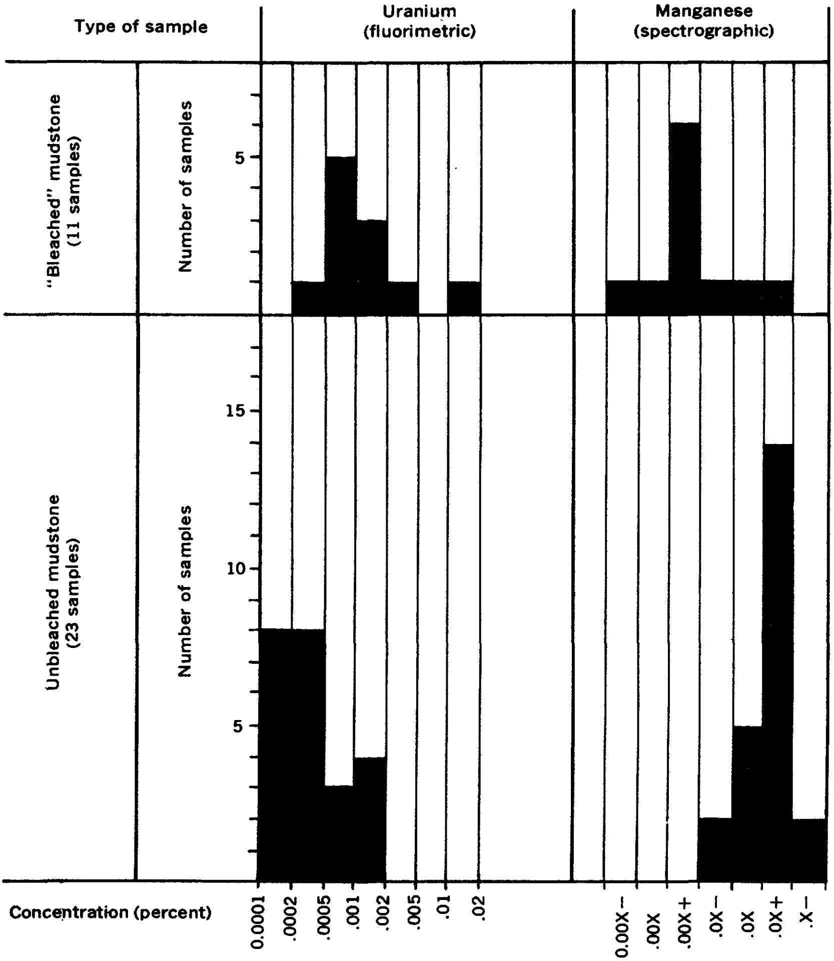

Figure 77.—Frequency distribution of uranium and manganese in "bleached" and unbleached mudstone of the Moenkopi formation.

concentrated by weathering processes during the Middle Triassic hiatus and may indicate the remnants of a fossil soil.

Within the Chinle formation, samples of mudstones from the Shinarump and Moss Back members contain significantly more barium and possibly more vanadium, nickel, lead, zinc, and arsenic than samples from other parts of the Chinle.

The arithmetic-mean composition of mudstone of Triassic age was calculated from analyses of mudstone of both the Moenkopi and Chinle formations and is shown in table 17. The average concentrations of aluminum, magnesium, sodium, strontium, zirconium, yttrium, vanadium, nickel, cobalt, and lead in mudstones of Triassic age are closely similar to the concentrations in shale (Rankama and Sahama, 1950, p. 226, table 5.52). However, mudstone of Triassic age, although containing more potassium, scandium, arsenic, and uranium, seems to be somewhat lower in iron, calcium, manganese, titanium, barium, boron, chromium, gallium, and copper.

TABLE 17.—*Estimated arithmetic-mean composition, in parts per million, of mudstone of Triassic age*

Element	*Mudstone of Triassic age (90 samples)*	*Average shale* [1]	*Element*	*Mudstone of Triassic age (90 samples)*	*Average shale* [1]
Al	97, 000	81, 900	B	54	310
Fe	22, 000	47, 300	Sc	20	6. 5
Mg	14, 000	14, 800	V	93	120
Ca	12, 000	22, 300	Cr	60	410–680
Na	9, 000	9, 700	Co	12	8
K	46, 000	27, 000	Ni	25	24
Ti	2, 900	4, 300	Cu	57	192
Zr	170	120	Ga	14	50
Mn	330	620	Y	30	28. 1
Ba	270	460	Pb	13	20
Sr	150	170	Zn	53	200–1, 000
Be	2	<3. 6	As	12	~5
			U	5	1. 2

[1] Rankama and Sahama, 1950, p. 226.

CHEMICAL COMPOSITION OF SOME MUDSTONES OF PRECAMBRIAN, PALEOZOIC, CRETACEOUS, AND TERTIARY AGES

Although mudstones of Triassic and Jurassic ages were studied more intensively, a few samples of mudstones from strata of Precambrian, Paleozoic, Cretaceous, and Tertiary ages were collected. The locations of these sampling sites are shown in figure 76; analyses of the samples are shown in table 32.

Mudstones were taken from exposures in the Grand Canyon, Ariz., of the Hakatai shale of Precambrian age, the Bright Angel shale of Cambrian age, the Supai formation of Pennsylvanian and Permian age, and the Hermit shale of Permian age, to determine if patterns of distribution of any elements were related to age. Elements that show little or no systematic variation in concentration with respect to age include aluminum, calcium, sodium, titanium, zirconium, barium, strontium, scandium, vanadium, chromium, cobalt, nickel, copper, and ytterbium; but the distribution of iron, potassium, gallium, yttrium, and lead seems to be related in a general way to the ages of the host rocks. Concentrations of these elements are slightly greater in older rocks than in younger rocks, and the older rocks seem to be more radioactive. Boron, however, appears to be somewhat higher in younger rocks.

Two samples of so-called black shales were collected from the Paradox member of the Hermosa formation of Pennsylvanian age from exposed parts of the evaporate cores of salt plugs in Fisher and Castle Valleys. Subsequent examination and X-ray analysis showed that the sample from Castle Valley (WLN–59–53) is a nearly pure dolomite (95.4 percent dolomite, 3.3 percent calcite). The sample from Fisher Valley (EMS–33A–52) is a highly gypsiferous claystone. Analyses for these two samples are shown in table 32.

Three samples of mudstone were collected from the Mancos formation at a road cut along U.S. Highway 6–50 near the Utah-Colorado State line. Sample WLN–53–53 was taken from a tan bed of bentonitic mudstone about 1 foot thick and several tens of feet in length. The bed of bentonite is between 60 and 100 feet above the contact between the Dakota and Mancos. Sample WLN–55–53 was taken from dark-gray shale just above the bed of bentonitic mudstone, and sample WLN 54–53 was taken from dark-gray fissile shale just below the bed of bentonitic mudstone. These samples were collected to determine the variations in chemical composition between typical mudstone and bentonitic mudstone of the Mancos shale.

The amounts of aluminum, iron, magnesium, calcium, sodium, and potassium in the bentonitic mudstone suggest the composition of a siliceous rhyolite tuff slightly charged with calcium carbonate. This mudstone now contains more calcium and is slightly more radioactive, but it contains less potassium, titanium, manganese, scandium, vanadium, chromium, cobalt, nickel, copper, yttrium, lanthanum, and lead than adjacent nonbentonitic mudstone. If leaching of some of these elements took place during devitrification of the volcanic debris, the elements were not concentrated in the adjacent mudstones to a significant degree.

Two samples of petroliferous "shale" (clayey carbonate rocks) were collected from the Green River formation within the oil shale mine at Rifle, Colo. One sample, WLN–7–52, was collected from a high-grade oil shale seam that produces from 50 to 60 gallons of crude shale oil per ton, whereas sample WLN–8–52 was collected from a seam of low-grade oil shale that produces about 10 gallons of crude shale oil per ton. These samples were collected to determine if the concentration of any of the elements was dependent upon the amount of petroliferous material in the shale.

The concentrations of certain of the elements appear to vary directly with the amount of contained oil. Aluminum, calcium, strontium, vandium, cobalt, nickel, and molybdenum are slightly more concentrated in high-grade oil shale than in low-grade shale. Erickson and others (1954) also have found that a suite of elements, including vanadium, cobalt, nickel, and molybdenum, is consistently present—at some places in exceptionally high concentrations—in ash of crude oil, asphalt, and petroliferous rock. Potassium and boron, however, seem to be slightly more concentrated in low-grade shale. The radioactivity of both grades of shale is identical and low.

LIMESTONE

Limestone comprises almost 40 percent of the sedimentary rocks of Paleozoic age on the Colorado Plateau, but only 5 percent of the sedimentary rocks of Mesozoic age (table 2). Beds of the Todilto limestone of Jurassic age (including the Pony Express limestone member of the Wanakah formation) although comprising less than 1 percent of the rocks of Jurassic age, have produced significant amounts of uranium-vanadium ore in New Mexico, whereas limestones of Paleozoic age are known to contain only a few deposits (Hilpert and Corey, 1955, p. 117). Thus, the apparent selectiveness of uranium for certain host rocks, as mentioned in a previous section on sandstone, (p. 388) is reemphasized by the restricted occurrence of uranium in limestone. The reason why beds of the Todilto limestone are favored over other units of limestone on the Colorado Plateau is not known, but a study of the distribution of elements in limestone was undertaken to provide background information by which limestones of the Todilto could be compared. The present study is restricted for the most part to the distribution of elements in limestone and evaporite of Precambrian and Paleozoic ages of the Colorado Plateau.

CHEMICAL COMPOSITION OF CARBONATE ROCKS OF PRECAMBRIAN AND PALEOZOIC AGES

Samples of carbonate rocks were collected from exposures along the Kaibab Trail, Grand Canyon, Ariz., from rocks of the Bass limestone of Precambrian age, the Muav limestone of Cambrian age, the Temple Butte limestone of Devonian age, the lower part of the Redwall limestone of Mississippian age, the Supai formation of Pennsylvanian and Permian age, and the Toroweap formation and Kaibab limestone of Permian age. One sample was collected from exposed rocks of the Rico formation of Pennsylvanian and Permian(?) age in Moab Valley, Utah, and one sample was collected from the Paradox member of the Hermosa formation of Pennsylvanian age in Castle Valley, Utah. The locations of the sampling sites are shown in figure 76; analyses of the samples are shown in table 35.

The average chemical composition of carbonate rocks of Precambrian and Paleozoic age (not including evaporites) is shown in table 18. Both geometric and arithmetic means are shown.

Comparison of the chemical composition of Precambrian and Paleozoic carbonates of the Colorado Plateau with average limestone of Rankama and Sahama shows that carbonates of the plateau contain about 2 times as much magnesium than average, indicating that they are or approach dolomites in composition. In addition, these carbonates contain about 5 times more silicon and 3 times as much aluminum, indicating the relative impurity of the samples.

Correspondingly, these carbonates also contain about 10 times as much chromium, and about 2 times as much iron, manganese, sodium, and vanadium as average limestone, but only about one-fifth or less as much strontium.

TABLE 18.—*Average chemical composition, in percent, of 19 samples of carbonate rocks of Precambrian and Paleozoic ages of the Colorado Plateau*

Element	Range of geometric mean		Geometric deviation [2]	Arithmetic mean [3]	Average limestone [4]
	Geometric mean	Confidence interval [1] × or ÷			
Si	2.3	4.6	9.5	~10.0	2.42
Al	.25	3.5	6.3	1.2	.43
Fe	.4	2.3	3.4	.9	.40
Mg	3.0	3.2	5.7	9.0	4.77
Ca	>10.0	------	------	------	30.45
Na	.05	1.9	2.6	.07	.037
K	<.5	------	------	------	.27
Ti	.012	4.1	8.2	.09	------
Zr	.0016	2.9	4.9	.005	------
Mn	.02	3.0	5.1	.07	.0385
Ba	.0018	4.8	10.3	.02	.012
Sr	.006	1.8	2.3	.009	.0425 –.0765
B	~.001	------	------	------	.0003
V	.0018	1.3	1.5	.002	<.0010
Cr	.0014	1.8	2.4	.002	.0002
Co	<.0002	------	------	------	0
Ni	.0004	1.9	2.6	.0006	0
Cu	.0006	2.2	3.1	.001	.00202
Pb	<.001	------	------	------	.0005 –.0010

[1] The 99 percent confidence interval for the geometric mean (see footnote 1, table 5).
[2] Antilog of the log standard deviation.
[3] The most efficient estimate of the arithmetic mean of a lognormal population may be obtained from the following equation when $n=19$:
Log_{10} estimated mean $=\text{Log}_{10}$ geometric mean $+\phi V$
where $V=(\text{Log}_{10}$ geometric deviation$)^2$ (5.3019).
ϕV = quantity obtained from tables by Sichel (1952, p. 286–287).
[4] Rankama and Sahama, 1950, table 5.52, p. 226.

STRATIGRAPHIC VARIATIONS IN COMPOSITION OF CARBONATE ROCKS

The analyses of carbonate rocks (table 35) show certain variations in chemical composition that seem to be related to the ages of the beds. Silicon is concentrated in carbonates of Precambrian and Cambrian ages, and becomes progressively less concentrated in carbonates of Devonian and Mississippian ages. Carbonates of Pennsylvanian and Permian ages contain about as much silicon as those of Precambrian and Cambrian age.

The aluminum content varies as much between samples of a formation as it does among the samples of the several formations studied. The Muav limestone, however, seems to contain the greatest amount of aluminum, whereas the Redwall limestone seems to contain the least amount of aluminum. Iron is slightly more concentrated in the oldest formations, except possibly the Redwall limestone which contains the least amount of iron of any of the formations studied.

The calcium content of carbonates of Precambrian, Cambrian, and Devonian ages is as much as 10 percent, whereas the calcium content of carbonates of Mississippian, Pennsylvanian, and Permian ages is greater than 10 percent. Magnesium, on the other hand, tends to be more abundant in the older carbonates and to become less in younger carbonates. The high silicon and magnesian content of the rocks of Precambrian and Cambrian ages shows that they are siliceous dolomites. The greatest change in magnesium content of the carbonate rocks studied occurs in the lower part of the Redwall limestone where samples show the magnesium content decreasing from more than 10 percent to about 0.07 percent. Daly (1909, p. 165) states: "The ratio (calcium-magnesium) abruptly rises in the Devonian and increases rapidly in the Carboniferous." Thus, the Redwall limestone of Mississippian age seems to be the turning point for changes in the chemical composition of carbonate rock. In addition to being somewhat lean in silicon, aluminum, iron, and magnesium, the Redwall also contains little sodium, potassium, titanium, zirconium, barium, boron, scandium, cobalt, nickel, gallium, yttrium, and ytterbium. As a general rule, carbonates older than the Redwall contain more of the elements listed above, whereas carbonates younger than the Redwall contain less of these elements. Concentrations of vanadium and chromium seem to vary little throughout Precambrian and Paleozoic time.

CHEMICAL COMPOSITION OF GYPSUM FROM THE PARADOX MEMBER OF THE HERMOSA FORMATION OF PENNSYLVANIAN AGE

A few samples of gypsum were collected from exposed parts of the Paradox member of the Hermosa formation of Pennsylvanian age in the salt anticline region of western Colorado and eastern Utah. The exposed rocks consist mainly of deformed black shale and gypsum which overlie salt and other evaporites that form the core or axial parts of large anticlines. Clusters of uranium deposits along the salt anticlines, notably in Paradox and Gypsum Valleys, have stirred interest in seeking some relations between the evaporite cores of these anticlines and the localization of uranium deposits.

To gain some measure of the distribution of elements in the evaporite cores, five samples of gypsiferous material were collected for analysis. Of these, 2 samples were collected from Paradox Valley, Colo., in the vicinity of the Jo Dandy area, 2 samples from Castle Valley, Utah, near Round Mountain, and 1 sample from Fisher Valley along Onion Creek. The average chemical composition of the gypsiferous material, based on these five samples, is shown in table 19. The locations of the sampling sites are shown in figure 77; analyses are shown in table 35.

TABLE 19.—*Average chemical composition, in geometric-mean percent, of five samples of gypsiferous material from the Paradox member of the Hermosa formation*

Element	Range of geometric mean		Geometric deviation[2]
	Geometric mean	Confidence interval[1] × or ÷	
Si	0.5	>20	4.9
Al	.1	>10	4.0
Fe	.05	>20	4.9
Mg	.2	>20	7.1
Ca	>10	----------	----------
Na	.03	3.0	1.7
K	<1	----------	----------
Ti	.006	>20	6.2
Zr	~.001	----------	----------
Mn	.0003	>20	6.0
Ba	.002	2.3	1.5
Sr	.1	3.0	1.7
B	.005	----------	----------
V	.0003	>20	4.8
Cr	.0005	2.3	1.5
Co	<.0005	----------	----------
Ni	.0001	6.8	2.7
Cu	.0005	2.3	1.5

[1] The 99 percent confidence interval for the geometric mean (see footnote 1, table 5).
[2] Antilog of the log standard deviation.

Of particular interest is the unusual occurrence of bismuth in samples of gypsum from the Jo Dandy area, Paradox Valley. Although the concentration of bismuth in these 2 samples of gypsum is low (about 0.005 percent or less), samples of selenite from the Mineral Jo mine, Jo Dandy area, and 5 samples of sedimentary rocks of the Salt Wash member of the Morrison formation in the Jo Dandy area (Newman and Elston, 1959) are the only ones of more than 600 samples of sedimentary rocks from many formations of the Colorado Plateau that contain amounts of bismuth detectable by the spectrographic method.

DISTRIBUTION OF SELENIUM

All the samples of sandstone from the basal units of the Chinle formation and the Salt Wash member of the Morrison formation were analyzed for selenium, as well as selected samples of sandstone from other formations, in order to gain some measure of the variations in concentration of selenium in sandstone.

The average concentration of selenium in sandstone seems to be less than 1 ppm. A series of samples collected from the Chinle, Wingate, Kayenta, Carmel, Entrada, Wanakah, Summerville, Burro Canyon, and Dakota formations, exposed at the Dry Creek anticline, Colorado (fig. 76), contained less than 0.5 ppm of selenium. Other samples of the Cedar Mesa, Organ Rock, De Chelly, and Hoskinnini members of the Cutler formation, and the Moenkopi, Navajo, Curtis, Cow Springs, Junction Creek, Bluff, Buckhorn conglomerate member of Stokes (1952) and the main part of the Cedar Mountain formation, from widely scattered localities, likewise contained less than 0.5 ppm of selenium. Results of more intensive sampling of the Salt Wash member and the basal Chinle units, however, show that the selenium content of unmineralized sandstone may be as high as 15 ppm, though most of the samples from these 2 members contained less than 0.5 ppm. The sample of sandstone that contained 15 ppm selenium was collected from the Shinarump member at Clay Hills Pass, Utah.

Almost all samples of mudstone of Triassic age (table 33) and 8 samples of mudstone of the Brushy Basin member (table 34) were analyzed for their selenium contents. Most of the samples of rocks of Triassic age contain less than 0.5 ppm of selenium, but the selenium content ranges from less than 0.5 to as much as 8 ppm. The sample of mudstone that contained 8 ppm of selenium was collected from the top of the Moenkopi formation at Clay Hills Pass, Utah, where a sample of sandstone of the Shinarump member of the Chinle formation also contained an above-average amount of selenium. Future investigations concerning resources of selenium should not overlook the Clay Hills Pass area of southern Utah.

Of the 8 samples of mudstone of the Brushy Basin member of the Morrison formation collected near the Cactus Rat mine, Thompsons district, Utah, 4 of the samples contained from 5 to 10 ppm of selenium. The other 4 samples contained less than 2 ppm of selenium. The Morrison formation of the Thompsons district of Utah has long been known to contain selenium, and, according to Cannon (1952, p. 737), selenium indicator plants of the astragalus group abound in the district.

SUMMARY OF THE CHEMICAL FEATURES OF SEDIMENTARY ROCKS

Available data indicate that the uranium deposits are not localized in formations whose rocks contain unusual amounts of the elements commonly found in the deposits. A comparison of the composition of sandstone of the Salt Wash member of the Morrison formation with the composition of average sandstone, as given by Rankama and Sahama (1950), shows remarkable similarity, particularly in the concentrations of uranium and vanadium. The same general conclusion can be drawn from a comparison of sandstone of the Salt Wash with the average for sandstone of Paleozoic and Mesozoic age.

The lack of correlation between the calculated mean vanadium content of the sandstone units studied and the frequency of occurrence of known uranium deposits in each unit, most of which are vanadiferous, leads to the conclusion that the number of uranium deposits in a given unit is unrelated to the concentration of vanadium in sandstones of the unit. The somewhat higher concentration of copper in sandstone of the Shinarump member is interesting because of the unusually high concentration of copper in certain uranium deposits in that member. The difference in copper content of the ores of the Shinarump member and the ores of the Salt Wash member may be interpreted as due to the difference in the supply of copper available in the sandstones of the two members. However, it should be noted that sandstones of the Shinarump are richer in vanadium than sandstones of the Salt Wash, but that the average deposit in the Shinarump contains less vanadium than the average deposit in the Salt Wash.

The number of uranium deposits in the various sandstone units studied appears to correlate with variations in the average potassium content of each of the units. However, the correlation is inverse, indicating that sandstone units that contain low average concentrations of potassium are more favorable host rocks than sandstone units that contain higher concentrations of potassium. The reason why this relationship exists is not known.

The general lack of correlation between the chemical composition of unmineralized sandstone and the frequency of occurrence of uranium deposits does not preclude the possibility that the major parts of the elements now concentrated in the deposits were derived from the host rocks. Sandstone of average composition contains far more than an adequate amount of the elements to form the deposits found in them. Sandstone of the Salt Wash member has an arithmetic-mean content of about 18 ppm of vanadium and about 2 ppm of uranium. Assuming that 1 ppm of uranium is available for solution and redistribution, a cylinder of sandstone 50 feet thick and having a diameter of about 2,000 feet could provide sufficient uranium to form an ore body that contains 5,000 tons of 0.3 percent uranium. Assuming all 18 ppm of vanadium were available for solution and redistribution, this volume of sandstone could provide 5,000 tons of material containing 4.5 percent vanadium. The vanadium-uranium ratio of 4.5 : 0.3 or 15 : 1 falls well within the range of ratios commonly found in uranium ores of the Colorado Plateau. These figures do not take into consideration the uranium and vanadium content of mudstones that may also serve as source beds. Amounts of other metals contained in such a cylinder of sandstone is greatly in excess of that required to form a 5,000-ton ore body with the average composition of the ore.

The source or sources of vanadium are as much of a problem, perhaps even more so, than the source of uranium. Vanadium is rarely a constituent of volcanic emanations, nor does it occur in fumarolic and hot-spring deposits. Likewise, almost none of the vein deposits of generally accepted hydrothermal origin in the Colorado Plateau, such as the copper deposits of the Cashin type (Fischer, 1936; Coffin, 1921) and the base and precious metal veins of the Henry Mountains (Hunt, 1953), the La Sal Mountains, and the San Juan Mountains (Cross and Larsen, 1935), contain more than trace amounts of vanadium. The uranium-bearing veins of the Front Range, Colo., do not contain vanadium except possibly in trace amounts (R. H. Moench, oral communication, 1955). However, the reported occurrences of vanadium with gold-bearing veins seems worthy of mention. Roscoelite, a vanadium mica, was first reported to be associated with small quartz veins near Coloma, Eldorado County, Calif., and subsequently reported in the Boulder district, Colorado, and in Kalgoorlie, western Australia (Lindgren, 1901, p. 643). In the gold veins of the Blue Mountains of Oregon, Lindgren reports that roscoelite is also associated with gold-bearing quartz veins. Of this occurrence Lindgren states (1901, p. 603) that roscoelite is an accessory constituent of the gangue, and further (p. 615) that "much of the gangue was doubtless extracted from the immediately surrounding country rock." In the La Plata Mountains of the Colorado Plateau the richest gold ore is associated with dull-green quartz colored by roscoelite (Eckel, 1949, p. 61). Possibly the roscoelite associated with gold veins was formed from vanadium contained in the host rocks and the mineralizing solutions contained little or no vanadium.

Tuffaceous beds now altered to bentonite in the Morrison and Chinle formations cannot be considered as exceptionally good source beds for both uranium and vanadium. The normal felsic volcanic material that is enriched in uranium (Adams, 1954; Larsen and others, 1956), tends to be impoverished in vanadium, which is generally concentrated in femic volcanic rocks (Nockolds and Allen, 1953, 1954). Volcanic material of the Chinle formation, as determined from volcanic pebbles and from clays, is largely sialic, probably mostly rhyolitic and latitic (Leonard Schultz, written communication, 1956). Thus, the volcanic debris of the Chinle is not a likely source of both uranium and vanadium.

Bentonitic mudstone of the Yellow Cat area, Utah, and Spring Creek Mesa, Colo., presumed to have formed from the devitrification of volcanic debris in the Brushy Basin member of the Morrison formation, is for the most part chemically undistinguishable from nonbentonitic mudstone. The volcanic debris of the Morrison formation is presumed to have a composition similar to that of the Chinle.

In conclusion, it seems possible that the vanadium now found reconstituted in the uranium deposits was an original constituent of the host rocks. The uranium may have had multiple sources, but possibly most of the uranium and associated elements were derived from the host rocks.

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