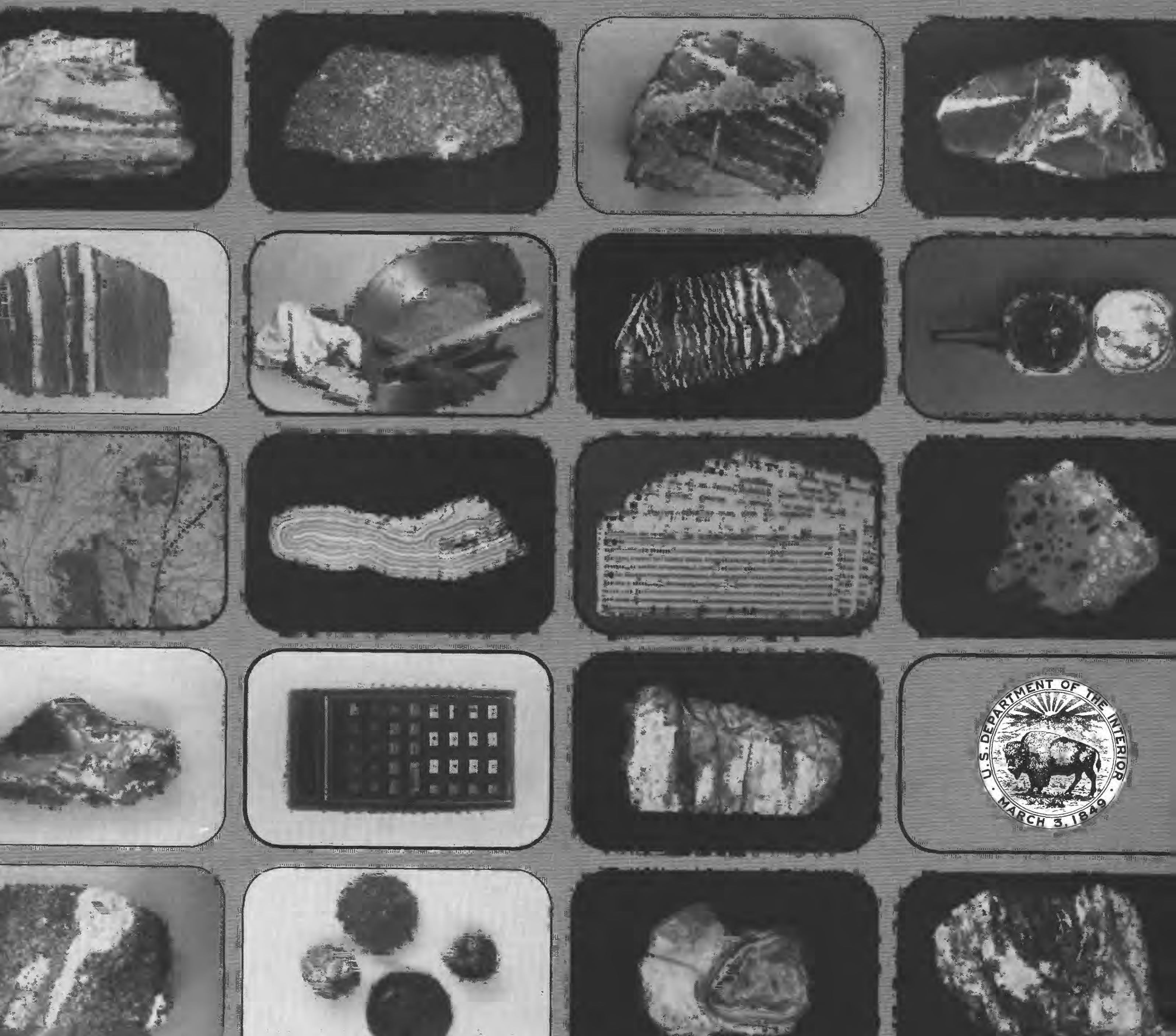
Uranium in Phosphate Rock
and
Uranium and Vanadium Resources in the Moab 1° x 2° Quadrangle, Utah and Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 988-A, B



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Uranium in Phosphate Rock

By JAMES B. CATHCART

and

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By A. P. BUTLER, JR., *and* R. P. FISCHER

GEOLOGY AND RESOURCES OF URANIUM DEPOSITS

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimates includes currently minable resources (*reserves*) as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the earth's crust, depends greatly on geologic availablity and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of uranium as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

Professional Paper 820—"United States Mineral Resources"
Professional Paper 907—"Geology and Resources of Copper"
Professional Paper 926—"Geology and Resources of Vanadium"
Professional Paper 933—"Geology and Resources of Fluorine in the United States"
Professional Paper 959—"Geology and Resources of Titanium in the United States"

Uranium in Phosphate Rock

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GEOLOGY AND RESOURCES OF URANIUM DEPOSITS

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A study of the distribution and occurrence of uranium in phosphate deposits of the world

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URANIUM IN PHOSPHATE ROCK

By JAMES B. CATHCART

ABSTRACT

Uranium is a trace constituent of all apatites in amounts that typically range from < 0.001 to 0.003 percent for guano and guano-derived deposits, from 0.001 to 0.010 percent for igneous apatites, and from 0.005 to 0.030 percent for marine phosphorites. Uranium may be enriched to as much as 0.05 percent in phosphorites reworked in a marine environment, and isolated bones and concretions may contain as much as 0.8 percent uranium as a result of enrichment by ground water.

Uranium as U(IV) replaces calcium in the apatite structure or may be absorbed as the uranyl ion on apatite crystal structures. Uranium is readily removed from apatite by weathering. Enrichment of phosphate after deposition may be entirely residual, as in the case of the brown rock deposits of Tennessee, or uranium may be added, as in the case of the lateritic weathering of the deposits in Florida.

Uranium has been recovered as a byproduct of the manufacture of phosphoric acid by the wet process. In 1972, about 15 million tonnes (metric tons) of phosphate rock was used to make phosphoric acid in the United States. This phosphoric acid probably contained about 1,500 tonnes of uranium. It seems likely that tonnages of uranium in phosphoric acid will reach 3,000 tonnes per year within the next 25 years because of the increased demand for phosphatic fertilizers and increases in the amount of phosphate rock used to make phosphoric acid. About twice this amount might be present worldwide. Thus, marine phosphorites are a significant source of uranium for the future.

INTRODUCTION

Uranium is present as a trace constituent in all apatites, in amounts that typically range from 0.003 to 0.030 percent. Strutt (1908) first discovered that phosphatic rocks and fossil bones are appreciably more radioactive than the average rocks of the crust. His data showing that certain British phosphorites and fossil bones contain from 0.005 to 0.015 percent U_3O_8 were remarkably accurate. R.C. Wells of the U.S. Geological Survey (unpublished data) noted in the late 1920's that a shark's tooth from the Pliocene of Florida contained 0.021 percent U—the first record of the uranium in the phosphate deposits of Florida. Hébert (1947) reported that the discovery of uranium in the Cretaceous and Eocene phosphorites of Algeria was made in 1924. The first mention of uranium in the Cretaceous and Tertiary phosphate deposits of the U.S.S.R. was published by Rusakov (1933).

The developments of uses of uranium as an energy source provided the impetus for research into all potential sources, and apatites were tested for uranium in all parts of the world. Detailed studies of uranium in phosphate have been made by Altschuler (1973), Altschuler, Clarke, and Young (1958), Altschuler, Jaffe, and Cuttitta (1956), Cathcart (1956), Davidson and Atkin (1953), McKelvey (1956), McKelvey and Carswell (1956), McKelvey, Everhart, and Garrels (1955), and Sheldon (1959). Much of the data presented in this paper is derived from these works, and each of them contains an extensive bibliography.

The tables that accompany this report relate only reserve data. Reserves are defined as identified mineral deposits whose grade and tonnage are reasonably evaluated, but which may not be economically recoverable under present conditions. All reserves are in tonnes and consist of material that contains at least 24 percent P_2O_5.

Phosphorus is found in minable concentration in three environments—as guano or in deposits derived from guano, as igneous apatite, as marine phosphate deposits—and in secondary deposits formed from each of these by weathering.

GUANO AND GUANO-DERIVED DEPOSITS

Guano deposits are formed from the excreta of sea birds at the surface and of bats in caves. Guano-derived deposits are formed when the soluble phosphate in guano is dissolved by ground water and reacts with the underlying rocks. Apatite is formed when the underlying rock is limestone, and iron and aluminum phosphates are formed when igneous rocks underlie the guano.

About 5 percent of the world's production of phosphate is from guano-derived deposits, and a very small amount is from guano deposits (table 1). Guano contains from less than 0.001 to 0.003 percent U (Altschuler and others, 1958), but gauno-derived deposits contain as much as 0.008 percent U (Davidson and Atkin, 1953). Recent analytical data (U.S. Geol. Survey Denver laboratory: E. J. Fennelly and Johnnie Gardner, analysts) show that guano-derived phosphate samples from Curacao contain 0.002 percent U, and that samples from Nauru contain 0.005 percent. The samples with higher uranium contents (0.005-0.008 percent) are also high in fluorine; the phosphate mineral is a carbonate fluorapatite, rather than a hydroxyapatite. The samples are from tidal zones where fluorine and uranium were added from seawater.

TABLE 1.—*Guano and guano-derived phosphate: reserves, production, and uranium content*

Location	Reserves (tonnes)	Production (tonnes/yr)	Uranium content (percent)
Bird guano (surface)			
Peru (Pacific Coast)	Limited, renewable	$0.1x10^6$	<0.001-0.003
Chile (Pacific Coast)	Small	$.01x10^6$	<.001-.003
Bat guano (cave)			
Mexico, Phillipines, and Africa.	Very small; total is about $3x10^6$.	$0.02\text{-}0.04x10^6$	<0.001-0.003
Guano-derived calcium phosphate minerals			
Nauru Island	$100x10^6$	$1.8x10^6$	0.005-0.007
Christmas Island	$30x10^6$	$.7x10^6$	.008
Makatea Island	$10x10^6$	$.3x10^6$	.006
Ocean Island	$10x10^6$	$.3x10^6$	.001-.002
Curacao	$30x10^6$	$.1x10^6$	.002
Anguar	$2x10^6$	None	.001
Guano-derived iron and aluminum phosphate minerals[1]			
Malpelo Island, Colombia	$0.4x10^6$	None	No data.
Trauira Island, Brazil	$11x10^6$	do	Do.
Saldanha Bay, South Africa	$.3x10^6$	do	Do.
Kito-Daito-Jima, Ryukyu Islands.	$2x10^6$	do	Do.

[1]Only the largest of the aluminum and iron phosphate deposits are listed. Others are known, but reserves are limited and none are being mined today. The deposits of Kito-Daito-Jima have been mined. Uranium contents of these deposits are not known, but are thought to be small, of the order of magnitude of 0.001 percent.

IGNEOUS APATITE DEPOSITS

Apatite deposits of igneous origin occur as intrusive masses, as veins, as marginal differentiates, or as pegmatites. The largest deposits are intrusive masses associated with alkalic rocks, such carbonatite, nepheline syenite, pyroxenite, and ijolite.

The apatite mineral, a fluorapatite, ranges in amount from a few percent as an accessory mineral to 80 percent in some pipes and sheets. The apatitic masses range in size from a few square meters to tens of square kilometers and the amounts of apatite present range from a few tonnes to hundreds of million of tonnes. The largest deposits include the Kola Peninsula (U.S.S.R.), Laokay (North Vietman), Palabora and eastern Uganda (Africa), and Araxa (Brazil). In 1970, about 17 percent of the world's production of phosphate came from igneous apatite deposits, and about 80 percent of this production was from the deposits of the Kola Peninsula.

The uranium content of primary fluorapatite in igneous rocks typically ranges from 0.001 to 0.010 percent (Altshuler and others, 1958; Davidson and Atkin, 1953), although individual samples may contain as much as 0.079 percent U (table 2). Thorium is not usually present, except in very minute amounts; however, an apatite sample from a pegmatite near Bahia, Brazil, contained 0.005 percent U and 1,500 ppm Th (Thorium analysis by Nancy Conklin, and uranium analysis by E. J. Fennelly, U.S. Geol. Survey).

TABLE 2.—*Igneous apatite: reserves, production, and uranium content*

[Leaders (...) indicate no data available]

Location	Reserves[1] (tonnes)	Production[2] (tonnes/yr)	Uranium content[3] (percent)
Kola Peninsula, U.S.S.R.	$2x10^9$	$10x10^6$	0.001-0.003
Laokay, North Vietnam	$.1x10^9$	$1x10^6$	......
Palabora, South Africa	$.4x10^9$	$1x10^6$	.003-.004
North Korea	$.1x10^9$	$.4x10^6$	......
Brazil (carbonatites)	$.15x10^9$	$.2x10^6$	[4].020
Dorowa, Southern Rhodesia	$.1x10^9$	$.1x10^6$	......
Uganda	$.2x10^9$	$.01x10^6$	[5].013-.030
Antofagasta, Chile	$.02x10^9$	$.01x10^6$	......
Mineville district, New York, U.S.A.	Very small	None	.079

[1]In metric tons of total rock containing more than 10 percent P_2O_5.
[2]In metric tons of apatite concentrate containing at least 25 percent P_2O_5.
[3]In percent, of the apatite concentrate.
[4]One sample, from Araxa. A sample of apatite from a pegmatite in Bahia, Brazil, contained 0.010 percent eU, 0.005 percent U, and 1,500 ppm Th.
[5]Percent U_3O_8, from Davidson and Atkin (1953).

MARINE PHOSPHORITE

Marine phosphorite deposits are known throughout the world and occur in all geologic ages, from Precambrian to Holocene. The richest of these deposits are formed in basins, in warm latitudes, in areas of upwelling water, and away from abundant sources of clastic material. Some deposits are very large—reserves in an individual deposit may be billions of tonnes; total reserves aggregate scores of billions of tonnes, and resources are proportionately larger (Cathcart and Gulbrandsen, 1973). About 84 percent of the world production of phosphate comes from marine phosphorites; from 1970 through 1972, production in the United States was about 40 million tonnes per year. U.S. production can be broken down into 83 percent from Miocene and Pliocene deposits in Florida and North Carolina, 11 percent from the Permian deposits of the Western States, and 6 percent from Ordovician deposits in Tennessee and Alabama. Some production from the Miocene of California is included in the total for the Western States.

Every deposit that has been analyzed contains uranium, in amounts that typically range from 0.005 to 0.030 percent, whereas the average uranium content for most deposits is in the range from 0.005 to 0.010 percent (table 3). The relative uniformity of the analytical data strongly indicates that deposits for which data are not available almost certainly contain similar amounts of uranium; that is, ranging from about 0.005 to 0.020 percent and averaging about 0.006-0.008 percent uranium.

Uranium is associated with the apatite mineral (carbonate fluorapatite), and most workers agree that uranium as U(IV)

TABLE 3.—*Marine phosphorite: reserves, production, and uranium content*

Location	Reserves[1]	Production[1]	Uranium content[2]
United States			
Central Florida	2.1x10^9		0.003-0.030; average concentrate 0.011; average pebble 0.015
North Florida South Georgia.	.3x10^9	35x10^6	.004-.011; average .006
North Carolina	2x10^9		.004-.011; average .006
North Georgia (Savannah River).	Reserves not measured; resources are billions of tonnes.	no production-	.005
South Carolina (Beaufort County)	do	do	.006
(Charleston area)	do	do	.005-.037
Florida-Georgia (Hawthorn Formation).	do	do	.003-.008; average .005
Idaho, Montana, Utah, Wyoming (Phosphoria Formation).	6x10^9	4x10^6	[3].002-.021; average .009
Utah (Brazer Dolomite, Deep Creek Formation, Lodgepole Limestone).	Measured reserves are small; resources, particularly in Alaska, are billions of tonnes.	No production-	.001-.006
Alaska (Permian)	do	do	[4].001-.024, average .008
Others (Ala., Ark., Ky., Iowa, Kans., Okla., Calif., Nev.).	do	do	Rock: .001-.014 nodules in black shale and limestone: .009-.030
Africa			
Algeria	20x10^9	0.8x 10^6	0.011-0.014
Angola		None	No data.
Morocco		20x10^6	.007-.023
Senegal		2x10^6	.012-.018
Togo		2x10^6	No data.
Tunisia		4x10^6	.004-.009
U.A.R. (Egypt)		.6x10^6	.007-.012
Spanish Sahara		2x10^6	.005-.011
Asia			
China (Mainland)	1x10^9	3x10^6	No data.
India	.1x10^9	.1x10^6	[5]0.003-0.100
Iran	.05x10^9	None	No data.
Iraq	.1x10^9	do	Do.
Israel	.1x10^9	1x10^6	[6].002-.020
Jordan	.1x10^9	1.5x10^6	No data.
Mongolia	1x10^9	No data	Do.
Saudi Arabia	.2x10^9	None	.002-.011; average .006
Turkey	.2x10^9	do	.004
Australia	1x10^9	do	[7].001-.013; average .006
Europe			
U.S.S.R.	1x10^9	10x10^6	[8]0.005-0.010
Others (Belgium, Germany, France, England, Spain).	Small	.1x10^6	.001-.021; average .006
Latin America			
Mexico	0.15x10^9	Production is a few tens of thousands of tonnes per year.	No data.
Colombia	.2x10^9		0.004-0.012; average .008
Venezuela	.1x10^9		.005
Peru (Sechura)	1+ x10^9		.006
Brazil (Bambui)	.3x10^9		.001-.005; average .002

[1]In tonnes of recoverable phosphate product containing at least 24 percent P_2O_5.
[2]Uranium, in percent, of the phosphate product, except as noted.
[3]Data from Gulbrandsen (1966).
[4]Data from Patton and Matzko (1959).
[5]Data from Saraswat and others (1972).
[6]Data from Wurzbuger (1968).
[7]Data from Cook (1972).
[8]Data from Bliskovskiy and Smirnov (1966).

replaces calcium in the apatite structure (Altschuler and others, 1958), or is in part adsorbed as the uranyl ion to apatite crystal surfaces (Sheldon, 1959).

The uranium-apatite association is clearly demonstrated in several ways: chemical analyses of the minerals associated with apatite in the Florida deposits show that they contain virtually no uranium; uranium varies directly with P_2O_5 content (Cathcart, 1956, Thompson, 1953 and 1954); and the amount of uranium dissolved on acidulation of phosphate rock varies directly with the amount of phosphate dissolved (Igelsrud and others, 1948).

The syngenetic character of uranium in marine phosphate is demonstrated by the distribution of uranium in the Florida phosphate deposits. Primary phosphate pellets in the Hawthorn Formation are low in uranium content, averaging about 0.005 percent. The phosphate pellets in the overlying Bone Valley Formation were reworked from the Hawthorn Formation in a marine environment, and the concentrate-size particles (the pellets) contain an average of 0.011 percent U (table 3). The pebble fraction (+1 mm) contains an average of 0.015 percent U. The coarse pebbles that show evidence of several cycles of reworking in the marine environment contain as much as 0.05 percent U (Cathcart, 1956, Altschuler and others, 1958). Thus, primary pellets contain the least amount of uranium, pellets reworked once in a marine environment contain much more uranium, and pebbles reworked several times contain the most uranium. The fine-grained pellets, highest in P_2O_5 content, always contain less uranium than the lower P_2O_5 content pebble fraction, even in deposits that contain 90 percent fine phosphate pellets and only 10 percent pebble size. This fact indicates that uranium was not emplaced by ground waters percolating through the deposits.

Uranium in ground-water solution is taken up by apatite, and phosphatic bones, concretions, pellets, and pebbles may be strongly enriched in uranium. Thus, isolated bones may contain as much as 0.83 percent uranium (Altschuler and others, 1958), individual concretions and nodules as much as 0.1 percent (Davidson and Atkin, 1953), and individual samples of pellets from Florida as much as 0.5 percent. These abnormally high contents of uranium are cited to illustrate the amount of enrichment than can be accomplished under special conditions.

The extremely small amounts of uranium in seawater under normal marine conditions probably accounts for the low, rather uniform content of uranium in these apatites.

SECONDARY DEPOSITS

Uranium is readily leached from apatite during weathering, and under acid ground-water conditions both apatite and uranium are dissolved. The type of source rock and the length and severity of the weathering determine the end products of weathering and the distribution of uranium in the products.

When the original rock is a phosphatic limestone, weathering removes calcite, leaving a residually enriched phosphorite. In the residual "brown rock" deposits of Tennessee, both the uranium and the P_2O_5 contents are increased in the residual material by the same factor, but uranium shows no preferential enrichment. After the calcite is gone, the apatite goes into solution, moves downward, and replaces the underlying limestone. In replacement deposits there tends to be a preferential enrichment in uranium. Uranium contents of as much as 0.1 percent have been noted in the secondary apatite hardpan on the Cooper Marl of South Carolina (Altschuler and others, 1958).

Replacement type deposits are known in many parts of the world. Individual deposits tend to be small, irregular in shape, and high in P_2O_5 content. Uranium contents typically range from 0.001 to 0.017 percent (table 4), although much higher contents are known. Measured reserves are small, but total resources may be fairly large.

TABLE 4.—*Secondary phosphate deposits: reserves, production, uranium content*

Location	Reserves (tonnes)	Production (tonnes/yr)	Uranium content (percent)
Calcium phosphate: replacement deposits			
Florida, hardrock	$0.05x10^9$	None	0.001-0.017; -200 mesh from .001-.023
Tennessee, "whiterock"	Small	do	.004
South Carolina "phosphatic hardpan."	Very small	do	.035-.12
Venezuela (Riecito area)	$.01x10^9$	([1])	No data
U.S.S.R.	No data	No data	[2].001-010
Calcium phosphate: residual deposits			
Tennessee, "brown rock"	$0.08x10^9$	$3x10^6$	[3]0.001-0.003
Aluminum phosphate deposits			
Florida, land-pebble district.	$0.05x10^9$	None	[4]0.004-0.040
Senegal	$.05x10^9$	$0.1x10^6$	No data.
Nigeria	Very small	None	.004-.011
Siberia, U.S.S.R.	No data, small(?)	do	No data.

[1]Few thousand tonnes per year.
[2]Uranium analyses by E. J. Fennelly and Johnnie Gardner, U.S. Geological Survey, Denver.
[3]Unaltered limestone from which the residual deposits formed contains 0.0004 percent U.
[4]Typical range in uranium contents. Individual samples may contain as much as 0.3 percent U.

Intensive weathering of sandy phosphorites by acid ground water produces irregular zones of porous, vesicular, light-colored, and lightweight rocks characterized by aluminum phosphate minerals. These zones have been described in Florida, Nigeria, Senegal, and Siberia (Altschuler, 1973). All of the deposits are similar; they are characterized by the change of apatite to crandallite or millisite and to wavellite as an end product. These changes are accompanied by the change of the original clay minerals (montmorillonite or illite) to kaolinite.

Uranium is enriched in these deposits, and it is associated almost entirely with the phosphate minerals, and preferentially with the calcium aluminum phosphate minerals crandallite and millisite, or with the calcium phosphate mineral apatite. The uranium minerals autunite (from Florida) and torbernite (from Morocco) have been reported from the aluminum phosphate zones, but only in trace amounts and only in limited areas within the deposits. Uranium is highest and most enriched in the porous, partly leached apatite pebbles at the base of the zone of leaching; amounts of uranium are as high as 0.3 percent in these pebbles. Concentrates of the calcium aluminum phosphate minerals crandallite and millisite contain as much as 0.05 percent uranium (Altschuler, 1973), but concentrates of the aluminum phosphate mineral wavellite contain an average of only about 0.003 percent uranium.

In Florida, the total zone of aluminum phosphate alteration may be enriched in uranium as much as 2-4 times over the original, unaltered calcium phosphate zone from which it was derived.

Uranium is liberated during the solution of the apatite, remains soluble in the descending acid solutions, and enriches the crandallite and the partly leached apatite pebbles at the base of the section. Because wavellite is continuously formed from crandallite in the middle parts of the zone, the uranium in the crandallite goes into solution and moves downward, further enriching the underlying apatite and accounting for the abnormally high uranium contents in some of this apatite.

OTHER DEPOSITS

LAKE BEDS

Tertiary lake beds in Wyoming and Nevada contain some layers of uraniferous phosphate. Lake beds near Tonopah, Nev., contains 6.7 and 11.0 percent P_2O_5 and 0.10 and 0.12 percent eU (unpub. analyses, U.S. Geo. Survey, by Carmen Johnson and Maryse Delevaux) (table 5). Lake beds of Eocene age in Wyoming and Utah contain as much as 0.27 percent U and 19 percent P_2O_5, although the average contents of both are much less (Love, 1964). Many very thin beds containing the phosphate and uranium are present; the beds average less than 30 cm in thickness. The uraniferous phosphate beds are thought to be syngenetic, and although these occurrences are not economic, they indicate the possibility that in other, similar lake basins, economic beds of uraniferous phosphate might be present. Tonnages are not known; they may be large in total because of the extent of the beds, but tonnages per unit area are probably small.

OFFSHORE DEPOSITS

Phosphate nodules and pellets are present on the floors of the modern oceans and have been investigated on the west coast of North America from Monterey Bay to Baja California, on the east coast of the United States from North Carolina to Florida, and along the west coast of Africa.

TABLE 5.—*Other phosphate deposits: reserves, production, and uranium content*

Location	Reserves (tonnes)	Production (tonnes/yr)	Uranium content (percent)
	Lake beds		
Nevada (Tertiary)	Probably small	None	0.10, 0.12
Wyoming, Utah (Eocene)	Area is large; beds only .08 to 1.8 m thick.	do	.001-.29; average .005.
	Offshore		
California (Monterey Bay) to Baja California.	Large	None	0.001-0.021
Florida, Georgia, South and North Carolina.	do	do	No data; probably average .005.
South Africa (Capetown)	No data[1]	do	No data.
Northwest Africa (Rabat to Mauritania).	No data[2]	do	No data.[3]

[1]Maximum apatite content 15 percent.
[2]Apatite content 10-60 percent, reworked from older beds.
[3]U content should be the same as the deposits of North Africa, from which these deposits probably were derived.

Some of the nodules are thought to be forming in the modern oceans, as those of offshore California; others are thought to be reworked from older phosphatic sediments, as those of offshore North Carolina and along the west coast of Africa.

Amounts of pellets and nodules in the modern sediments range from traces to 60 percent by volume, but probably average between 5 and 10 percent; resources probably aggregate billions of tonnes although adequate measurements of reserves have not been published.

Uranium contents range from 0.001 to 0.012 percent (Altschuler and others, 1958), but a single sample from offshore California contained 26.4 percent P_2O_5 and 0.021 percent U (U.S. Geol. Survey analysis by M. Finch, C. Angelo, and P. Schuch). The analytical data are similar to data from older marine phosphorites, and there is no reason to believe that other unanalyzed deposits will contain very different amounts of either uranium or phosphate.

PHOSPHATE RESOURCES

Data on phosphate resources of the world are given by Cathcart and Gulbrandsen (1973), and it is not necessary to repeat the data in this paper.

Uranium has been recovered as a byproduct of the manufacture of phosphoric acid by the wet process in the past. A plant to recover uranium from wet process phosphoric acid was completed in Florida in 1975 and plans have been announced for additional plants that would bring capacity to 1.3 million pounds of uranium per year (Engineering and Mining Journal, 1975). The latest available data show that about 15 million tonnes, about one-third of the total production of phosphate rock in the United States, went into the manufacture of wet process phosphoric acid (Stowasser, 1974). The phosphate rock used in phosphoric acid production probably contained an average of 0.010 percent U which would be 1,500 tonnes of uranium. An additional 60 million tonnes of phosphate rock was produced in the rest of the world, and of this, about 50 million tonnes were from marine phosphorites. Although precise data are not available, it is thought that about one-fifth of this total was used to make wet process acid; therefore, about 10 million tonnes, probably containing 0.010 percent U, was made into phosphoric acid. The total amount of uranium, recoverable under known processes, was about 2,500 tonnes in 1972. World production of phosphate will increase; if present trends continue, a greater percentage of the production will go into the manufacture of wet process phosphoric acid, and it follows that the amount of recoverable uranium will increase.

Projections into the future are very speculative, but an increasing population's need for fertilizer indicates that a doubling of production is the minimum that might be required in the next 25 years. The amount of uranium that could be recovered from wet process acid should also double, and a minimum of about 5,000 tonnes of uranium per year would be available for recovery.

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Uranium and Vanadium Resources in the Moab 1° x 2° Quadrangle, Utah and Colorado

By A. P. BUTLER, JR., and R. P. FISHER

GEOLOGY AND RESOURCES OF URANIUM DEPOSITS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 988-B

An outline of the geologic relations of the uranium and vanadium deposits provides a framework for evaluating undiscovered resources of those metals in the Moab quadrangle

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METRIC-ENGLISH EQUIVALENTS

Metric unit		English equivalent
meter (m)	=	3.28 feet
kilometer (km)	=	.62 mile
square kilometer (km^2)	=	.386 square mile
cubic meter (m^3)	=	35.31 cubic feet
kilogram (kg)	=	2.2 pounds
metric ton (t)	=	1.1 short tons

URANIUM AND VANADIUM RESOURCES IN THE MOAB 1° x 2° QUADRANGLE, UTAH AND COLORADO

By A. P. BUTLER, JR., and R. P. FISCHER

ABSTRACT

The Moab quadrangle, Utah and Colorado, includes highly productive uranium and uranium-vanadium deposits and has a significant resource potential.

Rocks in the quadrangle range in age from Precambrian to Cenozoic, but those exposed over much of the quadrangle consist of bedded sedimentary rocks of Paleozoic and Mesozoic ages. The Chinle Formation of Triassic age and the Morrison Formation of Jurassic age contain most of the known uranium deposits. The Chinle is ore-bearing in the western part of the quadrangle, where it is composed of light-colored conglomeratic sandstone at and near its base and overlying reddish-brown or varicolored mudstone, siltstone, and sandstone; ore deposits occur in the conglomeratic sandstone. The Morrison Formation is divided into the underlying Salt Wash Sandstone Member composed of light-colored lenticular sandstone strata interbedded with dominantly red mudstone, and the overlying Brushy Basin Shale Member, composed mainly of varicolored mudstone. Most of the ore deposits are in the uppermost sandstone lenses of the Salt Wash and in the central part of the quadrangle.

The primary ore minerals in the deposits consist of uranium and vanadium oxides and silicates; they mainly impregnate the sandstone. They form tabular orebodies that average somewhat less than a meter thick and are as much as one hundred meters across. These bodies lie nearly parallel to the bedding of the host sandstone, and they are mainly localized by sedimentary structural features. The deposits were probably formed from ground waters moving along the beds before the host beds became deeply buried.

Most of the deposits in the Chinle Formation are in the Big Indian mineral belt on the southwest side of the Lisbon Valley anticline. These deposits have yielded ore containing uranium worth about $500 million. They were probably formed in Late Triassic time, when the Chinle covered the anticline and was slightly arched owing to a minor upwelling of evaporites in the underlying core of the anticline. If these deposits were actually formed in this geologic situation, then the northeast flank of the anticline might also contain significant deposits, provided Chinle streams deposited favorable host beds there. Favorable locations for similar deposits might also be the flanks of the Dolores anticline and possibly the flank of the Moab anticline and ground bordering the southwest side of Spanish Valley. The Chinle probably contains undiscovered deposits in other places in the western part of the quadrangle, but these deposits are probably too small and widely scattered to be a resource of economic significance.

Deposits in the Salt Wash Member of the Morrison Formation have yielded a little more than 9,100,000 metric tons of ore and uranium and vanadium worth more than $600 million; more than 80 percent of this ore came from the Uravan mineral belt. The belt was probably localized along the toe of a subsidiary alluvial fan, which was formed by a distributary stream system on part of the main fan in an area of minor subsidence during Salt Wash time. The deposits in the belt and on the mid-slope of the fan west of the belt occur in sandstone lenses that formed along the courses of the major distributary streams; deposits outside the area of this alluvial fan also occur in sandstone lenses formed in major stream courses. The ore deposits were probably formed before burial by marine sedimentary beds in Late Cretaceous time. Reserves plus undiscovered resources in deposits in the Uravan mineral belt probably contain about 12,700 metric tons of U_3O_8; those in the fan area west of the belt about 7,900 metric tons of U_3O_8; and those in the Salt Wash in other parts of the quadrangle about 3,440 metric tons of U_3O_8.

INTRODUCTION

The Moab 1x2-degree quadrangle is in east-central Utah and west-central Colorado. The area of the quadrangle includes many of the major uranium and uranium-vanadium deposits and mining districts in the central part of the Colorado Plateau region (fig. 1). It also includes two of the major mineral belts in the Plateau region, namely the Uravan and Big Indian mineral belts. These deposits have yielded about 25 percent of the uranium and nearly 60 percent of the vanadium produced domestically. The known deposits contain substantial reserves of uranium-vanadium ore, and the area has a significant resource potential.

This report summarizes the geology of the area, and briefly describes the habits of the uranium and vanadium deposits. An appraisal is made of the uranium and vanadium resources of the area, and suggestions are made for prospecting several of the more favorable parts of the area.

This study is based on the knowledge and experience of the writers, on many published reports, and on production and reserve data obtained from the U.S. Atomic Energy

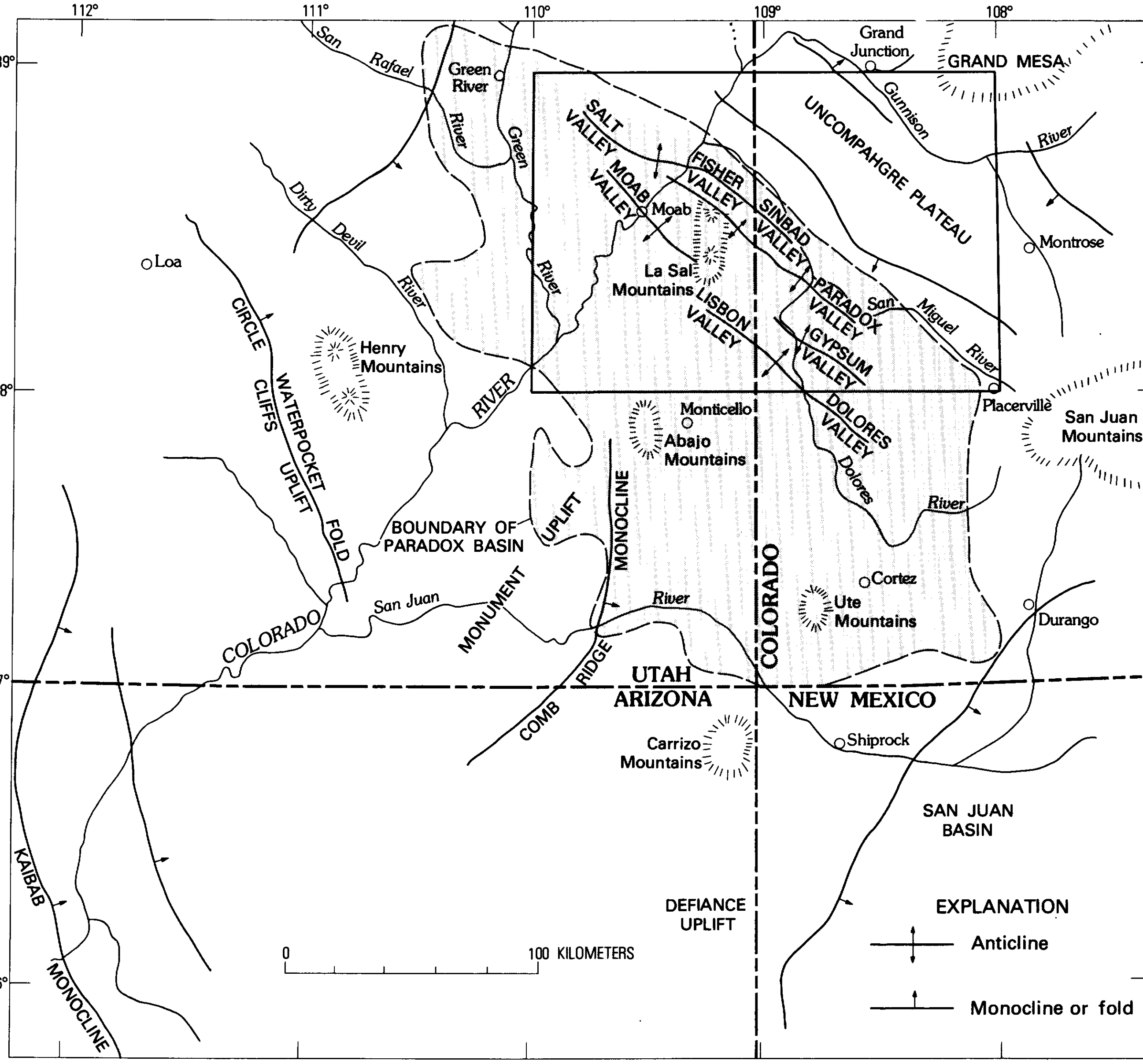


FIGURE 1. — Tectonic sketch map of part of the Colorado Plateau (modified from Cater, 1970) showing location of the Moab 1x2-degree quadrangle.

Commission. In addition, many peoplé in the U.S. Geological Survey, the U.S. Atomic Energy Commission, and in the mining industry have contributed information and ideas incorporated in this report. The geology and the location of most of the ore deposits are shown on a map by Williams (1964) and in simplified form by figures 3, 4, and 5 of this report.

GEOLOGIC SETTING

The Moab quadrangle is in the east-central part of the Colorado Plateau physiographic and structural province. Rocks in the area range in age from Precambrian to Cenozoic, but those exposed over much of the quadrangle are sedimentary rocks of Paleozoic and Mesozoic ages. The beds have been gently to moderately tilted by folding, and in places have been broken by high-angle faults of small to moderate displacement; in the central part of the quadrangle the rocks were invaded by moderate-sized bodies of magma, parent to the igneous rocks that form the cores of the La Sal Mountains, and in the northeast part of the quadrangle are capped by igneous rocks on Grand Mesa.

In the Moab quadrangle, Precambrian rocks are exposed only in places on the Uncompahgre Plateau; these rocks consist predominantly of granite, gneiss, and schist and locally of pegmatite. Rocks of similar lithologic character probably underlie the entire quadrangle. Evidence from scattered deep drill holes indicates that by the beginning of Paleozoic time, Precambrian rocks had been reduced by erosion to a moderately flat surface.

Paleozoic rocks of pre-Pennsylvanian age are not exposed in the quadrangle. They were removed by erosion in late Paleozoic time from the area of the Uncompahgre Plateau (Cater, 1970, fig. 13) but are presumed to underlie the southwestern two-thirds of the quadrangle. Wherever these rocks are cut in deep drill holes or are exposed in adjoining areas, they consist of marine carbonates and clastics and measure several tens of meters thick.

The rocks of the Moab quadrangle and surrounding region were disturbed by deformation in Pennsylvanian time (Cater, 1955). The deformation consisted mainly of vertical displacement of crustal blocks along northwest-trending faults; it resulted in the uplift of the ancestral Uncompahgre highland in the northeastern part of the quadrangle and the sinking of the Paradox Basin southwest of the highlands. The Hermosa Formation of Pennsylvanian age was deposited in this basin. It comprises two members, a lower one, the Paradox, and an unnamed upper member. The Paradox Member consists mainly of salt and sulfate evaporites. Originally this member was probably over a thousand meters thick in the deeper part of the basin, which was in the central part of the Moab quadrangle, and bordered on the southwest flank of the ancestral Uncompahgre highland. The original thickness of this member is not known, however, because its beds have subsequently been squeezed laterally into several large anticlines from the intervening synclines. The upper member, composed mainly of marine limestone, probably had a maximum thickness of about 600 m. The Hermosa Formation is exposed only along the cores of the salt anticlines that have been breached and eroded into elongate valleys.

The Hermosa Formation grades upward into the Pennsylvanian Rico Formation, a transitional unit consisting of as much as 50 meters of marine and nonmarine limestone, sandstone, and siltstone; the Rico in turn grades upward into the Permian Cutler Formation. The Cutler forms an asymmetric lens that is at least 3,000 m thick near the southwestern front of the ancestral Uncompahgre highland, where the formation is composed of coarse arkosic sandstone and conglomerate of granitic pebbles and boulders derived from the highland (Cater, 1970, p. 10-11). The Cutler pinches out abruptly to the northeast, thins gradually to the west, and has a maximum thickness of about 300 m in the western part of the Moab quadrangle. The grain size of the formation also decreases westward. In the western part of the quadrangle the Cutler is composed of sandstone, partly arkosic but predominantly muddy, with minor amounts of conglomerate, shale, and limestone; the sandstone beds are dominantly dark red, purple, or brown, but some are light-colored (McKnight, 1940).

While the Hermosa and Cutler Formations were being deposited, the ancestral Uncompahgre highland continued to rise and the Paradox Basin to sink. The evaporite and limestone members of the Hermosa were warped by tilting fault blocks under the basin, forming gentle anticlines above the uplifted edges of the blocks. Because of erosion or nondeposition along these anticlines, the limestone member was thinner on them than in the intervening synclines. The heavier loading on the synclines caused the evaporites to flow laterally from them to the anticlines and thence upward, initiating the salt anticlines. The added weight of the Cutler beds enhanced this movement of the evaporites, squeezing this material upward into and through the Cutler (Cater, 1970, fig. 13, sections *B*, *C*, and *D*).

The crustal movements associated with the uplift of the ancestral Uncompahgre highland virtually stopped by the end of Cutler time. Throughout the Mesozoic Era the entire Colorado Plateau region remained relatively stable except for a gradual subsidence that kept the region close to sea level. During this time about 2,400 m of sedimentary beds, mostly nonmarine, were deposited. In the area of the Moab quadrangle, however, minor upwelling of the evaporites along the salt anticlines was recurrent at least until Late Jurassic time; as a result, some beds of Triassic and Jurassic ages thin or wedge out by nondeposition or erosion along the upturned flanks of the anticlines (Cater, 1970, fig. 13, section *E*). In most places, these anticlines were covered by the rocks of Cretaceous age, and probably also by the Morrison Formation of Late Jurassic age. Cater (1970, p. 65) suggests that most or all of the evaporites had been squeezed from the synclinal areas into the salt anticlines by Late Jurassic time. Shawe (1970, p. C16) suggests, however, that some of the differences in the thickness of some Cretaceous beds between synclinal and anticlinal areas, in the southeastern part of the quadrangle, are probably a result of continued flow of these evaporites during the Cretaceous.

Subsequent deformation involving the Morrison and younger beds in the quadrangle probably resulted primarily from tectonic movements of the deep-seated fault blocks, rather than the flowage of the Hermosa evaporites. The conspicuous deformation consisted of arching of the Morrison and younger beds over the old salt anticlines, but evidence to date this folding is scant. Significant movements may have occurred during Laramide time in the Late Cretaceous and early Tertiary (Cater, 1970, fig. 13, section *F*) or in the early to middle Tertiary (Shawe, 1970, p. C17); probably the Lisbon Valley anticline was broken by its conspicuous fault during the Late Cretaceous to mid-Tertiary interval. Possibly some tectonic deformation occurred during the epeirogenic uplift of the entire Colorado Plateau region in middle to late Tertiary time. Certainly the anticlines were modified in detail by collapse of the crestal parts owing to removal of the evaporites, by erosion and solution, as the surface of the Plateau region was lowered by erosion in the late Tertiary and the Quaternary. Erosion is continuing. The uplift of the present Uncompahgre Plateau, marked by sharp flexing of the cover of Mesozoic beds and some faulting, occurred in the late Tertiary and Pleistocene.

The La Sal Mountains in the central part of the Moab quadrangle consist of three moderate-sized stocks and associated laccoliths composed mainly of dioritic, monzonitic, and syenitic porphyries (Hunt, 1958). The parent magma of these igneous bodies invaded and domed sedimentary beds of late Paleozoic and Mesozoic ages. Hunt (1958, p. 314) favored a middle Tertiary age for the intrusions, on the basis of the geologic record; Stern and others (1965) favored an age of about 25 million years, or about the end of the middle Tertiary, for the intrusions, as indicated by somewhat anomalous results of various methods of isotopic age determinations; and Armstrong (1969) reported a 23.5-million-year age on the basis of isotopic analysis of one sample.

STRATIGRAPHY

The stratigraphy of the Mesozoic formations in the Moab quadrangle is summarized in table 1. Readers desiring more information about the stratigraphy of these formations are referred to reports by Baker (1933), Dane (1935), McKnight (1940), Bush, Bromfield, and Pierson (1959), Carter and Gualtieri (1965), Shawe, Simmons, and Archbold (1968), and Cater (1970). The stratigraphy of the Chinle and Morrison Formations is described in more detail below, as these formations contain most of the known deposits of uranium and vanadium ore in the quadrangle.

CHINLE FORMATION

The Chinle Formation of Triassic age is widespread in the Colorado Plateau region. It is about 600 m thick in southwestern Utah and thins rather gradually to the east and north. It is composed principally of mudstone and sandstone including some partly conglomeratic sandstone. The conditions of deposition were virtually the same throughout the region with sediments accumulating in an environment of an alluvial plain with meandering streams, ephemeral lakes, and extensive mud flats. Sedimentary, metamorphic, and igneous rocks in the highland area of central Arizona and in southwestern New Mexico were probably the principal source of these sediments. The Chinle is divided into several members in the southern and western parts of the Plateau region (Stewart and others, 1959; Stewart, Poole, and Wilson, 1972), but only two members, the Moss Back and the Church Rock, are clearly recognized in the area of the Moab quadrangle; these are distinguished only in the southwestern part of the quadrangle. In most of the area the Chinle is not formally subdivided.

TABLE 1.—*Generalized section of Mesozoic formations in the Moab quadrangle*

System	Group or formation	Thickness (meters)	Character and distribution
Cretaceous	Mesaverde Group	370	Thick-bedded light-colored marine and nonmarine sandstone and shale; coal-bearing. Originally covered entire quadrangle; may have been thicker than that remaining in northeast and northwest corners.
	Mancos Shale	1,200	Dark-gray fissile marine shale with some thin sandstone beds. Originally covered entire quadrangle.
	Dakota Sandstone	15-60	Gray and brown partly conglomeratic sandstone, and gray to black shale; all nonmarine; coal-bearing in places. Originally covered entire quadrangle.
	Burro Canyon Formation	0-60	Light-colored sandstone and conglomerate, green and purplish shale, thin beds of limestone; all nonmarine. Originally widespread, locally absent.
Jurassic	Morrison Formation	75-150	Brushy Basin Shale Member: varicolored bentonitic mudstone, some sandstone lenses; nonmarine. Widespread.
		60-140	Salt Wash Sandstone Member: light-colored lenticular sandstone interbedded with dominantly red mudstone; nonmarine. Widespread.
	Summerville Formation	20-45	Predominantly brownish-red, gray, and green sandy shale and mudstone; nonmarine. Widespread.
	Entrada Sandstone	20-170	Light-colored fine- to medium-grained massive and crossbedded sandstone; predominantly eolian. Widespread.
Jurassic and Triassic?)	Navajo Sandstone	0-120	Light-colored fine-grained massive and crossbedded sandstone; eolian. Absent in eastern half of quadrangle.
Triassic (?)	Kayenta Formation	0-75	Predominantly red irregualarly bedded shale, siltstone, and sandstone, nonmarine. Absent in eastern part of quadrangle.
Triassic	Wingate Sandstone	0-105	Reddish-brown fine-grained massive and crossbedded sandstone; predominantly eolian. Widespread but thin or absent in eastern part of quadrangle.
	Chinle Formation	0-180	Reddish-brown or varicolored mudstone, siltstone, and sandstone, in part bentonitic, commonly with light-colored conglomeratic sandstone at or near the base; nonmarine. Widespread but locally absent along the salt anticlines.
	Moenkopi Formation	0-300	Chocolate-brown, reddish-brown, and purple shale, mudstone, and sandstone, in part arkosic and conglomeratic; marine and marginal marine. Widespread but locally absent along the salt anticlines and in the eastern part of the quadrangle.

MOSS BACK MEMBER

The Moss Back in the southwestern part of the Moab quadrangle ranges from less than 6 m to about 30 m in thickness and averages about 16 m. Its gross lithologic components are sandstone and mudstone, but in detail its lithologic characteristics are quite varied. Grains in the sandstone range from fine to coarse, and some layers contain pebbles and less commonly cobbles. Some beds are composed dominantly of quartz, some are highly feldspathic, and some contain abundant grains of calcareous siltstone and limestone. The pebbles in some conglomeratic layers are predominantly quartz, quartzite, and chert, and in other layers are mainly siltstone and limestone. The mudstone beds consist of siltstone, claystone, and argillaceous limestone. The sandy beds are dominantly light gray and the muddy beds are chiefly greenish gray. Coalified plant material, mostly in small fragments, is sparse to abundant in some sandstone and mudstone beds.

The bedding characteristics of the Moss Back are varied, ranging from sheetlike layers to small lenses; cut-and-fill channels are not conspicuous although some of small size occur at the base of the member. Crossbedding is common but not omnipresent. Sandy beds, especially the conglomeratic ones, are more abundant in the lower part of the member and muddy beds are more common in the upper part of the member. Sedimentary structures indicate deposition by streams flowing generally northwestward.

The northeastern limit of the Moss Back is recognized in exposures along the Colorado River about 16 km southwest of Moab; from there it is projected by interpretation southeastward to Slick Rock, Colo., passing several kilometers northeast of Lisbon Valley, Utah (Stewart and others, 1959). The Moss Back is host to the important uranium deposits in the Big Indian mineral belt along the southwest side of Lisbon Valley (Wood, 1968), to several dozen small deposits along the Green and Colorado Rivers in the west-central part of the quadrangle, and to three small deposits south of Slick Rock (Shawe, Archbold, and Simmons, 1959).

CHURCH ROCK MEMBER AND UNDIFFERENTIATED CHINLE

The Church Rock Member, in the southwestern part of the quadrangle, and the undifferentiated Chinle, in the other parts, are lithologically similar and probably largely equivalent. These units are absent in places along the salt anticlines; they average about 30 m thick on the Uncompahgre Plateau; and they range from about 90 to 180 m in thickness elsewhere. These beds are somewhat varicolored but are dominantly brick red or reddish brown. They are chiefly siltstone, but fine-grained sandstone is common, and thin layers of limestone-pebble conglomerate are present. The siltstone and sandstone are somewhat tuffaceous. They occur in thick, poorly defined layers that are massive or only vaguely laminated. In many places in the central part of the quadrangle a quartzose grit, commonly with quartz pebbles, is present in the lower part of the undifferentiated Chinle. Beds of this lithology may or may not be equivalent to the Moss Back (Carter and Gualtieri, 1965; Cater, 1970). Several uranium deposits in the Sevenmile Canyon area northwest of Moab are in lenses of gray siltstone, limestone-pebble conglomerate, and quartz-pebble conglomerate at the base of the Chinle (Finch, 1954); these beds are interpreted to be at the base of undifferentiated Chinle and stratigraphically higher than the Moss Back rather than equivalent to the Moss Back (Stewart and others, 1959, figs. 77 and 81).

MORRISON FORMATION

The Morrison Formation (fig. 5) in the Moab quadrangle comprises two members, the Salt Wash Sandstone Member at the base and the Brushy Basin Shale Member at the top. Each originally extended throughout the area of the quadrangle and beyond it in all directions. The Salt Wash Member has yielded most of the vanadiferous uranium ore in the quadrangle, and contains most of the known reserves.

SALT WASH SANDSTONE MEMBER

The Salt Wash Sandstone Member is composed of material derived mainly from preexisting sedimentary rocks from a source area of moderate elevation in western Arizona and the adjacent part of California. This material was probably carried by a major river that entered the Colorado Plateau region in an area about where the present Colorado River crosses the Utah-Arizona line. There the Salt Wash is thickest, about 180 m, and is composed almost wholly of sandstone, which is in part conglomeratic. From there the Salt Wash was spread to the east and north by a distributary river system as a broad alluvial fan, becoming finer grained and thinning gradually in these directions. In the Moab quadrangle the Salt Wash is composed of interbedded layers of sandstone and mudstone in about equal amounts, ranging from about 90 to 120 m in thickness (Craig and others, 1955, fig. 21). The Salt Wash is slightly thicker in the eastern part of the quadrangle than in the western part, and Shawe (1962) suggested that this local thickening resulted from the filling of a shallow basin that had developed in southwestern Colorado during Salt Wash time.

In the eastern part of the quadrangle the sandstone layers in the Salt Wash tend to be evenly bedded, perhaps the result of accumulation in broad shallow bodies of water in the basin, as suggested by Shawe (1962). However, in the western two-thirds of the quadrangle, where the Salt Wash is ore-bearing, the sandstone layers are ill-defined lenses that presumably were deposited by shifting streams. These lenses are commonly 1.5-8 km wide and as much as a few tens of meters thick; they interfinger laterally with mudstone, which probably accumulated on flood plains. Fluvial crossbedding and scour-and-fill bedding are conspicuous sedimentary structural features in the sandstone, and thin lenses of mudstone and mudstone-pebble conglomerate are common. The sandstone is light colored, generally grayish yellow or pale red at the outcrop and pale gray or pale red below the zone of ozidation. It is composed of fine to medium grains predominantly of quartz and subordinately of some feldspar and chert. Pieces of coalified fossil plants ranging from small fragments to large logs are scattered through the sandstone but are most abundant in the thicker central parts of the sandstone lenses.

The Salt Wash mudstone is indistinctly bedded and is in part silty or finely sandy. It is predominantly red, but in places is gray or greenish gray. Presumably it was deposited on flood plains and in ephemeral ponds or lakes.

BRUSHY BASIN SHALE MEMBER

The Brushy Basin Shale Member is composed predominantly of bentonitic claystone, which is in part silty and sandy. It also contains a minor amount of partly conglomeratic lenticular sandstone. The claystone is varicolored; red, purple, gray, and greenish gray are common. The sandstone is light colored; pebbles of red, green, white, and black chert are characteristic of the conglomeratic parts. The Brushy Basin was deposited in a mixed lacustrine and fluvial environment. It ranges from about 90 to 120 m in thickness in the Moab quadrangle.

URANIUM AND VANADIUM DEPOSITS

Uranium and vanadium deposits in sandstone are numerous and widespread in the Moab quadrangle. These deposits have yielded about 17 million t (metric tons) of ore, and they contain known reserves (minable under conditions prevailing in 1971-72) that total about 4.2 million t of ore. Almost all of the ore has come from tabular deposits that are nearly concordant to the bedding of the host sandstone; the term "peneconcordant" has been applied to this type of deposit (Finch, 1959). A little ore has come from vein deposits along fractures in sandstone and limestone. All of the known reserves are in peneconcordant deposits. The Salt Wash Member of the Morrison Formation is host to about 57 percent of the known ore (production plus reserves), the Chinle Formation about 39 percent, and the Cutler Formation about 3.6 percent. The Brushy Basin Member of the Morrison Formation, the Entrada Sandstone, the Wingate Sandstone, and the upper member of the Hermosa Formation are host to some small deposits that collectively represent a fraction of one percent of the total known ore.

The ore minerals below the zone of oxidation are low-valent oxides and silicates of uranium and vanadium: uraninite [UO_{2+}], coffinite [$U(SiO_4)_{1-x}(OH)_{4x}$], montroseite [$VO(OH)$] or paramontroseite, and vanadium-bearing mica, chlorite, and clay. The common copper sulfides are widespread in sparse amounts and conspicuous in a few places. Accessory minerals are mainly sulfides; pyrite and marcasite are common but not abundant, and trace amounts of galena and sphalerite are widespread. Minerals containing molybdenum, selenium, chromium, nickel, cobalt, and silver are also present; only in a few places are some of these minerals abundant enough to be recognized. Introduced gangue minerals other than those that commonly cement sandstone are inconspicuous or absent.

The vanadium silicates are virtually stable in the zone of oxidation, but montroseite and the two primary uranium minerals oxidize readily, and the contained metals are converted to a soluble higher valent state. Where sufficient vanadium is available, however, uranium is fixed almost in place as carnotite [$K_2(UO_2)_2V_2O_5 \cdot 3H_2O$] or tyuyamunite [$Ca(UO_2)_2V_2O_5 \cdot 5\text{-}8\frac{1}{2}H_2O$], both of which are quite stable in the zone of oxidation. Hence, in the vanadium-rich deposits, the mineralogy in the zone of oxidation is simple, and there has been little or no migration of either uranium or vanadium to cause enrichment or impoverishment of the deposit at and near the surface. On the other hand, in deposits that are low in vanadium, either the uranium is mobilized or it forms a variety of secondary minerals. Some of these secondary minerals are not very stable themselves, and migration of uranium may have impoverished parts of some deposits near the outcrop, perhaps with some secondary enrichment at some place behind the outcrop.

The ore minerals mainly coat the sand grains, partly filling the pore spaces of the sandstone; however, in places they replace the sand grains, and interstitial clay and the original calcite cement of the sandstone, and some of the coalified plant remains. The ore minerals are epigenetic, and they form orebodies that are crudely tabular or lenticular and nearly concordant to bedding but do not follow beds in detail. These bodies range from 0.3 m to several meters in thickness and average about 1 m thick; they range from bodies only 1 or 2 m across, which contain only a few tons of ore-bearing rock, to those that are many tens of meters across and contain many thousands of tons of ore. The orebodies are irregular in plan but tend to be elongate, generally parallel to the long axes of the host lenses. The grade of the ore varies considerably from place to place within an orebody, but the ore is mixed during mining and the product is rather uniform in grade and averages a few tenths of 1 percent U_3O_8; orebodies in the Morrison Formation commonly average about 1.5 percent V_2O_5, whereas those in the Chinle Formation contain only a few tenths of 1 percent or less V_2O_5. Characteristically, orebodies have well-defined edges, and the grade drops within a few inches at the edges; large halos of low-grade material are not common, although thin layers of ore-grade material are much more extensive than minable ore.

The uranium deposits in the Moab quadrangle are restricted to places where the enclosing rocks retain characteristics indicative of reduction in contrast to the absence of such characteristics in the surrounding rocks; these reduced rocks are generally referred to as "altered." The altered rock extends a few hundred meters laterally and up to several meters vertically from ore deposits. Altered sandstone below the zone of surface oxidation is light gray to buff and contains sparsely disseminated pyrite; recent oxidation of this pyrite imparts a yellowish cast to the altered sandstone at and near the surface. In contrast, unaltered sandstone is pale red to red, both above and below the zone of oxidation. Mudstone associated with the near surface altered sandstone is gray or green, whereas the unaltered mudstone is dominantly red; the altered mudstone contains disseminated pyrite below the zone of oxidation. These altered halos are a useful guide in exploration, as they indicate ground favorable for uranium deposits and offer a larger target for subsurface exploration than do the deposits themselves.

Stratigraphic, lithologic, and sedimentary structural factors are significant in the localization of many of the uranium and vanadium deposits in the Moab quadrangle: (1) The known deposits in the Chinle are all in the basal sandstone beds, and most of those in the Morrison are in the uppermost sandstone unit of the Salt Wash Member. (2) Almost all deposits are in permeable sandstone beds, and almost all except those in the Entrada Sandstone at Placerville contain coalified plant fossils. (3) Many deposits, especially those in the Morrison, are in the thicker central parts of sandstone lenses and are elongate parallel to the courses of the streams that deposited these lenses. In contrast, igneous activity, hydrothermal mineralization, and tectonic structures show no similarly consistent influence on localization.

The time of ore deposition is not definitely established, but it seems likely that the deposits are of Mesozoic age; perhaps the deposits in the Chinle formed during the middle of the era and those in the Morrison during the late part. Geologic field relations indicate a pre-Laramide age; the folds and faults of Laramide and Tertiary age show no obvious influence on the distribution and localization of the deposits, and all of the faults that cut the deposits displace the ore layers. Isotopic data permit interpretation of ages of ore emplacement that include Cenozoic as well as Mesozoic times. On the basis of their latest studies, however, Miller and Kulp (1963) suggest that the deposits in the Chinle in the Lisbon Valley area probably formed about 210 million years ago (during the late Triassic) and that those in the Morrison in the Uravan area probably formed about 110 million years ago (during the Early Cretaceous).

Various theories have been proposed to explain the origin of the peneconcordant uranium and vanadium deposits of the Colorado Plateau region. The concept currently favored by geologists assumes that the mineralizing solutions were ground waters that leached trace amounts of metals from the ore-bearing beds and associated strata and transported these metals in their high-valent states to places where they were precipitated by reduction; carbonaceous material or hydrogen sulfide formed by anaerobic bacteria are assumed to be the most likely reducing agents (Hostetler and Garrels, 1962; Motica, 1968; Wood, 1968). Ore formation could have occurred whenever and wherever these geochemical processes were operative; the movement of solutions and bacterial activity may have been greater before deep burial of the ore-bearing beds.

RESOURCE APPRAISAL

Many uranium deposits, some with significant amounts of vanadium, occur in the Moab quadrangle (fig. 2). Much of the area has been intensively prospected by surface-exploration methods, and probably all or nearly all of the deposits that crop out have been found. There has been moderate to intensive subsurface exploration in the vicinity of the deposits that crop out, and many buried deposits have been found. Continued subsurface exploration in the vicinity of the known deposits will find other buried deposits, but probably only a moderate amount of ore remains to be discovered near known deposits. On the other hand, there is much unexplored and partially explored ground farther away that could contain undiscovered ore deposits in the Moab quadrangle; attention from the standpoint of resource appraisal and suggestions for prospecting is focused mainly on this ground. Our resource appraisal and suggestions for prospecting are based on our understanding of the habits, distribution, and localization of the known deposits. The resources included in our appraisal are hypothetical resources as defined by Pratt and Brobst (1974, p. 2) in that they consist of material in undiscovered deposits like the numerous identified deposits in the same general area and geologic setting. The data about ore produced and in reserve were obtained from records made available by the U.S. Atomic Energy Commission.

About 96 percent of the known ore (production plus reserves) is in the Chinle and Morrison Formations, and the resource potential of only these formations will be discussed in detail. Undiscovered deposits undoubtedly occur in other

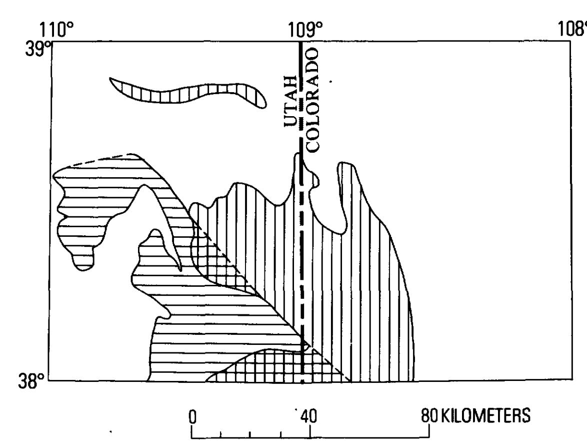


FIGURE 2. — Outline map of the Moab 1x2-degree quadrangle showing generalized areas within which deposits occur in the Chinle Formation (horizontal lines) and Morrison Formation (vertical lines).

stratigraphic units in the area, but with the possible exception of the Cutler Formation, the undiscovered deposits in these units are judged to be too small and widely scattered to justify intensive search for them. In recent years a few significant deposits have been found in the Cutler Formation. They are a short distance southwest of and downdip from deposits in the Chinle in the central part of the Big Indian mineral belt, Lisbon Valley area, Utah (fig. 4). It is possible that other deposits occur in the Cutler on the downdip side of this mineral belt, but we cannot adequately appraise this possibility without more knowledge of the known deposits in the Cutler. The known deposits in the Cutler are shown in figure 3. A few known deposits in formations other than the Cutler, Chinle, and Morrison in the Moab quadrangle are shown on a map by Williams (1964, sheet 2).

DEPOSITS IN THE CHINLE FORMATION

The Chinle Formation is the principal host to deposits in the southwestern part of the Moab quadrangle (fig. 3). The formation is present in most places in the rest of the quadrangle, but it is not known to be ore-bearing, and it generally lacks beds that are lithologically favorable for uranium deposits.

About 31,100,000 kg of U_3O_8 in 8,420,000 t of ore had been found in the Chinle Formation in the southwest part of the quadrangle by mid-1971. A large part of this, about 25,240,000 kg of U_3O_8 in 6,920,000 t of ore, had been mined by that time. Reserves as of July 1, 1971, amounted to about 5,900,000 kg of U_3O_8 in 1,500,000 t of ore.

MOSS BACK MEMBER

The bulk of the known deposits in the Chinle are in the Moss Back Member, which is the basal member of the Chinle in the southwestern part of the quadrangle. The Moss Back is a unit of varied lithology. Known deposits in the Moss Back are restricted to a northwest-trending zone 16-32 km wide (fig. 3) that borders the northeastern depositional edge of the Moss Back; the Moss Back in this ore-bearing zone is thinner and more lenticular than it is to the southwest, where the unit is apparently barren (Johnson and Thordarson, 1966). Almost all of the deposits in the Moss Back are in the basal sandstone beds; the deposits are tabular layers that lie nearly parallel to the bedding, but are not restricted by the bedding, and they show little or no preference for sandstone of a particular composition.

Highly productive deposits that have yielded uranium worth nearly $500 million have been mined from the Moss Back in the Big Indian mineral belt in the Lisbon Valley area (Wood, 1968). These deposits represent nearly 98 percent of the known resources in the Chinle within the quadrangle. If this group of deposits is unique to the Moss Back in the quadrangle, undiscovered resources in this member are probably small, and further intensive exploration of these beds would not be justifiable. If, on the other hand, undiscovered deposits similar to those in the Big Indian belt are present, substantial undiscovered resources would exist, and if target areas of ground geologically favorable for them can be selected, deep exploration for them would be justified. If such deposits are present, they probably were localized in geologic conditions similar to those in the belt. Although the geologic relations that localized the belt are not definitely recognized, some ideas of possible significance are discussed below. It is hoped that these ideas will help select target areas for fruitful exploration.

The Big Indian mineral belt is about 0.8 km wide and 24 km long. It is on the southwest flank of the Lisbon Valley anticline, and it trends virtually parallel to the structure contours on the base of the Chinle along this flank (fig. 4). The lower beds of the Chinle and the upper part of the underlying Cutler Formation have been altered ("bleached") by reduction along the mineral belt (Wood, 1968, p. 779). Miller and Kulp (1963, p. 627) suggested a Triassic age (about 210 million years) for these deposits, on the basis of isotopic age data. Wood (1968) suggested that the uranium was derived by ground waters from the volcanic ash in the beds in the upper part of the Chinle and it was moved by downward percolation into the permeable Moss Back beds, where the ore minerals were precipitated by reduction. He suggested that the leaching, movement, and precipitation began during diagenesis of the Chinle beds and continued during the deposition of the later Traissic and Jurassic beds, but that they ended prior to Laramide deformation. These relations and ideas are compatible with the geologic history of the anticline, and they permit optimism that similar deposits occur in Moss Back beds in other places where geologic relations are similar in the Moab quadrangle.

The Lisbon Valley anticline is one of several northwest-trending anticlines in this part of the Colorado Plateau region (fig. 1). All were arched by the upwelling of salt and gypsum in the Hermosa Formation. This upwelling occurred in two major stages, the first during the late Paleozoic and the second during Laramide time or later. Relative quiescence prevailed during the Mesozoic Era, although minor upwelling and arching occurred occasionally. The ancestral (late Paleozoic) Lisbon Valley anticline probably was a rather symmetrical structure that was truncated by erosion before Chinle time. It probably was completely covered by the Moss Back and overlying parts of the Chinle, but small variations in the thickness of these beds on the southwest flank of the present anticline suggest that minor uplift of parts of the anticline might have occurred during Chinle sedimentation. The anticline and Chinle beds were then covered by about 2,400 m of younger Mesozoic sedimentary rocks. During deformation in Laramide time, or later, the anticline was broken by an axial fault of about 900 m of displacement; the southwest flank was tilted to its present attitude, but the northeast flank was relatively undisturbed. Regional uplift and subsequent erosion has

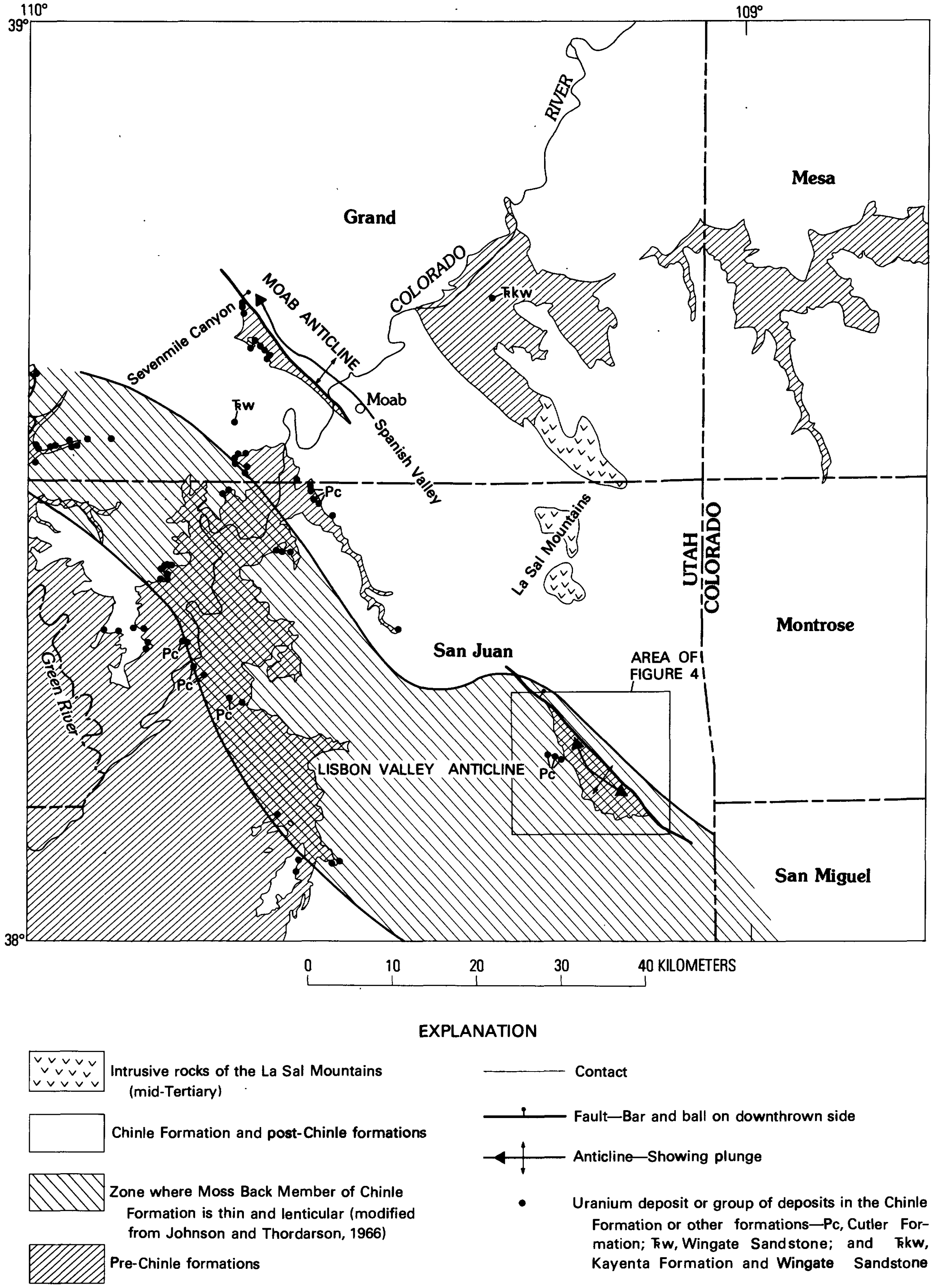


FIGURE 3. — Simplified geologic map of the western two-thirds of the Moab 1x2-degree quadrangle showing uranium deposits in the Chinle Formation, except those in Lisbon Valley, and in some other formations as indicated by letter symbol. Only those faults mentioned in text are shown.

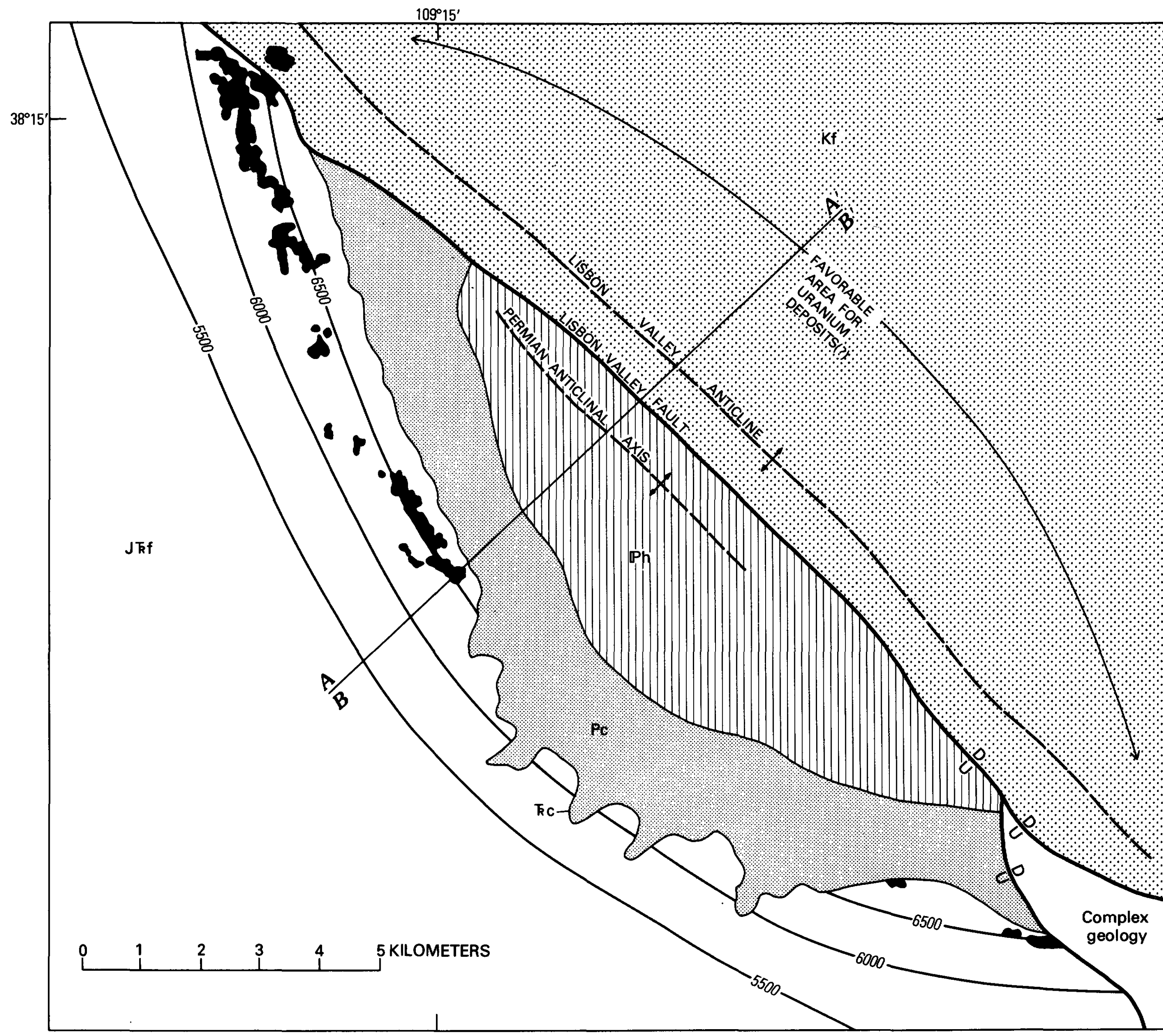
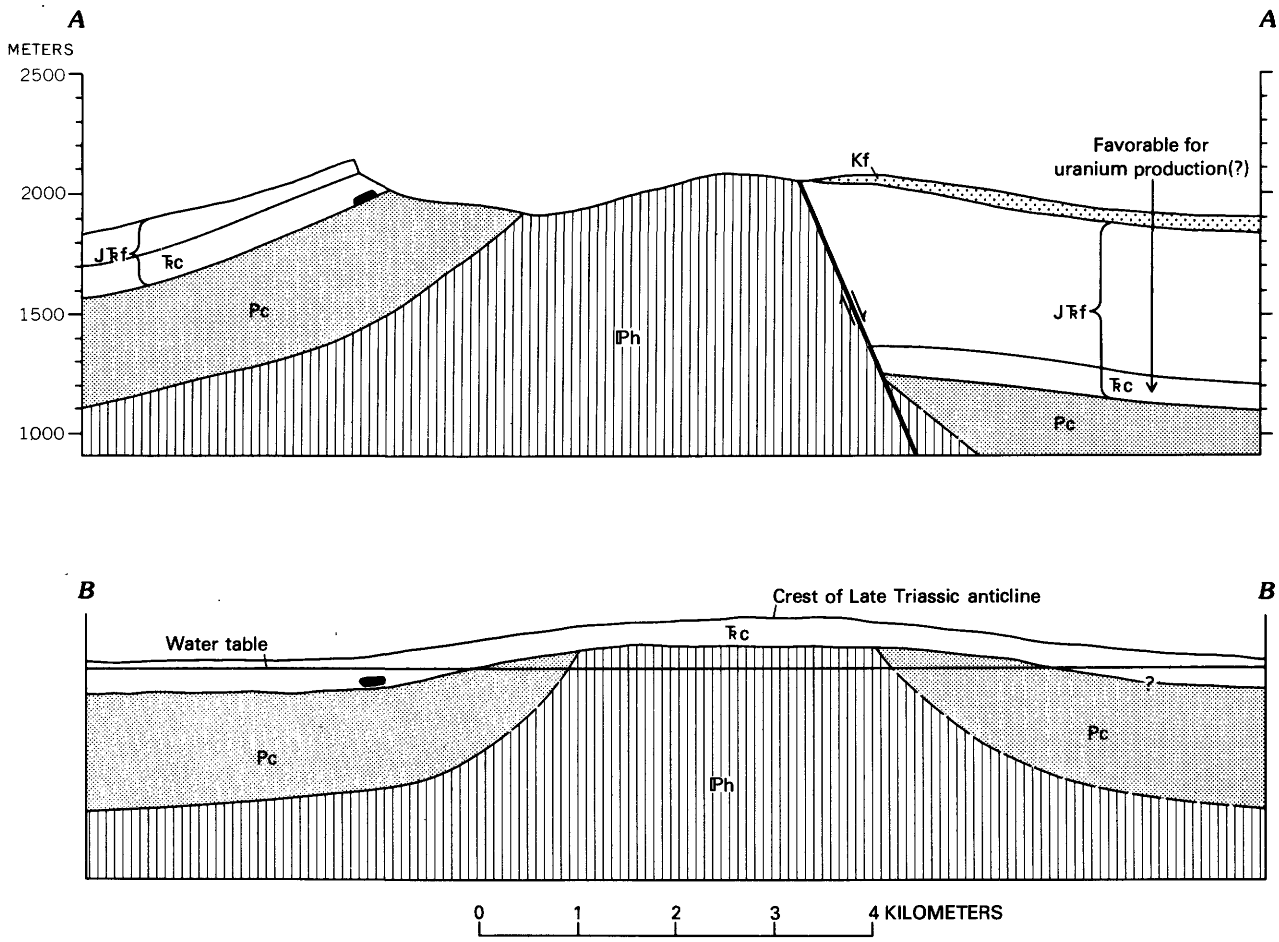


FIGURE 4. — Simplified geologic map of the Lisbon Valley area, Utah (modified from Wood, 1968), showing uranium deposits (black) of the Big Indian mineral belt projected vertically to surface, and structure contours in feet (1,000 feet equals 305 m) on the base of the Chinle Formation on the southwest side of the anticline. Section *A-A′* shows present geologic relations; section *B-B′* shows hypothetical relations during Late Triassic time. **Kf**, mostly Cretaceous formations; **JTRf**, Jurassic and Triassic formations; **TRc**, Chinle Formation; **Pc**, Permian Cutler Formation; (?)**IPh**, Pennsylvanian Hermosa Formation. U, upthrown block; D, downthrown block. Arrows indicate relative movement of fault blocks.

exposed the Chinle on the southwest flank of the anticline, but these beds are about 760 m below the present surface on the northeast flank (fig. 4, section *A-A′*).

The localization of the Big Indian mineral belt can be explained if a minor upward movement of the salt and gypsum during Chinle time is assumed. Ground water seeping downward along the crest of the anticline could have leached uranium from the upper Chinle beds and moved it downward along the Moss Back to a favorable reducing environment, probably somewhere below the water table (fig. 4, section *B-B′*). This flow of ground water may have continued for a while after Chinle time.

From a practical standpoint, the model shown on figure 4, section *B-B′*, suggests that the northeast flank of the anticline is also favorable for uranium deposits, provided that lithologically favorable host beds were deposited there by Moss Back streams. In recent years, exploration near the northwest end of the northeast flank of the anticline has found enough ore in the Moss Back to justify sinking two shafts, each about 760 m deep. Whether the ore deposits



being mined from these shafts are a downfaulted northerly extension of the Big Indian mineral belt or the northerly end of a belt on the northeast flank of the anticline cannot be determined at the present stage of exploration and development. But the presence of these deposits, and the geologic rationale presented above, would seem to offer justification for exploration drilling on the northeast flank of the anticline. Actually, some exploratory drilling has been done on this flank, and is reported to have shown mineralized rock and sandstone beds resembling those that are ore-bearing in the Big Indian mineral belt. Although this exploration has not resulted in an announced discovery of an exploitable deposit that might confirm the existence of a belt of deposits on the northeast side of the anticline, it is possible that not enough drilling has been done to negate the possibility of a mineral belt. Should such a belt exist, resources in the Moss Back on the northeast side of this anticline might be as significant as those on the southwest side, which contained about 25,000 t U_3O_8.

The Dolores anticline extends from the Lisbon Valley anticline southeastward beyond the southern edge of the Moab quadrangle (fig. 1). The Dolores anticline, like the Lisbon Valley anticline, has a thickened core of salt and gypsum, but these evaporites probably did not penetrate the overlying beds and the crest of the anticline has not been breached to expose the evaporites (Shawe, 1970). There is no definite evidence of upwelling of salt and gypsum along the Dolores anticline during Chinle time or immediately afterward, which might have arched the Chinle over the anticline, as was suggested in the case of the Lisbon Valley anticline. Nevertheless, some other units of Mesozoic age are thicker in the adjoining Disappointment syncline, northeast of the Dolores anticline, than they are over the anticline, suggesting that some flowage of evaporites recurred at times during the Mesozoic (Shawe, 1970, p. C7). Perhaps during Chinle time and shortly afterwards ground-water flow in the Chinle beds over the Dolores anticline was similar to that suggested in the Chinle beds over the Lisbon Valley anticline; if favorable host beds are present, deposits similar to those in the Big Indian mineral belt might have formed.

Where the Moss Back is exposed in the Dolores River canyon south of Slick Rock, it is composed of gray limy arkosic and quartzose sandstone, which is in part conglomeratic, with some gray and reddish mudstone. Coalified and silicified plant fossiles are locally abundant in the sandstone and mudstone. Beds of similar lithology were cut in drill holes in Summit Canyon (Shawe and others, 1968, p. A28 and pls. 2 and 4). The lithology of these beds is reasonably favorable for uranium deposits. Three small deposits are exposed in the Moss Back in the Dolores River canyon, and anomalous radioactivity was detected at other places in these beds along the river and in some drill holes in Summit Canyon (Shawe and others, 1968, p. A29).

Without more information, the uranium resources of the Moss Back beds along the Dolores anticline cannot be appraised accurately; they could range from insignificant to the same order of magnitude as those along the Lisbon Valley anticline (about 29,000 t of U_3O_8). These beds on the flanks of the Dolores anticline, however, are judged to be reasonably favorable exploration targets. Any exploratory drilling should be done with an initial pattern of holes spaced 300 m to 1,000 m apart, and they should have the principal objective of obtaining geologic information, such as determining if altered beds of favorable lithologic characteristics are present. If favorable ground is found, closer spaced drilling to seek ore deposits should be justifiable.

About three dozen deposits have been found along 460 km of outcrop of the Moss Back along the Colorado and Green Rivers and their tributaries west and south of Moab (fig. 3), an area of about 1,300 km^2. Most of these deposits are small, but five of them are of medium size. These five deposits contained at least 45,000 kg or U_3O_8 each, and collectively account for 95 percent of the total 350,000 kg of U_3O_8 in the three dozen deposits. If it is assumed that the outcrop exposes a true sample of deposits by size and distribution, and this assumption is judged to be reasonable, the calculated total U_3O_8 in deposits in the 1,300-km^2 area amounts to about 5,300 t. If most of this U_3O_8 is in deposits that contain about 45,000 kg each, the average incidence of such deposits would be about 1 in every 16 km^2. Exploration to find such deposits in the Moss Back, which lies at depths of 240-365 m in most of the area, would be so costly that the estimated amount of uranium in them could be considered an economically viable resource only if the likely positions of the deposits could be more closely defined than is possible with information now available.

UNDIFFERENTIATED CHINLE

Lenses of gray siltstone, limestone-pebble conglomerate, and quartz-pebble conglomerate are host to several uranium deposits in or near Sevenmile Canyon northwest of Moab (Finch, 1954). These beds are interpreted to be at the base of the undifferentiated part of the Chinle and to be stratigraphically higher than the Moss Back (Stewart and others, 1959, figs. 77 and 81). The deposits are on the southwest flank of the Moab anticline near its northwestern end. This structure, like the Lisbon Valley anticline, is a salt anticline that was broken by an axial fault of large displacement, and the southwest flank was uplifted relative to the northeast flank. These deposits occupy about the same position on the Moab anticline as does the northwest part of the Big Indian mineral belt on the Lisbon Valley anticline. By analogy, the deposits in the Sevenmile Canyon area might be part of a mineral belt similar to the Big Indian mineral belt. The likely projection of this hypothetical belt, however, is not exposed, and it has not been tested by subsurface exploration because the basal beds of the Chinle are deeply buried and the topography is so rough that access by drill rigs would be difficult. Nevertheless, exploration to test the basal beds of the Chinle might be fruitful along the southwest flank of the Moab anticline, and even farther southeast along the southwest flank of the structures bordering Spanish Valley on the southwest.

The axial length of the Moab anticline is about the same as that of the Lisbon Valley anticline, but the presently known deposits are confined to about the northwest one-fifth of the southwest flank. The average size of deposits in the Moab anticline area is only one-twentieth that of the average deposit in the Lisbon Valley area. Thus, although the southwest flank of the Moab anticline is very incompletely explored and although the extent of host rocks that might be favorable for deposits is only approximately delineated, it is unlikely that resources along that flank would be more than 5 percent of the resources on the southwest side of the Lisbon Valley anticline.

The distance between the southeast end of the Moab anticline and the northwest end of the Lisbon Valley anticline is about twice the length of the latter. The Chinle is largely concealed throughout this distance. Direct evidence about the characteristics of rocks near the base is lacking, but Johnson and Thordarson (1966, pl. 1) imply that the Moss Back Member, which is host to the Lisbon Valley deposits, pinches out only about 8 km northwest of the Lisbon Valley deposits.

If Johnson and Thordarson are correct, beds low in the Chinle that are favorable for deposits may be confined, as indicated on their map (1966, pl. 1), to a relatively narrow strip on the southwest flank of the structures on the southwest side of Spanish Valley. If so, resources between the northwest end of the Lisbon Valley anticline and the Colorado River are probably no more, and may be much less, than on the southwest flank of the Moab anticline.

Estimates of resources of U_3O_8 in the Chinle Formation are summarized in table 2.

Information about vanadium content of deposits in the Chinle is too incomplete to warrant more than a general estimate for the Chinle as a whole. To judge from incomplete data about vanadium produced from deposits in the Lisbon Valley (Wood, 1968, p. 776), resources of V_2O_5 are probably not more than two-thirds those of U_3O_8.

DEPOSITS IN THE MORRISON FORMATION

The Morrison Formation is the principal host to deposits in the central and northwestern part of the Moab quadrangle

TABLE 2.—*Resources of uranium in the Chinle Formation in the Moab quadrangle, Utah-Colorado*

[Reserves compiled from data made available by Grand Junction office, ERDA (formerly U.S. Atomic Energy Commission). Neg., negligible]

Area	Reserves as of July 1, 1971 (metric tons)		Estimated (hypothetical) resources (metric tons)			
	Ore	U_3O_8	Ore		U_3O_8	
			minimum	maximum	minimum	maximum
Moss Back Member						
Lisbon Valley anticline	1,491,000	5,853	360,000	4,500,000	900	18,000
Dolores anticline	0	0	Neg.	7,200,000	Neg.	27,000
Area tributary to Colorado and Green Rivers.	8,378	23	[1]1,800,000		[1]5,000	
Undifferentiated Chinle						
Moab anticline	([2])	([2])	[1]450,000		[1]1,360	
Southwest side of Spanish Valley.	0	0	Neg.	450,000	Neg.	1,360
Total (rounded for resources)	1,499,378	5,876	1,700,000	[1]13,500,000	7,300	53,000

[1]Where only one number is given for a particular area that quantity is included in the sum of both the maximum and minimum columns. See text discussion of individual areas for explanation of range in estimate for some areas.

[2]Included with area tributary to Colorado and Green Rivers to avoid disclosing information about individual properties.

(fig. 2). The formation has been eroded from much of the western part of the quadrangle. Although it is present in much of the eastern part, no deposits are known and the formation is judged to be unfavorable for deposits there. Most of the deposits in the Morrison are in sandstone in the uppermost part of the Salt Wash Member. A moderate number of deposits, most of them small but a few of medium size, occur in sandstone beds lower in the Salt Wash; deposits at this stratigraphic position are more abundant in the Bull Canyon and the Carpenter Ridge-Martin Mesa areas, Colorado, and the Thompson area, Utah, than elsewhere. Several deposits occur in sandstone lenses in the Brushy Basin Member; they are widely scattered and although most are small, a few are of medium size.

The uranium-vanadium deposits in the uppermost sandstone of the Salt Wash Member tend to be clustered in ill-defined patches of ground (fig. 5). These patches range from several hundred meters to several kilometers; they are irregular in shape but they tend to be elongate parallel to the long axes of the host sandstone lenses. The sandstone and associated mudstone layers in these patches have certain geologic characteristics that are rather consistently associated with ore deposits; for that reason these characteristics are thought to be indicative of favorable ground and collectively are useful guides in exploration and resource appraisal. These characteristics are as follow:

(1) The sandstone is generally about 12 m or more thick.
(2) Below the zone of surface oxidation the sandstone is light gray to buff in color and contains sparse and finely disseminated pyrite and in the zone of oxidation it has a yellowish cast, in contrast to a light pink or pale red color in unfavorable ground in both zones.
(3) The mudstone that occurs as thin layers or pebbles in the sandstone and the mudstone in contact with the bottom or top surfaces of the sandstone is altered to gray or green, in contrast to a red color in unaltered mudstone; the altered mudstone contains finely disseminated pyrite below the zone of oxidation.
(4) The sandstone contains more coalified fossil wood in and near ore deposits than remote from deposits.

Weir (1952) has suggested a scheme of numerical evaluation of these geologic guides as they can be recognized in drill holes.

By the middle of 1971 nearly 12,200,000 t of ore containing almost 31,500 t of U_3O_8 had been found in the Salt Wash Member of the Morrison Formation within the Moab quadrangle. About 80 percent of the ore found had been mined and the remaining 20 percent was in reserves considered by the Atomic Energy Commission to be minable at $8 per pound of U_3O_8. The areas that are comprised by the Uravan mineral belt (fig. 5) and ground in Colorado immediately adjoining the belt account for about 90 percent of the ore produced.

The U_3O_8 contained in ore was apportioned among deposits of a wide range in size as shown in the tabulation below. The table includes deposits in the extreme southwestern part of the Uravan mineral belt, which extends into the adjoining Cortez quadrangle, and therefore the total of the amounts entered in the table is larger than the amount given above for the Moab quadrangle. Distribution of U_3O_8 by size ranges of deposits in the Salt Wash Member of the Morrison Formation, based on production to July 1, 1971, and reserves, mostly of that data are tabulated below.[1]

[1]Compiled primarily from information supplied by the Grand Junction Office, ERDA (formerly U.S. Atomic Energy Commission); supplemented in some areas by field inspection and estimates adapted from published data.

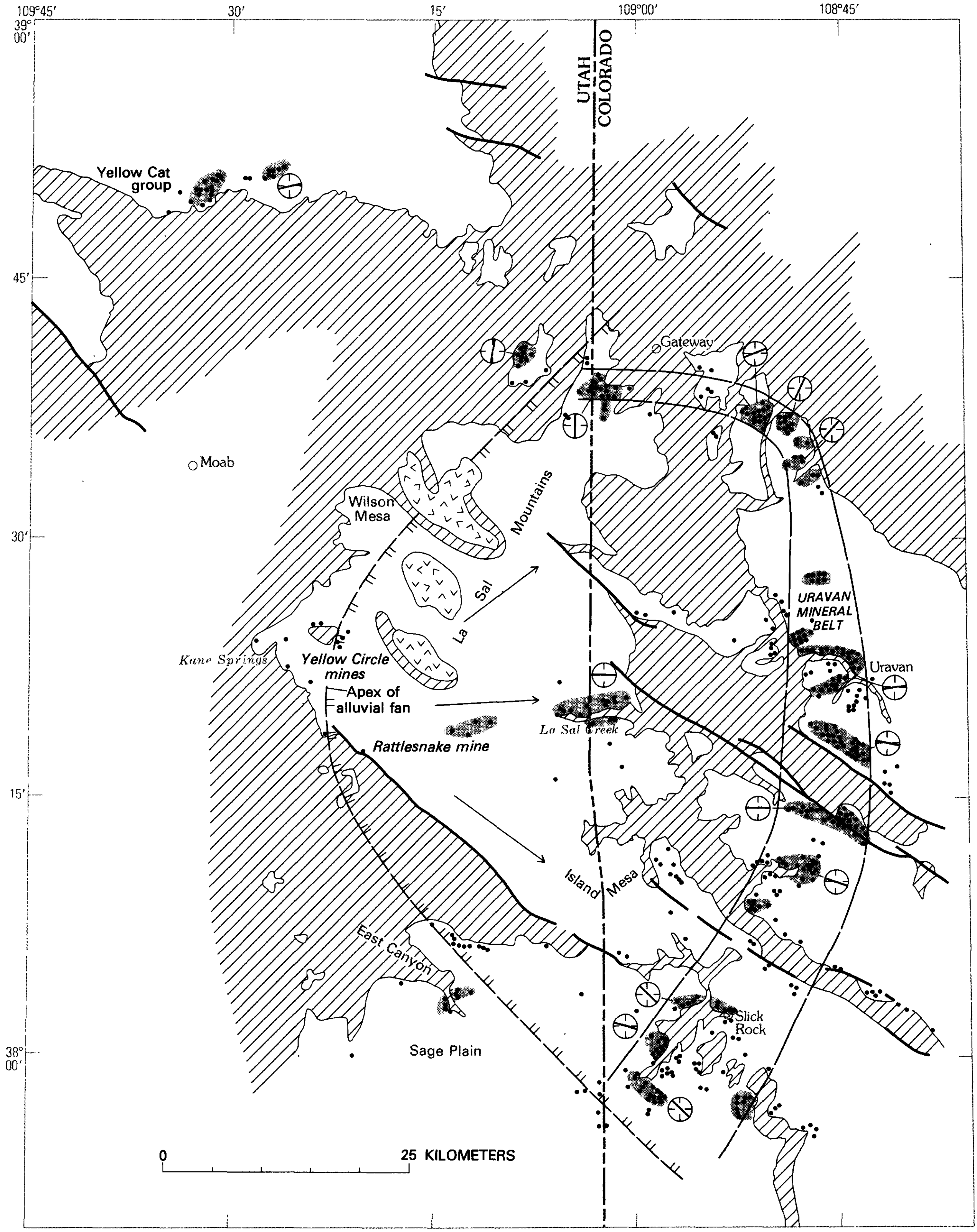


FIGURE 5. — Simplified geologic map of the central part of the Moab 1x2-degree quadrangle showing uranium-vanadium deposits in the Morrison Formation and the significant geologic relations of these deposits.

EXPLANATION

Intrusive rocks of the La Sal Mountains (mid-Tertiary)

Morrison Formation and post-Morrison formations

Base of Morrison Formation and borders of intrusive rocks—Dashed where covered

Pre-Morrison formations

Fault—Dashed where covered

Significant uranium deposit or group of deposits

Approximate area of ground favorable for uranium deposits

Edge of alluvial fan and area of subsidence

General direction of flow of Salt Wash distributary streams in area of fan

Dominant trend of ore rolls, fossil logs, and sedimentary structures

Size range (pounds U_3O_8)	No. of Deposits	Contained U_3O_8	
		Total pounds	Percent of total
0-200	322	22,478	0.027
200-2,000	282	235,969	.28
2,000-20,000	317	2,562,569	3.05
20,000-200,000	309	22,001,658	26.2
200,000-2,000,000	85	45,127,918	53.7
More than 2,000,000	5	14,154,675	16.8
Totals	1319	84,105,267	100.037

As can be seen from the table, nearly 97 percent of the uranium contained in known deposits in the Salt Wash is in the larger deposits, those that contain at least 20,000 pounds (9.1 t) of U_3O_8 each, and 70 percent of the total uranium is in deposits that contain at least 200,000 pounds (91 t) each. In view of the rather wide distribution of deposits, as shown in figure 5, and because the size-range distribution of known deposits in each of the principal areas of their occurrence is fairly similar to the distribution of all deposits, as shown in the table, it is likely that undiscovered deposits are apportioned among the size intervals in about the same proportions as the known deposits.

Several areas potentially favorable for significant resources in the Morrison will now be discussed.

URAVAN MINERAL BELT

Uravan mineral belt is the name applied to a narrow, elongate area in southwestern Colorado in which the uranium-vanadium deposits in the Morrison Formation generally are closer spaced, larger in size, and higher in grade than those in adjoining areas (Fischer and Hilpert, 1952). The belt extends from Gateway through Uravan to Slick Rock, a distance of about 115 km (fig. 5). The patches of favorable ground in which the deposits occur, the orebodies themselves, and the so-called ore rolls — small, podlike bodies of ore — tend to be elongate normal to the trend of the belt. In addition, sedimentary structures in the host rock, such as current-lineation marks and the dip of crossbedding planes and fossil logs, which were rafted into place, are generally oriented normal to the belt. The belt crosses tectonic structures which show little or no apparent localizing influence on the belt; some deposits, however, lie outside the general limits of the belt near fault zones in Gypsum Valley and southeast of Slick Rock.

The area of the mineral belt probably was made especially favorable for ore by geologic conditions extant during the accumulation of the Salt Wash Member of the Morrison. The favorable host rocks are sandstone lenses that were formed by streams. The trend of these lenses perpendicular to the arcuate mineral belt (fig. 5) resembles the pattern of ribs of a fan, the apex of which would be a vaguely defined point several tens of kilometers west of the belt. Shawe (1962, fig. 62.2) suggested that this pattern of sedimentary structure along the mineral belt resulted from deposition along the toe of a subsidiary fan locally superposed on the larger fan that formed the entire Salt Wash Member; perhaps this smaller fan formed in an area of shallow subsidence that developed during Salt Wash time, for the member is a little thicker in this area than in other places. A few miles east of the belt the host sandstone beds are finer grained and more thinly and evenly bedded, as if they were deposited in a shallow body of standing water. Immediately west of the belt, coalified fossil plants are not present in many of the Salt Wash sandstone lenses; either the plant material was never present, or it was destroyed after burial in the beds. Where deposits occur west of the belt, however, coalified fossil plants are present and probably were preserved by locally high water tables.

The observed relations and the hydrologic system that would likely develop in this geologic environment permit the following hypothesis regarding belt localization: The belt extended along the toe of an east-facing alluvial fan. Standing water persisted a short distance east of the belt; as a result, the water table along the belt was virtually at the surface while the host sandstone lenses accumulated, preventing destruction by oxidation of plant material buried in the sand. Because of the original sedimentary dip of the beds, a gravity flow of ground water in an easterly direction would have started during the accumulation of the Salt Wash sand lenses and probably would have been most active from then until the invasion of Mancos seas in the Late Cretaceous. The deposits probably formed from these ground waters in this interval.

Undiscovered resources in the part of the Uravan mineral belt within the Moab quadrangle as estimated by methods described in the section on methodologies are about 6,800 t of U_3O_8, contained in about 2,700,000 t of ore. Most of these resources are judged to be in deposits in and close to the patches of favorable ground that contain most of the known deposits (fig. 5). These undiscovered resources amount to only about 20 percent of the total resources originally present in the area of the belt.

LA SAL MOUNTAIN-ISLAND MESA AREA

The La Sal Mountain-Island Mesa area is west of the Uravan mineral belt and near its eastern side straddles the Utah-Colorado State line (fig. 5). It is roughly triangular in shape with its base along the irregular line of Morrison outcrops that extend from Island Mesa northward to a point about 16 km southwest of Gateway, and its apex is in the vicinity of Kane Springs. If the Uravan mineral belt lies along the toe of an alluvial fan, as suggested above, most of the La Sal Mountains-Island Mesa area would be on the mid-slope and apex parts of this fan; the Kane Springs-Wilson Mesa part of the area might be north and west of the fan (fig. 5).

Significant deposits have been found at and near the outcrop along La Sal Creek. These deposits are in an east-trending patch of favorable ground, similar to the favorable patches in the Uravan mineral belt. Presumably the host rock of the La Sal Creek deposits accumulated along one of the distributary streams that formed the supposed alluvial fan; the presence of coalified fossil wood in the ore indicates that at least locally the water table during accumulation of the host rock was high enough to prevent destruction of the plant fossils by oxidation.

A large deposit at the Rattlesnake mine has been exploited, and numerous deposits, mostly small but some of moderate size, have been found at and near the outcrops near the Yellow Circle mines (fig. 5). In addition, at least two large deposits have been found by subsurface exploration midway between the Rattlesnake mine and the deposits along La Sal Creek. It will not be known until exploration and mine development progresses farther whether these groups of deposits are all on a continuous favorable trend, as suggested by Johnson and Thordarson (1966), or in separate favorable patches that are approximately alined, because the Salt Wash does not crop out along this trend.

South of the trend between La Sal Creek and the Rattlesnake and Yellow Circle mines the Salt Wash is not exposed, except in the vicinity of Island Mesa, where some small- to medium-sized deposits occur, and along the line of outcrop from Island Mesa to La Sal Creek, where only a few small deposits are known. In the concealed Salt Wash of this area, however, there is room for one or more favorable patches or trends. If present, the favorable patches or trends are probably elongate in a southeasterly direction, more or less radial from the apex of the alluvial fan. This part of the La Sal Mountains-Island Mesa area could be tested for favorable ground with a pattern of drill holes 300 to 600 m apart.

The Salt Wash underlies a considerable part of the east, north, and northwest flanks of the La Sal Mountains. Much of this part of the area probably is also on the midslope of the Uravan mineral belt alluvial fan (fig. 5); therefore, this area might also contain some patches of favorable ground. Appraisal, however, is difficult. No deposits have been found in the Salt Wash high on the flanks of the mountains, where exposures, because of more soil and vegetation, are not as good as in other parts of the Moab quadrangle. Nevertheless, continued exploration by surface methods around the La Sal Mountains might find a few deposits or patches of ground lithologically favorable for ore, in which case subsurface exploration behind the outcrop might be rewarding; without these guides, subsurface exploration would be blind and probably not justifiable.

Undiscovered resources in the La Sal Mountains-Island Mesa area, as estimated in the manner described in the section on methodologies, are about 8,200 t of U_3O_8 in 2.7-3.2 million t of ore. Much of this, perhaps 75 percent, is judged to be in the central part of the area, extending from La Sal Creek on the east to Kane Springs on the west, including the ground between the Rattlesnake mine and the Yellow Circle mines (fig. 5). This area is about 337 km^2, and the known deposits at the two ends permit an estimate with moderate confidence that undiscovered resources are about 6,800 t of U_3O_8 in 2,300,000 t of ore. The moderately large deposits recently found in the middle of this area by subsurface exploration support this optimistic appraisal.

The southern part of the La Sal Mountains-Island Mesa area, roughly bounded by lines connecting the Rattlesnake mine, Island Mesa, and La Sal Creek, probably contains one or more favorable patches of ground, like those known in the La Sal Creek-Kane Springs trend. On this assumption, and by comparison with an adjoining area on the east described in the section on methodologies, resources of 900 t or more of U_3O_8 have been assigned to the southern part of the La Sal Mountains-Island Mesa area. The scant exposures of the Salt Wash in this part of the area do not permit appraisal with much confidence.

Appraisal of the ground on the east, north, and northwest flanks of the La Sal Mountains, where virtually no deposits have been found, is made with even less confidence; nevertheless, as explained in the section on methodologies, resources containing about 540 t of U_3O_8 are estimated for this part of the area.

SAGE PLAIN AREA

The Sage Plain area is along the southern edge of the Moab quadrangle, partly in Colorado but mostly in Utah. It is west of the Uravan mineral belt and probably southwest of the mineral belt fan. Exposures are limited to the northern edge of the area. These exposures have not been studied adequately to permit a sound interpretation of the geologic environment of deposition of the Morrison Formation relative to its mineral potential, even though numerous small- to medium-sized and a few large deposits have been found in the upper sandstone layer of the Salt Wash at and near its outcrops. A conspicuous, ore-bearing, northeast-trending sandstone lens is exposed on both sides of East Canyon (fig. 5), and two other ore-bearing northeast trends are suggested by Johnson and Thordarson (1966, pl. 1) nearby. These authors (1966, p. H46) also suggested that the northeast-flowing streams that deposited the host lenses in these ore-bearing trends were deflected southeastward by slightly higher ground over the ancestral Lisbon Valley salt anticline, and that these trends perhaps connect with the ore-bearing northwest-trending patches of ground in the Uravan mineral belt of Slick Rock (fig. 5). This relationship is possible, and perhaps likely, and it permits optimism that ground favorable for uranium deposits lies in the Sage Plain area and suggests the pattern and orientation of this favorable ground.

If the deposits that have been found at the outcrop along the northern edge of this area are a representative sample of the area, undiscovered resources in the area estimated by a method described in the section on methodologies, probably total about 2,000 t of U_3O_8 in about 1,200,000 t of ore. On the other hand, a few moderately large deposits have been found by subsurface exploration in the eastern part of the area near the Uravan mineral belt; if these deposits are more nearly representative of part or all of this area, resources could be somewhat larger.

THOMPSON AREA

In the Thompson area, Utah, the Morrison Formation crops out for about 50 km along a west-trending line from a point several kilometers west of the State line (fig. 5). Numerous deposits have been found along these outcrops. Except for some in the Yellow Cat group and in two other groups a short distance east of the Yellow Cat group, most of them are small. Almost all of these deposits are in the lowest sandstone in the Salt Wash Member of the Morrison, except in the vicinity of the principal groups, where some deposits are in sandstone beds higher in the Salt Wash and some are in sandstone in the basal part of the Brushy Basin Member. All of the larger deposits are in rather well-defined sandstone lenses that trend northeasterly or easterly. Favorable ground might continue northeast of the known deposits in the vicinity of the Yellow Cat group, but the Salt Wash is covered by an increasing thickness of younger beds in this direction, and any deposits present might not be large enough to justify the cost of deep exploration and development.

About 270,000 kg of U_3O_8 in 122,000 t of ore have been discovered in deposits in the Thompson area. These deposits are distributed in an area of about 39 km^2 underlain by the Morrison Formation that is estimated to be fully explored. The Morrison Formation becomes progressively deeper northward from the fully explored ground. Nevertheless, in an area of about 78 km^2 adjoining it on the north, along the general trend of the lenses of ore-bearing sandstone, the depth to the base of the formation is mostly less than 300 m and probably averages no more than 150 m. It is possible that undiscovered deposits in this unexplored area contain proportionately about as much uranium as in the fully explored area or about 540 t of U_3O_8 in 240,000 t of rock. If uranium is apportioned among undiscovered deposits as it is among those that have been discovered, about two-thirds of the estimated amount would be in those containing 9,070-90,700 kg.

SUMMARY OF RESOURCES IN THE SALT WASH MEMBER

Hypothetical resources of uranium and vanadium estimated to be present in undiscovered deposits in the Salt Wash Member of the Morrison within the area of the Moab quadrangle are about 18,000 t of U_3O_8 and 110,000 t of V_2O_5 contained in about 7,300,000 t of mineralized rock. The estimates for each area are summarized in table 3.

The resources listed in table 3 correspond approximately to material from which the U.S. Atomic Energy Commission

TABLE 3.—*Resources in the Salt Wash Member of the Morrison Formation in the Moab quadrangle, Utah-Colorado*

[Reserves complied from data made available by Grand Junction Office, ERDA (formerly U.S. Atomic Energy Commision). Reserves and resources of V_2O_5 calculated by using an average content of 1.5 percent as given in the text in the section "Uranium and vanadium deposits"]

Area	Reserves as of July 1, 1971 (metric tons)			Estimated (hypothetical) resources (metric tons)		
	Ore	U_3O_8	V_2O_5	Ore	U_3O_8	V_2O_5
Uravan mineral belt	2,053,500	5,790	30,800	2,700,00	6,800	41,000
La Sal Mountains-Island Mesa:						
Central part	105,600	299	1,590	2,450,000	6,700	36,000
South part				450,000	900	6,800
North part				240,000	590	3,600
Sage Plain	203,300	322	3,050	1,200,000	2,000	18,000
Thompson	19,300	57	290	240,000	540	3,600
Totals (rounded for resources).	2,381,700	6,468	35,730	7,300,000	17,500	109,000

estimated in 1971 that uranium could be recovered at forward costs of $8 per pound.

In addition to the resources discussed thus far, a relatively substantial amount of uranium oxide is present in leaner rock containing at least 0.02 percent U_3O_8. Most of this leaner rock is in the same deposits as and adjoins the richer rock composing those resources. Data about leaner rock obtained by the U.S. Geological Survey in the 1950's in exploring for deposits by drilling is somewhat scanty but suggest that, if all such leaner rock were included in the estimate of hypothetical resources, the amount of contained U_3O_8 would probably be from 25 to 50 percent, 4,500-9,000 t more than the amount in table 3. Similarly, the amount of V_2O_5 would be increased by 27,000-54,000 t.

SUMMARY OF RESOURCES

Undiscovered (hypothetical) resources in the Moab quadrangle are probably at least 22,700 t of U_3O_8, and may be a few times more than that; those of V_2O_5 are about 113,000 t. Most of the U_3O_8 resources are in the Chinle and Morrison Formations which are the hosts to the bulk of the resources already discovered, and most of the V_2O_5 resources are in the Morrison Formation. A small but indeterminate amount of U_3O_8 resources is probably present in the Cutler Formation. Like the discovered resources in the Cutler, it is probably only a fraction of the amount in the other two formations as mentioned earlier in the section "Uranium and vanadium deposits."

Undiscovered resources in the Chinle Formation could be about twice the 30,800 t of U_3O_8 already found in it, if the Dolores anticline and the northeast flank of the Lisbon Valley anticline should prove to be as favorable for deposits as the southwest flank of the Lisbon Valley anticline. Otherwise, undiscovered resources in the Chinle may be somewhat less than 9,000 t.

Resources in the Salt Wash Member of the Morrison Formation are estimated to be about 18,000 t of U_3O_8 and 109,000 t of V_2O_5. Approximately three-fourths of the totals are about evenly divided between the Uravan mineral belt and the central part of the La Sal Mountains-Island Mesa area. The other one-fourth is distributed unevenly among the other areas listed in table 3.

The resources of U_3O_8 summarized represent the amount in rock that would have constituted ore under conditions that prevailed in 1970-71. In addition, a substantial volume of mineralized rock adjacent to ore in most deposits contains at least 0.02 percent U_3O_8, but less than the 0.10 percent U_3O_8 cutoff grade for ore. Incomplete data about the amount of such leaner rock and its U_3O_8 content suggests that the estimates of resources given above would be larger by 25 to 50 percent if such leaner rock were included.

METHODOLOGIES

METHODS OF ESTIMATING RESOURCES IN THE SALT WASH MEMBER OF THE MORRISON FORMATION

Two basic methods were used to estimate the hypothetical resources in the Salt Wash Member of the Morrison Formation; each was applied in different parts of the Moab quadrangle, distinguished in figure 6. One method makes use of a factor derived by dividing the aggregate length of outcrop of exposed ore deposits in the Salt Wash by the total length Salt Wash outcrop in a given area. It is assumed that the outcrop is random relative to the distribution of deposits, and therefore, it serves as a slice exposing a representative sample of the deposits present in the area to which the outcrop is related. The length of ore-bearing outcrop relative to the total outcrop represents the percentage of ground underlain by ore behind the outcrop. Multiplying this factor by the measured size of an area yields an estimate of the number of square meters occupied by ore within the area. The volume of ore was calculated by applying an assumed average thickness of ore ranging from 0.5 to 0.6 m. A factor of 0.437 m^3/t was used to convert volume to tons of ore. As used in connection with this scheme, ore consists of a layer of mineralized rock at least 0.3 m thick containing at least 0.1 percent U_3O_8 or 1 percent V_2O_5 (Bush and Stager, 1956).

In the second method it is assumed that the tons of ore discovered (reserves plus production) per unit area in well-explored parts of a general area are indicative of the tons-per-unit-area in the adjoining sparsely explored parts of that area judged to be equally favorable for ore. The application of both of these methods in various areas will be described in the following paragraphs. The areas will be discussed in the same order as in the main text.

URAVAN MINERAL BELT

The first of the methods just described is particularly well adapted to estimating resources of the area in the general vicinity of the Uravan mineral belt where numerous deposits are exposed along many tens of kilometers of outcrop on the sides of canyons and valleys. The percentage of area underlain by ore was estimated individually by this method for all but two of the subareas related to the mineral belt. The percentages were determined indirectly for the other two, the Bull Canyon and Gypsum Valley areas (fig. 6).

By the mid-1950's, results of exploration and geologic study suggested that the incidence and sizes of deposits in the Bull Canyon area were probably at least intermediate between those characteristics of the East Gateway and Uravan segments. Thus, rather than assembling the detailed information that is the basis for estimating resources in other parts of the belt, it is assumed that the fraction of the area underlain by ore in this segment of the belt is the mean of the fractions of the Uravan and East Gateway areas as given in a subsequent list, weighted according to their respective areas.

Much of the Morrison Formation in the Gypsum Valley area is in structural blocks downfaulted as the result of collapse of a salt-cored anticline. Margins of many tracts underlain by the Morrison are faults along which it abuts against older rocks so that the edges of its component beds are not exposed to the extent that they are elsewhere in the mineral belt. This lack of continuity for the outcropping edge of the ore-bearing interval precludes determing the fractional length of the outcrop that is ore-bearing, as an index of the adjoining area that may be ore-bearing. Hence the simple method based on the mineralized fraction of total outcrop cannot be used to estimate resources for this area. Instead, that method was used indirectly, by comparing the Gypsum Valley area with the East Gateway area, as follows:

1. We believe that in 1954 both areas had been explored to approximately the same extent and that the ratio of ore in known deposits (including production) to that in undiscovered deposits, and hence to total resources, was about the same for the Gypsum Valley area as it was for the East Gateway area.
2. Strobell and others (1954) and C. G. Gilbert (U.S. Geological Survey, written commun., 1954) used results of mine mapping and drilling to estimate the percentage of each total area that was then known to be ore-bearing. According to these estimates, the percentage of the Gypsum Valley area known to be ore-bearing was only about one-third of the percentage of the East Gateway area known to be ore-bearing; that is, the Gypsum Valley area was mineralized only about one-third as much, per unit area, as the East Gateway area.
3. On the assumption that this ratio of one-third, derived from known mineralization, also applies to total mineralization in the two areas, it follows that the total percentage of the Gypsum Valley area underlain by ore (that is, production + reserves + undiscovered resources) is 0.20 or about one-third of the percentage of the East Gateway area underlain by ore.

The percent of each subarea estimated to be underlain by the Salt Wash Member, mineralized with a content of at least 0.1 percent U_3O_8 across a thickness of 0.3 m, and the area of the Salt Wash in each are listed in the following table.

Name of subarea	Area (sq. km)	Estimated area underlain by ore as percent of total area
West Gateway	145	0.38
East Gateway	212	.61
Uravan	373	1.10
Bull Canyon	370	.92
Carpenter Ridge-Martin Mesa	96	.54
Gypsum Valley	130	.21
Slick Rock	243	1.11

The fraction of each area underlain by ore as set forth in the list yields a rounded estimate of 13,500,000 t of ore originally present in the Salt Wash Member of the Morrison Formation in about 1,550 km² of the Uravan mineral belt within the Moab quadrangle.

The estimate of resources still undiscovered in mid-1971 is 6,800 t of U_3O_8 in 2,700,000 t of ore. It is the amount by which the estimate of the resources originally present in the area of the mineral belt exceeds the resources discovered (production plus reserves) up to that time.

LA SAL MOUNTAIN-ISLAND MESA AREA

If the distribution of deposits close to the outcrop of the Salt Wash Member at places along the periphery of the La Sal Mountain-Island Mesa area is a general indication of the distribution of concealed deposits, about 75 percent of the undiscovered resources are probably in the central part of the area on the south and west sides of the La Sal Mountains (fig. 6). Most of the remainder is thought to be in the southern part south of a line extending generally eastward from the Rattlesnake mine.

The distribution of discovered deposits in the vicinity of La Sal Creek and along the western belt of outcrop of the Morrison northwestward from the vicinity of the Rattlesnake mine is assumed to be generally representative of the general distribution and incidence of deposits throughout the 344 km² of the central part of the area. The known deposits along La Sal Creek occupy an area of about 57 km². Production plus reserves total about 980,000 kg of U_3O_8, or about 17,100 kg/km². The deposits between the Rattlesnake and Yellow Circle mines occupy an outcrop length of about 32 km; assuming that a strip averaging 0.65 km wide behind this outcrop has been reasonably well explored, these deposits occupy an area of 21 km². Production plus reserves total about 966,000 kg U_3O_8, or about 46,800 kg/km². If the average of these amounts, weighted according to the area of each, is used as an index of the average amount of ore that may be present in the unexplored ground between La Sal Creek and Kane Springs, the undiscovered resources should be about 6,700 t of U_3O_8 in 2,500,000 t of ore.

Identified deposits in the Salt Wash Member are few in the southern part of the La Sal Mountain-Island Mesa area. Nearly all are small and confined to the immediate vicinity of the outcrop. If these deposits are truly representative of the area the hypothetical resources in the area are trivial.

On the other hand, the cluster of deposits in Gypsum Valley near its northwest end may be a better indication of the amount of resources in the southern part of this area. These deposits are just outside the area on the east and are within an arbitrarily outlined rectilinear block of ground about 5 km wide extending 20.3 km north from the south edge of the cluster to the north edge of this southern area. The Morrison Formation is present in about 85 km² of the

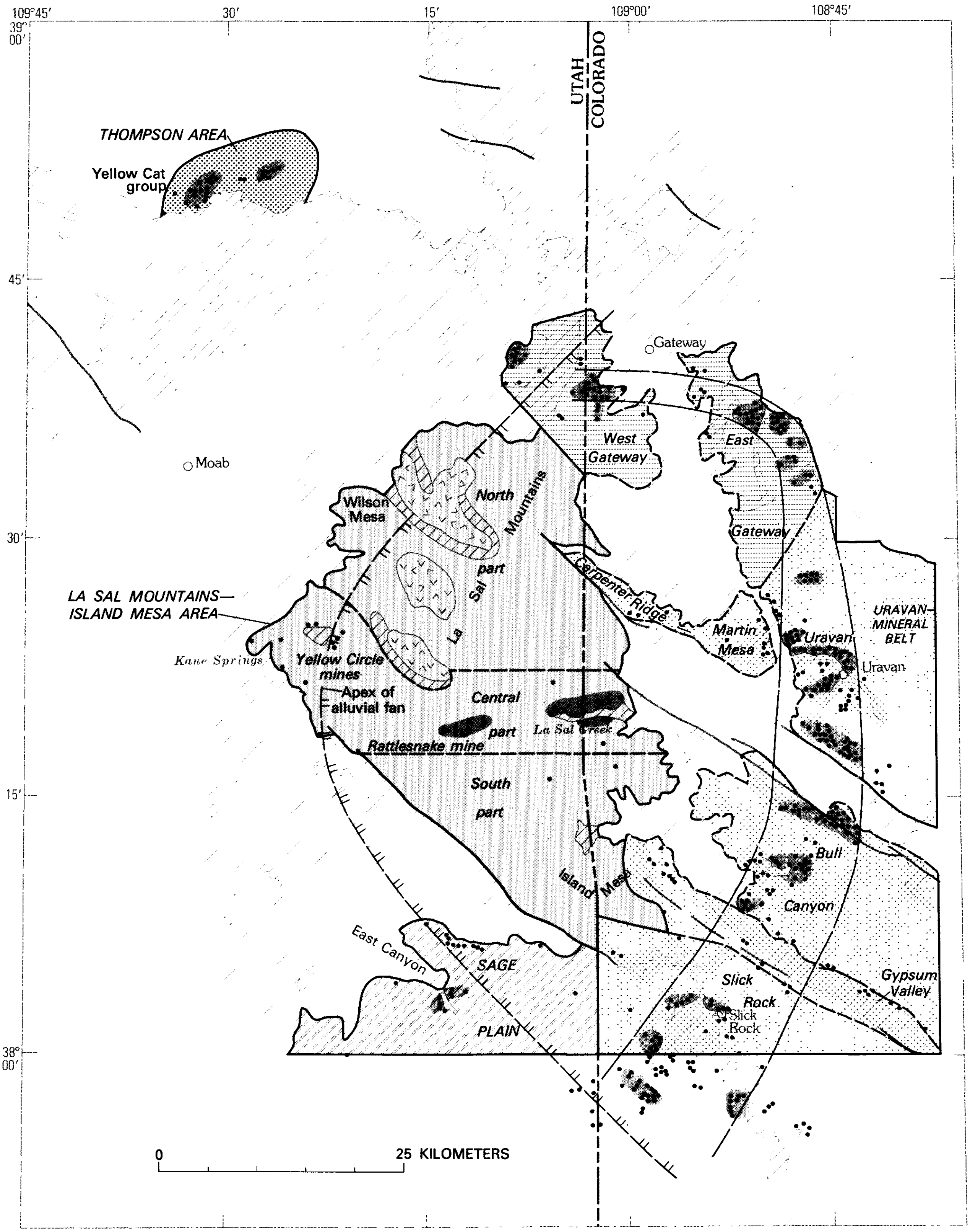


FIGURE 6. — Map showing outlines of areas distinguished in estimating resources in the Salt Wash Member of the Morrison Formation.

EXPLANATION

Intrusive rocks of the La Sal Mountains (mid-Tertiary)

Morrison Formation and post-Morrison formations

Base of Morrison Formation and borders of intrusive rocks—Dashed where covered

Pre-Morrison formations

Fault—Dashed where covered

Significant uranium deposit or group of deposits

Approximate area of ground favorable for uranium deposits

Edge of alluvial fan and area of subsidence

Boundaries of areas distinguished for resource estimation—Solid line, major division in table 3; dashed lines, subareas

arbitrary block. Dividing the amount of U_3O_8 discovered in the Gypsum Valley cluster and in one deposit within the southern subarea near the north end of that valley by the area of the arbitrary index block yields a quantity of 3,000 kg/km². Assuming that the incidence of deposits in this arbitrarily defined area is indicative of the incidence of deposits in the adjoining area, uranium resources in undiscovered deposits within the 310 km² of the southern part of the La Sal Mountain-Island Mesa area would be about 900 t of U_3O_8 in 360,000 to 450,000 t of mineralized rock.

Deposits in the part of the La Sal Mountains-Island Mesa area north of the belt extending west from La Sal Creek, are mostly small. All but one are distributed along the outcrops of the Morrison from Kane Springs to Wilson Mesa on the northwest side of the mountains. As the largest of these contained only a little more than 1,360 t of ore it is assumed that the maximum extent of fully explored ground in this part of the area is a strip no more than 0.16 km wide adjacent to 60 km of outcrop of the Salt Wash Member. Nearly 11,000 kg of U_3O_8 has been found in deposits within the 9.6 km² of strip of about 1,130 kg/km². If the sample strip adjacent to the outcrop is representative of the whole 520 km² underlain by the Salt Wash Member in this part of the area, resources in undiscovered deposits within it are about 590 t of U_3O_8 in a little more than 230,000 t of mineralized rock. The size of deposits in the sample strip suggests that estimated undiscovered resources might be in similarly small deposits; however, the general distribution of discovered resources among deposits in different ranges of size in the other parts of the La Sal Mountains-Island Mesa area suggests that if the estimated amount of resources is actually present, at least 80 percent may be in 10 to 15 deposits with masses of 3,200 to 32,000 t.

SAGE PLAIN AREA

Deposits in the part of the Sage Plain area within the Moab quadrangle are irregularly distributed mostly at or close to 72 linear kilometers of outcrop of the Salt Wash Member of the Morrison Formation along the north edge of the plain. Most of these deposits had some exposure at the outcrop and were delimited by exploration in their immediate vicinity. The amount of uranium in discovered deposits, presumed to have had some outcrop expression, when recalculated as the amount per unit area of a strip of fully explored ground bordering the outcrop, is considered to indicate the amount of uranium present per unit area in the unexplored part of the Sage Plain. In the absence of specific information about exploration in the area, the width of the strip of ground considered to be fully explored is assumed to be not less than the estimated length of the largest deposit and not more than twice that length. The mass of ore discovered in the largest outcropping deposit is 34,172 t. Calculated at 0.437 m³/t and an average thickness of 0.61 m, the area of such a deposit would be 24,480 m². The actual shape is not known, but as many deposits in the Morrison are somewhat elongate, although not excessively so, it is assumed to be generally rectilinear with a length to width ratio of 4 to 1. For the area calculated above the length would be about 0.32 km. The amount of U_3O_8 discovered in deposits within a strip considered to be fully explored along 72 km of outcrop of the Salt Wash Member is about 360,000 kg. This is equivalent to 15,650 kg/km² in the 23 km² of the strip, if the width of the strip equals the maximum dimension of the largest deposit, and 7,800 kg/km² if the width of the strip is assumed to be twice that dimension.

Resources mostly in undiscovered deposits in the remaining unexplored portion of the area for each of these alternatives would be 4,300 of U_3O_8 in 2,500,000 t of rock or 1,950 of U_3O_8 in 1,200,000 t of rock in areas of 275 or 251 km² respectively. The larger estimate is probably an upper limit for resources in the area, because the presence of this amount of resources would be possible only if the Salt Wash Member were as favorable for deposits in this portion of the Sage Plain as it is on the average in the Uravan mineral belt. The position of the Sage Plain relative to the inferred edge of the subsidiary Salt Wash fan (fig. 5) suggests, however, that the portion of the plain within the Moab quadrangle is not as favorable for deposits as the Uravan mineral belt.

If, as seems probable, the amount of undiscovered resources is closer to the lesser of the amount given above, 1,950 t of U_3O_8 in 1,200,000 t of rock and if the number of undiscovered deposits of different sizes is proportionately about the same as that of discovered deposits, nearly 1,800 t of U_3O_8 would be in 22 deposits that contain at least 9 t of U_3O_8. Of these five or six would be likely to contain at least 90 t of U_3O_8.

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