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April 30, 1956

Mr. Robert D. Nininger, Assistant Director
Division of Raw Materials
U. S. Atomic Energy Commission
Washington 25, D. C.

Dear Bob:

Transmitted herewith are three copies of TEI-446, "Elemental composition of Colorado Plateau sandstone-type uranium deposits," by E. M. Shoemaker, A. T. Miesch, W. L. Newman, and L. B. Riley, November 1955.

We are asking Mr. Hosted to approve our plan to publish this report as a chapter of a Geological Survey bulletin on mineralogy and geochemistry of the ores of the Colorado Plateau. Acknowledgment of AEC sponsorship will be made in the introductory chapter.

Sincerely yours,

John H. Eric
for W. H. Bradley
Chief Geologist

JAN 22 2001

Geology and Mineralogy

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

ELEMENTAL COMPOSITION OF COLORADO PLATEAU SANDSTONE-TYPE URANIUM DEPOSITS *

By

E. M. Shoemaker, A. T. Miesch,
W. L. Newman, and L. B. Riley

November 1955

Trace Elements Investigations Report 446

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TEPCO, Denver	2
TEPCO, RPS, Washington (including master)	2
	49

CONTENTS

ILLUSTRATIONS

TABLES

ELEMENTAL COMPOSITION OF COLORADO PLATEAU SANDSTONE-TYPE URANIUM DEPOSITS

By E. M. Shoemaker, A. T. Miesch,
W. L. Newman, and L. B. Riley

ABSTRACT

The gross chemical composition of sandstone-type uranium ores and unmineralized sandstones from the Colorado Plateau has been investigated chiefly by spectrographic analysis. Over 400 samples of ore and nearly 300 samples of unmineralized sandstone were analyzed for about 60 elements by a rapid semiquantitative technique, and more restricted suites of samples were analyzed for 5 elements by chemical techniques. The spectrographic and chemical analyses were treated by conventional mathematical methods for grouped data.

The average chemical composition of sandstones from the principal host rocks of Colorado Plateau uranium deposits--the Shinarump conglomerate and Moss Back member of the Chinle formation, both of Late Triassic age, and the Salt Wash member of the Morrison formation, of Late Jurassic age--differs only moderately from the average composition of sandstones from most of the formations of Paleozoic and Mesozoic age on the Colorado Plateau. Average Shinarump-Moss Back sandstones appear to contain significantly more aluminum, iron, titanium, zirconium, vanadium, chromium, copper, and probably more cobalt and nickel than average Colorado Plateau sandstones and less magnesium, calcium, barium, and probably less potassium. Average Salt Wash sandstones contain significantly more calcium, manganese, and copper than average Colorado Plateau sandstones and significantly less iron and probably less potassium, boron, cobalt, nickel, and yttrium.

A sandstone-type uranium deposit may be considered as composed of two fundamental parts; an indigenous part and a foreign part which was added to the indigenous part to form the deposit. The indigenous part comprises all elements that would have occupied the space of the uranium deposit had uranium mineralization never occurred; these elemental components are called intrinsic. The foreign part comprises all elements that were added to the indigenous part by the processes of mineralization;

these elemental components are called extrinsic. Almost all elements in sandstone-type uranium deposits are probably partly intrinsic and partly extrinsic, but each element may be classified according to the dominant role it plays in a majority of the deposits.

Elements, detected by the analyses used in this study that are interpreted as dominantly intrinsic in the uranium deposits of both the Morrison and Upper Triassic formations, include silicon, aluminum, iron, magnesium, calcium, sodium, potassium, titanium, zirconium, barium, strontium, manganese, beryllium, boron, scandium, chromium, zinc, gallium, silver, lanthanum, and antimony. Dominantly extrinsic elements in the deposits of both the Morrison and Upper Triassic formations include uranium, vanadium, cobalt, nickel, copper, arsenic, molybdenum, and lead. Two elements, selenium and yttrium, are interpreted as dominantly extrinsic in the deposits of the Morrison formation but dominantly intrinsic in the deposits of the Upper Triassic formations. Other elements, not detected by the analyses used in this study but known from other work which may be extrinsic components of some of the sandstone-type uranium ores on the Colorado Plateau, include sulfur, phosphorous, ytterbium, tin, cadmium, tellurium, and thallium.

INTRODUCTION

A regional study of the distribution of elements in the rocks and ores of the Colorado Plateau was begun in 1951 to provide information on the geochemical environment of the uranium deposits. Study of the gross elemental composition of the uranium ores provides a broad basis and, for some problems, a starting point for more detailed geochemical and mineralogical investigations. This report summarizes information obtained to date on the gross elemental composition of the uranium deposits and the role or roles played by each element in the history and composition of the ore. The investigation is still in progress and all histograms and averages given are subject to minor revision.

Methods of sampling and sample preparation

Two general types of samples have been used in the study of the composition of the rocks and ores. Most samples of unmineralized sandstones from formations under study were collected from outcrops during detailed stratigraphic investigations (Craig and others, 1955; Williams, 1954, p. 33-35) and were supplied by R. A. Cadigan of the U. S. Geological Survey. Some samples were collected by the writers from drill core and from outcrop. Samples of uranium ore were obtained from mechanical splits of ores shipped to mills and buying stations.

The samples of unmineralized sandstones are essentially grab samples selected to be representative of randomly distributed individual sandstone strata or parts of strata. Samples were taken without regard to proximity to known uranium deposits, but no samples that were visibly mineralized or found to have a radioactivity greater than 0.005 percent eU were incorporated in this study of unmineralized rocks. Two to 5 pounds of rock, as fresh as could be obtained, were originally collected, from which about 250 grams of fragments were picked out by hand. Where further crushing before grinding was necessary, the samples were crushed in a jaw crusher with iron jaws, and all samples were ground to -80 mesh in a disk grinder with ceramic plates (Barnett, and other, 1955).

The samples of uranium ores obtained from mills and buying stations are pulverized quarters of splits or pulps that were assayed to determine payment to the shippers. Most of the samples studied were obtained from the U. S. Atomic Energy Commission's Monticello plant, operated by the American Smelting and Refining Company (for description of sampling process see Colorado School of Mines Research Foundation, 1954, p. 46-49). The pulps were ultimately ground to -120 mesh in cast iron disk grinders. Nearly all the pulps are probably contaminated slightly with tramp iron. The average introduced amount of iron is estimated to be about 0.1 percent by weight. If the composition of the tramp iron is similar to that analyzed by Myers and Barnett (1953, table 2), the amounts of spectrographically detectable minor elements introduced with the iron are probably below or near the spectrographic limit of sensitivity.

Samples representing individual shipments or suites of shipments were combined, according to weight of ore represented, into composite samples for each mine. Final samples submitted for analysis consisted of 100 to 250 gram splits of the composite pulps. Samples from some mines were divided into two or more groups, and two or more composite pulps were prepared, representing different grades of ore or ore shipped from different parts of the mine. The amount of ore represented by the samples from each mine ranges from 1 to more than 5,000 tons, and averages about 250 tons.

The term ore in this report refers to mineralized rock mined and shipped to the mills for payment. A surprising proportion, about 20 percent, of the shipments studied contained less than 0.10 percent U_3O_8, the minimum grade for ore established by the U. S. Atomic Energy Commission (1948). Not all of the material mined and classed as ore in this report, therefore, is of ore grade under the present economic conditions.

Analytical methods

Most of the analyses were done by a rapid semiquantitative spectrographic method in the Denver laboratory of the U. S. Geological Survey under supervision of A. T. Myers, (report in preparation). R. G. Havens was the principal analyst, but large numbers of analyses were done by P. R. Barnett, G. W. Boyes, Jr., and P. J. Dunton; 428 samples of ore pulps and 289 samples of unmineralized sandstones were analyzed spectrographically.

Sixty elements are detectable with one exposure by the spectrographic method employed for this study. Of these elements, 22 are present in more than 65 percent of the ores in concentrations _/ above the spectrographic limits of sensitivity, and 9 elements are present in less than half of the ores in concentrations above the limits of sensitivity. The remaining 29 elements looked for were not detected

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_/ Concentration is used throughout this chapter in the conventional chemical sense of fractional weight contained.

in either the ores or the unmineralized sandstones. Study of the composition of the ores by the rapid spectrographic method is thus limited to about 30 elements.

The limits of sensitivity for each element are in general those listed by Myers (1954, p. 195). As the analytical work has extended over a period of 3 years and some changes were made in the details of the technique during this time, and as the individual analysts followed slightly different practices in reporting elements near the limit of sensitivity, the limit of sensitivity actually attained or reported for each element has varied slightly. Histograms given in figures 3 to 7 are cut off at the highest limits of sensitivity reported, but averages given in tables 1 and 2 and the correlation coefficients shown in figure 2 incorporate some determinations below the highest limit used. A majority of the statistics are subject to minor revision, pending review of some analyses and incorporation of additional samples.

Spectrographic data on arsenic, antimony, and zinc have been supplemented by colorimetric analyses (Lakin, Almond, and Ward, 1952, p. 14-16; Ward and Lakin, 1953; Almond, 1953) because these elements are generally present in the sandstones and ores in concentrations below the spectrographic limit of sensitivity. Selenium analyses were done by colorimetric methods (Lovering, and others, 1955). The colorimetric analyses were done by H. E. Crow, J. H. McCarthy, A. P. Marranzino, J. Meadows, and J. L. Silverly under the supervision of H. W. Lakin and L. F. Rader.

Mathematical treatment of analyses

The concentrations of the elements, as determined by semiquantitative spectrographic analysis used in this study, are reported in a series of 15 equal logarithmic classes that span the range from 0.0001 to 10 percent. Concentrations greater than 10 percent or less than 0.0001 percent are generally beyond the range of sensitivity of the spectrographic technique employed, and are noted but not classified. Each class interval is equal to 0.3333 in $\log_{10}$ values and the class limits form a geometric series that may be generated by integral powers of the cube root of 10 (2.154). After log transformation the analytical data may be treated with conventional mathematical methods for grouped data described in elementary statistics texts (see, for example, Waugh, 1943, p. 81-154, 372-430; Snedecor, 1946, p. 31-74, 137-168; or Hoel, 1947, p. 3-20, 78-92, 128-166) _/.

The number of significant figures that may be retained for $\bar{x}$ and s is a function of the number of samples and the magnitude of s up to a limit determined by the precision with which the standards used in the analysis were prepared. No assumptions or judgments on the precision or accuracy of the analyses or on the frequency distribution of the analytical results are involved in the statistical theory of the formulae employed. The computed values of $\bar{x}$ and s may be assigned some probability determined by the precision and accuracy of the analyses. If an analyst can assign the correct class to an element in 60 percent of the determinations (a conservative estimate), the minimum probability for the computed value of $\bar{x}$ recorded to the maximum number of allowable significant figures is 60 percent. By dropping one significant figure the probability of $\bar{x}$ and s is greatly increased.

_/ The formulae used are as follows:

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

where $\bar{x}$ = mean log

n = total number of samples

x_i = class midpoint of the i th class in logs

f_i = frequency of ith class

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

where s = log standard deviation

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

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

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

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_/ In the case that some determinations fall below the spectrographic limit of sensitivity the population mean log and log standard deviation can be estimated with least bias from the probability function for the truncated normal distribution (Fisher, 1931, p. xxxiii).

$$df = \frac{1}{\sigma\sqrt{2\pi}\,I_0(\xi)}\, s^{-\frac{(x-s)^2}{2\sigma^2}}\, dx$$

where σ = population standard deviation

m = population mean

ξ = difference between m and limit of sensitivity in σ values, limit of sensitivity $= m + \sigma\xi$

and the I_0 function has the form

$$I_0 = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{1}{2}t^2}\, dt$$

and log standard deviation are given by Hald (1952, p. 62-63) as well as tables for the one-sided censored normal distribution with which account may be taken of the number of analyses below the limit of sensitivity. Though the use of these tables (for the truncated or censored normal distribution) introduces the least bias in the calculation of mean log and log standard deviation, several other methods of approximate calculation give closely comparable results. Where a majority of analyses are below the limit of sensitivity, a rough estimate of the mean log may be obtained from the percent above the limit of sensitivity by use of the area tables for the normal curve and by assuming an average value for the log standard deviation. The means obtained by use of the area tables and an assumed standard deviation should be considered only as indicating the probable order of magnitude of the mean of the samples analyzed.

The simplest and generally most useful measure of central tendency that may be computed from the spectrographic analyses in the arithmetic mean of the logs, the antilog of which is the geometric mean. For a lognormal distribution the geometric mean is an estimate of the population median or true median. The most efficient (Fischer, 1921, p. 309-310) estimate of the true or population arithmetic mean may also be obtained from the geometric mean by methods given by Sichel (1952, p. 265-285). For purposes of comparison, the geometric mean is generally the most satisfactory measure of central tendency for lognormal or approximately lognormal distributions, because the logarithmic variance of geometric means of small sets of samples drawn from a lognormally distributed population is less than the logarithmic variance of the arithmetic means (the geometric mean is a more efficient or more stable statistic). All means given in this report are geometric means except where otherwise noted.

It must be emphasized that the geometric means given in this report should not be compared directly with published estimates of element abundance which are reported as arithmetic means. The geometric means for all the elements reported are invariably less than the estimated true arithmetic means by an amount that is a function of the log standard deviation. (See footnote table 2 .) For a majority of distributions studied the arithmetic mean is 2 to 3 times greater than the geometric mean.

COMPOSITION OF COLORADO PLATEAU SANDSTONES AND SANDSTONE-TYPE URANIUM ORES

Uranium deposits have been found on the Colorado Plateau in most of the principal formations of Permian through Tertiary age in three kinds of sedimentary rocks, limestone, mudstone, and sandstone. Some uranium deposits are also known in igneous rocks of Tertiary and possible Cretaceous age. More than 85 percent of the known uranium deposits are in sandstone and conglomeratic sandstone strata of the Shinarump conglomerate and Moss Back member of the Chinle formation of Late Triassic age, and of the Morrison formation of Late Jurassic age. Most of the ore produced from the Morrison formation has come from the Salt Wash member, and most of the known uranium deposits are located in the central part of the Colorado Plateau.

Composition of unmineralized sandstone from the principal uranium ore-producing strata

Two principal uranium ore-producing groups of strata are distinguished for purposes of discussion. The first group comprises the Shinarump conglomerate and the Moss Back member of the Chinle formation. Nearly all of the uranium ores from Upper Triassic rocks included in this study are from these two units. The second group of strata make up the Salt Wash member of the Morrison formation which contains most of the ore deposits in the Morrison formation included in this study. Only 32 samples of Shinarump and Moss Back sandstones from the central part of the Colorado Plateau (fig. 1) are included in the study, and averages calculated for this group of samples should be considered preliminary. The statistics for sandstones from the Salt Wash member, on the other hand, are based on 96 samples from localities distributed over the area occupied by the Salt Wash member. Many unmineralized sandstone samples were taken from several different sandstone strata in the Salt Wash member; and, in general, samples taken from a single stratigraphic section are similar in major and minor element composition. The samples taken from the Salt Wash are thought to be fairly representative of the sandstones of this member.

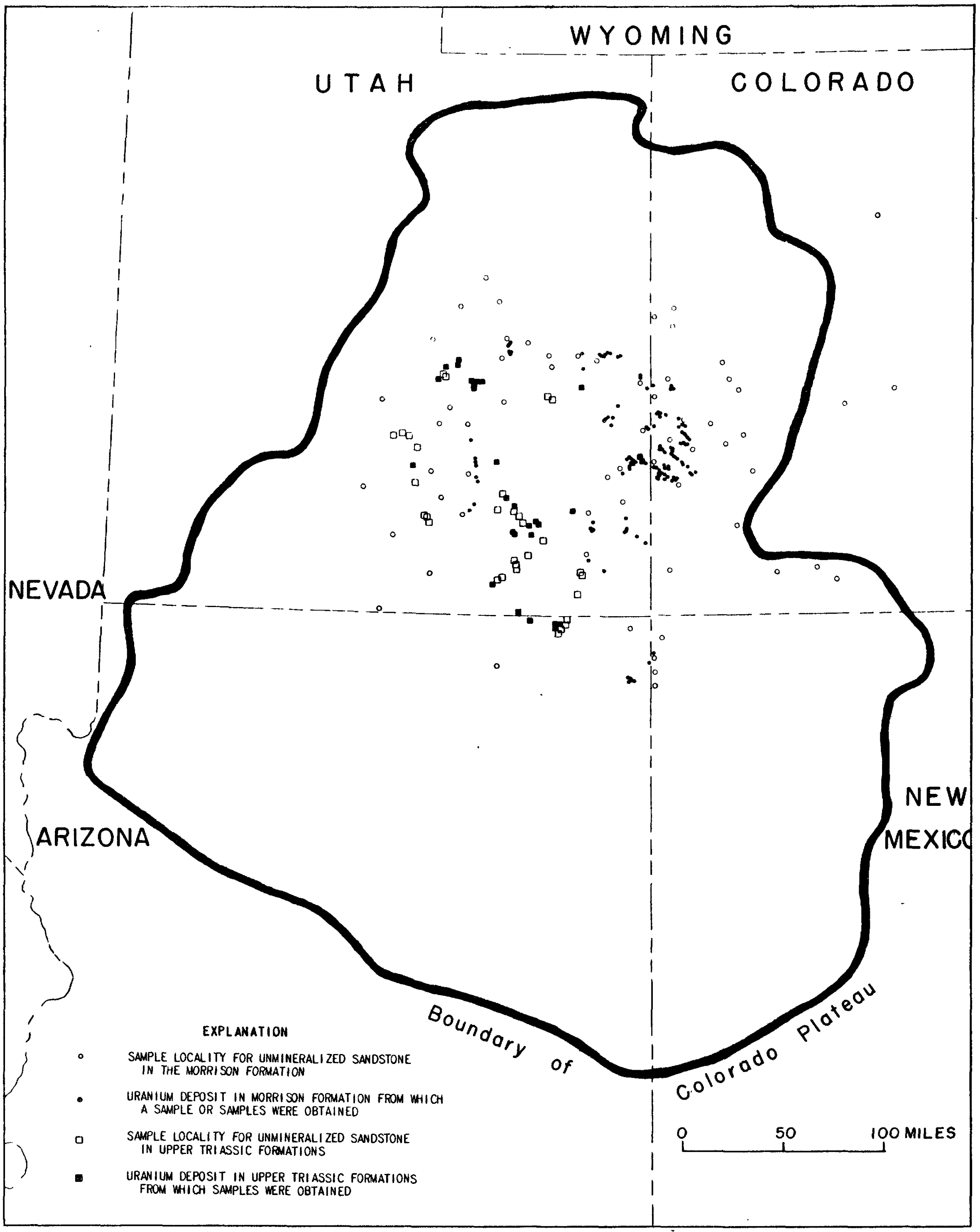

FIGURE 1. MAP OF THE COLORADO PLATEAU SHOWING LOCALITIES FOR SAMPLES OF UNMINERALIZED SANDSTONE AND URANIUM DEPOSITS FROM WHICH SAMPLES WERE OBTAINED.

The chemical composition of unmineralized sandstones from the principal uranium ore-bearing formations differs moderately from the average chemical composition of Colorado Plateau sandstones (table 1). The average Shinarump-Moss Back sandstones appear to contain significantly _/ more aluminum, iron, titanium, zirconium, vanadium, chromium, copper, and probably more cobalt and nickel than the average Colorado Plateau sandstones. Aluminum in the unmineralized sandstones is contained chiefly in feldspar and clay minerals and the greater content of aluminum in the Shinarump-Moss Back sandstones indicates a greater content of feldspar and clay than is found in average sandstones of the Colorado Plateau. Iron, titanium, and zirconium, have a moderate to high correlation and vanadium, chromium, and copper a low to moderate correlation with aluminum in unmineralized Salt Wash sandstone (fig. 2) and probably have similar correlations in the Shinarump-Moss Back sandstones. The above average amounts of iron, titanium, and zirconium and perhaps also of cobalt and nickel in the Shinarump-Moss Back sandstones are probably in part a reflection of the above average content of feldspar and clay. The concentration of copper in the average of Shinarump-Moss Back sandstones, which is more than 10 times the average in Plateau sandstones, is noteworthy. Visible traces of copper carbonates are widespread in Shinarump and Moss Back beds.

_/ For large sample sets drawn from normal populations the standard deviation of the difference between two means may be approximated without serious bias from the following equation:

$$\sigma_{\bar{x}-\bar{y}} \approx s_{\bar{x}-\bar{y}} \approx \sqrt{\frac{s_x^2}{n_x} + \frac{s_y^2}{n_y}}$$

and the significance of $\bar{x} - \bar{y}$ may be determined from ordinate tables for the normal curve of error. The precise determination of significance of the difference between two means for small sample sets, in the general case that the variances are not equal, is mathematically more complex. In this report, for purposes of simplicity, a difference is judged significant if one mean lies outside the 99 percent confidence interval of another mean. (See table 2 for confidence intervals of the means.)

Table 1.--Average chemical composition of Colorado Plateau sandstones and unmineralized sandstones from the principal uranium ore-bearing formations (Composition shown in parts per million)

Element	Paleozoic-Mesozoic sandstones from the Colorado Plateau 1/	Unmineralized sandstones of the Shinarump conglomerate and Moss Back member of the Chinle formation 2/	Unmineralized sandstones of the Salt Wash member of the Morrison formation 3/
Si	>100,000	>100,000	>100,000
Al	10,000	33,000	11,900
Fe	3,700	12,000	2,400
Mg	2,700	1,300	2,300
Ca	12,000	2,500	33,000
Na	690	900	890
K	4,300	∼2,000	∼ 3,000
Ti	580	1,800	510
Zr	88	250	103
Mn	140	120	220
Ba	280	520	340
Sr	45	60	49
B	16	∼ 16	∼ 8
V	11	30	10
Cr	7	14	6.6
Co	1	∼ 5	∼ 0.5
Ni	2	∼ 9	∼ 0.5
Cu	9	100	13
Y	4	16	∼2
U	-	-	∼ 1 4/

1/ Geometric mean of the geometric mean composition of sandstones in each of 24 formations on the Colorado Plateau ranging in age from Cambrian through Cretaceous (289 samples averaged by formations).

2/ Geometric mean composition (32 samples).

3/ Geometric mean composition (96 samples).

4/ Geometric mean of 23 samples analyzed by fluorimetric method (Grimaldi, May, and Fletcher, 1952).

Magnesium, calcium, barium, and probably potassium appear to be significantly lower in Shinarump-Moss Back sandstones than in average Plateau sandstones. The low concentration of magnesium and calcium reflects a less than average content of carbonate in Shinarump-Moss Back sandstones.

Average Salt Wash sandstones contain significantly more calcium, manganese, and copper than average Colorado Plateau sandstones. Calcium and manganese have a high correlation (fig. 2) and are contained mainly in carbonates, which are the principal cements of the Salt Wash sandstone. Salt Wash sandstones are significantly lower than average in iron and probably in potassium, boron, cobalt, nickel, and yttrium.

Salt Wash sandstones, in general, are more like the average Colorado Plateau sandstones than are the Shinarump-Moss Back sandstones. Only two elements show a similar significant departure from the Colorado Plateau sandstone average in both major groups of ore-bearing strata. Copper is significantly higher in both the Salt Wash sandstones and the Shinarump-Moss Back sandstones than in the average Plateau sandstones, and potassium appears to be significantly lower in both. In comparing sandstones of the important ore-bearing formations with other sandstones it should be noted that the estimates of geometric mean concentrations of each of the elements in unmineralized Salt Wash sandstones would fall within the confidence interval of the mean (table 2) for all elements, if the elements contained in all the ore estimated to have been present in the Morrison formation were dispersed in sandstones. In other words, the estimate of average concentration of elements in the sandstones of a given formation is not significantly changed if the ore deposits are included with the unmineralized sandstones, even in the most intensely mineralized formation.

Composition of sandstone-type uranium ores from Upper Triassic rocks and from the Morrison formation

Most of the uranium deposits of the Colorado Plateau consist of sandstone and minor amounts of mudstone impregnated with and partly replaced by minerals of uranium, vanadium, and in some cases by copper or other heavy metals. To this kind of deposit the name sandstone-type uranium deposit has been applied. The discussion of uranium deposits in this report is restricted to sandstone-type deposits in Upper Triassic rocks and in the Morrison formation.

All of the deposits studied in the Morrison formation are in the Salt Wash member except for a small number that are in sandstone lenses near the base of the overlying Brushy Basin member. More than 200 deposits or approximately 10 percent of the known deposits in the Morrison formation, and about 40,000 tons of ore from the Morrison formation are represented by the samples studied. The arithmetic mean grade of uranium and vanadium in 211 deposits, averaged by tonnage, is very close to the weighted arithmetic mean grade for all ore produced from the Morrison formation for successive 6 months periods in 1953 and 1954. The samples of Morrison ores are therefore considered representative of producing deposits in uranium and vanadium content and are thought to be probably representative in their content of most other elements as well.

All but two of the sampled deposits in Upper Triassic rocks are in the Shinarump conglomerate or Moss Back member of the Chinle formation, and the remainder are in other members of the Chinle formation. Only 38 deposits in Upper Triassic rocks, about 6 percent of the known deposits in these rocks, have been studied, and these may not be fully representative of the deposits now producing ore from the Shinarump and Chinle formations. A disproportionate number of deposits in Upper Triassic rocks studied are in one relatively small area at Temple Mountain, in central Utah.

The average composition of sandstone-type uranium ores from the Shinarump conglomerate and the Chinle formation and from Morrison formation is given in table 2 along with the average composition of the unmineralized sandstones. The frequency distributions on which these averages are based are shown in figures 3 to 7. Class intervals used in the histograms for spectrographic analyses are the same as the class intervals by which the analyses were reported, and the class intervals used in the histograms for colorimetric analyses are approximately the same as those used for the spectrographic analyses.

Table 2. Average composition of uranium ores and unmineralized sandstones of the principal uranium ore-bearing formations on the Colorado Plateau.

Element	(1) Uranium ores from the Morrison formation (chiefly the Salt Wash member) GM 1/		GD 2/	(2) Unmineralized sandstones from the Salt Wash member of the Morrison formation GM 1/		GD 2/	(3) Uranium ores from Upper Triassic rocks (chiefly the Shinarump conglomerate) and Moss Back member of the Chinle formation GM 1/		GD 2/	(4) Unmineralized sandstones from the Shinarump conglomerate and Moss Back member of the Chinle formation GM 1/		GD 2/
Al 3/	2.48	×÷ 1.14	2.03	1.19	×÷ 1.18	1.89	2.2	×÷ 1.42	2.21	3.3	×÷ 1.66	2.85
Fe 3/	0.90	×÷ 1.12	1.89	0.84	×÷ 1.19	1.91	1.5	×÷ 1.33	1.90	1.2	×÷ 1.81	3.40
Mg 3/	0.68	×÷ 1.19	2.60	0.23	×÷ 1.33	2.85	0.17	×÷ 1.61	2.99	0.13	×÷ 2.12	4.78
Ca 3/	1.97	×÷ 1.22	3.07	3.3	×÷ 1.40	3.47	0.7	×÷ 1.87	4.14	0.85	×÷ 2.60	7.19
Na 3/	0.091	×÷ 1.23	3.19	0.089	×÷ 1.42	3.73	0.08	×÷ 1.63	3.04	~0.1		--
K 3/	~0.27		--	<0.37 ~0.3 6/		--	~0.48		--	<0.15 ~0.2 6/		--
Ti 3/	0.104	×÷ 1.13	1.95	0.051	×÷ 1.20	1.96	0.13	×÷ 1.43	2.86	0.18	×÷ 1.96	2.90
Zr 3/	0.0237	×÷ 1.14	2.11	0.0103	×÷ 1.27	2.40	0.018	×÷ 1.36	2.03	0.025	×÷ 1.81	3.30
Mn 3/	0.031	×÷ 1.15	2.17	0.022	×÷ 1.33	2.89	0.024	×÷ 1.58	2.85	0.012	×÷ 3.05	10.00
Ba 3/	0.084	×÷ 1.16	2.32	0.034	×÷ 1.34	3.00	0.07	×÷ 1.87	3.22	0.05	×÷ 1.97	4.06
Sr 3/	0.0122	×÷ 1.13	2.00	0.0049	×÷ 1.28	2.50	0.014	×÷ 1.92	2.59	0.006	×÷ 2.21	5.13
Be 3/	<0.0001		--	<0.0001		--	~0.000072 6/		--	<0.0001		--
B 3/	~0.0015		--	<0.001 ~0.0008 6/		--	0.0014		--	~0.0016		--
Sc 3/	<0.001		--	<0.001		--	<0.001 ~0.0005 6/		--	<0.001 ~0.0004 6/		--
V 3/	0.49	×÷ 1.15	2.14	0.0010	×÷ 1.32	2.81	0.063	×÷ 1.92	4.40	0.0030	×÷ 2.08	4.92
Co 3/	0.00169	×÷ 1.14	2.03	0.00066	×÷ 1.25	2.27	0.0030	×÷ 1.96	2.74	0.0024	×÷ 1.54	2.44
Cr 3/	0.00104	×÷ 1.27	3.77	<0.0002 ~0.0005 6/		--	0.0025	×÷ 2.00	4.16	~0.0005		--
Ni 3/	0.00084	×÷ 1.28	4.02	<0.0002 ~0.00005 6/		--	0.0025	×÷ 1.87	3.22	~0.0009		--
Cu 3/	0.0086	×÷ 1.30	4.34	0.0013	×÷ 1.28	2.49	0.090	×÷ 2.76	10.20	0.010	×÷ 1.79	3.33
Zn 4/	0.0116	×÷ 1.44	2.58	0.0053	×÷ 1.53	2.09	0.031	×÷ 3.11	4.16	--		--
Ga 3/	<0.0005		--	<0.0005		--	<0.0005 ~0.0002 6/		--	<0.0005 ~0.0002 6/		--
As 4/	0.0168	×÷ 1.42	2.48	<0.001		--	0.020	×÷ 1.85	2.16	--		--
Mo 3/	0.00118	×÷ 1.48	4.45	<0.0002		--	~0.0006		--	~0.0002		--
Y 3/	0.00129	×÷ 1.21	2.86	<0.0005 ~0.0002 6/		--	0.0027	×÷ 1.76	3.61	0.0016	×÷ 1.90	2.31
Nb 3/	~0.0013		--	<0.0005		--	~0.0017		--	<0.0005 ~0.0002 6/		--
Ag 3/	<0.0001 ~0.00005 6/		--	<0.0001 ~0.00003 6/		--	<0.0001 ~0.00004 6/		--	<0.0001		--
Sb 4/	~0.0001		--	~0.0002		--	~0.0002		--	--		--
La 3/	<0.002		--	<0.002		--	<0.002 ~0.001 6/		--	<0.002 ~0.0008 6/		--
Yb 3/	--		--	<0.0001 ~0.00003 6/		--	--		--	0.00024	×÷ 1.42	2.42
Pb 3/	0.0088	×÷ 1.29	4.10	<0.0001		--	0.0064	×÷ 1.66	3.16	~0.002 6/		--

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1/ Geometric mean (percent) showing the 99 percent confidence interval for the population geometric mean: the limits of the confidence interval are determined from Student's t distribution (Fisher and Yates, 1953, p. 1 and 40) where t is the deviation (or range of the population mean), in units of estimated standard error, for a normal distribution:

$$\text{confidence interval of the mean} = \pm t \frac{s}{\sqrt{n-1}}$$

or for a lognormal distribution

$$\text{confidence interval of GM} = \overset{\times}{\div}\ \text{antilog} \left[t \frac{(\log GD)}{\sqrt{n-1}} \right]$$

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

$$\log_{10} \text{estimated arithmetic mean} = \log_{10} GM + 1.1513\ (\log_{10} GD)^2$$

2/ Geometric deviation or antilog of the log standard deviation.

3/ Semiquantitative spectrographic analyses: column(1) 211 deposits, column(2) 96 samples, column(3) 38 deposits, column(4) 32 samples.

4/ Colorimetric analyses: column(1) 49 deposits, column(2) 23 samples, column(3) 14 deposits.

5/ Colorimetric analyses: column(1) 102 deposits, column(2) 8 samples, column(3) 30 deposits, column(4) 30 samples.

6/ Estimated geometric mean. Estimated by assuming the part of the frequency distribution below the limit of sensitivity conforms to part of a lognormal distribution, where a majority of analyses are below the limit of sensitivity the geometric mean is estimated from the frequency above the limit of sensitivity by assuming a lognormal distribution for the total frequency and by assuming for the element in question an average log-standard deviation computed for elements in the type of rock or ore analysed.

In table 2 a factor is given for each mean that lies above the analytical limits of sensitivity which defines the limits of the 99 percent confidence interval for the true geometric mean of the type of rock from which the samples were taken. For the elements that lie mainly or entirely above the analytical limits of sensitivity, a measure of the dispersion or variation of concentration of each element in the ores and rocks (the geometric deviation) is also given. The geometric deviation is the antilog of the logarithmic standard deviation and is a measure of dispersion that is independent of the order of magnitude of the mean concentration. If the frequency distribution of an element is approximately lognormal, the range of concentration between the limits defined by the geometric mean divided by the geometric deviation and the geometric mean multiplied by the geometric deviation will include about 68 percent of the analyses.

As an example, the table may be read for aluminum as follows: the geometric mean concentration of aluminum in 211 sandstone-type uranium ores from the Morrison formation is 2.48 percent. Assuming the selection of deposits studied to be representative and the spectrographic analyses unbiased, then the true geometric mean of the aluminum concentration in all uranium deposits in the Salt Wash member and overlying parts of the Brushy Basin member of the Morrison formation, of which there are about 2,000 known at the present time, would lie (with 99 percent confidence) between 2.83 percent (2.48 x 1.14) and 2.18 percent (2.48 ÷ 1.14). About 68 percent of the deposits may be expected to have an aluminum concentration between 5.0 percent (2.48 x 2.03) and 1.22 percent (2.48 ÷ 2.03). The calculated geometric mean concentration of aluminum in 96 samples of the unmineralized sandstone host rocks in the Salt Wash member of the Morrison formation is 1.19 percent, and, if the samples are representative, the geometric mean of all Salt Wash sandstone lies between the limits of 1.40 percent and 1.01 percent at 99 percent probability. About 68 percent of the sandstone of the Salt Wash member may be expected to have between 0.63 percent and 2.25 percent aluminum. The estimated geometric mean or median concentration of aluminum in Morrison uranium deposits is 2.08 times as great as the estimated median concentration in unmineralized Salt Wash sandstone, and the median concentration of aluminum in all Morrison uranium deposits may be expected (with about 99 percent confidence) to be between 1.77 and 2.46 times as great as the median concentration in Salt Wash sandstone.

The correlation of elements in unmineralized sandstones of the Salt Wash member of the Morrison formation and in sandstone-type uranium deposits of the Morrison formation is given in chart form in figure 2. Each number on the chart is a linear correlation coefficient between the logs of the concentration of two elements. The distribution of the logs of most pairs of elements in the samples studied approximates a normal correlation surface. The pair of elements for which each correlation coefficient stands is determined, as in a mileage chart, by the headings of the column and row in which the coefficient is found. In figure 2 the correlation between pairs of elements is given for all elements that occur above the spectrographic limit of sensitivity in more than 63 percent of the 211 Morrison uranium deposits studied.

The correlation coefficient may be taken as a measure of the geochemical coherence (Rankama and Sahama, 1950, p. 48) between two elements in a given type of rock. The coefficients may range in value from minus one to plus one. Values near either plus or minus one indicate a nearly linear relation or proportional variation between the logs of two elements, a positive linear relation or direct proportionality if the coefficient is positive and a negative linear relation or inverse proportionality if the coefficient is negative. A coefficient near zero indicates there is no relation between two elements (that the covariation is essentially random) or that the relation, if one exists, is nonlinear. In general terms the correlation coefficients on the chart show which elements vary sympathetically, which elements vary antipathetically, and which elements show no significant correlation. The lowest significant value for the correlation coefficient for a normal correlation surface is a function of the number of samples and may be determined from tables (Fisher and Yates, 1953, p. 54) for a given probability.

Study of figure 2 will reveal the general degrees of association or coherence of the elements in Morrison uranium deposits and unmineralized Salt Wash sandstones. No negative correlation coefficients that are significant at 99 percent confidence were found. All significant correlations are positive, and the correlation of most elements with aluminum in both the ores and the unmineralized rocks is significant or nearly significant. The causes of some of the element associations are fairly well understood at the present time and for others are largely unknown. Interpretation of some of the correlations are given in the discussion that follows. For purposes of discussion a significant correlation below 0.35 will be spoken of as low, from 0.35 to 0.49 as moderate, from 0.50 to 0.74 as high, and above 0.74 it will be spoken of as very high. These designations are purely relative and are used merely to distinguish the ranges of correlation observed on the chart.

CORRELATION OF ELEMENTS IN URANIUM DEPOSITS

CORRELATION OF ELEMENTS IN UNMINERALIZED SANDSTONES

	V	Ni	Cu	Pb	Mo	Cr	Y	Ti	Zr	B	Mn	Ba	Sr	K	Na	Ca	Mg	Fe	Al	U
V	V	+07	+ 23	+.35	+.07	+.22	+.26	+.15	+.37	+.27	+.07	+.34	+.34	+.15	+.09	+.03	+.36	+ 28	+.50	+.32
Ni		Ni	+.08	+.14	+.49	+.10	+.27	+.14	+.08	+.12	,00	+.02	+.08	+.03	+.05	-.04	-.06	+.37	+.11	+.10
Cu	+06		Cu	+.56	+.16	+.30	+ 04	+ 27	+.29	+.23	+.26	+.15	+.31	+.27	+.26	+.32	+.36	+.07	+ 36	-.04
Pb				Pb	+.14	+ 33	+.07	+ 21	+.25	+.15	+.26	+.14	+.23	+.29	+.21	+.23	+.39	+.25	+.49	+.11
Mo					Mo	+.25	+.24	+.04	+ 22	-.09	.00	+.01	+ 13	+ 14	+ 10	+.04	.00	+.34	-.13	+.06
Cr	+38		.00			Cr	+.12	+.22	+.20	+.32	+.21	+.20	+.25	+ 38	+ 21	+.20	+.27	+.20	+.36	+ 10
Y							Y	+.25	+ 39	+.39	+.05	+.25	+.11	+.08	+.15	-.04	+.11	+.31	+ 22	+.18
Ti	+.17		+.28			+.21		Ti	+.41	+.22	+37	+.26	+.34	+.44	+.39	+.35	+ 25	+.17	+ 50	+.19
Zr	+.28		+.01			+.42		+.50	Zr	+.26	+35	+.25	+.14	+.19	+.43	+.39	+.38	+.31	+.46	+.15
B										B	+.10	+.21	+.17	+ 28	+.21	+.13	+.23	+ 16	+.35	+.11
Mn	+.16		+.22			+.24		+.02	-.05		Mn	+.19	+.28	+.37	+.56	+.75	+.30	+.20	+.47	-.09
Ba	+.11		-.08			+.20		+.08	+.16		-.03	Ba	+.37	+.27	+.19	+.11	+ 15	+.15	+.28	+.05
Sr	-.04		+.39			+.15		+.31	+.05		+.34	+.34	Sr	+ 42	+.26	+.36	+.19	+.10	+.40	+.10
K														K	+34	+.45	+.22	+.02	+.45	+.06
Na	+.04		-.22			+.26		+.35	+ 14		+.47	-.09	+.31		Na	+.56	+.45	+37	+.47	+08
Ca	+08		+.26			+.22		-12	-.12		+.83	-.05	+.41		+.39	Ca	+48	+.12	+.46	-.14
Mg	+.30		+.20			+.16		+.09	+.14		+.22	+.19	+.07		+.19	+.17	Mg	+.34	+.58	+.11
Fe	+ 20		+.32			+.29		+ 30	+.20		+.21	+.19	+.16		+.27	+.05	+.44	Fe	+.30	+.23
Al	+.24		+.35			+.25		+.60	+.40		+.12	+.23	+.24		+.30	+.04	+.16	+.48	Al	+.14
U																				U

CORRELATION OF ELEMENTS IN UNMINERALIZED SANDSTONES

CORRELATION OF ELEMENTS IN URANIUM DEPOSITS

NUMBERS ARE LINEAR CORRELATION COEFFICIENTS CALCULATED AFTER LOG TRANSFORMATION

LOWEST SIGNIFICANT VALUE AT 99 PERCENT CONFIDENCE IS 0.19 FOR CORRELATION OF ELEMENTS IN URANIUM DEPOSITS AND 0.26 FOR CORRELATION OF ELEMENTS IN UNMINERALIZED SANDSTONES

Figure 2. CORRELATION OF ELEMENTS IN URANIUM ORES FROM THE MORRISON FORMATION AND IN UNMINERALIZED SANDSTONES FROM THE SALT WASH MEMBER OF THE MORRISON FORMATION.

Classification of elements in sandstone-type uranium deposits

For convenience of discussion the following classification has been adopted for the elemental components of the sandstone-type uranium deposits. This classification applies and has meaning only for ore or mineralized rock. The purpose of the classification is to provide a simple frame-work of concepts with which the role of each element in the mineralogy and history of the ore deposits may be discussed.

Intrinsic elemental - components	Syngenetic components
	Epigenetic (diagenetic) components
Extrinsic elemental - components	Ore components
	Accessory components

Two basic assumptions are involved in this classification system. First, that the minerals that contain the bulk of the elements of economic importance, the ore elements, are epigenetic components of the ores, in the strict sense of the term epigenetic (Lindgren, 1933, p. 154) that the minerals are introduced or formed in a preexisting rock or sediment. Because the distribution of ore minerals does not follow in detail the lamination of the sedimentary rocks in which the ore is contained, the emplacement of the ore minerals is believed to have been later than the deposition of the individual laminae in which the ore minerals are now found. This interpretation has been explicitly stated by Lindgren (1911, p. 568), Coffin (1921, p. 159 and 176), and Fischer (1937, p. 943). The ore deposits are thus conceived as composed of two fundamental parts, (1) a mass of sediment or rock formed prior to emplacement of the ore minerals and (2) minerals carrying the bulk of the ore elements and other associated minerals introduced or formed in the mass of sediment or rock that today constitutes the ore deposit. The first part may be thought of as the indigenous or intrinsic part of the ore deposits, corresponding approximately in composition to the rocks that would have occupied the space of the ore deposits if mineralization had not occurred; the second part may be thought of as foreign or extrinsic to the individual rock masses that constitute the deposits. The concepts of intrinsic and extrinsic, as here defined, are restricted in their application to mineral deposits of epigenetic origin.

It is assumed secondly that the processes by which the minerals carrying the bulk of ore elements were emplaced in the ore deposit are distinct and can be distinguished from other processes which induced postdepositional changes in the sedimentary beds in which the ore deposits are located, processes that are commonly lumped under the broad ill-defined category of diagenesis. Empirically, the distinction between uranium mineralization and diagenesis is largely based on the spatial distribution of the products of the two processes; the uranium deposits are localized whereas diagenetic minerals such as calcite and authigenic quartz are widely distributed in the sediments, apparently irrespective of the distribution of uranium deposits. Such products are in both cases epigenetic. It is entirely possible, and even likely, that the processes of uranium mineralization may have affected rocks away from the uranium deposits and produced minerals indistinguishable from the minerals formed by unrelated diagenetic processes, but the distinction between intrinsic and extrinsic components applies only to rock that is recognizably mineralized with uranium.

Intrinsic elements are defined as the elements whose presence in the ore is unrelated to processes of uranium mineralization. Empirically, they are defined as elements found in the ores in amounts comparable to the amounts found in the unmineralized parts of the strata that contain the ore deposits. The intrinsic elements fall into two broad groups, (1) the syngenetic elements, or those elements contained originally in the clastic components and the elements contained originally in precipitates in the mineralized rock that were strictly simultaneous in deposition with the clastic components and, (2) epigenetic elements or elements introduced (during diagenesis) into the locus of the ore deposit after deposition of the ore-bearing strata by processes unrelated to uranium mineralization. Both syngenetic and epigenetic intrinsic elements may have been partly rearranged during uranium mineralization and incorporated in ore minerals or other minerals formed during mineralization.

Depending upon the stage in the history of the mineralized rock that the uranium was introduced into the deposits, the introduction of epigenetic intrinsic elements may have either preceded or followed the introduction of uranium. Calcium, for example, which is contained largely in the abundant calcite cement of the Salt Wash sandstones may have been introduced and precipitated in the individual bodies of ore or mineralized rock early in the history of the rock, prior to the introduction of extrinsic uranium (Waters and Granger, 1953, p. 15-20), but may also have been partly introduced, rearranged, or leached away after uranium mineralization.

The extrinsic elements of a uranium deposit are elements that have been introduced by processes of or related to uranium mineralization into the body of sediment or rock that became the uranium deposit. The extrinsic elements are contained largely in minerals formed or crystallized in situ, though some may be merely adsorbed on or absorbed in preexisting minerals. No sources for the extrinsic elements are implied by this definition nor does it imply that all the extrinsic elements had the same source as the uranium. In particular, no implication is intended that the extrinsic elements were derived either from the beds that enclose the uranium deposits or from sources external to these beds. Neither is it implied that all the extrinsic elements were necessarily introduced into the uranium deposit at the same time, though the simultaneous introduction of extrinsic elements into most of the uranium deposits seems likely. The extrinsic elements are further subdivided for discussion into ore elements and accessory elements on the somewhat arbitrary basis of whether a given element contributes to the economic value of the ore.

The extrinsic elements are empirically defined as those elements that are more abundant in the uranium ores than in the equivalent unmineralized rocks. Because of selectivity of uranium mineralization for certain parts of the host strata the average intrinsic composition of mineralized rock in the sandstone-type uranium deposits differs somewhat from the average composition of unmineralized sandstone. Uranium ore in the Morrison formation contains, on the average, twice as much aluminum as the unmineralized Morrison sandstones, probably because the ore is localized in sandstone units that initially contained on the average twice as much clay or mudstone. All other intrinsic elements in the ore that correlate positively with aluminum in the unmineralized sandstones are, as may be expected, higher in the average ore than in the average unmineralized sandstone.

Probably no single chemical element in the sandstone-type uranium ores belongs exclusively to either the intrinsic or extrinsic components of any given ore, as each element is present in some concentration, however small, in the detrital minerals of the sandstone and a certain amount, however small, was probably carried in the solutions that introduced the uranium. The problem of classification, therefore, is to assess the relative importance of the roles played by each element in the ores. An element is here considered dominantly of one classification or another if the major part of the element is believed to fall in a given classification in a majority of the deposits studied. The classification of individual elements in the following discussion is based mainly on the comparison of the averages given in table 2.

No consideration has been given in this investigation to the radioactive daughter products of uranium that are present in the sandstone-type uranium ores. Paired radiometric and fluorimetric uranium analyses of thousands of samples of the sandstone-type ores from the Morrison formation indicate that the great majority of the ores are nearly in equilibrium. The content of radioactive daughter elements, therefore, tends to be proportional to the content of uranium in the ores. In the theoretical terms of the proposed classificiation of elements the radioactive daughter elements are neither intrinsic nor extrinsic. They are neither an indigenous part of the uranium deposits, nor were they introduced by the processes of mineralization, but were generated in place; hence, they could be spoken of as authigenic elements.

Dominantly intrinsic elements

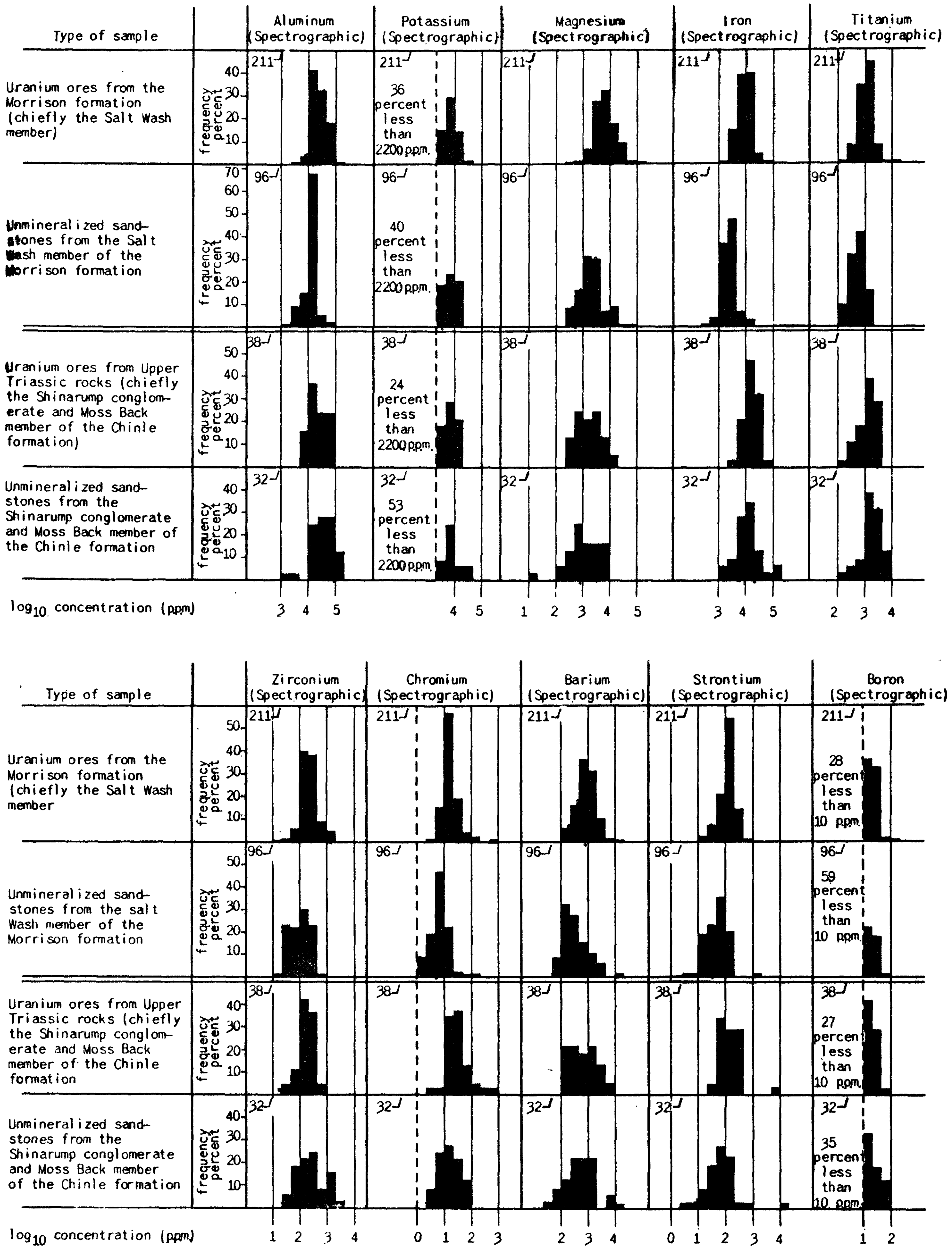
Silicon.--Silicon and oxygen occur mainly in the various mineral forms of silica and constitute the large bulk of the sandstone-type uranium deposits as well as the unmineralized rocks that enclose the deposits. The concentration of silicon in both the ores and unmineralized rocks is too high to be estimated by the semiquantitative spectrographic analysis but some idea of the arithmetic mean concentration of silica may be obtained by subtraction of the oxide equivalents of the arithmetic means of all other elemental constituents from 100 percent. If carbonate is assigned to all the calcium a fair estimate of the arithmetic mean silicon concentration in unmineralized Salt Wash sandstone may be obtained by this method, and it has been found to be approximately 36 percent (77 percent SiO_2).

No account of sulfate, sulfide, phosphate, carbonates other than calcium carbonate, or organic carbon is taken in such an estimate; but, since the estimated arithmetic mean concentration of only two spectrographically detectable elements (Al and Ca) other than silicon are greater than 1 percent, the estimate for silicon is probably correct to within 1 or 2 percent silicon.

The concentrations of nearly all elements other than silicon and oxygen tend to be higher in Morrison ores than in the unmineralized Salt Wash sandstones, but calcium, the second most abundant metallic element in the sandstones, is less abundant in the average of the ores. Because of the uncertainties involved in the estimations by subtraction it cannot be definitely said whether the silicon content of the ores is significantly different from that of the unmineralized Salt Wash sandstones. In any event the difference is probably very small in proportion to the total silicon content and the great bulk of silicon is intrinsic in the ore deposits.

Fischer (1942, p. 380) and Waters and Granger (1953, p. 15-20) have shown that quartz has been dissolved and locally removed in apparently significant amounts in parts of some Morrison ore deposits, probably during mineralization. These observations suggest that some loss of total silica from the sandstone-type uranium deposits may have commonly taken place during mineralization. Differences in silicon content between host rocks and ores in Triassic formations are expected to be similar to the relations observed in the Morrison deposits.

Aluminum.--Aluminum (figs. 2 and 3) in the unmineralized sedimentary rocks and in the uranium deposits is contained largely in various kinds of clay, claylike micaceous minerals, and in detrital feldspars. Rough estimates of the distribution of aluminum between the clay and feldspar components of unmineralized Salt Wash sandstones, based on size and mineralogical analyses by R. A. Cadigan (unpublished data), suggest that about one-third to one-half of the aluminum is generally contained in the clay-silt size fraction and the remainder is contained largely in sand size detrital feldspar. The two-fold difference between the concentration of aluminum in the Morrison ores and the concentration in unmineralized Salt Wash sandstones is believed to be due almost entirely to the presence of higher initial amounts of mudstone in the ores, mainly in the form of interstitial clay and silt, mudstone pebbles, and



^{J}Number of uranium deposits or number of samples of sandstone

FIGURE 3. FREQUENCY DISTRIBUTION OF THE DOMINANTLY INTRINSIC ELEMENTS OF URANIUM ORES CONTAINED IN URANIUM ORES AND IN UNMINERALIZED SANDSTONES OF THE COLORADO PLATEAU (ALUMINUM THROUGH BORON).

thin mudstone beds. Selective mineralization of mudstone-bearing parts of the sandstone strata in the Morrison formation has been recognized for some time (Fischer, 1942, p. 380-381; Waters and Granger, 1953, p. 10).

Aluminum is an essential constituent of some of the major vanadium ore minerals, which include clays and micaceous claylike minerals (Fischer, 1942, p. 370). Some of the vanadium in the ore appears to have been taken up in preore clay minerals, but some is also present in more coarsely crystalline claylike or micaceous minerals that appear to have crystallized in the ore (Hess, 1933, fig. 2; Fischer, 1942, p. 377 and fig. 54A; Waters and Granger, 1953, p. 12-20). Even though aluminum is an essential constituent of some of the major vanadium ore minerals, it is believed that most or nearly all of the aluminum in the ores was contained originally in the detrital components of the host sandstones, because the ratio of aluminum in ore to aluminum in unmineralized sandstone is closely comparable to similar ratios for titanium and zirconium, elements that are not known to be significant constituents of the ore minerals crystallized in place. (See section on titanium and zirconium.)

The average concentration of aluminum in 38 ores from Triassic rocks is lower than the average obtained for unmineralized Shinarump-Moss Back sandstones. As in the Morrison deposits this difference may be interpreted as due to selective mineralization, but in this case the selectivity would be for parts of the ore-bearing strata that contain less than average amounts of aluminum. The difference in aluminum concentration between the ores and the unmineralized sandstones is close to the limit of significant at 99 percent probability. The average aluminum content of the ores from Upper Triassic rocks is closely comparable to the average of the Morrison ores.

Potassium.--Potassium (figs. 2 and 3), like aluminum, is contained chiefly in feldspars and clay minerals, both in unmineralized sandstones and in the uranium ores. The distribution of potassium between the clay and feldspar components of unmineralized Salt Wash sandstones is estimated to be closely similar to the distribution of aluminum, approximately one-fourth to one-third in the clay fraction and the remainder mainly in the feldspars. Unlike aluminum, however, potassium appears to have nearly the same concentration in the ores as in the unmineralized rocks. Some factor such as selectivity of mineralization for potassium-lean but clay-bearing rocks or leaching of potassium by mineralizing solutions may be required to explain the observed differences in the potassium-aluminum ratios between Morrison ores and unmineralized rocks. Part of the observed difference between the potassium-aluminum ratio in the ore and the ratio in the unmineralized sandstones is probably due to the fact that most of the ores studied are from the uppermost sandstone strata of the Salt Wash member of the Morrison formation which appear to contain less potassium on the average than the remainder of Salt Wash sandstones.

The reverse differences between the potassium-aluminum ratios are represented in the ores and unmineralized sandstones from Upper Triassic rocks; the average of the samples studied suggest the ores contain slightly less aluminum whereas potassium appears to be higher in the ores than in the unmineralized sandstones. In a majority of the sandstones potassium is below the limit of sensitivity, however, and the apparent reversal of the aluminum-potassium relations in the Triassic rocks compared with the relations in the Morrison formation may be partly due to uncertainties of estimation or inadequate sampling of the ores and unmineralized rocks from the Upper Triassic. Potassium is considered to be almost entirely an intrinsic component of the ores in both the Morrison and Upper Triassic formations.

Iron.--Iron (figs. 2 and 3) in unmineralized Salt Wash sandstones is contained largely in clay minerals and oxides physically inseparable from clay minerals, in detrital heavy minerals, and in authigenic sulfides, oxides, and carbonates. The average iron content of 14 chemically analyzed claystones from the Salt Wash (Weeks, 1951, table 2) is 2.4 percent (arithmetic mean of average for 6 gray clays and average for 8 red clays). If the arithmetic mean content of silt and clay (corresponding approximately to claystone or mudstone in composition) in the Salt Wash sandstones is about 6.5 percent (R. A. Cadigan, unpublished data), the arithmetic mean content of iron attributable to the clay would be about 0.15 percent. The estimated arithmetic mean content of iron in Salt Wash sandstones calculated from table 2 is 0.30 percent. (See footnote 1, table 2.) Iron directly associated with clay may thus account for about half of the total iron in Salt Wash sandstones, and this association is brought out by the moderately high iron-aluminum correlation (fig. 2). Part of the iron with the clay is contained in the clay mineral lattices and part in the red clays as an extremely finely divided pigment, possibly hematite, which evidently imparts the red color (Weeks, 1951, p. 11-12). Perhaps one-fourth to one-third of the remaining iron may be attributable to opaque detrital heavy minerals and the rest mainly to authigenic iron minerals--pyrite, marcasite, hematite, goethite, and ferriferous carbonates.

Iron is nearly four times as abundant _/ in the samples of Morrison ores as in the unmineralized Salt Wash sandstones. Roughly a two-fold difference would be expected from the correlation of iron with aluminum, leaving about half of the iron in the ores or about 0.4 percent in the median case to be accounted for. On the order of 0.1 percent of this "excess" iron is estimated to be tramp iron introduced into the samples during grinding. The proportions of tramp iron might vary considerably, but the majority of "excess" iron appears to represent a real difference between the ores and equivalent unmineralized rocks and is considered an extrinsic component of the ores. If about 0.3 percent iron in the average ore is extrinsic and about 0.4 percent intrinsic, the bulk of the iron would be intrinsic but the extrinsic part of the iron would be the second most abundant extrinsic component of the Morrison ores. In many Morrison ore deposits iron may be dominantly extrinsic.

The estimated mean concentration of iron in the ores from Triassic rocks is greater than the estimated mean concentration in the unmineralized sandstones, but the difference is within the limits of confidence at 99 percent probability. It is possible that about the same quantity of iron is extrinsic in the average ore from Triassic rocks as in the average Morrison deposit, but the bulk of iron in ores from Triassic rocks is clearly intrinsic.

_/ The term abundance is generally reserved for the arithmetic mean concentration in conventional geochemical usage. In this report relative abundances or abundance ratios are computed from the geometric means because the abundance ratios are sensitive to small errors of estimation and the geometric mean is a more stable statistic than the arithmetic mean. If the log-standard deviation is the same for two distributions for which an abundance ratio is calculated, then the same ratio is obtained for the geometric means as would be found for the arithmetic means. The standard deviations for most pairs of distributions compared in this report are closely similar.

Magnesium.--The distribution of magnesium (figs. 2 and 3) among the mineral components of unmineralized Salt Wash sandstone is probably similar in some respects to the distribution of iron, with which magnesium has a moderate correlation. If two Salt Wash clays for which chemical analyses are available (Weeks, 1951, table 1) may be considered typical, about one-third of the magnesium in the average Salt Wash sandstone could be directly associated with the clay. About the same proportion is obtained if the geometric mean concentration of spectrographically determined magnesium in 32 mudstones (Newman, 1954, p. 44) is used as a basis of estimation. Part of this magnesium is in the clay lattice but part may also be commonly present as very fine-grained dolomite (Weeks, 1951, p. 8). The association of magnesium with clay, however, is much less strong than that of iron with clay, as brought out by the subsignificant magnesium-aluminum correlation coefficient. The greater part of the magnesium in a majority of the sandstones is probably contained in dolomite independent of the clay, perhaps some of detrital origin but most of it probably in authigenic form. The lack of significant correlation (fig. 2) between magnesium and calcium, which is the principal cation associated with carbonate in Salt Wash sandstones, indicates that the amount of magnesium is largely independent of the total carbonate content of the rocks. The magnesium-calcium scatter diagram (not illustrated) reveals that the concentration of magnesium never exceeds the concentration of calcium, and the bulk of magnesium in any sample could, therefore, be contained in dolomite. If all the magnesium and calcium in the median unmineralized Salt Wash sandstone were calculated as dolomite and calcite, the proportion of dolomite to calcite would be about 1 to 4. The moderate correlation of magnesium with iron suggests much of the dolomite may be ankeritic.

Magnesium is three times as abundant in the average of the Morrison ores as in the Salt Wash sandstones, and in the ores it has a high correlation with aluminum and also a moderate correlation with calcium. Part of the observed differencee may be due to selective mineralization of rocks with above average magnesium content. The studies of Waters and Granger (1953, p. 14-15) suggest a possible selectivity of mineralization for rocks rich in the magnesian group of clays, the montmorillonites and chlorites, and the high correlation of magnesium with aluminum in the ores might be considered as suggestive that a major part of the magnesium in the ores was contained originally as an essential component of the original clays. On the other hand, Keller, (1955) does not find an association of mineralized rock with montmorillonite, and three other elements, calcium, manganese, and sodium, thought to be contained or associated largely with carbonates also have a moderately high correlation with aluminum in Morrison ores. The bulk of the magnesium in a majority of Morrison ores is considered to be present as a carbonate, probably in the mineral form dolomite, as suggested by the moderately high magnesium-calcium correlation in the ores. The reason that magnesium has a moderately high correlation with calcium in the Morrison ores and not in the unmineralized Salt Wash sandstone is probably because a much higher fraction of calcium is present in dolomite in the ores than in the unmineralized sandstone. If all the magnesium and calcium in the median ore were calculated as dolomite and calcite, the proportion of dolomite to calcite would be greater than 2 to 1, as contrasted with 1 to 4 in the unmineralized sandstones. Because of the three-fold higher concentration of magnesium in the ores, it seems likely that a considerable part of the magnesium is extrinsic, though how much cannot at present be estimated. As in the case of iron, probably less than half of the magnesium in the average ore is extrinsic.

The difference in magnesium concentration between ores and unmineralized sandstones in Upper Triassic rocks is well within the 99 percent confidence interval of the means, and magnesium may be considered a dominantly intrinsic element in the majority of these ores with reasonable confidence.

Titanium and zirconium.--Titanium and zirconium (figs. 2 and 3) exhibit high and moderate correlation in the unmineralized Salt Wash sandstones and in the Morrison ores respectively, and their manner of occurrence in both sandstones and ores is probably similar. Titanium has a high correlation and zirconium a moderate correlation with aluminum in both the ores and unmineralized sandstones, and the ratio of abundance of each element in the ores to the abundance in the sandstones is essentially the same as the ratio for aluminum in both the Morrison and Upper Triassic formations. This high degree of coherence suggests the factors controlling the distribution of titanium and zirconium are essentially the same as those controlling aluminum, and both titanium and zirconium as well as aluminum are considered to be almost entirely intrinsic in the sandstone-type ores. Neither titanium nor zirconium are known to be essential or major constituents of any of the ore minerals in the sandstone-type uranium deposits, and only rarely are they reported even as trace constituents in qualitative spectrographic analysis of the ore minerals (Weeks and Thompson, 1954).

Titanium in the unmineralized sandstones is associated closely with the clay component. The arithmetic mean titanium content of 14 chemically analyzed claystones and siltstones from the Salt Wash (Weeks, 1951, table 2) is 0.32 percent, and the geometric mean titanium content of 32 Salt Wash mudstones analyzed by semiquantitative spectrographic methods (Newman, 1954) is 0.1 percent. On this basis about one-fifth to one-fourth of the titanium in average unmineralized Salt Wash sandstones would be contained in the clay-silt component of sandstones. Whether any of this titanium is present in the clay lattice or whether most of it is present as a minutely divided titania polymorph, perhaps anatase, is not clear (Grim 1953, p. 49), but titania in amounts found in Salt Wash claystones are commonly found in kaolin group clays (Ross and Kerr, 1931, p. 163). The bulk of the remainder of the titanium is probably present in detrital heavy minerals such as ilmenite, ilmenomagnetite and ilmenohematite, and rutile, or alteration products of these heavy minerals, mainly leucoxene and anatase. The high correlation of titanium with aluminum suggests that perhaps a major part of these heavy minerals is contained in the fine-grained fraction of the sandstones along with the clays.

Some zirconium is closely associated with the clay fraction of the sandstones, perhaps partly as a trace constituent of the clay minerals, but the bulk of the zirconium is evidently contained as zircon, about half of which can be separated as sand-size detrital grains. As in the case of titanium heavy minerals, probably much of the rest of the zircon present in the sandstones is in the fine fraction, which may partly account for the correlation of zircon with aluminum, but some zircon could also be enclosed as minute inclusions in the light sand-size mineral fractions, perhaps in feldspars.

Barium, strontium, and chromium. -- The distribution of barium, strontium, and chromium (figs. 2 and 3) in the Salt Wash sandstones has been partially evaluated from analyses of the clay-silt- and sand-size fractions and of heavy mineral separates (Riley and Shoemaker, 1952). An appreciable part of the barium is in the fine fraction of the sandstones, though the bulk is evidently contained in coarser-grained interstitial barite, a large part of which is recovered in heavy mineral separates (R. A. Cadigan, oral communication). About one-third part of the strontium may commonly be associated with the fine fraction of the sandstones and the bulk of the remainder possibly substitutes as a trace constituent for calcium in the abundant calcite cement and for barium in the interstitial barite, as suggested by moderate strontium-calcium and strontium-barium correlation coefficients in the Salt Wash sandstones and Morrison ores. Chromium occurs in such low concentrations in the unmineralized sandstones that its distribution is difficult to account for. Analyses of heavy minerals indicate that perhaps one-fifth to one-third of the chromium is in the heavy mineral fraction, which probably accounts for the moderate chromium-zirconium correlation in Salt Wash sandstones, and another part of the chromium, perhaps one-tenth to one-fifth is in the clay-silt fraction. The remainder of the chromium is dispersed in an unknown way in the sandstones.

Barium, strontium, and chromium each have a correlation with aluminum in unmineralized Salt Wash sandstones that is close to the lowest significant value at 99 percent confidence, and each element has a low to moderate correlation with aluminum in the Morrison ores. The ratio of abundance of the barium, strontium, and chromium, in the unmineralized Salt Wash sandstones to their abundance in the Morrison ores is nearly the same for each element and is somewhat greater than the ratio for aluminum. In the Triassic rocks all three elements are more abundant in the ores than in the unmineralized sandstones in contrast to aluminum, which is lower in the ores, though the difference in barium concentration between ore and unmineralized sandstone is within the confidence intervals of the means. A part of the barium, strontium, and chromium, in both the Morrison and Triassic ores is interpreted as extrinsic, though the bulk of these elements in the majority of ores is probably intrinsic.

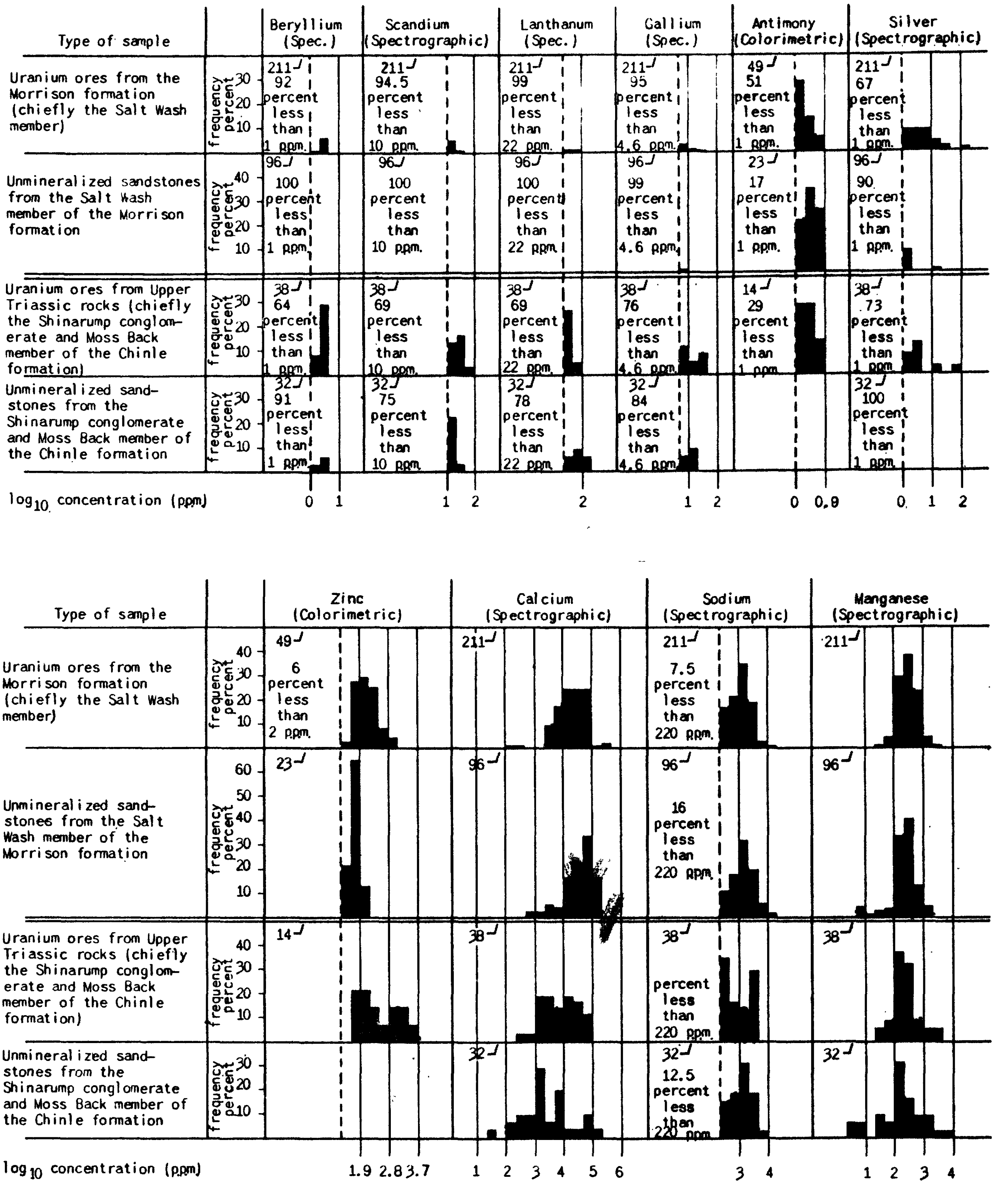
In a few Morrison and Triassic sandstone-type uranium deposits any one of the three elements, barium, strontium, or chromium may possibly be a major extrinsic component of the ores. Barium has been found to be a major extrinsic element in uraniferous and nonuraniferous deposits along faults in Jurassic sandstones and in the Brushy Basin member of the Morrison formation north of the Ute Mountains, Colorado. Garrels and others (written communication, 1955) have found barium to be locally enriched within a Salt Wash uranium deposit. Similarly, strontium has been found to be a major constituent of a uraniferous vein deposit in the vicinity of sandstone-type uranium deposits in the Morrison formation (Riley and Shoemaker, 1952) and has been found to be locally enriched within a Salt Wash ore deposit. Sandstone with more than average chromium is closely associated with vanadium-uranium deposits in the Entrada sandstone of Jurassic age on the eastern margin of the Colorado Plateau (Bush and Bryner, 1953), (Fischer, Haff, and Rominger, 1947, p. 125 and plate 1; chap. 18). In Sinbad Valley, in westernmost Colorado, chromium-rich sandstone has been found in an unidentified formation (Hillebrand and Ransome, 1905, p. 21), probably the Wingate sandstone of Triassic age, in the vicinity of uranium and copper deposits. Chromium has also been found in a conspicuous concentration associated with uranium deposits in the Wingate sandstone of Temple Mountain, in central Utah, and near uranium deposits in the Morrison formation in the vicinity of Grants in northwestern New Mexico (L. S. Hilpert, oral communication).

Boron.--On the basis of spectrographic analysis of heavy mineral and clay fraction separates and of mudstones, about half or more of the boron (figs. 2 and 3) in Salt Wash sandstones is estimated to be contained in the heavy mineral fraction of the sandstones and a significant part of the remainder in the fine fraction. Probably the bulk of the boron is carried in tourmaline, which is the only detrital mineral that has been identified in the Salt Wash sandstones that contains boron as an essential constituent. Some of the boron associated with the fine fraction is probably present in soluble borates (A. D. Weeks, personal communication). In Morrison ores boron has a moderate correlation with aluminum and a low to moderate correlation with a number of other elements that are associated with aluminum probably because of association of detrital heavy minerals and soluble salts with the clay-silt fraction of the rocks.

The estimated mean boron content of the ores is about twice the estimated mean boron content of the unmineralized sandstones, a difference that could be attributed to the higher mudstone content of the ores. The boron content of ores from Upper Triassic rocks is estimated to be essentially the same as the content of the unmineralized sandstones. In ores from both the Morrison formation and Upper Triassic rocks boron is considered almost entirely intrinsic.

Beryllium.--The distribution of beryllium (fig. 4) in the unmineralized sandstone can be inferred only from indirect evidence. It has not been detected by spectrographic methods in tthe Salt Wash sandstones and only rarely in Shinarump-Moss Back sandstones, but it has been detected in many Salt Wash mudstones. The bulk of the beryllium may be contained in the clay fraction of the unmineralized rocks. A few Morrison ores and about one-third of the ores from upper Triassic rocks contain beryllium in detectable concentrations. The occurrence of detectable beryllium in the few Morrison ores can probably be attributed to high mudstone content of the ores in which beryllium is detected. About 75 percent of the ores from Triassic rocks which contain detectable beryllium have more than average concentrations of aluminum. The bulk of beryllium may be intrinsic in both Morrison ores and ores from Triassic rocks, but a significant part of the beryllium in ores from Triassic rocks could also be extrinsic.

Scandium, lanthanum, and gallium.--Scandium and lanthanum have not been detected and gallium only rarely detected in unmineralized Salt Wash sandstones (fig. 4). Each of these elements occurs in concentrations above the spectrographic limits of sensitivity in only a few of the Morrison ores studied, though gallium was detected in trace amounts (less than 4.6 parts per million (ppm)) in more than 50 percent of the ores and hence its median concentration is essentially at the limit of sensitivity. The mean content of scandium and gallium of 32 Salt Wash mudstones, on the other hand, is above the spectrographic limit of sensitivity (Newman, 1954, p. 44); lanthanum has been detected in many mudstones and has been found in concentrations considerably above the limit of sensitivity in heavy mineral separates. Most of the scandium, lanthanum, and gallium may be contained in the fine fraction of the sandstones, either in clays or associated heavy minerals. These elements occur in concentrations above the spectrographic limit of sensitivity mainly in the more aluminous Morrison ores in which their infrequent occurrence is probably accounted for by above average mudstone content.



^{J}Number of uranium deposits or number of samples of sandstone

FIGURE 4. FREQUENCY DISTRIBUTION OF THE DOMINANTLY INTRINSIC ELEMENTS OF URANIUM ORES CONTAINED IN URANIUM ORES AND IN UNMINERALIZED SANDSTONES OF THE COLORADO PLATEAU (BERYLLIUM THROUGH MANGANESE).

In Upper Triassic rocks scandium, lanthanum, and gallium occur in concentrations above the spectrographic limit of sensitivity in 15 to 25 percent of the sandstones studied and are found in the ores with somewhat greater frequency. Lanthanum and gallium are high mainly in high aluminum ores and scandium appears to have a moderate tendency to accompany high aluminum ores. The abundance of these elements is probably related to the initial mudstone content of the ores. All three elements are considered mainly intrinsic in ores both from the Morrison formation and from Upper Triassic rocks.

Antimony. -- The distribution of antimony (fig. 4) has been studied by colorimetric analyses of about one-fourth of the samples of ores and of Salt Wash sandstones; no analyses have been completed for unmineralized Shinarump-Moss Back sandstones. The estimated mean concentration of antimony in 49 Morrison ores is about half the estimated mean for 23 samples of Salt Wash sandstone and the estimated mean for 14 ores from upper Triassic rocks is about the same as the mean for Salt Wash sandstones. These data, though incomplete, strongly suggest that antimony is almost entirely intrinsic in the ores.

Silver and zinc. -- The distribution of silver and zinc (fig. 4) in the unmineralized sandstones is largely unknown. Silver has been reported in concentrations above the spectrographic limits of sensitivity in a few percent of the unmineralized Salt Wash sandstones, but most of the analyses in which silver was detected may be slightly biased. Zinc has not been detected by spectrographic methods in the unmineralized sandstones and the statistics on zinc are based entirely on colorimetric analyses of a limited suite of samples. Rankama and Sahama (1950, p. 713) reported concentrations of zinc in clays and shales that are considerably higher than the estimated arithmetic mean zinc content of 24 Salt Wash sandstones (calculated from table 2). An appreciable part of the zinc in the sandstones may be in the clay fraction, though zinc does not appear to correlate with aluminum in the samples studied. Rankama and Sahama (1950, p. 706), also, reported that silver is enriched in some argillaceous rocks, and clays could be the dominant carriers of silver in the Salt Wash sandstones.

The estimated mean concentration of silver in 211 ores and the mean concentration of zinc in 49 ores from the Morrison formation are each about twice as great as the corresponding means for unmineralized Salt Wash sandstones, though little confidence should be attached to the ratio for silver. If silver and zinc are contained largely in the clay fraction of the sandstones, this difference could be largely due to selective mineralization of mudstone-bearing sandstone. On the other hand, the higher concentrations of both silver and zinc in the Morrison ores, tend to occur with high concentrations of copper and lead, elements which are interpreted as mainly extrinsic, and silver occurs locally in concentrations from 10 to more than 100 times higher than the spectrographic limit of sensitivity. In a majority of Morrison ores silver and zinc may be mainly intrinsic, but in those deposits that contain high concentrations of silver and zinc both elements are probably mainly extrinsic. The ratios of abundance of silver and zinc in ores from Upper Triassic rocks to their abundance in the unmineralized sandstones is unknown, but both elements could be mainly extrinsic in these ores. Silver has been the principal ore element in sandstone-type uranium deposits in the Chinle formation at Leeds in southwestern Utah (Hess, 1933, p. 452-455; Proctor, 1953, p. 78-96).

Calcium, sodium, and manganese.--Calcium and manganese are contained principally as carbonates and sodium, partly as a bicarbonate in the unmineralized Salt Wash sandstones (fig. 2 and 4). Calcium, the second most abundant element in the sandstones, occurs mainly in calcite, which is the dominant cement of the Salt Wash sandstones, but a significant part is also contained in dolomite. Locally, in the vicinity of salt structures, a major part of the calcium is also present as the sulfate, gypsum. Traces of calcium are present in soluble bicarbonate form, in plagioclase, and in other detrital minerals. Most of the calcite in the sandstones forms a relatively coarse-grained interstitial cement, but some is also fine-grained and associated with the clay (Weeks, 1951, p. 8-10; 1953, table 1). On the order of one-tenth to one-fifth of the calcium may be contained in the fine fraction of the sandstones.

Manganese has a very high correlation with calcium in both the unmineralized sandstones and in the Morrison ores and is probably contained largely in calcite into which it enters readily in solid solution. The proportion of manganese to calcium in the sandstones is so low that if all the calcium and manganese were calculated as carbonate less than 1 percent of the combined carbonate would be rhodocrosite in the average sandstone. A minor proportion of the manganese is probably present in the oxide form, perhaps mainly as pyrolusite, and a trace of manganese is contained in heavy minerals. Locally the Morrison formation contains ore grade deposits of manganese oxides in the sandstones (Baker, Duncan, and Hunt, 1952, p. 66-68).

Sodium is contained principally in plagioclase feldspars and in nonsilicate sodium salts in the Salt Wash sandstones. Flame photometric analyses of the sand-size fraction of 14 Salt Wash sandstones (R. A. Cadigan, unpublished data) suggest that the sodium in the feldspars represents about half of the total sodium in the Salt Wash sandstones. The remainder of the sodium is thought to be contained mainly in soluble salts, principally sodium bicarbonate. Extraction of salts by water at 100° C. from a core of carnotite ore in the Salt Wash sandstone yielded 28,900 ppm soluble solids per unit volume of pore water, of which 1,330 ppm, or about 0.006 percent by weight of the total rock was sodium (calculated from data by Manger, 1954a, p. 62 and 63). The principal anion was bicarbonate, but carbonate, sulfate and a trace of chloride were also present. Similar quantities of soluble solids were extracted from other segments of sandstone core, both mineralized and unmineralized (Manger, 1954b, p. 92). Weeks (1953, table 1) reports extracting burkeite ($Na [CO_3] [SO_4]_2$), thenardite (Na_2SO_4), halite, and soda niter ($NaNO_3$) from Salt Wash clays. The present ground-waters in the Salt Wash member are principally bicarbonate solutions, and it is likely that the bulk of the soluble sodium is combined with bicarbonate. A moderate correlation of sodium with calcium and with manganese in the sandstones and high correlation in the ores suggests the bulk of the sodium (as bicarbonate) is physically associated with the carbonates. Some of the soluble sodium may also be contained in montmorillonite clays (Weeks, 1953, p. 10). Probably only a fraction of the soluble sodium is extracted by a hot water leach if the bulk of the sodium salts is intimately mixed with the carbonate cement of the sandstones.

The ratio of abundance in the Morrison ores to the abundance in unmineralized Salt Wash sandstones is about 0.6 for calcium, approximately 1.0 for sodium, and 1.4 for manganese. Calcium is the only element that is lower in the Morrison ores than in the unmineralized sandstones. Among the various factors that have contributed to the apparent "deficiency" of calcium in the ores, two are probably the most important. It is possible that the present milling practice on the Colorado Plateau, which has resulted in a penalty for high lime ores from which vanadium is extracted (U. S. Atomic Energy Commission, 1948), has caused ore producers to mine and ship ore preferentially from deposits with low calcium content and has introduced bias into the sampling of ore deposits with respect to calcium and closely associated elements. The effect of this bias is thought to be negligible. The principal factor contributing to the apparent "deficiency" is probably selective mineralization of sandstones with low content of carbonate cement. The samples studied of unmineralized sandstone from the uppermost Salt Wash sandstone strata, the principal host of the producing ore deposits, have an average calcium content only half as great as the average for the remainder of Salt Wash sandstones. Another likely significant factor may have been actual leaching of calcite from the ore deposits either during or after mineralization. Leaching of the calcite cement during intermediate stages of oxidation of the ores, due to low pH conditions produced by alteration of sulfides, has been suggested by Weeks and Coleman (personal communication). Most of the Morrison ores studied are at least partially oxidized and many are nearly completely oxidized. In the ores, but not in the unmineralized sandstones, calcium and manganese have a moderate correlation with titanium, zirconium, potassium, and aluminum, elements associated with the clay-silt fraction, suggesting that a significant part of the carbonate left in the ores is contained in the mudstone component where it would be the least subject to leaching.

Despite the fact that calcium content is lower in the Morrison ores than in the unmineralized sandstones, manganese, which has a very high correlation with calcium in both the ores and sandstones, has a higher value in the ores. The explanation for this apparently anomalous relation may lie partly in the redistribution of calcium and manganese during oxidation. Calcium may tend to be flushed out of the deposits by acid oxidizing solutions, whereas, the manganese originally contained in carbonate probably would tend to reprecipitate as the relatively insoluble tetravalent oxide. Some of the manganese may also be extrinsic. The bulk of manganese as well as calcium and sodium, however, is considered intrinsic in the Morrison ores.

In the ores from Upper Triassic rocks calcium and manganese are 3 and 2 times respectively more abundant than they are in the unmineralized sandstones. Whether this indicates introduction of carbonate into the ores or perhaps selective mineralization of carbonate rich sandstones is not clear. It should be noted that the confidence interval of the mean is fairly high for calcium in the ores and exceptionally high for manganese in the sandstones. Though the observed differences are probably significant, too great a weight should not be placed on the calculated abundance ratios.

Ore elements

Uranium contributes the bulk of the value to the ores now mined on the Colorado Plateau, though in a few ores, vanadium, which is also extracted, may be the principal ore element in terms of its contribution to the price of the ore. In all ores produced from the Morrison formation vanadium as well as uranium is an ore element. Copper is paid for by uranium ore buyers in a few uranium ores produced from the Shinarump conglomerate in southeastern Utah. Selenium has been considered as a possible byproduct of some ores, but to date it has not been extracted. In a few sandstone-type ores mainly from Triassic beds and in limestone ores from northwestern New Mexico, uranium is the only element that contributes to the value of the ore.

Uranium and vanadium.-- Uranium and vanadium (figs. 2, 5, and 6) are not only the principal ore elements but are also the elements that have the highest ratios of abundance in the ores to their abundance in unmineralized sandstones in both the Morrison and Upper Triassic formations. The minimum acceptable grade (0.1 percent uranium) established by U. S. Atomic Energy Commission Domestic Uranium Program Circular 3 (1948) is about 1,000 times as great as the mean concentration of uranium in 23 samples of unmineralized Salt Wash sandstone (table 1). The ratio of the mean for vanadium in ores and in unmineralized sandstones is about 500 in the samples from the Morrison formation and about 20 in the Upper Triassic rocks. Though the ratio is less for vanadium than for uranium, vanadium is the most abundant extrinsic element in the Morrison ores.

Some comparisons can be drawn between the uranium content of the samples studied and the uranium content of the ore produced over a considerable period without specifying arithmetic mean concentrations, which are withheld for security reasons. The arithmetic mean concentration of uranium, weighted according to tonnage, in all ore represented by the samples for which tonnage data are available from 197 deposits in the Morrison formation, is identical (to two significant figures) to the arithmetic mean concentration of uranium in all ore produced from the Morrison formation for each of four 6-month periods in 1953 and 1954 (exclusive of ore produced from the Grants district of New Mexico, for the period July 1 to December 31, 1954). The frequency distribution of U_3O_8 by tonnage (calculated from total tonnage and weighted average uranium content of ore from each deposit) for the 197 deposits is closely similar to the frequency distribution by tonnage of all ore produced from the Morrison formation, exclusive of the Grants district, (calculated from total tonnage and weighted average uranium content of ore produced from each deposit per month or semimonthly settlement) for the period July 1 to December 31, 1954 (fig. 5).

The arithmetic mean concentration of uranium, weighted according to tonnage, in all ore represented by the samples from 38 deposits in Upper Triassic rocks is 12 percent less than the arithmetic mean concentration of uranium in all ore produced from the Shinarump conglomerate and Chinle formation in 1953 and 1954, but it is identical (to two significant figures) to the arithmetic mean concentration of uranium in all ore produced from the Chinle formation in the latter half of 1954.

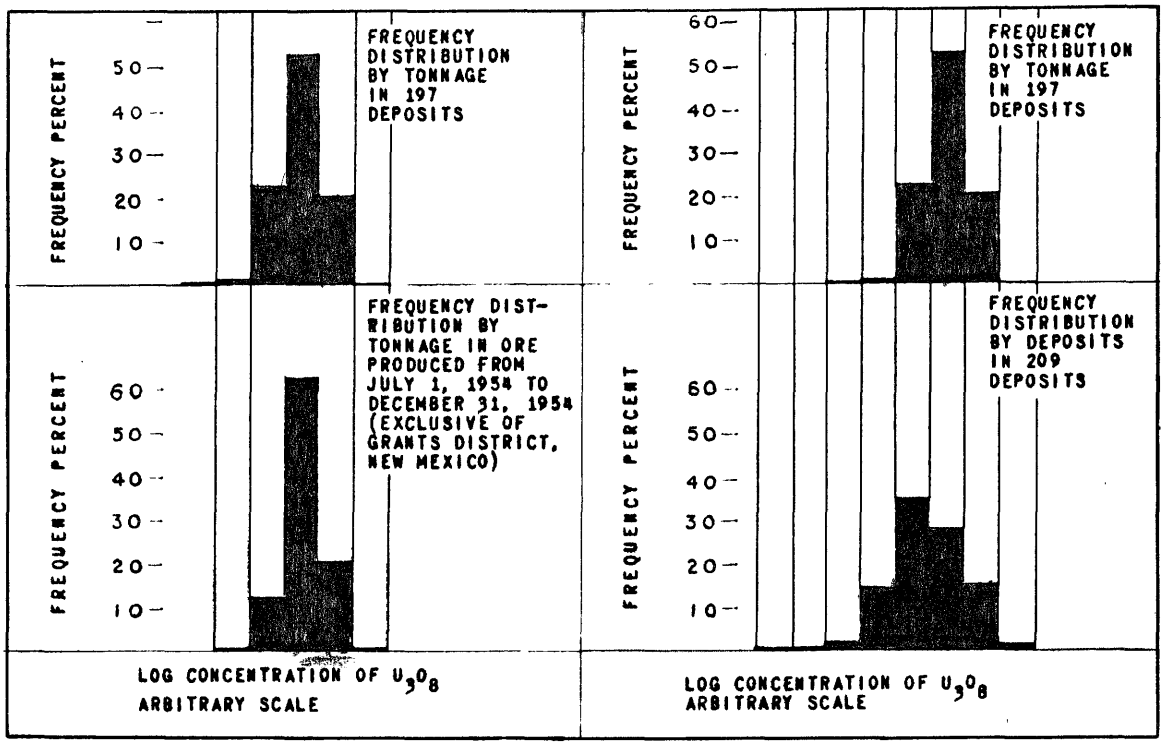


Figure 5. FREQUENCY DISTRIBUTION OF U_3O_8, AS DETERMINED BY FLUORIMETRIC ANALYSIS, IN URANIUM ORES FROM THE MORRISON FORMATION.

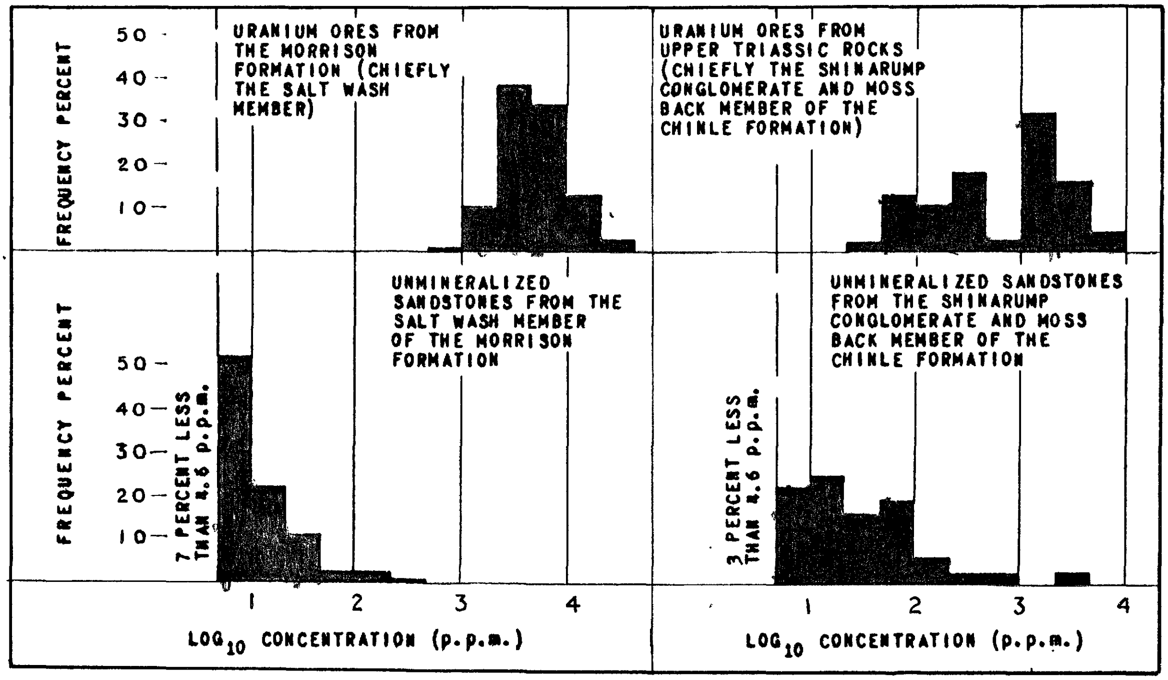


Figure 6. FREQUENCY DISTRIBUTION OF VANADIUM AS DETERMINED BY SPECTROGRAPHIC ANALYSIS IN URANIUM ORES AND UNMINERALIZED SANDSTONES ON THE COLORADO PLATEAU.

The frequency distribution of U_3O_8 by tonnage in the 197 deposits from the Morrison formation may be compared in figure 5 with the frequency distribution of U_3O_8 by deposits in 209 of the deposits studied for which fluorimetric assays are available. The first distribution weights the frequency heavily in favor of large producers, whereas, in the second distribution each of the 209 deposits is given equal weight, whether the amount of ore represented is large or small. It is the second type of distribution that is represented by all the histograms given for spectrographic and colorimetric analyses. The two types of distributions provide estimates of two entirely different parameters of the uranium distribution which should be carefully distinguished: the arithmetic mean of the distribution by tonnage, when multiplied by the total tonnage, gives the total quantity of U_3O_8 produced, whereas, the geometric mean of the distribution by deposits gives an estimate of the median grade of uranium in randomly selected deposits. It is of interest that, though the modes of the two types of distribution are significantly displaced, the estimated arithmetic mean concentration of U_3O_8 calculated from the distribution by deposits is only 15 percent less than the estimated arithmetic mean calculated from distribution of tonnage.

Concentrations of most elements in the ores from the Morrison formation are virtually independent of the grade of uranium. Only vanadium, iron, and titanium correlate significantly with uranium, and all three of the correlations are low, that of titanium at the limit of significance. Even though deposition of the uranium ore appears to have been selective with respect to mudstone content and other lithologic features of the host sandstone strata, and although several accessory elements appear to have been introduced by the mineralizing processes, uranium exhibits no strong affinities in its grade distribution among deposits either for detectable intrinsic elements or for acessory extrinsic elements. The distribution of uranium may, however, have been strongly influenced by the distribution of organic carbon, analyses for which are not yet available.

The arithmetic mean grade of V_2O_5, weighted according to tonnage, for the samples of Morrison ores studied is 6 percent less than the mean of all the Morrison ore (exclusive of ore from the Grants district) produced in 1953 and 1954 (table 3). This small difference may be due to weight given among the samples studied to deposits in the Slick Rock district of southwestern Colorado. The weighted mean for the samples from 38 deposits in Upper Triassic beds is significantly lower than the mean of ore produced from Upper Triassic beds in 1953 and 1954. Ore produced from the Upper Triassic formations during this period is heavily weighted toward one large mine in the Shinarump conglomerate, whereas, the more than half of the tonnage represented by the samples studied is from mines in a small area around Temple Mountain in central Utah, all producing from the Moss Back member of the Chinle formation. The mean for the samples studied from deposits in the Upper Triassic is nearly the same as the mean for ore produced from the Chinle formation in the latter half of 1954, both for V_2O_5 and U_3O_8.

The frequency distribution of vanadium in the ores and unmineralized sandstones, based on semiquantitative spectrographic analyses, is given in figure 6. Histograms given for the ores are for frequency by deposits, not by tonnage, and as in the case of uranium, neither these histograms nor the means computed from them given in table 2 can be compared directly with production data. In the histograms for deposits given in figure 6 equal weight is given to all deposits, whether large or small, whereas, the great bulk of production from deposits in Upper Triassic rocks, in particular, is from only a small percentage of the mines producing at present.

Vanadium in the ores from the Morrison formation has a high correlation with aluminum, a moderate correlation with lead, zirconium, magnesium, and uranium, and a low correlation with many other elements including several that tend to correlate with aluminum. The high correlation with aluminum illustrates a strong tendency for vanadium to be more abundant in the more aluminous ores of the Morrison formation, a relation interpreted as due to selective precipitation of vanadium by clay minerals in the rocks that received the ore elements. In the oxidized deposits the bulk of the vanadium is contained in micaceous or claylike silicates.

Table 3. Comparison of weighted arithmetic mean grade of vanadium pentoxide in ores produced in 1953 and 1954 and in ores represented by samples studied.

Formation from which ore is produced	Six-month period ending	V_2O_5 Percent 1/
Undifferentiated Triassic formations	June 30, 1953	1.08
Shinarump conglomerate	January 1, 1954	1.25
	July 1, 1954	1.07
	December 31, 1954	0.92
Chinle formation	January 1, 1954	0.87
	July 1, 1954	0.72
	December 31, 1954	0.58
Weighted mean for all Triassic formations January 1, 1953 to December 31, 1954		0.85
Weighted mean for samples from 38 deposits in Triassic formations		0.59

Formation from which ore is produced	Six-month period ending	V_2O_5 Percent 1/
Morrison formation 2/	June 30, 1953	1.65
	January 1, 1954	1.66
	July 1, 1954	1.64
	December 31, 1954	1.67
Weighted mean for Morrison formation 2/ January 1, 1953 to December 31, 1954		1.65
Weighted mean for samples for 197 deposits in Morrison formation		1.55

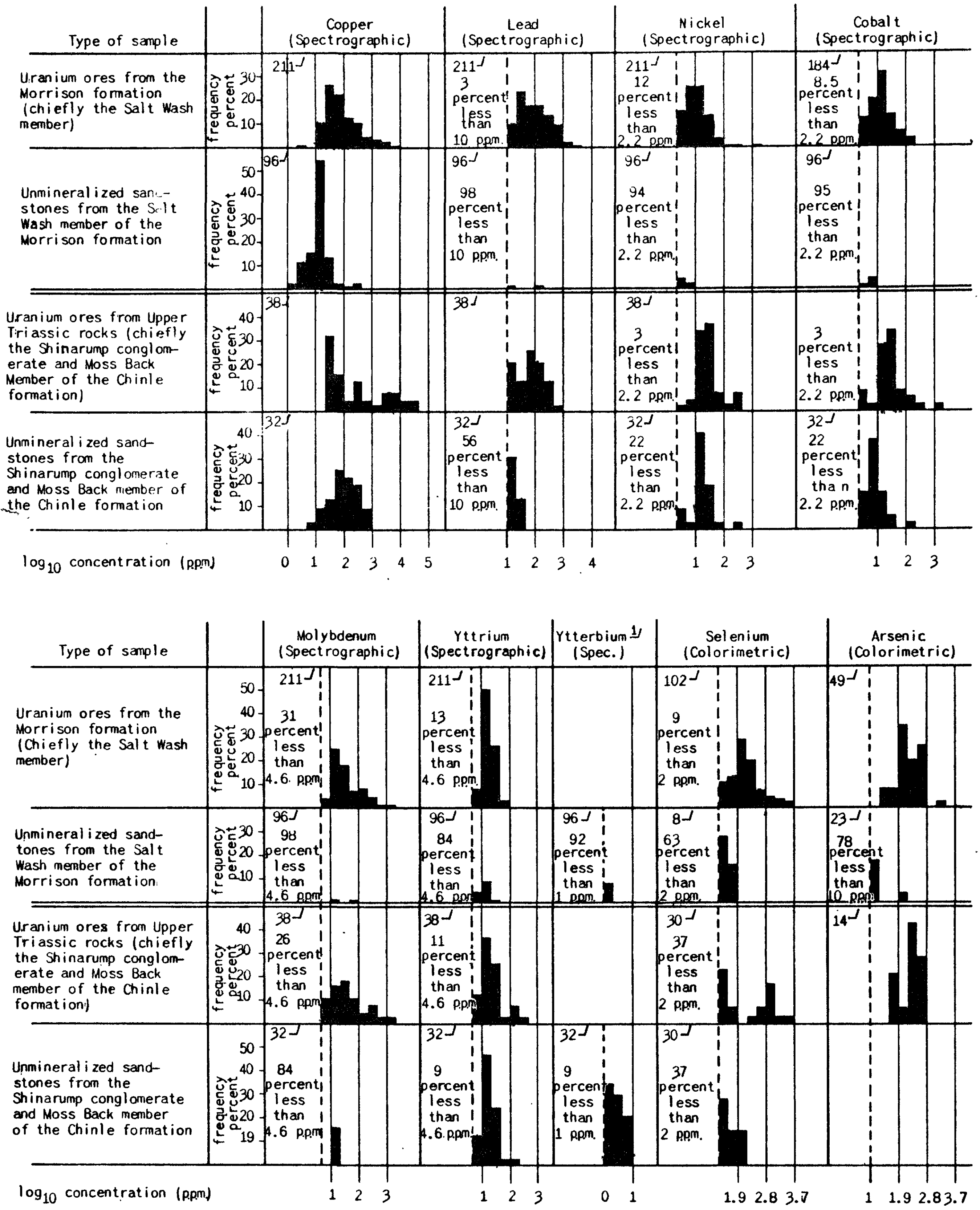
1/ Arithmetic mean grade weighted according to tonnage; based on chemical assays by ore buyers.

2/ Exclusive of ores produced from Grants district, New Mexico, during the six-month period ending December 31, 1954.

Accessory extrinsic elements

Most of the accessory extrinsic elements in the sandstone-type uranium ores of the Colorado Plateau were recognized more than 30 years ago. With reference to the Colorado Plateau uranium-vanadium deposits Lindgren wrote (1923, p. 440-441), "The ores are later than the beds which they follow, and are characterized by a very strange assortment of elements among which, besides the two already mentioned, are copper, lead, silver, barium, chromium, nickel, molybdenum, and selenium." To this list can be added only three other elements, cobalt, arsenic, and possibly yttrium, which can be shown from the present study to be characteristic extrinsic elements in the sandstone-type uranium ores. The principal elements detectable by the spectrographic method that are extrinsic in a large majority of ores from both the Morrison and Upper Triassic formations are uranium, vanadium, cobalt, nickel, copper, arsenic, molybdenum, and lead.

Copper and lead. -- The abundance of copper (figs. 2 and 7) is about 7 times greater in Morrison ores than in unmineralized Salt Wash sandstones and about 3 times greater in ores from Upper Triassic rocks than in unmineralized Shinarump-Moss Back sandstones. Lead is more than 9 times as abundant in Morrison ores as in the unmineralized sandstones and about 6 times as abundant in the ores as in the sandstones in Upper Triassic rocks. Though the ratio of abundances for copper is lower for ores and rocks from the Triassic than for the Morrison formation, because of the unusually high concentration of copper in the unmineralized Triassic sandstones, the amount of copper that has probably been introduced into the average ore in the Triassic beds is more than twice as great as the amount probably introduced into average Morrison ores.



-ᒧNumber of uranium deposits or number of samples of sandstone

1/Spectrographic analysis of ytterbium in uranium ore is interferred with by vanadium

FIGURE 7. FREQUENCY DISTRIBUTION OF THE DOMINANTLY ACCESSORY EXTRINSIC ELEMENTS OF URANIUM ORES CONTAINED IN URANIUM ORES AND IN UNMINERALIZED SANDSTONES ON THE COLORADO PLATEAU.

Lead (figs 2 and 7) in the sandstone-type uranium ores is of at least three origins: (1) intrinsic lead contained in the rocks just prior to mineralization, (2) extrinsic lead introduced into the deposits, probably at the time of initial uranium mineralization and, (3) radiogenic lead derived in the deposits by decay of the uranium in the deposits since initial mineralization. Isotopic analyses of lead extracted from some of the pulp samples included in this study (Stieff, Stern, and Milkey, 1953, p. 19, samples GS-40, 41, 42, 47, 48, and 49) indicate that the proportion of radiogenic lead derived in place, in bulk samples of Morrison ore, ranges from about 5 to more than 80 percent of the total lead. The content of radiogenic lead derived in place tends to be proportional to the uranium content of the ores, and the highest proportions of radiogenic lead derived in place generally are found in ores that have the lowest concentrations of total lead. On the basis of the analyses given by Stieff, Stern, and Milkey (1953, p. 18 and 19) it is estimated that less than half of the lead in ores from the Morrison and Upper Triassic formations with average grade and average lead content is derived by decay of uranium at the locus of the present deposits.

In the ores from the Morrison formation copper and lead are closely related, as is shown by a high correlation. Both copper and lead have low to moderate correlation with the elements associated with carbonates in the ores. A moderate correlation of copper and lead with aluminum, and low to moderate correlation of copper with some elements associated with aluminum and calcium in the unmineralized Salt Wash sandstones also suggests some affinity of copper and lead both for the aluminous or clay-silt fraction of the rocks and for the carbonate cement. The distribution of lead in the unmineralized sandstones is largely unknown, but lead is generally present in detectable concentrations in Salt Wash mudstones (Newman, 1954, p. 44) even though rarely reported in Salt Wash sandstones, suggesting that much of it may be contained in the clay-silt fraction. Higher frequency of detectable lead in the Shinarump-Moss Back sandstones may be due to higher average content of clay. In the low-valent ores extrinsic copper and lead are probably contained primarily as sulfides.

Copper and lead correspond closely in their regional distribution in the ores. Both elements have greater frequency of high concentration in uranium deposits, mainly in the Morrison formation, in an area partially coincident with a region of salt structures that lies athwart the Colorado-Utah state line (Shoemaker, 1954, p. 71 and 76). Both elements also have a greater frequency of high concentrations in uranium deposits, mainly in Upper Triassic beds, in an area between the San Juan and Colorado Rivers in southeastern Utah and in an area on the San Rafael Swell in central Utah. The regional distribution of above average concentrations of silver (Shoemaker, 1954, p. 77) and zinc in the ores resembles that of copper and lead.

Nickel, cobalt, and molybdenum.--Nickel and cobalt (figs. 2 and 7) are estimated to be about 20 times as abundant in ores from the Morrison formation as in unmineralized Salt Wash sandstones, though so few samples of the sandstones contain detectable concentrations of nickel and cobalt that these estimates should be regarded only as indicating the order of magnitude of the ratio. Molybdenum (figs. 2 and 7) is more than three times as abundant in the Morrison ores as in the sandstones and the ratio of abundance for molybdenum is probably as large as the ratios for nickel and cobalt. In the Upper Triassic formations the estimated ratios of abundance between ores and unmineralized sandstones are about 3 for nickel, 5 for cobalt, and 9 for molybdenum. Again, the estimated ratio for molybdenum should be regarded as indicating only the order of magnitude. The ratios of abundance for nickel and cobalt are low in the Triassic formations because of the much higher concentrations of these two elements in unmineralized Shinarump and Moss Back sandstones as compared with Salt Wash sandstones.

Nickel and molybdenum have a moderately high correlation in Morrison ores. Like uranium and unlike all other elements for which the correlation in the ores has been calculated, nickel and molybdenum show no significant correlation with aluminum. Both nickel and molybdenum exhibit a moderate correlation with iron and low correlation with yttrium; molybdenum has a significant but low correlation with chromium and zirconium as well. The correlation of cobalt has not been calculated because of interference by uranium in some of the cobalt analyses, but cobalt is known to correlate highly with nickel and probably has associations similar to those of nickel in the ores. The correlation of nickel with iron probably reflects an association with iron sulfides, which commonly contain appreciable concentrations of nickel and cobalt (Hegemann, 1942, p. 124-138) and which are known to contain relatively high concentrations of nickel and cobalt in some of the sandstone-type uranium deposits of the Colorado Plateau The bulk of nickel and cobalt in the low-valent ores may be contained in bravoite or nickeliferous and cobaltian pyrite. Molybdenum may enter the iron sulfides to some extent, but the molybdenum sulfides molybdenite and jordisite have also been found.

The concentration of nickel and cobalt in the uranium deposits tends to be broadly zoned across the central part of the Colorado Plateau. Nickel and cobalt tend to be higher in ores from both the Morrison and Upper Triassic formations toward the west or northwest part of the region and lower toward the east or southeast (Shoemaker, 1954, p. 75). Molybdenum appears to follow a similar pattern in deposits in the Morrison formation but is more erratically distributed in the deposits in Upper Triassic rocks (Shoemaker, 1954, p. 74).

Yttrium and ytterbium. -- Yttrium (figs. 2 and 7) is tentatively considered a dominantly extrinsic element in the ores from the Morrison formation. It is estimated to be about eight times more abundant in the ores than in unmineralized Salt Wash sandstones. This estimate is subject to large uncertainties because the large majority of sandstones analyzed did not contain detectable yttrium and because some variation exists in the limit of sensitivity as estimated by individual analysts. In the ores yttrium has a moderate correlation with iron, nickel, molybdenum, vanadium, titanium, barium, and aluminum. The correlations with zirconium, boron, and titanium suggest a part of the yttrium in the ores is in detrital heavy minerals, which spectrographic analyses show to be the principal carriers of yttrium in the unmineralized Salt Wash sandstones. The correlations with iron, nickel, and molybdenum suggest some affinity of yttrium with the nickel-cobalt-molybdenum group of extrinsic elements. As in the case of iron, about half of the yttrium in Morrison ores may be intrinsic and about half extrinsic. In Upper Triassic rocks the concentration of yttrium in ores and in unmineralized sandstones is practically identical, and yttrium is considered largely intrinsic in the ores. The regional distribution of yttrium in all ores is similar to the distribution of nickel, cobalt, and molybdenum but is more erratic (Shoemaker, 1954, p. 72).

Spectrographic analyses of ytterbium (figs. 2 and 7) in the ores have been prevented by interference from high concentrations of vanadium. Ytterbium has a very high correlation with yttrium in heavy mineral separates from Salt Wash sandstones and is a member of the yttrium group rare earths which are generally associated in nature (Rankama and Sahama, 1950, p. 517). Ytterbium may be partly extrinsic in ores in the Morrison formation.

Selenium. -- Selenium (fig. 7) is more than six times as abundant in the average of the Morrison ores as in the unmineralized Salt Wash sandstones and about twice as abundant in the average of ores from Upper Triassic rocks as in the unmineralized Shinarump-Moss Back sandstones. Unlike the distribution of all other elements investigated, the distribution of selenium in the ores studied from Triassic rocks is bimodal. One mode corresponds with the probable modal concentration in the unmineralized sandstones and the other mode is about 50 times higher. This unusual distribution is due to the high proportion of deposits represented from one small area, at Temple Mountain in central Utah, where the uranium deposits are unusually rich in selenium. Nearly all other ores studied from Triassic rocks are comparable in selenium content to the unmineralized sandstones. The distribution of selenium in Morrison ores is more nearly lognormal. Selenium is considered dominantly extrinsic in Morrison ores and in ores from Upper Triassic beds at Temple Mountain but dominantly intrinsic in most other ores from Upper Triassic formations.

The regional distribution of selenium in ores of the Morrison formation (Shoemaker, 1954, p. 73) is similar to the regional distribution of nickel, cobalt, and molybdenum. A majority of the more richly seleniferous ores are found northwest of the Colorado River. The association of selenium with elements that may be contained mainly in sulfides in low-valent ores is an expectable one. Iron sulfides, into which selenium will enter by substitution for sulfur (Williams and Byers, 1934), locally contain as much as 1 percent selenium in the Colorado Plateau ores and appear to be the most likely hosts for the bulk of extrinsic selenium in low-valent ores. Some ores also contain traces of selenides such as eucairite (CuAgSe) and clausthalite (PbSe) and also native selenium.

Arsenic. -- Arsenic (fig. 7) as determined by colorimetric analyses of a limited suite of samples, is more than 17 times as abundant in ores from the Morrison formation as in the unmineralized Salt Wash sandstones. The content of arsenic in ores from Upper Triassic formations appears to be similar to the content in Morrison ores, but no data are yet available on the arsenic content of unmineralized Shinarump and Moss Back sandstones. In terms of abundance ratio arsenic may be the third or fourth most important extrinsic element in the sandstone-type uranium ores, and in terms of actual amount or quantity contained it is the fifth most important extrinsic element among the elements studied in Morrison ores.

The manner in which arsenic is contained in the ores is not fully known. In low-valent ores the arsenides domeykite and arsenopyrite and realgar, as well as, native arsenic have been reported but appear to be rare. Arsenic has been found associated with coffinite, one of the major uranium minerals in low-valent ores, but apparently it is not an essential constituent of the mineral (Stieff, Stern, and Sherwood, 1955, p. 609). In oxidized ores arsenic occurs in the arsenates, zeunerite, metazeunerite, and in rare occurrences in abernathyite, novacekite, and conichalcite (Weeks and Thompson, 1954, p. 59), and it also enters into phosphates such as autunite and torbernite (Weeks and Thompson, 1954, p. 24 and 36) and vanadates similar to calciovolborthite. Most of these minerals are extremely rare in vanadiferous ores, however, and the bulk of arsenic in oxidized ore may be contained as a minor constituent in some of the common vanadates.

The regional distribution of arsenic in the ores appears to be nearly or essentially random, in contrast to the relatively systematic distribution of most other accessory extrinsic elements. Probably the distribution of arsenic is more closely related to the distribution of uranium than any other extrinsic element.

Elements not detected

Table 4 gives the spectrographic limits of sensitivity for 29 elements that, with the exceptions of neodymium and niobium, have not been detected in samples representing more than 1 ton of ore from sandstone-type uranium deposits in the Morrison and Upper Triassic formations or in whole samples of unmineralized sandstones from these formations. Traces of niobium have been detected in the ores of 8 and neodymium in the ores of one of 211 deposits in the Morrison formation, but neither element has been detected in unmineralized Salt Wash sandstones or in ore or unmineralized sandstones in Upper Triassic rocks.

A number of the elements not detected in pulp samples of the ores or in whole samples of the sandstones have been found in detectable quantities in heavy minerals or in clay fractions of the sandstones. These include cerium, erbium, hafnium, tin, and phosphorous in the heavy minerals and lithium in the clay fractions. Bismuth has been detected in samples of gypsum from salt intrusions in southwestern Colorado and has been found in gypsiferous Salt Wash sandstones and in gypsum from the sandstones in places where the Salt Wash sandstone is adjacent to the salt intrusions. Indium has also been detected in gypsiferous Salt Wash sandstones and mudstones associated with the bismuth. Any of these elements might be detected spectrographically in small samples and perhaps even pulp samples of the uranium ores. Some of these elements, as well as others, are probably partly extrinsic in a number or perhaps even most of the sandstone-type uranium deposits. Tin occurs locally in moderate concentration in the uranium ore at the Peanut mine, in southwestern Colorado (Roach and Thompson, unpublished data), and phosphorous may be a significant constituent of some sandstone-type uranium deposits where it forms phosphates in the oxidized ore. Cadmium has been noted in the mineral greenockite and may be widespread in the ores in concentrations slightly below the spectrographic limit of sensitivity. Mercury has been reported from shales in the Chinle formation northern Arizona (Lausen, 1936) and could possibly be an extrinsic component in the uranium ores. Tellurium has been reported from highly vanadiferous and seleniferous "alluvium" overlying ore in the Morrison formation at Thompson in southeastern Utah, by Beath (1943, p. 701 and 704). Thallium was detected spectrographically in a grab sample of uranium ore from the Navajo sandstone of Jurassic and Jurassic (?) age in northern Arizona (Shoemaker, 1955), and might also be an extrinsic component of ores in the Morrison and Upper Triassic formations.

Table 4. Elements looked for but not detected in pulp samples of ores from 249 uranium deposits and in 128 grab samples of unmineralized sandstones from the Morrison and Upper Triassic formations.

Element	Spectrographic limit of sensitivity (percent)	Element	Spectrographic limit of sensitivity (percent)
Au	0.005	Os	0.005
Bi	0.001	P	0.5
Cd	0.005	Pd	0.0005
Ce	0.05	Pt	0.005
Dy	0.05	Re	0.005
Er	0.005	Rh	0.005
Gd	0.05	Ru	0.005
Ge	0.0005	Sm	0.01
Hf	0.1	Sn	0.001
Hg	1.0	Ta	0.05
In	0.001	Te	0.5
Ir	0.005	Th	0.05
Li	0.01	Tl	0.05
Nb 1/	0.001	W	0.01
Nd 2/	0.01		

1/ Traces found in ores from eight uranium deposits in the Morrison formation.

2/ Traces found in ore from one uranium deposit in the Morrison formation.

SUMMARY

A sandstone-type uranium deposit may be considered as composed of two fundamental parts, an indigenous part and a foreign part which was added to the indigenous part to form the deposit. The indigenous part consists of all elements that would have occupied the space of the uranium deposit if uranium mineralization never had occurred; these elements of the uranium deposit are called intrinsic. The foreign part consists of all elements that were added to the indigenous part by processes of mineralization; these elemental components are called extrinsic. Nearly all elements in sandstone-type uranium deposits are probably in part intrinsic and in part extrinsic, but each element may be classified according to the dominant role it plays in a majority of the deposits.

The classification of elements studied in this investigation in the uranium deposits of the Morrison formation and of the Shinarump and Chinle formations is given in table 5. Dominantly intrinsic elements are further subdivided according to whether they are contained principally in syngenetic minerals in the uranium deposits or whether they are contained principally in authigenic minerals formed after the deposition of the sediments that ultimately were transformed into uranium deposits. Dominantly extrinsic elements are subdivided according to their economic importance into ore elements and accessory elements. The classification of elements as intrinsic or extrinsic rests primarily on the ratios of their abundance in unmineralized sandstones to their abundance in the uranium deposits. Because of selectivity of mineralization, account must be taken of the fact that the average intrinsic composition of the rocks or sediments mineralized is not equivalent to the average composition of unmineralized sandstones. In uranium deposits in the Morrison formation most of the dominantly intrinsic elements are more abundant than they are in the unmineralized sandstones.

Several elements not detected by the spectrographic method in the sandstone-type uranium ores are probably present as dominantly extrinsic elemental components of the ores. Two of possible importance in the composition of the ores are sulfur and phosphorous. Iron, though dominantly intrinsic, is also present as one of the most abundant extrinsic elemental components of the ores, and the extrinsic iron is probably contained mainly in the sulfides pyrite and marcasite in low-valent ores. Much of the sulfur

Table 5. Classification of elements in sandstone-type uranium deposits from the Morrison formation and from Upper Triassic formations.

		Morrison formation		Upper Triassic formations	
		Element	Abundance ratio 1/	Element	Abundance ratio 1/
Dominantly intrinsic	Dominantly syngenetic	Si	~1	Si	~1
		Al	2.1	Al	0.7
		Fe	3.7	Fe	1.3
		K	~1	K	~2
		Ti	2.0	Ti	0.7
		Zr	2.3	Zr	0.7
		Be	-	Be	-
		B	~2	B	~1
		Sc	-	Sc	~2
		Cr	2.6	Cr	2.1
		Zn	2.2	Zn	-
		Ga	-	Ga	~2
				Y	1
		Ag	~2 (?)	Ag	-
		Sb	~0.5	Sb	-
		La	-	La	~1
				Yb	-
	Dominantly epigenetic	Mg	3.0	Mg	1.3
		Ca	0.6	Ca	3
		Na	~1	Na	~1
		Mn	1.4	Mn	2
		Ba	2.4	Ba	1.4
		Sr	2.5	Sr	2
Dominantly extrinsic	Ore elements	U	>1000	U	-
		V	500	V	20
	Accessory elements	Co	~20	Co	~5
		Ni	~20	Ni	~3
		Cu	7	Cu	3
		As	>17	As	-
		Se	> 6	Se	~2
		Y	~ 8		
		Mo	> 3	Mo	~9
		Yb	-		
		Pb	>9	Pb	~6

1/ Ratio of estimated goemetric mean concentration in uranium ores to estimated geometric mean concentration in unmineralized sandstones.

combined with extrinsic iron in the sulfides may have been introduced into the ores with the iron. On oxidation, the sulfur may tend to be lost from the ore, but some is retained as sulfate. Phosphorous is identified in some ores in various phosphorous minerals. Among other elements that could be dominantly extrinsic in the ores but are below the spectrographic limit of sensitivity in bulk samples are tin, cadmium, tellurium, and thallium.

Though all elements were probably carried in some concentration, however small, in the solutions that introduced uranium into the ores, only a limited suite of elements from the recognizable extrinsic components of the ores. Those elements that are now thought to be or are likely to prove to be identifiable members of the extrinsic suite of elements are listed in table 6 in the estimated order of abundance of their extrinsic fraction in the average ore from the Morrison formation. No great weight should be placed on the exact position of each element in the order given; in particular, the positions of sulfur and phosphorous, which have been estimated for relatively oxidized ore mainly from indirect lines of mineralogical evidence, are in considerable doubt. The list of possible extrinsic elements whose concentrations are below the spectrographic limit of sensitivity shows only those elements suggested by some specific analytical or mineralogical evidence and should not be considered inclusive.

Table 6. Extrinsic elemental components of average uranium ore from the Morrison formation in their estimated order of abundance

Probably extrinsic in more than half of the uranium deposits	Vanadium
	Iron
	Magnesium
	Uranium
	Sulfur
	Arsenic
	Phosphorous
	Copper
	Lead
	Molybdenum
	Selenium
	Cobalt
	Nickel
	Yttrium
Probably extrinsic in less than half of the uranium deposits	(Barium)
	(Strontium)
	(Zinc)
	(Chromium)
	(Silver)
Possibly extrinsic in the uranium deposits but not detected spectrographically in bulk samples of the ores	Ytterbium(?)
	Tin (?)
	Cadmium (?)
	Tellurium (?)
	Thallium (?)

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