Distribution of Elements in Colorado Plateau Uranium Deposits—A Preliminary Report

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GEOLOGICAL SURVEY BULLETIN 1147-E

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

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By A. T. MIESCH

CONTRIBUTIONS TO GEOCHEMISTRY

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A regional study, with special reference to the Frenchy Incline deposit, San Miguel County, Colorado

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By A. T. Miesch

ABSTRACT

The regional distributions of elements in uranium deposits in the Salt Wash Member of the Morrison Formation of Late Jurassic age provide clues to the sources of the elements. Iron, cobalt, nickel, molybdenum, arsenic, selenium, yttrium, and to a lesser extent, zinc, tend to be more highly concentrated in deposits on the western and northwestern parts of the Colorado Plateau and in this respect conform roughly to the distribution of tuffaceous materials in unmineralized sandstones of the Salt Wash Member. Copper, silver, lead, and zinc are highly concentrated in deposits in the salt anticline area of western Colorado and eastern Utah, an area that has been extensively fractured and which includes the La Sal Mountains laccoliths. Vanadium is unique in that it is more highly concentrated in deposits on the eastern part of the plateau, with the exception of deposits near the Henry Mountains on the western part. Heavy minerals in the unmineralized sandstones of the Salt Wash Member, like vanadium in most of the uranium deposits, tend to be more abundant on the eastern part of the plateau. Because of sample bias with respect to uranium grade the regional variation of uranium in the deposits cannot be determined with available data.

The compositions of the Frenchy Incline uranium deposit in the Legin area of southwest Colorado and its host sandstone and mudstone in the vicinity of the deposit have been determined from semiquantitative spectrographic analyses of 219 drill-core samples. Comparison of the compositions of the mineralized and unmineralized rocks shows that in the formation of the deposit the host rocks were enriched in vanadium, iron, uranium, strontium(?), zinc, lead, copper, chromium(?), nickel, cobalt, molybdenum, and silver, in decreasing order of abundance. In general, this is the same suite of elements which has been found to be concentrated in other uranium deposits in the Salt Wash Member of the Morrison Formation on the Colorado Plateau.

Quantitative considerations show that most elements concentrated in the Frenchy Incline deposit could have been derived from altered sandstone adjacent to the deposit without changing the composition of the sandstone by any detectable amount. However, uranium and probably vanadium must have been derived from sources external to the altered part of the sandstone lens in which the deposit occurs; an unknown amount of lead in the deposit originated from the radioactive decay of uranium within the deposit.

Copper, silver, some lead, and part of the zinc, because of their regional variations among all deposits in the Salt Wash Member, are interpreted to have been derived from sources external to the Salt Wash in the salt anticline area. Iron, cobalt, nickel, molybdenum, arsenic, selenium, yttrium and some zinc are interpreted to have been derived from tuffaceous materials in the Salt Wash Member, possibly in the altered sandstone adjacent to the deposits. Uranium and vanadium could have been derived from a number of sources, but there is some evidence that vanadium was derived from heavy minerals.

If the elements were transported to the deposit by flowing ore solution, the required minimum concentrations of each element in the solution depends on the volume of solution which passed through the deposit. Assuming that the hydraulic gradient which caused solution flow resulted from differences in hydrostatic head caused only by the dip of the aquifer, the maximum volume of the solutions which passed through the deposit per unit time, for a given structural gradient, may be estimated from Darcy's law. The required minimum concentration of each element in the ore solution, then, becomes a function of the duration of mineralization and the structural gradient.

It is possible that some of the elements concentrated in the deposit were transferred to the site of mineralization by diffusion processes rather than by flowing solutions. Thermodynamic considerations suggest that concentration gradients of iron in solution may have been established in the host sandstone during a period of relatively stagnant ground-water conditions. Iron and other elements may have been transferred by solute diffusion which occurred in response to the concentration gradients. Roll-type ore structures in the deposit can be interpreted as having resulted from diffusion of elements toward a solution interface within the host sandstone.

Two hypotheses of origin of uranium deposits in the Salt Wash Member of the Morrison Formation are considered. One hypothesis involves a single stage of mineralization, whereas the other involves multiple stages.

Some important similarities and some differences have been found between the distributions of elements in uranium deposits in the Salt Wash Member and in other stratigraphic units on the Colorado Plateau.

INTRODUCTION

The problem of the origin of sandstone-type uranium deposits on the Colorado Plateau is complex and involves questions regarding the time of formation, source of the elements and of the ore-transporting fluid, chemical and physical character of the fluid, the form in which the ore elements were contained in the fluid, and the cause and mechanism of deposition of the elements to form the deposits. Final answers to all these questions will be necessary before the origin of the deposits is known. To date, varying degrees of progress have been made toward answering each question, but none has been answered completely. The investigation described here has been directed primarily at the phase of the problem concerning the source or sources of the elements in the deposits; the source of the elements may or may not be the same as the source of the fluid that transported the elements, and it is not necessary, nor likely, that all the elements in all the deposits were derived from the same source. Some other aspects of the problem of origin are dependent partly on the sources of the elements in the deposits, and these aspects are considered to a lesser extent. Two mechanisms that may have been responsible for transporting elements from their sources to the deposit (solution flow and solute diffusion) are discussed.

This work was done primarily by the U.S. Geological Survey on behalf of the Raw Materials Division of the U.S. Atomic Energy Commission. During an early part of the study, from September 1958 to June 1959, some of the initial laboratory work was supported by Shell Companies Foundation, Inc., which provided a graduate-student fellowship while the author was attending Northwestern University. Much of the analytical data was obtained in previous investigations by E. M. Shoemaker, W. L. Newman, L. B. Riley, and myself. I am indebted to R. A. Cadigan for the data pertaining to the mineral composition of the host rocks of the uranium ores and to the analysts of the Geological Survey for the chemical and spectrographic data. R. G. Havens was principal analyst. Considerable geologic information pertaining to the area that contains the Frenchy Incline uranium deposit was obtained from unpublished work of Henry Bell. In preparation of the final manuscript I had the benefit of suggestions and criticisms of A. L. Howland, W. C. Krumbein, and L. H. Nobles of Northwestern University, and R. P. Fischer and K. G. Bell of the U.S. Geological Survey.

GEOLOGY

Sandstone-type uranium deposits on the Colorado Plateau (fig. 1) consist of sandstone, mudstone, and conglomerate which have been impregnated with uranium, vanadium, and a suite of other extrinsic elements (Shoemaker and others, 1959, p. 33) including iron, cobalt, nickel, molybdenum, arsenic, yttrium, selenium, zinc, copper, lead, silver, and locally antimony, barium, beryllium, gallium, chromium, strontium, and rare earths. The elements are contained as major and minor constituents in a variety of minerals which include oxides, carbonates, sulfides, sulfates, phosphates, arsenates, silicates, vanadates, arsenides, and selenides (Weeks and Thompson, 1954; Weeks and others, 1959). Clay minerals may be an important host for some of the minor elements. The deposits have been classified by their vanadium : uranium ratios and the varying degrees of oxidation they have undergone as these factors have been important controls in the formation of the present mineral suites (Weeks and Thompson, 1954; Botinelly and Weeks, 1957).

The uranium and vanadium minerals in the deposits are epigenetic as indicated by the fact that layers of mineralized rock commonly cut across bedding in the host sandstones that enclose the deposits. The primary ore minerals in the deposits are generally of the low-valent

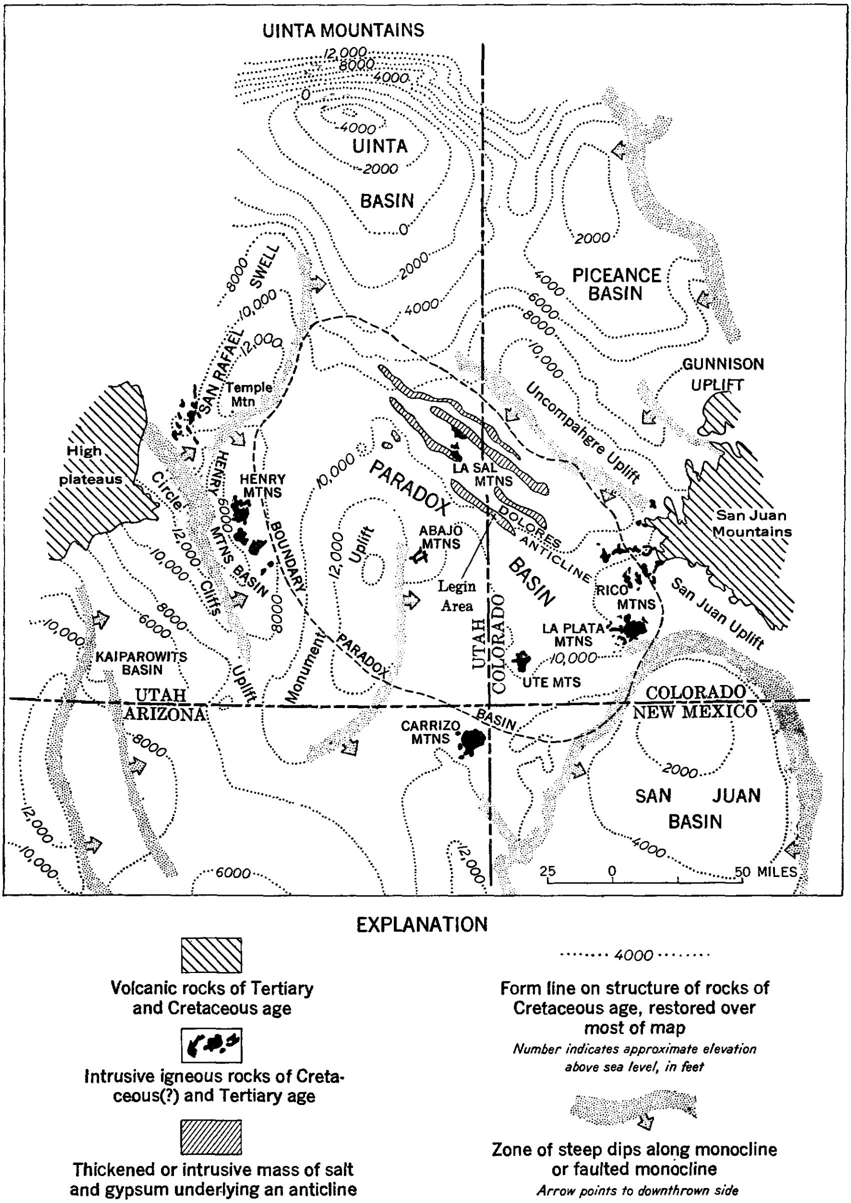

FIGURE 1.—Tectonic sketch map of part of the Colorado Plateau region (modified from Shoemaker, 1956a).

type, consisting of oxides and silicates of uranium (IV) and vanadium (III and IV), and sulfides of iron (II) and copper (I). A few selenide minerals are present locally. Most of the deposits show partially coalified plant remains, and chemical analyses indicate that organic carbon is present in virtually all of the ores. The organic carbon is probably present almost entirely in the plant remains (K. G. Bell, written communication, 1961) and along with associated H_2S may have served as a reducing and precipitating agent for the ore elements (Jensen, 1958; Garrels and Pommer, 1959). The organic carbon now present is thought to be an excess remaining after oxidation and removal from the ores, partly during the process of precipitation of the low-valent ore minerals. Ore minerals of the high-valent type, containing uranium (VI), vanadium (IV and V), iron (III), copper (II), in addition to sulfates and native selenium, occur in many of the uranium deposits on the Colorado Plateau, especially those in the Salt Wash Member of the Morrison Formation and are thought to be secondary. Such deposits, unlike those containing the low-valent suite of ore minerals, commonly occur in the zone of aeration, above or near the present ground-water table. Quantitative aspects of both the reducing capacities of woody materials and the oxidation of the uranium ores have been studied by Pommer (1957) and Garrels and Pommer (1959).

Few uranium deposits on the Colorado Plateau are directly associated with faults which have clearly undergone pre-ore movement, and the distribution of deposits seems to be, at the most, only vaguely related to centers of igneous intrusion. The deposits occur largely as tabular layers in the sandstone. Many of the layers conform in a gross manner to beds within the host sandstones, but the boundaries of other layers clearly cross the bedding in the sandstone. Layers of ore which are not tabular form many other configurations and are commonly referred to as C-rolls, S-rolls, etc., depending on their trend in a cross-sectional view (Fischer, 1942, p. 382–385; Shawe, 1956, p. 239–242). Most of the deposits consist of several closely spaced ore layers which are commonly several hundred feet across and less than 1 foot to as much as several feet thick. Many of the deposits consist of several thousand tons of minable ore, but the total range in size is from less than 1 ton to more than several million tons.

The uranium deposits in sedimentary rocks on the Colorado Plateau and along its margins are mainly in late Paleozoic and Mesozoic units, but deposits in rocks as old as Precambrian (Granger and Raup, 1954) and as young as Pliocene (Shoemaker, 1956b) are known. Most of the uranium ore production on the plateau has been from mines in fluvial sandstones of the Chinle and Morrison Formations. Within the Morrison Formation most of the deposits are in the Salt Wash Member. Characteristics of sandstone lenses within the Salt Wash Member that appear to be typically associated with the occurrence of ore have been tabulated by Weir (1952, p. 26) and include (1) thickness of more than 40 feet, (2) light brown rather than reddish color, (3) presence of gray and green rather than red mudstone, and (4) abundant carbonized plant fossils. Sandstone lenses with these characteristics are generally regarded as favorable for the occurrence of uranium ore.

REGIONAL VARIATION AND GEOCHEMICAL COHERENCE OF ELEMENTS IN URANIUM DEPOSITS IN THE SALT WASH MEMBER OF THE MORRISON FORMATION AS CLUES TO THEIR SOURCES

Regional variation patterns of element concentrations in the uranium deposits may be important in determining sources of elements if the patterns correspond to the distributions of any known geologic features, such as centers of igneous intrusion, areas of structural uplift or subsidence, or petrology and chemistry of the host rock. If a particular element in the deposits was derived largely from the intrusive rocks, for example, the regional variation of this element in the deposits may correspond in some way to the regional distribution of the intrusives, or if an element was derived from the host sandstone its distribution in the deposits may correspond partly to its regional distribution in the sandstone.

Geochemically coherent elements (Rankama and Sahama, 1950, p. 48) are related in such a way that higher concentrations of one tend to be associated with high concentrations of others. Geochemical coherence does not necessarily imply chemical coherence or similarity of chemical behavior in the environment in which the elements are or have been present; all that may be involved is a tendency for elements to associate. The reasons for the association may be chemical similarities, but other reasons may have been important. It is apparent that geochemical coherence, as used here, and regional variation are not completely separate properties of element distributions.

Geochemically coherent elements are described by Rankama and Sahama (1950, p. 48) as those elements "which are always found together in Nature." The term "Nature" is interpreted here in a sense which may be more restricted than that intended by Rankama and Sahama. Elements are recognized as geochemically coherent or noncoherent in samples from predefined specific bodies of rock, rock units, or rock types—in this case samples of the uranium ores from the Salt Wash Member of the Morrison Formation. Moreover, it is recognized that there exist varying degrees of geochemical coherence among various elements in different groups of samples.

The geochemical coherence of elements in the uranium deposits is important because it identifies elements that tended to accumulate in the same places, even though they may have responded in different ways to specific chemical and dynamic processes that led to the formation of the deposits. In addition to this, however, geochemical coherence is useful in studying regional variation of the compositions of the deposits because elements that have strong geochemical coherence have similar regional variations among the deposits.

We need not be concerned here with the matter of whether similarity in spatial or regional variation of elements causes geochemical coherence, or whether the opposite is true, because similarity in spatial variation and geochemical coherence, as used here, are nearly the same. However, although elements that are strongly coherent necessarily have the same spatial variation, the opposite may not be true. Elements may have simliar broad-scale regional variations but will not be strongly coherent unless the variations tend to be similar in detail.

Geochemical coherence of minor elements in a group of samples is conveniently measured by the log correlation coefficient (Miesch and Riley, 1961, p. 250) ; log correlation coefficients between some elements in ores from the Salt Wash Member are given in table 1. The ore samples are of mill pulps and have been described by Shoemaker and others (1959, p. 27). It is important to note that they represent mined ore and not various types of mineralized rock that may be associated with the ores but not considered economically valuable in the mining operations. All the elements listed in table 1, except aluminum, are largely extrinsic or introduced in the ores. The log correlation coefficient is the correlation coefficient computed between the logarithms of the element concentrations. Correlation between the logarithms was studied because the frequency distributions of the log element concentrations and correlation surfaces for log concentrations tend to be approximately normal (Hoel, 1954, p. 76, 149). Statistical problems involving highly skewed frequency distributions and correlation surfaces are avoided.

The skewness appears not to be related entirely to the sampling plan and the broad regional variation of the composition of the uranium deposits, because it is also found in samples taken from a single mining district and from a single mine. High skewness may be related in part to the nature of the analytical error introduced by the spectrographic method. Evidence of this is the fact that replicate determinations of an element concentration in a single sample tend to exhibit a skewed distribution. Skewed distributions, however, also arise in replicate determinations by other analytical methods.

Geochemical coherence, as measured by the log correlation coefficient, does not necessarily indicate a direct relation between elements. Many correlations are spurious, occurring because the elements have only indirect relationships to each other. This does not alter the fact that the elements tend to be associated in the rock samples being studied; it is important only in the interpretation of why the elements tend to

TABLE 1.—*Correlation coefficients, r, between logarithms of element concentrations in uranium ore samples from the Salt Wash Member of the Morrison Formation* [1]

	Fe	Ag	As	Co	Cu	Mo	Ni	Pb	Se	U	V	Y	Zn
Al	0. 25	0. 31	−0. 12	0. 15	0. 41	0. 13	0. 14	0. 42	0. 06	0. 05	0. 44	0. 23	0. 08
Fe		. 06	. 34	. 42	. 12	. 44	. 50	. 19	. 44	. 17	. 19	. 33	. 29
Ag			. 10	. 17	. 78	. 14	. 02	. 72	−. 02	−. 06	. 27	. 12	. 21
As				. 57	. 08	. 51	. 52	. 15	. 41	. 17	−. 05	. 29	. 40
Co					. 15	. 53	. 78	. 25	. 35	. 15	. 06	. 55	. 33
Cu						. 17	. 03	. 66	. 03	−. 04	. 29	. 10	. 14
Mo							. 54	. 24	. 40	. 08	−. 01	. 13	. 32
Ni								. 10	. 36	. 11	. 03	. 49	. 24
Pb									. 09	. 10	. 30	. 18	. 32
Se										. 34	. 13	. 10	. 28
U											. 29	. 09	. 18
V												. 19	. 02
Y													. 25
Zn													

[1] Each coefficient is based on 215 pairs of analyses. The analyses were made on mill-pulp samples (Shoemaker and others, 1959, p. 27). Arsenic, selenium, and zinc were determined by colorimetric methods. Other elements were determined by a semiquantitative spectrochemical method (Myers and others, 1961).

be associated. The correlation coefficients in table 1 are actually only a first approximation to a thorough study of the relations among the elements in the uranium deposits. Further study, using statistical techniques such as partial correlation and multiple correlation and regression, may help unravel some of the complex relations not recognizable by simple correlation methods.

The antilogarithms of the numbers on which the correlation coefficients in table 1 were computed are compositional data and, as such, are expressed in units of weight per total weight. Thus, they are a part of an array of numbers which has a constant sum, and the problem of interpreting correlation coefficients among the numbers may require interpretation of the effect of the constant sum, as described by Chayes (1960, p. 4190). Chayes' mathematical analysis of the problem cannot apply strictly here because the sums of the logs of compositional data are not constant, but the same underlying principles affect the correlations to some unknown degree. The effect is probably small because most of the elements considered are present in only minor quantities.

Examination of the correlation coefficients, *r*, in table 1 shows that the elements may be classed into 4 groups and 3 subgroups on the basis of geochemical coherence, according to the scheme shown in figure 2. All elements within a subgroup have at least moderate correlations with every other element in the subgroup. Elements within a group, but in different subgroups, have high to moderate or weaker correlations with each other. Elements in different groups have few or no significant correlations with each other (the lowest significant correlation coefficient for 200 pairs is 0.18 at the 99-percent confidence level and 0.14 at the 95-percent confidence level.) All elements in Group 1 (fig. 2) have moderate or nearly moderate correlations with iron, and none, except yttrium, has a significant (99-percent level) correlation with aluminum. All elements in Group 2 have moderate or nearly moderate correlations with aluminum, and their correlations with iron are lower than moderate. Elements in Groups 3 and 4, vanadium and uranium, respectively, do not have moderate or higher correlations with any of the other extrinsic elements studied. Examination of the low correlation coefficients, however, suggests that vanadium in the deposits has greater affinities for aluminum and Group 2 elements than for the Group 1 elements.

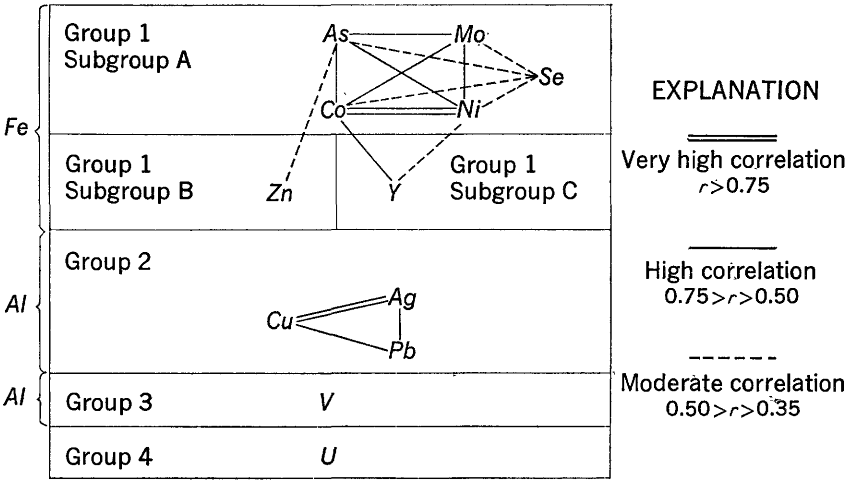

FIGURE 2.—Groups of geochemically coherent elements in uranium ores from the Salt Wash Member of the Morrison Formation on the Colorado Plateau (based on data from table 1).

The regional variations of elements in uranium deposits in the Salt Wash Member are complex because the concentrations of the elements vary widely even for closely spaced deposits in the same mining district, but variations between average compositions of deposits in widely separated areas are also large. As the area of interest here is the entire Colorado Plateau, an attempt was made to smooth out local variations in compositions in order to see the nature of the broader regional variations more clearly. This was done by a moving average method, whereby averages were computed for overlapping areas. A grid overlay was placed on a map showing the distribution of deposits; the grid interval was equivalent to 16 miles and the origin of the grid was placed at the common corner of the States of Utah, Colorado, New Mexico, and Arizona. The average (geometric mean) composition of all deposits within a 16-mile radius of each grid point was then computed and plotted on separate overlays for each element. The mean element concentrations plotted at the grid points were then classified into ranges and representative symbols were plotted on the final maps.

The samples and analyses used in examining the regional variations of elements among the deposits are the same as those used in examining geochemical coherence (table 1). The distribution of deposits represented by the samples is given in figure 3.

The regional variation pattern for cobalt in uranium deposits in the Salt Wash Member (pl. 1*A*) shows that cobalt tends to be more highly concentrated in deposits on the western and northwestern parts of the plateau; highly geochemically coherent nickel, arsenic, and molybdenum must display similar patterns. Similarly, selenium (pl. 1*B*), zinc (pl. 1*C*), and yttrium (pl. 1*D*) tend to be more highly concentrated in deposits on the western and northwestern parts of the plateau, though zinc also tends to be highly concentrated in deposits in the vicinity of salt anticlines, and the distribution of yttrium is partly erratic. Iron (pl. 1*E*), as may be expected from its geochemical coherence, also tends to be more highly concentrated in deposits on the western and northwestern parts of the plateau. The distribution of copper in the deposits (pl. 1*F*) is clearly related to the distribution of the salt anticlines, and groups of deposits in the Salt Wash Member that are rich in copper occur almost exclusively in the area containing these structures. Silver and lead, which are geochemically coherent with copper, have a similar regional distribution. The regional variation pattern of vanadium (pl. 1*G*) in the deposits shows that, in general, vanadium tends to be more highly concentrated in deposits on the eastern part of the plateau, but a striking exception to this general pattern exists in the vicinity of the Henry Mountains laccoliths on the western part of the plateau. Ores from

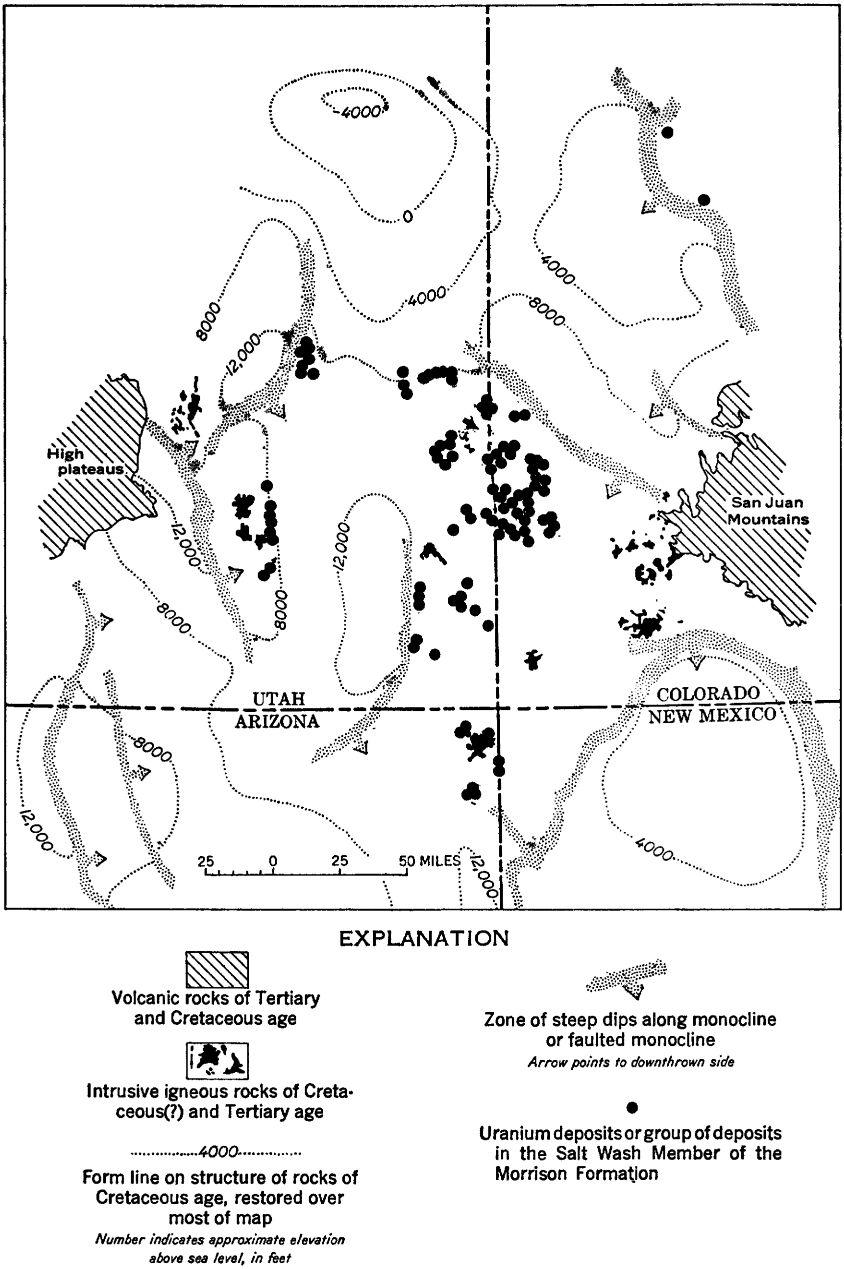

FIGURE 3.—Tectonic sketch map of part of the Colorado Plateau region (modified from Shoemaker, 1956a) showing locations of uranium deposits that were sampled in the Salt Wash Member of the Morrison Formation.

uranium deposits in the Salt Wash Member in this area are generally richer in vanadium than ores from any other deposits in this member elsewhere on the plateau.

The regional variation pattern of uranium in the deposits could not be determined because the mill-pulp samples that were studied represent ore shipments that are biased with respect to uranium grade. Commonly, ores were selectively mined and mixed before shipment to the mills in order to attain grades that would yield the highest profit. The optimum uranium grade for a particular ore shipment was determined by characteristics of the mine operation and various regulations and payment procedures administered by the U.S. Atomic Energy Commission. Fortunately, the uranium grade of an ore shipment is not strongly related (geochemically coherent) to the concentrations of other elements in the ore (table 1; fig. 2), and the concentrations of other elements in the shipments are generally not affected by these mining practices.

Therefore, at least three general types of regional variation patterns are exhibited by the minor elements in uranium ores in the Salt Wash Member. Iron, cobalt, nickel, molybdenum, arsenic, selenium, zinc, and yttrium tend to be more highly concentrated in deposits to the west and northwest; copper, silver, lead, and zinc tend to be high in deposits in the area of the salt anticlines; vanadium tends to be high in deposits to the east but appears to be exceptionally high in deposits in the vicinity of the Henry Mountains to the west.

None of the regional variation patterns appear to correspond to the distribution of igneous centers on the plateau or to the distribution of broad structural features, except to the salt anticlines. The Salt Wash Member in the salt anticline area has been fractured to a greater extent than is common in other large areas on the plateau, and the fractures are known to contain vein-type deposits of copper, lead, zinc, and silver (Fischer, 1936), the same elements which tend to be highly concentrated in the uranium deposits in this area. Moreover, Shawe and others (1959, p. 403, 411) found that copper and lead are distinctly more abundant in uranium deposits in and near a zone of faults on the Dolores salt anticline (fig. 1) than in deposits more distant from the faults. Thus, the distributions of copper and lead are related to faults associated with salt anticlines, not only on a broad regional scale, but also on more detailed scales. Shawe and others (1959, p. 411) report further than molybdenum and "some other" trace elements in deposits on the Dolores anticline show no recognizable patterns of distribution relative to the fault zone.

Each of the three general types of regional variation patterns corresponds at least roughly to the regional variation of some petrographic or chemical feature of the host sandstone. Tuff fragments appear to be more abundant in sandstones from the Salt Wash Member on the western part of the plateau (pl. 2*A*), perhaps because the tuff emanated from volcanic sources to the west in the Great Basin area during Late Jurassic time, when the Salt Wash Member was deposited on the plateau. Western and northwestern sources of tuff in sandstones of the Salt Wash and Brushy Basin Members are suggested by Craig and others (1955, p. 149–151) and Craig and Cadigan (1958, p. 191). The regional variation of tuff fragments in sandstone of the Salt Wash Member is similar to the regional variation of iron, cobalt, nickel, molybdenum, arsenic, selenium, zinc, and yttrium in the Salt Wash uranium deposits.

Heavy minerals in sandstone of the Salt Wash Member tend to be more abundant on the eastern part of the plateau and in this respect correspond to the regional variation of vanadium in the uranium deposits (pl. 2*B*). Heavy minerals in the Salt Wash Member consist mostly of black opaque minerals, and these have been suggested as a possible source of vanadium and other elements in the uranium deposits by Shawe and others (1959, p. 413–414). A significant part of the iron in sandstones from the Salt Wash Member is contained in black opaque heavy minerals, and the regional variation of iron in the Salt Wash is similar to that of heavy minerals (pl. 2*C*).

Unmineralized sandstones of the Salt Wash in the area of the salt anticlines tend to contain relatively high concentrations of copper (pl. 2*D*), as do Salt Wash uranium deposits in the same area. It is unknown whether the copper was deposited in the sandstone syngenetically or introduced later, perhaps from the same solutions which deposited veins of copper in the salt anticline area.

The regional variation pattern of uranium in unmineralized sandstones of the Salt Wash is complex (pl. 2*E*) and shows no correspondence to other variation patterns determined in this study or to the regional distribution of known uranium deposits in the Salt Wash Member. (See Finch, 1955.)

COMPOSITION OF THE FRENCHY INCLINE DEPOSIT AND ITS BEARING ON THE PROBLEM OF SOURCE

Having considered the regional variation of elements in uranium deposits in the Salt Wash Member of the Morrison Formation over the entire Colorado Plateau and the geochemical coherence of the elements, and having gained some clues regarding sources of the elements, a more detailed analysis is now presented of the distribution of elements in and around a single deposit. The chemical compositions of mineralized and unmineralized rocks in and adjacent to the Frenchy Incline uranium deposit, which is rather typical of the uranium deposits in the Salt Wash Member of the Morrison Formation, are examined and compared with the compositions of other mineralized and unmineralized rocks from the Salt Wash Member on other parts of the plateau. This is done mainly to determine the quantitative aspects of the chemical changes that have occurred with ore formation, especially the amount of each element that was added to the sandstone and mudstone to form the ore.

DESCRIPTION AND GEOLOGIC SETTING OF THE FRENCHY INCLINE URANIUM DEPOSIT

The Frenchy Incline uranium deposit is in the Legin mining area in southwest Colorado (fig. 1), approximately 4 miles northwest of Egnar. The geology of the Egnar quadrangle has been described by Cater (1955).

The Legin area is on the southwest flank of the Dolores anticline, an asymmetrical arch with gently dipping flanks underlain by thickened masses of salt in the Paradox Member of the Hermosa Formation of Pennsylvanian age. According to Cater, dips on the northeast flank of the Dolores anticline are as much as 7° whereas those on the southwest flank are $1\frac{1}{2}°$ or less. Exposed sedimentary units in the Egnar quadrangle are principally sandstones and shales of Jurassic and Cretaceous age (fig. 4).

All the known uranium ore in the Legin area is in the upper sandstone lens of the Salt Wash Member of the Morrison Formation. This lens consists of medium- to fine-grained sandstone composed largely of subangular quartz grains in a matrix of carbonate minerals and clay. Carbonate minerals form 5 to 10 percent of the sandstone and clay less than 5 percent. Small amounts of altered tuffaceous fragments, potassium feldspar, and minor accessory minerals are also present. Within the mining area most of the lens is light brown, but the parts of the lens more distant from mineralized rock are reddish brown. Thin mudstone layers adjacent to ore are green, but some mudstone in the upper parts of the sandstone lens is reddish brown.

Sandstone in the lower parts of the Salt Wash Member in the Legin area is not greatly different texturally and mineralogically from the upper sandstone lens, but there is a pronounced difference in color. In the area containing most of the deposits, the sandstone lenses beneath the upper lens are reddish brown rather than light brown, and all of the mudstone within the lower lenses and between them is similarly reddish brown.

Less than a mile southwest of the area containing most of the uranium deposits, where the entire Salt Wash Member is exposed, all but the lowermost lenses are light brown, and the relationships shown diagrammatically on the cross section in figure 4 appear to be present.

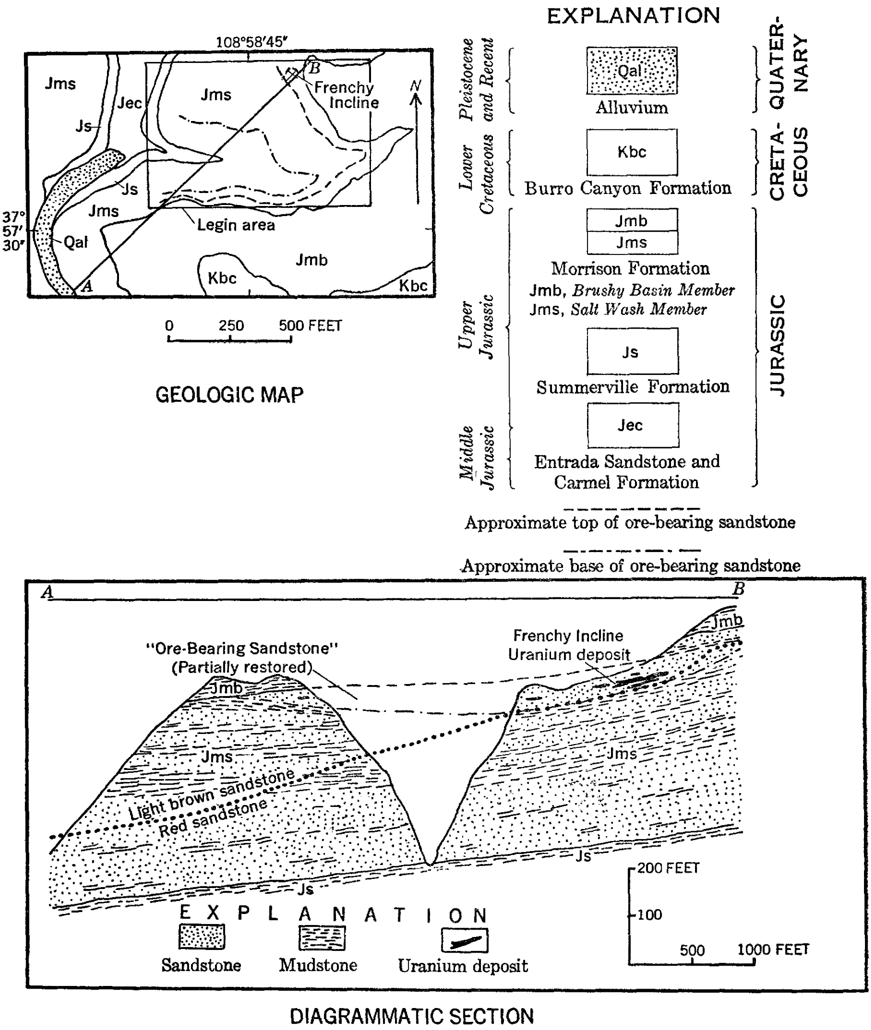

FIGURE 4.—Geologic map and diagrammatic cross section of the Legin area and vicinity, San Miguel County, Colo. (adapted from Cater, 1955, and Henry Bell, written communication, 1952).

The color difference in the sandstones is due to the different colors of the interstitial clay and iron minerals. In reddish sandstones iron is contained largely in magnetite and hematite, whereas in light-brown sandstones some, commonly most, of the iron is in pyrite (Shawe and others, 1959, p. 405) and various hydrated iron oxides collectively referred to as limonite.

Most of the upper sandstone lens of the Salt Wash Member in the Legin area meets the requirements tabulated by Weir (1952, p. 26) for sandstone favorable for the occurrence of uranium ore, and extensive drilling in the area has shown that minable ore is distributed rather evenly throughout the favorable part of the sandstone lens (Henry Bell, written communication, 1952). The favorable part of the sandstone lens underlies an area of about one-fifth of a square mile and has been penetrated by more than 400 drill holes. In regard to geologic setting, configuration, and chemical and mineralogic composition, the uranium deposits in the Legin area are not unlike the great majority of deposits in the Salt Wash Member of the Morrison Formation on other parts of the Colorado Plateau, and the Frenchy Incline deposit is considered typical of deposits in the Salt Wash Member.

The Frenchy Incline uranium deposit, in the northern part of the Legin area, consists of numerous closely spaced discontinuous layers of mineralized sandstone and mudstone which aggregate about 10,000 tons. The mineralized layers occur 40 to 70 feet below the surface in the lower part of the upper sandstone lens. Many of the mineralized layers cross the bedding in the sandstone at large angles to form rolls, but other layers conform closely to the bedding. The thicker parts of the mineralized layers have been mined out and few layers exceeding 1 foot in thickness remain exposed in the mine. Most of the uranium in the French Incline deposit is in carnotite $(K_2(UO_2)_2(VO_4)_2\cdot 1\text{–}3H_2O$, and although most of the vanadium appears to be present in clay minerals, some corvusite, $V_2O_4\cdot 6V_2O_5\cdot nH_2O$(?), as well as brightly colored pascoite, $Ca_2V_6O_{17}\cdot 11H_2O$, and volborthite, $Cu_3(VO_4)_2\cdot 3H_2O$, were observed. Pascoite is present only as an oxidation product on the walls of the mine workings. Iron is present largely as limonite and hematite, but in lower levels of the mine pyrite is present with corvusite. Small quantities of malachite and azurite are present in some parts of the ore, as well as gypsum in thin irregular seams. Some mineralized layers are rich in carbonized stems and leaves of fossil plants. No carbonized logs are present, but one nonuraniferous silicified log, about 1 foot in diameter, was observed.

The Frenchy Incline deposit underlies an area about 500 feet in length and 150 feet across. Prior to mining, the average total thickness of the mineralized layers at any point within this area was about 2 feet.

COLLECTION OF SAMPLES

During exploration of the Legin area in the period 1948 to 1951, 7 diamond drill cores were taken from mineralized layers in the Frenchy Incline deposit. The holes were drilled vertically from the surface about 50 to 100 feet apart, and 45 feet of mineralized drill core was obtained. The core was split and assayed primarily to determine uranium and vanadium reserves in the deposit. The 45 feet of core was subdivided into 114 individual samples, each about 1 inch in diameter and about 5 inches in average length. The uranium and vanadium assays originally made on these core samples have been used in the present study. In 1955 the samples were analyzed spectrographically for major and minor elements.

In 1953, 28 mill-pulp samples of ore shipments from the Frenchy Incline deposit were obtained from the U.S. Government mill at Monticello, Utah. These are splits of the samples assayed to determine payment to the mine operators; each sample was cut from 20 to 40 tons of mined ore. The mill-pulp samples of highest uranium grade were combined into one composite sample (PMS–79), and the samples of lower uranium grade were combined into another composite sample (PMS–80). The two composite samples were analyzed for selected minor elements.

In 1956, 13 holes were drilled vertically from the surface through the upper sandstone lens around the Frenchy Incline deposit in the interval 10 to 150 feet from known mineralized rock. The holes were placed along three radii extending outward from points directly over the mine; the holes were placed along the radii at geometric intervals, the intervals increasing away from the mine. In addition 3 horizontal holes were drilled from the mine workings outward for 150 feet; 2 of the horizontal holes were collared in mineralized layers, but in each of these holes the drill encountered unmineralized sandstone within 9 feet from the drill collar. None of the horizontal drill holes intersected mineralized rock beyond 9 feet of the mine workings, and only 2 of the 13 vertical holes, both drilled within 30 feet of the mine workings, intersected mineralized layers. Eighty-five samples of unmineralized sandstone were taken from the core of the 13 vertical holes and the 3 horizontal holes at evenly spaced intervals. Twenty samples of unmineralized mudstone were taken of core from holes that penetrated mudstone layers within and immediately above and beneath the upper sandstone lens.

COMPOSITION OF THE URANIUM ORE

Statistical summaries of analyses of the 114 drill-core samples of mineralized rock from the Frenchy Incline deposit are given in table 2, along with the geometric mean composition of uranium ores from 215 other mines in the Salt Wash Member of the Morrison Formation on the Colorado Plateau. The mean composition of ores from other deposits was computed partly from data originally presented by Shoemaker and others (1959) and subsequently revised. Partial analyses of the two composite mill-pulp samples (PMS–79 and PMS–80) are given in table 3.

TABLE 2.—*Mean compositions (in percent) of uranium ore samples from the Frenchy Incline mine and other mines in the Salt Wash Member of the Morrison Formation*

1	2	3	4	5	6
Element[1]	Drill core samples from the Frenchy Incline mine				Mill-pulp samples from 215 other mines[5]
	Detection ratio[2]	Geometric mean (percent) and 99-percent confidence interval	Geometric deviation[3]	Arithmetic mean[4] (percent)	Geometric mean (percent) and 99-percent confidence interval
Al	114:114	2.1 ×÷1.2	2.1	2.8	2.5 ×÷1.2
Fe	114:114	1.1 ×÷1.1	1.5	1.2	.87 ×÷1.1
Ca	114:114	.95 ×÷1.4	4.4	2.8	2.0 ×÷1.2
Mg	114:114	.30 ×÷1.2	2.2	.40	.76 ×÷1.2
Na	65:114	≈.05	-----------	≈.08	.11 ×÷1.2
K	89:114	≈.8	-----------	≈1.	≈.6
Ag	30:114	≈.00003	-----------	≈.00005	≈.00005
B	31:114	≈.001	-----------	≈.002	≈.002
Ba	114:114	.055 ×÷1.2	2.2	.074	.075 ×÷1.2
Be	17:114	≈.00004	-----------	≈.00006	≈.00003
Co	75:93	.00042 ×÷1.2	2.2	.00056	.0011 ×÷1.2
Cr	114:114	.0015 ×÷1.2	1.8	.0018	.0016 ×÷1.1
Cu	114:114	.0093 ×÷1.2	1.9	.011	.0090 ×÷1.3
Ga	5:114	≈.00006	-----------	≈.00009	≈.00008
La	1:114	≈.0003	-----------	≈.0005	≈.0004
Mn	114:114	.028 ×÷1.2	2.2	.038	.031 ×÷1.1
Mo	64:114	≈.0002	-----------	≈.0003	≈.002
Ni	112:114	.00091 ×÷1.1	1.8	.0011	.00098 ×÷1.2
Pb	89:114	.0031 ×÷1.6	6.0	[6] .015	.0096 ×÷1.2
Sc	0:114	<.0001	-----------	<.0002	≈.0001
Sr	114:114	.023 ×÷1.2	1.8	.027	.012 ×÷1.1
Ti	114:114	.055 ×÷1.1	1.6	.061	.095 ×÷1.1
U	114:114	.084 ×÷1.6	6.3	[6] .45	.15 ×÷1.1
V	114:114	.49 ×÷1.3	3.0	[6] .90	.68 ×÷1.2
Y	57:114	≈.0005	-----------	≈.0008	.0014 ×÷1.1
Zn	42:114	≈.008	-----------	≈.01	≈.01
Zr	114:114	.010 ×÷1.2	2.3	.014	.021 ×÷1.1

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[1] Concentrations of all elements except uranium and vanadium were determined by a semiquantitative spectrographic method. Analyst: R. G. Havens, U.S. Geol. Survey. Concentrations of uranium and vanadium in drill-core samples determined by fluorimetric and wet chemical methods, respectively; data from Henry Bell (written communication, 1952). Concentrations of uranium and vanadium in mill—pulp samples determined at various mills and buying stations on the Colorado Plateau.

[2] Detection ratio is the ratio of the number of samples in which the element was detected to the number of samples analyzed. (See plate 3.)

[3] Geometric deviation is the antilog of the standard deviation of the logs of the analyses.

[4] Arithmetic mean estimated from geometric mean and geometric deviation by method of Sichel (1952). See figure 5. Where geometric deviation is unknown the arithmetic mean is considered to be approximately 1.5 times greater than the geometric mean.

[5] See figure 3 for locations of the 215 mines.

[6] Estimated arithmetic means are subject to large error when the geometric deviation is large. Values for Pb, U, and V are not used in subsequent calculations. More accurate values for U and V, taken from mine production records, are 0.18 and 1.12 percent, respectively. A value that is probably more accurate for Pb is given in table 3.

TABLE 3.—*Partial composition of mill-pulp samples of uranium ore from the Frenchy Incline mine*

Element	Composition (in percent)		Weighted average
	Sample PMS-79[1]	Sample PMS-80[1]	
Pb[2]	0.01	0.007	0.009
As[2]	.012	.012	.012
C (organic)[3]	.23	.20	.22
Hg[4]	$<.0001$	$<.0001$	$<.0001$
P_2O_5[5]	.052	.052	.052
S[6]	.06	.07	.06
Sb[2]	.0001	$<.0001$	$<.0001$
Se[7]	.0008	.0005	.0007

[1] Sample PMS-79 was split from 388 tons of uranium ore; sample PMS-80 was split from 282 tons of uranium ore.
[2] Colorimetric analyses, by H. E. Crowe and J. H. McCarthy, U.S. Geol. Survey.
[3] Analyst: Alice Caemmerer, U.S. Geol. Survey.
[4] Analyst: J. J. Fahey, U.S. Geol. Survey.
[5] Analyst: E. C. Mallory, Jr., U.S. Geol. Survey.
[6] Analyst: J. P. Schuch, U.S. Geol. Survey.
[7] Analyst: J. H. McCarthy, U.S. Geol. Survey.

The 114 drill-core samples of mineralized rock were analyzed by a rapid semiquantitative spectrographic method, described by Myers and others (1961). Results of the semiquantitative spectrographic analyses are reported in a series of geometric classes having theoretical class boundaries equal to the concentrations of the elements in the standard samples used to calibrate the method. Each geometric class boundary is 2.15 times greater than the next lower class boundary. When the geometric classes are converted to logarithmic classes each has a width of one-third of a common log unit (pl. 3). Myers and others (1961, p. 220) report that "* * * several years of experience in applying this method to many routine determinations indicate that similar precision and accuracy are obtained for all elements included in this procedure, that is, the assigned one-third order of magnitude includes the quantitative value at least 60 percent of the time." This amount of variation probably has less effect on the computed mean values than on estimates of variance and geometric deviation.

Although 68 elements are looked for in the analytical procedure fewer than 20 are generally detected. The remainder may be present but in concentrations that are lower than the respective limits of sensitivity for the analytical method. The limits of sensitivity for each element are, in general, those listed by Myers and others (1961, p. 215). Histograms of the analytical data for some elements are truncated at the limits of sensitivity for those elements indicated by vertical dashed lines on plate 3.

The 85 samples of unmineralized sandstone and 20 samples of unmineralized mudstone were analyzed by the same semiquantitative spectrographic procedure used in the analysis of the mineralized samples. Although the unmineralized samples were analyzed more than two years later than the mineralized samples, all spectrographic analyses were made by the same analyst in the same laboratory.

Histograms of the analytical data are more symmetrical on logarithmic scales than or arithmetic scales, and the frequency distributions of the original data appear closer to a lognormal than to a normal form. Thus, the geometric mean of the original data is a more consistent (Fisher, 1950, p. 11) measure of central tendency than the arithmetic mean, and the geometric mean and the geometric deviation are more efficient measures than the arithmetic mean and standard deviation, respectively (Fisher, 1950, p. 11–12). A consistent measure of central tendency is one that tends toward the true mode of the population from which the sample is drawn; an efficient statistic is the one that is the most stable (least subject to change with the addition of new data). The geometric mean is the antilogarithm of the arithmetic mean of the logs of the analyses; the geometric deviation is the antilogarithm of the standard deviation of the logs of the analyses.

The error of the mean log of the analyses is taken as:

$$\text{Error of mean log} = \pm\, ts/\sqrt{n-1}, \quad \text{(Hoel, 1954, p. 226)}$$

where n is the number of analyses, s is the standard deviation of the logs of the analyses, and t is an error term taken from a table of t (Fisher and Yates, 1953, p. 40) for a given probability and $n-1$ degrees of freedom. Consequently, the error of the geometric mean (column 3, table 2) is taken as:

$$\text{Error of the geometric mean} \quad \overset{\times}{\div} 10^{(ts/\sqrt{n-1})}$$

Although in comparison to the arithmetic mean the geometric mean of the analyses is the more consistent measure of central tendency of the population of analyses from which the data were drawn and is, therefore, a better estimate of the typical or characteristic abundance of the element in the individual samples, the arithmetic mean of the analyses is still a necessary statistic. The arithmetic mean more closely approximates the concentration present in a composite prepared by combining the individual samples (Miesch and Riley, 1961, p. 249) and, therefore, is a better estimate of the true abundance of the element in the rock body represented by the samples. The geometric mean characterizes the samples whereas the arithmetic mean gives an estimate of the absolute amount of the element present in the rock body, the amount, for example, that is available for extraction in a milling operation.

In connection with his work on gold ores of the Witwatersrand, Sichel (1947, p. 403–407; 1952, p. 263) demonstrated that the arithmetic mean of assays of representative samples from an ore body is the correct expression of the abundance of metal in the ore body, but he pointed out that samples from a mine are commonly too few in number to be representative. Because of this, the true arithmetic mean is estimated better by methods other than the common method of dividing the sum of a number of assays by this number. A method proposed by Finney (1941) but developed independently and introduced into the mining literature by Sichel (1952, p. 267) is used to compute the arithmetic mean of the analyses from their mean log and log variance. The method provides an arithmetic mean estimate which is more efficient (lower variance) than that provided by the ordinary method of computation but also has the advantage of being usable in studies where analytical data are provided in geometric classes, where computation of the arithmetic mean by the ordinary method is not possible. An equation and tables given by Sichel (1952, p. 275, 284–288) are expressed here as curves showing the arithmetic mean: geometric mean ratio of a lognormal distribution as a function of the variance of the logarithms to the base 10 of the data or as a function of the geometric deviation of the data (fig. 5). Various curves are given for various numbers of analyses being studied.

When an element was detected in only some of the samples analyzed (see detection ratio, column 2, table 2) geometric and arithmetic means were estimated by approximate methods. When the element was undetected in only a few of the samples analyzed, the concentrations of the element in these samples were assumed to fall in the spectrographic class immediately below the limit of sensitivity for that element. (See, for example, the distribution of cobalt in mudstones and of chromium in sandstones, pl. 3.) Geometric and arithmetic means and geometric deviations were then computed by the same methods used when the element was detected in all of the samples analyzed. If the element was not detected in a larger number of the analyzed samples a second approximate method was used (Miesch and Riley, 1961, p. 248-294). This method is based on two assumptions, (1) that the total frequency distribution of the logs of the element concentrations approximates a normal curve, and (2) that the standard deviation of this distribution is equal to the mean log standard deviation of all elements whose log standard deviation is known. Proceeding with these assumptions, the mean log silver content of uranium ore samples (pl. 3), for example, is taken as 0.64 units of log standard deviation below the log of the sensitivity of the analyses for silver, or the point of truncation of the histogram on plate 3. The figure 0.64 is determined from a table of

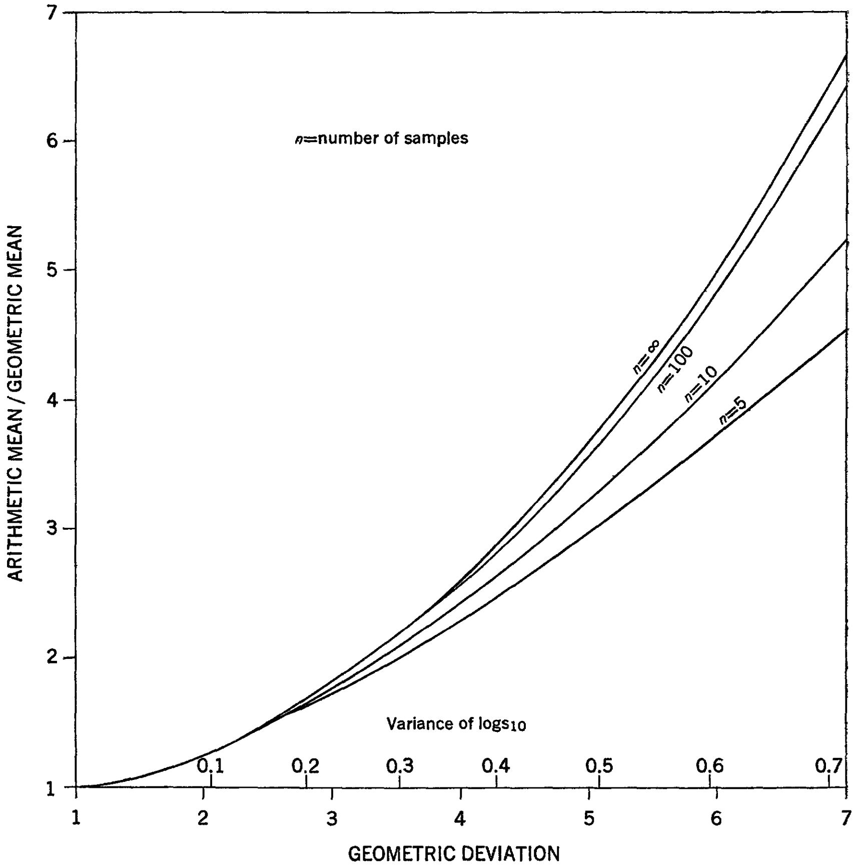

FIGURE 5.—Graphs showing relation of arithmetic mean: geometric mean ratio to log variance and geometric deviation according to equation of Sichel (1952, p. 275).

areas under the normal curve, such as that given by Hoel (1954, p. 315) or Waugh (1943, p. 509). As 74 percent of the area under the frequency curve of concentrations of silver in ore samples (pl. 3) lies below the sensitivity of the analyses, and 50 percent must lie below the mean, 24 percent of the area under the curve lies between the mean and the sensitivity. When the geometric mean is estimated, the arithmetic mean is taken as about 1.5 times greater because arithmetic means which are known more precisely are commonly about 1.5 times greater than the corresponding geometric means.

When an element was detected in none of the analyzed samples only a maximum estimate of the mean could be given. This maximum was taken as two mean log standard deviations below the limit of sensitivity of the analyses because if the mean were higher by any considerable amount the element should have been detected in a small number of the analyzed samples. This procedure, again, rests on the two previous assumptions regarding the form of the distribution and its standard deviation. Estimates of means based on these assumptions are only approximate and are subject to revision when more complete analytical data are available. For the present they provide the most complete interpretation of the means of data represented on plate 3.

As an example in reading table 2, the distribution of calcium in uranium ore from the Frenchy Incline deposit may be interpreted as follows. The most characteristic or frequently encountered calcium concentration in drill-core samples is given by the geometric mean 0.95 percent, and we may be about 99 percent confident that the true geometric mean lies within the range 0.95÷1.4 to 0.95×1.4 (0.68 to 1.3) percent. If the sampling, analyses, and computations were repeated 100 times, 99 of the computed geometric means would theoretically lie within this range. Approximately two-thirds of the concentrations of calcium in drill-core samples which could be taken from the deposit should lie within the range of the geometric mean divided by the geometric deviation (0.95÷4.4) to the geometric mean times the geometric deviation (0.95×4.4); the range extends from 0.22 to 4.2 percent. Approximately 95 percent of the concentrations should lie within the range $0.95\div(4.4)^2$ to $0.95\times(4.4)^2$, or 0.049 to 18.4 percent. According to the computed arithmetic mean, the Frenchy Incline deposit consists of 2.8 percent calcium, and if the deposit is 10,000 tons it contains 10,000×0.028 (280) tons of calcium.

In column 6 of table 2 the geometric mean composition of mill-pulp samples of ores from 215 other mines in the Salt Wash Member of the Morrison Formation is given for comparison purposes. As the mill-pulp samples represent relatively large portions of uranium deposits, their geometric mean composition is thought to characterize the deposits, or represent the composition of a typical deposit. The arithmetic mean composition of the drill-core samples from the Frenchy Incline deposit is an estimate of the composition of this deposit and is appropriate for comparison with the geometric mean composition of other deposits. The composition of the Frenchy Incline deposit apparently is not greatly different from that of typical ore from other deposits in the Salt Wash Member, except with regard to a few elements notably molybdenum, cobalt, and strontium (table 2).

COMPOSITION OF THE UNMINERALIZED HOST ROCKS

The geometric and arithmetic mean compositions of unmineralized sandstones and mudstones adjacent to the Frenchy Incline uranium deposit are given in tables 4 and 5, respectively. The statistics were computed and are interpreted in the manner described in the preceding section.

TABLE 4.—*Mean compositions (in percent) of sandstones from the Salt Wash Member of the Morrison Formation in the Frenchy Incline mine area and in other areas on the Colorado Plateau*

1	2	3		4	5	6	
Element[2]	Drill-core samples from the Frenchy Incline mine area					Outcrop samples from 66 other areas[1]	
	Detection ratio[3]	Geometric mean (percent) and 99 percent confidence interval		Geometric[4] deviation	Arithmetic mean[5] (percent)	Geometric mean (percent) and 99-percent confidence interval	
Al	85:85	1.5	$\overset{\times}{\div}1.2$	1.8	1.8	1.2	$\overset{\times}{\div}1.2$
Fe	85:85	.29	$\overset{\times}{\div}1.2$	2.1	.38	.27	$\overset{\times}{\div}1.2$
Ca	85:85	2.3	$\overset{\times}{\div}1.4$	2.9	4.0	2.9	$\overset{\times}{\div}1.4$
Mg	85:85	.25	$\overset{\times}{\div}1.3$	2.5	.38	.24	$\overset{\times}{\div}1.3$
Na	37:85	≈.04		-----	≈.06	≈.1	
K	22:85	≈.3		-----	≈.5	≈.5	
Ag	11:85	≈.00002		-----	≈.00003	≈.000003	
B	27:85	≈.001		-----	≈.002	≈.001	
Ba	85:85	.044	$\overset{\times}{\div}1.4$	3.3	.090	.032	$\overset{\times}{\div}1.3$
Be	0:85	<.00002		-----	<.00003		
Co	26:85	≈.0001		-----	≈.0002	≈.00005	
Cr	78:85	.00028	$\overset{\times}{\div}1.3$	2.4	.00041	.00086	$\overset{\times}{\div}1.3$
Cu	85:85	.0016	$\overset{\times}{\div}1.4$	3.6	.0036	.0017	$\overset{\times}{\div}1.3$
Ga	2:85	≈.00003		-----	≈.00005	≈.00007	
La	0:85	<.0003		-----	<.0005		
Mn	85:85	.019	$\overset{\times}{\div}1.3$	2.8	.032	.022	$\overset{\times}{\div}1.3$
Mo	4:85	≈.00005		-----	≈.00008	≈.00003	
Ni	47:85	≈.0001		-----	≈.0002	≈.00008	
Pb	25:85	≈.0003		-----	≈.0005	≈.00007	
Sc	5:85	≈.0001		-----	≈.0002	≈.00004	
Sr	85:85	.0067	$\overset{\times}{\div}1.3$	2.4	.0097	.0057	$\overset{\times}{\div}1.2$
Ti	85:85	.070	$\overset{\times}{\div}1.2$	1.7	.080	.053	$\overset{\times}{\div}1.2$
U	7:85	≈.00006		-----	≈.00009	.00018	$\overset{\times}{\div}1.2$
V	85:85	.0036	$\overset{\times}{\div}1.5$	3.7	.0085	.0012	$\overset{\times}{\div}1.3$
Y	39:85	≈.0005		-----	≈.0008	≈.0002	
Zn	0:85	<.002		-----	<.003	≈.001	
Zr	85:85	.012	$\overset{\times}{\div}1.2$	1.9	.014	.0089	$\overset{\times}{\div}1.3$

[1] Data from W. L. Newman (1958, written communication). See plate 2*C* or 2*D* for locations of areas.

[2] Concentrations of all elements except uranium were determined by a semiquantitative spectrographic method. Analyst: R. G. Havens, U.S. Geol. Survey. Concentrations of uranium in drill core samples determined by chromatographic method. Analyst: C. E. Thompson, U.S. Geol. Survey. Concentrations of uranium in outcrop samples determined by fluorimetric method. Analysts: Wayne Mountjoy and Jesse Meadows, U.S. Geol. Survey.

[3] Detection ratio is the ratio of the number of samples in which the element was detected to the number of samples analyzed. (See plate 3.)

[4] Geometric deviation is the antilog of the standard deviation of the logs of the analyses.

[5] Arithmetic mean estimated from geometric mean and geometric deviation by method of Sichel (1952). See figure 5. Where geometric deviation is unknown the arithmetic mean is considered to be approximately 1.5 times greater than the geometric mean.

TABLE 5.—*Mean composition (in percent) of mudstone samples from the Salt Wash Member of the Morrison Formation in the Frenchy Incline mine area*

1	2	3	4	5
Element[1]	Detection ratio[2]	Geometric mean (percent) and 99-percent confidence interval	Geometric deviation[3]	Arithmetic mean[4] (percent)
Al	20:20	9.3 $\overset{\times}{\div}1.4$	1.7	10.7
Fe	20:20	1.7 $\overset{\times}{\div}1.3$	1.5	1.9
Ca	20:20	3.7 $\overset{\times}{\div}2.2$	3.3	7.4
Mg	20:20	1.2 $\overset{\times}{\div}1.3$	1.6	1.3
Na	20:20	.21 $\overset{\times}{\div}1.3$	1.5	.23
K	20:20	4.1 $\overset{\times}{\div}1.3$	1.5	4.5
Ag	4:20	.00003	-------------	.00005
B	20:20	.0063 $\overset{\times}{\div}1.4$	1.7	.0072
Ba	20:20	.036 $\overset{\times}{\div}1.3$	1.6	.040
Be	11.20	.0001	-------------	.00015
Co	19:20	.00045 $\overset{\times}{\div}1.7$	2.2	.00061
Cr	20:20	.0018 $\overset{\times}{\div}1.3$	1.6	.0020
Cu	20:20	.0035 $\overset{\times}{\div}1.6$	2.0	.0045
Ga	14:20	.00045 $\overset{\times}{\div}1.8$	2.5	.00068
La	9:20	.002	-------------	.003
Mn	20:20	.030 $\overset{\times}{\div}1.7$	2.3	.042
Mo	1:20	.00009	-------------	.0001
Ni	20:20	.0015 $\overset{\times}{\div}1.3$	1.4	.0016
Pb	19:20	.0026 $\overset{\times}{\div}2.2$	3.4	.0054
Sc	20:20	.0010 $\overset{\times}{\div}1.4$	1.6	.0011
Sr	20:20	.025 $\overset{\times}{\div}1.4$	1.8	.030
Ti	20:20	.28 $\overset{\times}{\div}1.3$	1.6	.31
U	9:20	.0002	-------------	.0003
V	20:20	.020 $\overset{\times}{\div}1.9$	2.7	.033
Y	20:20	.0030 $\overset{\times}{\div}1.3$	1.5	.0033
Zn	0:20	<.003	-------------	<.005
Zr	20:20	.021 $\overset{\times}{\div}1.3$	1.5	.023

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[1] Concentrations of all elements except uranium were determined by a semiquantitative spectrographic method. Analyst: R. G. Havens, U.S. Geol. Survey. Concentrations of uranium determined by a chromatography method. Analyst: C. E. Thompson, U.S. Geol. Survey.

[2] Detection ratio is the ratio of the number of samples in which the element was detected to the number of samples analyzed. See plate 3.

[3] Geometric deviation is the antilog of standard deviation of the logs of the analyses.

[4] Arithmetic mean estimated from geometric mean and geometric deviation by method of Sichel (1952). (See figure 5.) Where geometric deviation is unknown the arithmetic mean is considered to be approximately 1.5 times greater than the geometric mean.

The samples of unmineralized sandstone and mudstone were taken originally in a search for metal zoning or geochemical halos in the host rock adjacent to the Frenchy Incline mine, but thorough study of the data shows little evidence of metal zoning within 150 feet of the deposit.

In comparing the mean compositions of sandstone from the Frenchy Incline mine area and from other areas on the plateau (table 4) it is probably most appropriate to compare the geometric means. The samples from other areas are about the same size as the drill-core samples from the mine area. Except for a few elements, the geometric mean composition of sandstones from the Frenchy Incline mine area is not greatly different from that of sandstones from other areas. Some of the differences may possibly be due to the fact that the samples from other areas were taken from outcrops and may be impoverished or enriched in minor elements as a result of weathering, but no evidence for this is known. Most of the samples from the Frenchy Incline mine area are light brown, whereas those from other parts of the plateau are, in large part, reddish brown. However, Newman and Elston (1959, p. 135–136) and Newman (1962, p. 420) have shown that the colors of sandstones and mudstones from the Salt Wash Member in the same area have little relationship to their bulk chemical compositions.

The geometric mean concentrations of silver, lead, and vanadium appear to be significantly higher in the sandstones from the mine area, and the geometric mean concentration of uranium in these sandstones appears to be significantly lower. The occurrence of low concentrations of uranium in altered sandstone near the deposit is inconsistent with results from previous studies in the Henry Mountains area of Utah (Miesch and Connor, 1956, p. 137).

QUANTITIES OF EXTRINSIC ELEMENTS

The mineralized rock in the Frenchy Incline uranium deposit consists of both sandstone and mudstone, and it is likely that prior to mineralization it was similar in composition to unmineralized sandstone and mudstone which occurs on the periphery of the deposit. The latter may have been somewhat altered in bulk chemical composition during mineralization but not by a great amount judging from the comparison of sandstones from the mine area with sandstones from other areas on the Colorado Plateau (table 4). Selective mineralization of sandstones rich or deficient in certain elements probably occurred, but this process must have been directed toward only a few elements, such as organic carbon in coalified plant remains or calcium in carbonate minerals.

Ore from the Frenchy Incline deposit contains 2.8 percent aluminum (table 2), an amount equivalent to that in a hypothetical mixture of 89 percent sandstone (containing 1.8 percent aluminum; table 4) and 11 percent mudstone (containing 10.7 percent aluminum; table 5). Assuming that none of the aluminum was added to the deposit with mineralization, the lithologic composition of the deposit was probably close to 89 percent sandstone and 11 percent mudstone. This proportion checks roughly with visual estimates made in the mine. This proportion may be used to obtain an estimate of the intrinsic or original composition of the Frenchy Incline deposit. The intrinsic composition of the deposit is the composition the rock which now forms the deposit would have if mineralization had not occurred (Shoemaker and others, 1959, p. 35).

The extrinsic or introduced amount of an element in the deposit is estimated by subtracting the estimated intrinsic amount from the actual amount present. Estimated extrinsic amounts of elements in the Frenchy Incline deposit are given in table 6. The estimated extrinsic quantities of the elements are the quantities believed to have been added to the deposit with mineralization but not necessarily at the same time nor by exactly the same process. Elements that have only a slightly lower mean concentration in the hypothetical composite (column 2, table 6) than in the uranium ore (column 3, table 6) are regarded as entirely intrinsic, unless, as in the case of silver, the element is known to be partly extrinsic in some other uranium ores in the Salt Wash Member on the Colorado Plateau. Only calcium, titanium, and possibly scandium are significantly more highly concentrated in the hypothetical composite than in the uranium ore. These elements could have been leached during the formation of the deposit, but it is also possible, especially in the case of calcium, that rocks containing low concentrations of these elements were selectively mineralized (Miesch and others, 1960, p. 28).

Table 6 shows that about one-third of the silver in the Frenchy Incline deposit, about one-half of the iron and strontium, about two-thirds of cobalt, nickel, chromium, copper, and molybdenum, and virtually all the lead, zinc, uranium, and vanadium are estimated to be extrinsic. All these elements, except strontium, are major or minor constituents of minerals common in low-valent types of uranium ores in the Salt Wash Member. Pyrite is found in nearly all low-valent ores, and most of the pyrite contains detectable quantities of nickel and cobalt in addition to selenium (Coleman and Delevaux, 1957, p. 506). Chromium occurs in a green-colored chromium-bearing micaceous mineral which is associated with some uranium ores in the Salt Wash Member of the Morrison Formation and is found

Table 6.—*Estimated quantities of extrinsic elements in the Frenchy Incline uranium deposit*

1	2	3	4	
Element	Concentration (Cm) in hypothetical composite of 89 percent sandstone and 11 percent mudstone (in percent)[1]	Arithmetic mean contration in uranium ore (in percent; from table 2)	Amount estimated to be extrinsic in uranium ore	
			Percent	Grams per 10,000 tons[2]
Al	2.8	2.8		
Fe	.55	1.2	0.6	5.4×10^7
Ca	4.4	2.8		
Mg	.48	.40		
Na	$\approx$.08	$\approx$.08		
K	$\approx$.9	$\approx$1		
Ag	$\approx$.00003	$\approx$.00005	$\approx$.00002	$\approx2\times10^3$
B	$\approx$.003	$\approx$.002		
Ba	.084	.074		
Be	$\approx$.00002–.00004	$\approx$.00006		
Co	$\approx$.0002	.00056	$\approx$.0004	$\approx3.6\times10^4$
Cr	.00058	.0018	.0012	1.1×10^5
Cu	.0037	.011	.007	6.4×10^5
Ga	$\approx$.0001	$\approx$.00009		
La	$\approx$.0003–.0008	$\approx$.0005		
Mn	.033	.038		
Mo	$\approx$.00008	$\approx$.0003	$\approx$.0002	$\approx2\times10^4$
Ni	$\approx$.0004	.0011	$\approx$.0007	$\approx6.4\times10^4$
Pb	$\approx$.001	.009	.008	7.3×10^5
Sc	$\approx$.0003	$<$.0002		
Sr	.012	.027	.015	1.4×10^6
Ti	.11	.061		
U	$\approx$.0001	.18	.18	1.6×10^7
V	.011	1.12	1.11	1.0×10^8
Y	$\approx$.001	$\approx$.0008		
Zn	$<$.003	$\approx$.01	$\approx$.01	$\approx9\times10^5$
Zr	.015	.014		

[1] Cm=Css+0.11 (Cms−Css), where Css is the arithmetic mean concentration of the element in the sandstone (table 4) and Cms is the arithmetic mean concentration of the element in the mudstone (table 5).

[2] Estimated size of Frenchy Incline uranium deposit, past production plus total reserves, equals about 10,000 tons.

abundantly in highly vanadiferous ores in the Entrada Sandstone (Botinelly and Fischer, 1959, p. 217–218) of Late Jurassic age. Copper, lead, zinc, and molybdenum occur in the sulfides, chalcocite, chalcopyrite, galena, sphalerite, and molybdenite in low-valent types of ore (Roach and Thompson, 1959, p. 201) in the Salt Wash Member. A high correlation between copper and silver in 215 ores from the Salt Wash Member (correlation coefficient between logs of analyses equals + 0.78) is an indication that silver may be contained largely in copper minerals. In unmineralized sandstones from the Salt Wash Member most of the strontium appears to be present in the calcite cement (Shoemaker and others, 1959, p. 40), but the dominant mineral host for strontium in the ores is unknown. About one-half of the strontium in the Frenchy Incline deposit is interpreted to be extrinsic (see table 6), but this interpretation is subject to doubt because of unknown mineral relations.

The suite of extrinsic elements in the Frenchy Incline uranium deposit is about the same as the suite of extrinsic elements found in other uranium deposits in the Salt Wash Member in preliminary studies (Shoemaker and others, 1959, p. 52) and in my current studies but includes also chromium and possibly strontium which are not extrinsic in most other deposits in the Salt Wash Member. The Frenchy Incline deposit does not contain extrinsic yttrium, an element which is dominantly extrinsic in many of the other deposits.

The most apparent source of error in the estimates of amounts of extrinsic elements in the Frenchy Incline deposit (column 4, table 6) is the estimated composition of the intrinsic fraction of the deposit (column 2, table 6). However, the amounts of uranium, vanadium, zinc, and lead in the deposit are so large in comparison to the estimates in column 2 that a large proportional error in the latter would have little significance. The accuracies of other estimates of extrinsic amounts depend to a greater degree on the accuracy of the estimated intrinsic composition.

SIGNIFICANCE OF VOLUME RELATIONSHIPS BETWEEN URANIUM ORE AND ALTERED SANDSTONE

Light-brown sandstone in the vicinity of uranium ore in the Salt Wash Member of the Morrison Formation is commonly regarded as epigenetically altered. This view was advanced by Shawe and others (1959, p. 405) who found that the light-brown (or light greenish-gray to gray) sandstones near uranium ore contain almost no magnetite, ilmenite, or hematite, in contrast to the typical reddish-brown sandstones. The alteration of the sandstone probably is related indirectly to the formation of the uranium deposits because (1) most uranium ore in the Salt Wash Member is surrounded by large volumes of altered sandstone, and (2) both the alteration of the sandstone and the formation of the ores occurred in a chemically reducing environment, as indicated by the presence of authigenic pyrite in the sandstone (Shawe and others, 1959, p. 405) and the presence of low-valent uranium, vanadium, iron, copper, and other elements in ores which have not undergone secondary alteration by oxidizing ground-water solutions. In addition, the solutions which transported uranium and vanadium to the present site of the ore may have been moderately reducing (Garrels, 1957, p. 4).

The alteration of the sandstone and the formation of the ores may have occurred during different, though perhaps overlapping, spans of geologic time. The time of introduction of some elements may have coincided closely to the time of alteration of the sandstone.

The abundance of coalified plant remains in the altered sandstone suggests that a moderately reducing environment has existed in the sandstone for long continuous periods of time. A strongly reducing environment may have been maintained in parts of the sandstone in the more immediate vicinity of the plant remains, as indicated by the

Eh–pH stability relations of the uranium and vanadium minerals (Garrels, 1953 and 1955) deposited near them.

The average distance between the center of the Frenchy Incline ore deposit and the centers of adjacent ore deposits in the same sandstone lens of the Salt Wash Member is about 600 feet. The 10,000-ton deposit may be thought of as occurring in the center of a cylinder of sandstone 50 feet high, the thickness of the upper sandstone lens, with a radius of 300 feet. A cylinder of sandstone with these dimensions weighs about 1 million tons. If each million tons of altered sandstone in the area contains 10,000 tons of ore, about 200,000 tons of ore should be present. Total production plus known reserves for the area show 114,000 tons (Henry Bell, written communication, 1952). Therefore, these proportions of altered sandstone and ore are at least of the correct order of magnitude for the entire Legin area. The volume relationships between altered sandstone and ore in the Legin area are similar to those in extensively studied areas near Gateway and Uravan, Colo. (J.D. Strobell and others, written communication, 1954).

The cylinder of altered sandstone in which the Frenchy Incline deposit occurs may have been the source of at least some of the extrinsic elements in the deposit. The altered sandstone does not contain significantly lower concentrations of elements than sandstone elsewhere on the Colorado Plateau (table 4); so it is unlikely that the sandstone has undergone a large reduction in minor element content in order to provide the elements for the formation of the deposit. If it is assumed, however, that all of the extrinsic amounts of elements estimated in table 6 were derived from the altered sandstone the restored composition of the sandstone may be computed. This is done by adding the extrinsic amounts of the elements in the ore to the 1 million tons of sandstone in the cylinder of the sandstone that encloses the deposit (table 7). The increase over the present concentration in the sandstone (column *c*, table 7) is less than 4 percent for iron, silver, cobalt, chromium, copper, molybdenum, nickel, strontium and possible zinc. The increase in concentration of lead in the sandstone is about 16 percent and about 130 percent for vanadium. The increase in the concentration of uranium is 2,000 percent.

Obviously, sandstone in the upper lens of the Salt Wash Member in the Legin area, unless it originally contained about 20 times more uranium than it does now, could not have provided all the uranium in the ore deposits in the district. The original uranium content of the sandstone would have had to be about 0.002 percent. Of 96 sandstone samples from the Salt Wash Member studied by Newman (1962, table 28), only 5 were found to contain as much as 0.001 percent uranium, and none contained as much as 0.002 percent.

TABLE 7.—*Estimated restored partial composition (in percent) of sandstone in the Frenchy Incline mine area*

	a	*b*	*c*	*d*
Element	Present arithmetic mean concentration in sandstone (from table 4)	Restored concentrations of element in sandstone [1]	Increase in *b* over *a* in percent of *a*. $\frac{100(b-a)}{a}$	Increase in *b* over *a* in percent of *b*. $\frac{100(b-a)}{b}$
Fe	0.38	0.386	1.6	1.6
Ag	≈.00003	≈.0000302	.7	.7
Co	≈.0002	≈.000204	2.0	2.0
Cr	.00041	.000422	2.9	2.8
Cu	.0036	.00368	1.9	1.9
Mo	≈.00008	≈.000082	2.5	2.4
Ni	≈.0002	≈.000207	3.5	3.4
Pb	≈.0005	≈.00058	16.0	13.8
Sr	.0097	.00985	1.5	1.5
U	≈.00009	.00189	2000	95
V	.0085	.0196	130	57
Zn	<.003	<.0031	>3.3	>3.2

[1] Restored concentration of an element in the sandstone is computed as the present concentration *a* plus the concentration which would be attained if the extrinsic quantities of the elements in the Frenchy Incline uranium ore (column 4, table 6) were added to 1 million tons of sandstone. This quantity of sandstone, 1 million tons, is equivalent to a cylinder of sandstone 50 feet high with a radius of 300 feet. For calculation purposes the estimates in this column are carried beyond the appropriate number of significant figures.

The restored concentration of vanadium in the altered sandstone is more than twice as high as the present concentration (table 7), nearly 0.02 percent. Few sandstone samples from unaltered parts of the Salt Wash Member contain more than 0.01 percent vanadium, and the geometric mean or most typical concentration is near 0.001 percent (table 4).

Much of the lead in the ores in the Salt Wash Member is known to have been derived from radioactive decay of uranium in place (Stieff and others, 1953), but the proportion of radiogenic lead in the Frenchy Incline deposit is unknown.

If the 1-million-ton cylinder of altered sandstone did supply the metals for the 10,000-ton deposit, the efficiency of the leaching or secretion process would have had to be at least 95 percent for uranium and 57 percent for vanadium, though relatively small proportions of the other elements in the sandstone cylinder would have been sufficient (table 7, column *d*). The quantitative aspects of the leaching or secretion hypotheses for Colorado Plateau uranium deposits in general are considered elsewhere (Miesch, 1962).

It is doubtful that the cylinder of altered sandstone that encloses the Frenchy Incline deposit provided any significant part of the uranium and vanadium in the deposit, and it is similarly doubtful that the altered part of the sandstone lens that encloses the deposits in the Legin area provided the uranium and vanadium for the deposits in the area. However, these conclusions regarding uranium and vanadium do not eliminate the possibility that uranium and vanadium in the Frenchy Incline deposit or in the Legin area deposits were derived from altered sandstone exterior to the lens in which the deposits occur. As shown in figure 4, altered sandstone is abundant throughout the Salt Wash Member southwest of the Legin area. If the total uranium and vanadium in the deposits in the Legin area were redistributed through all the altered sandstone adjacent to the area, the concentrations of the two elements in the sandstone would not be significantly larger.

The volume relationships and compositional differences between uranium ore and altered sandstone in the Legin area do indicate, however, that all of the extrinsic quantities of elements in the deposits, except those of uranium and vanadium, could have been derived from altered sandstone in the upper lens of the Salt Wash Member. This would be possible even if the original concentrations of the elements in the altered sandstone were not significantly greater than those present in unaltered sandstone.

Some of the lead in the deposits may have been derived from the sandstone or other sources, but much of it is probably radiogenic and originated in the deposits after the introduction of uranium.

MECHANISMS OF TRANSPORTATION OF THE ELEMENTS

The configurations of ore layers within the Frenchy Incline deposit and within other deposits in the Salt Wash Member indicate that the elements in the ore minerals were transported to their present sites sometime after the formation of the host sandstone. The distance of transport may have been less than a few hundred feet or may have been many miles, and it is possible that the distance was different for each particular element. The most likely mechanisms of transport seem to be (1) movement of solutions through pore spaces in the sandstone (solution flow) and (2) movement of solute through solutions in the pore spaces (solute diffusion). It is also likely that both of these mechanisms acted, either simultaneously or during separate periods of time, in transporting the elements to the present site of the deposit and that the two mechanisms were of different relative importance in the transportation of different elements.

SOLUTION FLOW

In this section it will be assumed that the transportation of the quantities of elements judged to be extrinsic (table 6) was by the mechanism of solution flow only, that the contribution of solute diffusion to this transportation was negligible; the possibility that solute diffusion was an important process is discussed in a later section. It may be correct to assume absence or relative unimportance of diffusion if the deposition of the elements occurred during periods when solution flow within the Salt Wash Member was restricted only by the interstitial permeability of the sandstone, or if the hydraulic gradient causing flow was more than that resulting from gravity alone. During periods of greater restriction of solution flow, solute diffusion may have been of greater importance.

The quantities of extrinsic elements in the Frenchy Incline deposit are known (table 6) and the required minimum concentrations of the elements in the solutions that transported them to the deposit could be determined if the volumes of the solutions were also known. This information could be of considerable use in determining other chemical requirements of the solutions and, therefore, possibly their source or origin. Unfortunately, neither the volume of the ore solution nor a way of estimating it precisely are known. It is known, however, that the flow of solution through the Frenchy Incline deposit was mainly by way of pore spaces in the sandstone and mudstone because fractures in the deposit are exceedingly few and those present are probably postore, perhaps a result of unloading due to recent erosion. The hydraulic gradient or driving force that caused the solution flow may have been simply a difference in hydrostatic head due to the dip of the aquifer, but differential pressures established by the intrusion of igneous rocks at some distance or by other tectonic events may also have been responsible.

Regardless of the cause, or causes, of the solution flow and the fact that it was limited by the permeability of the rocks, little flow could have occurred in the Salt Wash Member if it was completely saturated and sealed off effectively from other permeable units. The Summerville Formation, immediately beneath the Salt Wash Member on most parts of the plateau, and the Brushy Basin Member in the upper part of the Morrison Formation, are both regionally continuous and relatively impermeable units. During the period immediately following the deposition of the Salt Wash, and perhaps for some time afterward, the sandstone unit was not effectively sealed and movement of the solutions could have easily occurred. Reduction in discharge area must have occurred soon after the Brushy Basin Member began forming or after it had suffered loss in initial permeability through alteration and compaction. The regional gradient of the Salt Wash Member was to the northeast, toward an impervious mudstone facies. Later, tectonic activity on the plateau led to the development of faults which, perhaps, accommodated the flow of solutions to and from the Salt Wash Member. Most of the faults in the salt anticline area (fig. 1), where most of the uranium deposits in the Salt Wash Member are located, are in zones on the flanks of the anticlines. Mobility of the salt cores within the anticlines caused the crests to collapse and the faults to form, possibly during early Tertiary time (Cater, 1955).

If the Salt Wash Member was not completely saturated the flow of ground waters or ore solutions within it was restricted to a far lesser extent and could have been maintained by hydrostatic head resulting from tilting of the aquifer on both local and regional scales.

If the flow of ground water is caused merely by hydrostatic head resulting from a structural gradient, the hydraulic gradient may, in some cases, be estimated. The volume of water that passes through a given cross-sectional area of sandstone per unit time may be computed from Darcy's law, which, according to Wenzel (1942, p. 4–7), may be expressed as:

$$Q=PIA,$$

where Q is the volume of water per unit time passing through cross-sectional area A, under an hydraulic gradient I (change in pressure per unit distance down the slope of the aquifer). The term P is the coefficient of permeability expressed as meinzer units when Q is in gallons per day, A is in square feet, and I is in feet of water per foot. The velocity of flow is computed from the relation:

$$\frac{V=PI}{7.48\ pC_t}$$

where P is permeability in meinzer units, I is hydraulic gradient in feet of water per foot, p is the porosity as a decimal fraction, V is the velocity in feet per day, and C_t is a temperature correction (Wenzel, 1942, p. 71).

The cross-sectional area of the total Frenchy Incline deposit is in the order of 1,000 square feet, and it is probable that the ore solutions passed through this entire area. The permeabilty of the sandstone prior to mineralization may have been about 0.1 darcy, or 1.8 meinzer units, judging from measurements on unmineralized samples by Phoenix (1956, p. 216).

The duration of mineralization and the hydraulic gradient under which the ore solutions moved are unknown. The duration of mineralization processes that deposited any of the extrinsic elements may have extended continuously from the time the Salt Wash Member was deposited to the time the deposit was elevated above the present water table (about 130 million years), or it may have been discontinuous throughout this time. If the flow of solution in the Salt Wash Member was appreciable only after regional deformation of the Colorado Plateau in Late Cretaceous and early Tertiary time, the duration of mineralization may have been less than 60 million years.

The present dip of the Salt Wash strata in the Legin area is about 160 feet per mile, and it is doubtful that the dip has ever exceeded this amount in the past. If the slope of the water level in the unsaturated aquifer was about equal to the dip of the strata, the hydraulic gradient in the aquifer was about equal to the sine of the angle of dip (Wenzel, 1942, p. 72). For low angles of dip the sine is about equal to the tangent, and the hydraulic gradient may be taken as equal to the dip of the aquifer. It is assumed here that the hydraulic gradient resulted only from differences in hydrostatic head caused by the dip of the aquifer. However, the hydraulic gradient could not have been very effective in causing the ore solutions to flow unless permeable fractures or other channelways were present through which unrestricted discharge could occur. If the aquifer in the Salt Wash was completely filled and no permeable channelways were present restricted discharge, or slow leakage, could occur by mass permeation of overlying relatively impermeable rocks, but this would allow only slow restricted movements of the ore solutions.

The curves in figure 6 are based on Darcy's law and give the volume of water in sandstone (permeability of 0.1 darcy) passing through a cross-sectional area of 1,000 square feet as a function of time and hydraulic gradient. If the hydraulic gradient resulted only from hydrostatic head caused by the dip of the aquifer, the volumes in figure 6 may be considered as maximum volumes when equating hy-

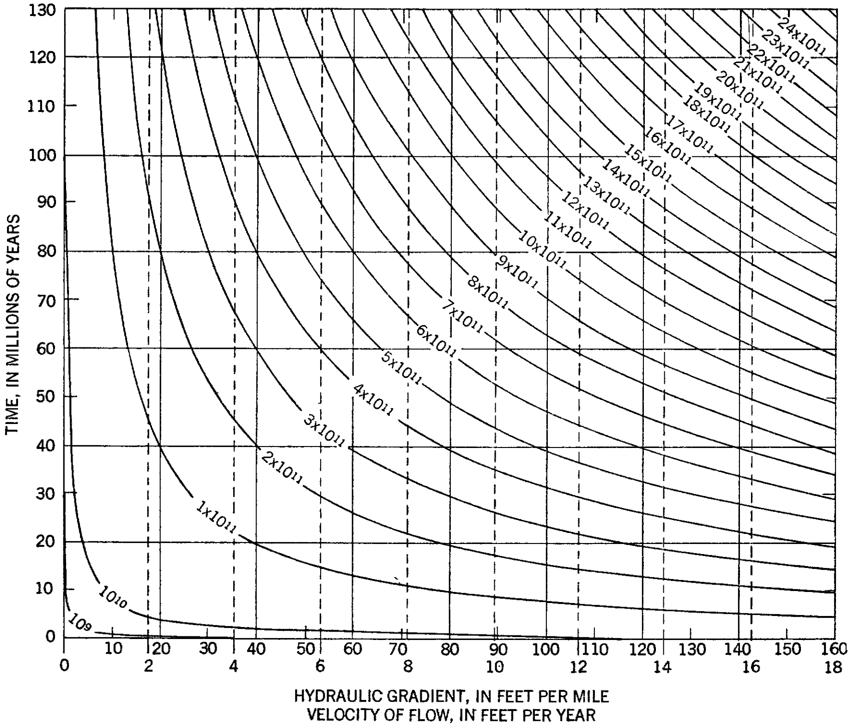


FIGURE 6.—Volume of water, in gallons, moving in sandstone through a cross-sectional area of 1,000 square feet, either as a function of time and hydraulic gradient or of time and velocity of flow (permeability of sandstone=0.1 darcy or 1.8 meinzer units; porosity of sandstone=15 percent).

draulic gradient with structural gradient or dip. The volumes are maximum because (1) if the aquifer were saturated the hydraulic gradient may have been less than the structural gradient, (2) discharge and recharge of the aquifer may have been restricted, and (3) the permeability of the mineralized sandstone may have been appreciably reduced by the precipitation of ore minerals in the grain interstices.

Nevertheless, it may be seen from figure 6 that during any period exceeding a few million years, as much as 10^9 to about 2.6×10^{12} gallons of water may have passed through the Frenchy Incline deposit if the hydraulic gradient was more than a few feet per mile but less than the present structural gradient and if the permeability was similar to the present permeability of the Salt Wash Member. During 60 million years, under these conditions, about 10^9 to 10^{12} gallons could have passed through the deposit.

If mineralization occurred before cementation of the sandstone with carbonate minerals or before compaction, the permeability of the sandstone was undoubtedly higher than its present average permeability of 0.1 darcy. The permeability of sand with a mean grain diameter and sorting coefficient equal to that of the sand in the Salt Wash Member may be about 3 darcies, according to the empirical formula developed by Krumbein and Monk (1943, p. 161).

According to L. C. Craig (oral communication, 1960), the gradients of the streams that deposited the Salt Wash Member, judging from channel characteristics and stream gradient relationships described by Leopold and Wolman (1957, p. 59), may have been less than 5 feet per mile, though this estimate is admittedly rough because of the difficulty in interpreting the character of the former channels. If this maximum gradient is correct, however, and the permeability of the sand was about 3 darcies, less than 50 gallons of water per day passed through the sand now occupied by the Frenchy Incline uranium deposit. During the 10,000 years that may have elapsed between the deposition of the sandstone now forming the deposit and the origin of the relatively impermeable cap formed by the Brushy Basin Member, about 2×10^8 gallons of water may have passed through the deposit.

Figure 7 shows the required minimum concentrations of elements in solutions which may have transported them to the Frenchy Incline deposit. The required minimum concentrations are, of course, inversely related to the volume of the solution. If uranium, for example, were transported to the deposit by 10^9 to 10^{12} gallons of solution, its concentration in the solution would have necessarily been at least 0.005 to 5 parts per million. If the uranium was transported by as much as 3×10^{12} gallons of solution, however, its concentration in the

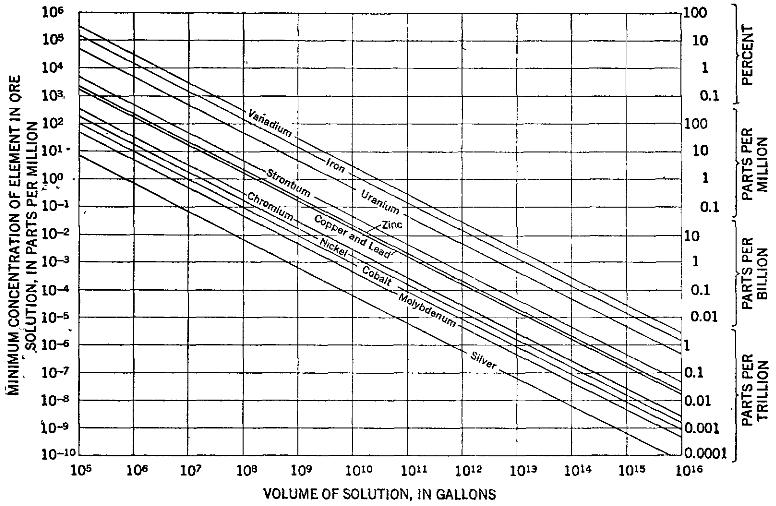


FIGURE 7.—Required minimum concentrations of elements in ore solutions of various volumes.

solution could have been as low as 2 parts per billion. Unless the volume of the solution which deposited the extrinsic silver was less than 10^9 gallons, the solution had to contain only 1 part per billion silver at the most. If the uranium, vanadium, and iron mineralization occurred in the 10,000 years following the deposition of the host sandstone (volume of solution$=2\times10^8$ gallons), the concentrations of these elements in the solutions had to be in the order of 20 to 150 parts per million or more.

If the concentrations of the elements in the ore solutions were similar to the maximum concentrations of the elements in uncontaminated Morrison ground waters studied by Phoenix (1959, p. 60–61) the volumes of the solutions must have equaled or exceeded about 10^{11} gallons for vanadium and iron, 10^{10} gallons for uranium and copper, and 10^9 gallons for lead.

SOLUTE DIFFUSION

In a previous section it was shown from compositional and abundance relations between the uranium ore in the Legion area and the altered sandstone lens in which it occurs, that most of the extrinsic elements in the ore could have been derived from the sandstone lens without changing its composition appreciably. Uranium, and probably vanadium, could not have been derived from the sandstone lens; much of the lead in the ore was derived by radiogenic decay of uranium in place and therefore was not derived from the sandstone lens. Elements which were derived from the sandstone lens may have traveled less than 300 feet, and it is possible that solute diffusion, without appreciable solution flow, was an important process in transferring these elements from the sandstone to the site of ore deposition.

Soon after the deposition of the upper lens of the Salt Wash Member in the Legin area plant debris within the lens undoubtedly began a complicated process of decay, and strong reducing environments were established locally within the lens near pockets or local concentrations of plant materials. It is likely that sulfate-reducing bacteria associated with the decaying plant materials brought about relatively high concentrations of H_2S which effected the precipitation of pyrite and other sulfides in local concentrations. A study by Jensen (1958) of sulfur isotopes from sulfide minerals in the deposits has shown that this process probably took place. As the concentrations of iron and other elements in solution near the plant materials diminished, concentration gradients in the water saturating the sandstone lens were established. The concentration gradients brought about the migration of ions toward the pockets of decaying plants. As the water saturating the lens tended to become depleted in the elements which were being deposited in the reducing environments, solid phases containing the elements in the sandstone tended to dissociate. This may have been especially true if the process operated over a long period of time and equilibrium conditions prevailed. Thus, the process may have involved a chemically driven half-cycle consisting of (1) dissociation of solid phases in the sandstone lens, (2) migration of ions by solute diffusion to the more reducing environment, and (3) precipitation by reduction or by reaction with H_2S or its ionization products. Thus, elements sufficiently abundant in the sandstone lens, including silver, cobalt, chromium, copper, molybdenum, nickel, strontium, and zinc, in addition to iron, may have accumulated in the present uranium deposits without solution flow.

Geologic evidence for the operation of diffusion processes in forming uranium deposits in the Salt Wash Member is given by Huff and Lesure (1962) who describe the occurrence of ore layers in rolls which form complete shells around pockets of altered sandstone and fossil plant remains. Shawe (1956, p. 241) has interpreted the configurations of other roll structures as having formed at fixed interfaces between flowing ore solutions and cooler connate solutions. Judging from the low flow velocities in figure 6 it appears reasonable that a fixed solution interface could be maintained over a relatively short period of time under nonstagnant conditions, but how long such an interface could be maintained is questionable. Configurations of most individual rolls can be interpreted as having originated under nonstagnant conditions as well as under stagnant conditions or as having formed with elements being transported by solution flow, solute diffusion, or by both processes acting together. Under nonstagnant conditions the configurations could arise largely from dynamic processes, whereas under stagnant conditions the configurations arise from chemical processes which respond to the distribution of reducing and precipitating agents in the sandstone. The long sinuous axis of a roll (Shawe, 1956, p. 240), for example, might form near the periphery of an elongate body of ore solution migrating through the sandstone along a sinuous path, or it may result from diffusion of ions toward a sinuous Eh-pH front which reflects the distribution of decaying plant materials deposited by a meandering stream.

If the chemical environment at the site of mineralization was different from that away from the site of mineralization solute diffusion of some constituents certainly occurred, but the effectiveness of diffusion in transferring constituents from the sandstone to ore depends on (1) the relative concentrations of the constituent in solution in the ore and sandstone environments, in addition to the absolute concentration in the sandstone environment, (2) the diffusion coefficient of the constituent, and (3) the duration of time throughout which diffusion operated. Even if all the above conditions were favorable it is still possible that diffusion was unimportant compared to the transfer of constituents by solution flow, if the flow was appreciable compared with the rate of diffusion.

The chemical environment at the site of mineralization was one in which pyrite, FeS_2, was the stable, or at least metastable, mineral phase. According to Hostetler and Garrels (1962), this environment was also one in which sulfide and sulfate species existed in approximate equilibrium. In the sandstone environment pyrite was stable at least locally, but because of the comparative sparsity of decaying plant remains the Eh and pH of the environment were probably somewhat higher than they were at the site of mineralization. In figure 8, Eh–pH stability relations are shown for iron minerals in aqueous solutions containing total sulfur (HSO_4^{-1}, SO_4^{-2}, H_2S, HS^{-1}, and S^{-2} species) and total CO_2 (H_2CO_3, HCO_3^{-1}, CO_3^{-2} species) equal to the maximum and minimum concentrations of these constituents in ground water from the Salt Wash Member studied by Phoenix (1959, p. 60–61). Iron minerals considered include pyrite, hematite, siderite; magnetite and pyrrhotite (FeS) could have been included, but their stability fields are small and would occur only in the lower right portions of the diagrams. Authigenic magnetite and pyrrhotite have not been identified in either the sandstones or the uranium ores. On each diagram in figure 8 the relative solubility of iron is shown by contours of the activity of the ferrous ion in equilibrium with each of the mineral phases. The dashed line on these diagrams shows the Eh–pH conditions where sulfate and sulfide species are in equilibrium and marks the Eh–pH conditions which could have existed

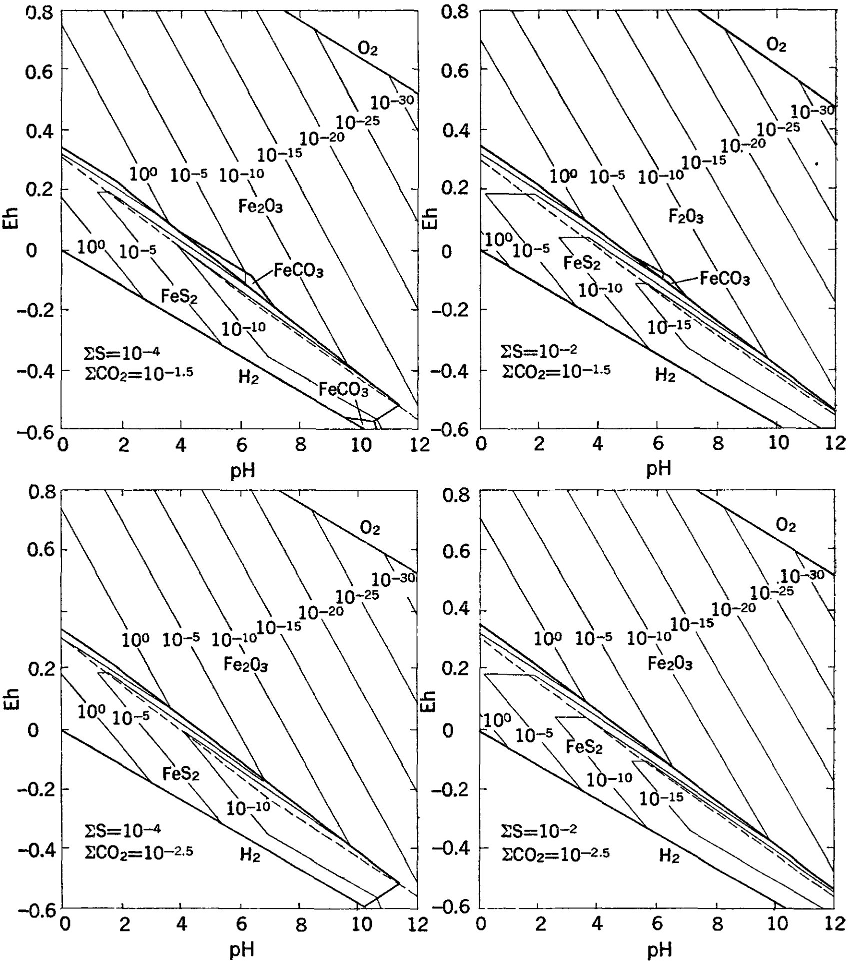


FIGURE 8.—Eh-pH stability fields of iron minerals at various molal concentrations of total sulfur and CO_2. Contours show molal activity of ferrous ion (temperature=25° C; pressure=1 atm; thermodynamic data from compilation by Garrels, 1960).

near decaying organic matter according to Hostetler and Garrels (1962). Along the sulfate-sulfide line the contours, which are at logarithmic intervals, form an abrupt trough of low values which is flanked on the northeast, toward higher Eh and pH, by a steep ridge of high values whose southwest flank lies completely within the pyrite field. The depth of the trough relative to the ridge is proportional to the total sulfur content of the solution. Thus, if these diagrams are correct in representing the relative solubilities of iron in the Eh-pH environment where pyrite is stable and in the environment likely to occur near decaying organic matter, it may be expected that the iron solubility was highly sensitive to Eh, pH, and sensitive to total sulfur to a lesser degree. It is possible that a steep concentration gradient existed between ferrous ion in solutions saturating the sandstone and ferrous ion in solution in the environment of mineralization, even though both environments were such that pyrite was the stable mineral phase and the solutions in each environment may have contained the same amount of total sulfur.

The rate of diffusion (quantity of constituent per unit time) is proportional to the steepness of the concentration gradient and may be computed for certain ideal conditions from a relation given by Garrels and others (1949, p. 1826). This relation applies only after the diffusion process reaches a steady-state and when the concentration of the constituent in the solution acting as the source is constant. Furthermore, the effective pore area through which diffusion takes place and the distance the constituents diffused must be known, as well as the diffusion coefficient of the constituent at the conditions of temperature, pressure, and concentration of ionic species (conductance) which existed. As these factors cannot be specified with any reasonable degree of certainty for the particular problem of interest the exact rate of diffusion cannot be computed. However, it is possible to specify what seem to be reasonable conditions in this problem to find if the rate of diffusion for a particular constituent is possibly adequate or entirely inadequate. The relation giving the rate of diffusion is:

$$q/t=DCA/L \text{ (Garrels and others, 1949, p. 1826),}$$

where q is the quantity of the constituent diffused (in equivalents) over a distance L (in centimeters) through an effective pore area A (in square centimeters) in time t (in days). The term D is the diffusion coefficient in square centimeters per day, and C is the concentration of the constituent in the solution (in equivalents per cubic centimeter) which acts as the source of the constituent, in this case solutions saturating the sandstone adjacent to the site of mineralization. Considering diffusion of a divalent ion, reasonable values for the terms on the right side of the equation may be taken as:

$D=2$ sq cm per day (conservative in view of diffusion coefficients of divalent cations at 100°C given by Garrels and others, 1949, p. 1819)

$C=10^{-5}$ molal, or 2×10^{-8} eq per cc for a divalent ion

$A=2\times10^{7}$ sq cm (fractional porosity of sandstone, 0.15, times surface area of volume of rock with dimensions 500×150×2 feet. Actual surface area of the Frenchy Incline ore body is large as the ore occurs in a number of vertically separated layers).

L=300 feet, or 9,000 cm (about one-half the average distance between the centers of the Frenchy Incline and adjacent deposits in the Legin area; maximum distance of diffusion).

With these values the rate of diffusion of divalent constituents from the sandstone to the site of mineralization is 0.025 equivalents per year. If, for example, the diffusion coefficient of ferrous ion at the conditions of temperature, pressure, and concentration that existed was close to 2 sq cm per day, and the concentration of ferrous ion in solutions saturating the sandstone was about 0.5 ppm (10^{-5} molal), it may be expected that at least 0.025 equivalents of ferrous ion per year would diffuse into and be precipitated in the Frenchy Incline deposit. This computation depends on the assumption of the existence of a steady-state; that is, a linear concentration gradient between the source and destination of the diffusing constituent (Garrels and others, 1949, p. 1821). For the present problem the distance between the source and destination of the diffusing constituent is not a simple fixed value because the constituents are probably derived from sandstone immediately adjacent to the ore deposit as well as from sandstone perhaps several hundred feet from the deposit. Thus, although a concentration gradient may certainly have existed, the steepness of the gradient is difficult to represent by a single precise value, and the distance over which a steady-state of diffusion could have been maintained is unknown.

Nevertheless, if ferrous iron diffused into the Frenchy Incline ore deposit at the rate of 0.025 equivalents per year the extrinsic iron present in the deposit (table 6) could have accumulated in less than 80 million years, little more than the amount of time betwen the deposition of the host rock and the structural deformation which occurred in Late Cretaceous or early Tertiary time. If the aquifer in the Salt Wash was isolated from other permeable units from the time it was covered by the mudstones of the Brushy Basin Member until early Tertiary time, it was saturated with stagnant solutions during this time, and diffusion processes must have operated. Whether these processes operated at the rate computed above, however, is highly uncertain, but at least this rate is not unreasonable from what is known of solute diffusion processes.

In summary, attempts to make quantitative tests for both solution flow and solute diffusion as mechanisms for transporting extrinsic elements suggest that both mechanisms could produce results of the right order of magnitude. The choice between the two mechanisms, or judgment concerning their relative importance, then, must rest on other criteria, in particular on the abundances of elements in the deposits and on the structural and hydrologic histories of the sandstone unit in which the deposits occur. When structural and hydrologic conditions favored solution flow, solute diffusion was relatively unimportant as a transporting mechanism, but when ground waters were more stagnant the diffusion processes must have become increasingly more important. From compositional and volume relationships between uranium ore and associated altered sandstone, it is apparent that solution flow was an important process, at least in the transportation of uranium and probably vanadium because uranium and vanadium were derived from sources other than the altered sandstone surrounding the deposits; solute diffusion could not have been an effective transporting mechanism over the required distance. Moreover, it is apparent that a major part of the copper, lead, silver, and zinc in the deposits were transported by flowing solutions because their distribution among the deposits conforms well with the distribution of faults and vein-type deposits of the elements.

BEARING OF THE DATA ON THE ORIGIN OF URANIUM DEPOSITS IN THE SALT WASH MEMBER OF THE MORRISON FORMATION

Some of the main points which have been brought to the reader's attention in the foregoing discussion are:

1. Certain elements in the uranium deposits in the Salt Wash Member of the Morrison Formation on the Colorado Plateau are mutually associated, or geochemically coherent, and fall into classes or groups which can be defined in terms of log correlation coefficients between element pairs.

2. Elements in Group 1 (As, Mo, Co, Ni, Se, Y, and Zn) and iron tend to be more highly concentrated in deposits on the western and northwestern parts of the Colorado Plateau. In this respect their distribution corresponds at least roughly to the distribution of tuffaceous materials in unmineralized sandstones of the Salt Wash Member. The mean concentrations of these elements in altered sandstones near uranium deposits tend to be about the same as their mean concentrations in all Salt Wash sandstones. The elements have not been found to be more abundant in uranium deposits near faults.

3. Elements in Group 2 (Cu, Ag, and Pb) tend to be highly concentrated in deposits in the folded and faulted area of the salt anticlines in western Colorado and eastern Utah. Zinc is also highly concentrated in deposits in the salt anticline area, in addition to being highly concentrated in deposits on the western and northwestern parts of the plateau. Unmineralized sandstone from the Salt Wash Member in the salt anticline area tends to contain more copper than sandstones from the same unit elsewhere on the plateau. The mean concentrations of silver and lead in altered sandstones near uranium deposits, unlike those of Group 1 elements, are appreciably higher

than their mean concentrations in all sandstones of the Salt Wash. Vein-type deposits containing copper, silver, lead, and zinc are present in the salt anticline area, and copper and lead, at least, are distinctly more abundant in uranium deposits near faults than in those more distant from faults.

4. Vanadium tends to be more highly concentrated in Salt Wash uranium deposits on the eastern part of the plateau, but deposits in the vicinity of the Henry Mountains laccoliths appear to be exceptionally vanadium-rich. Excluding the Henry Mountains area, the regional distribution of vanadium in the Salt Wash deposits corresponds to the regional distribution of heavy minerals and iron in the unmineralized sandstones. The mean concentration of vanadium in altered sandstones near uranium deposits, like that of silver and lead, is appreciably higher than its mean concentration in all Salt Wash sandstones.

5. Most of the extrinsic or introduced quantities of various elements in the Frenchy Incline deposit, and probably in other deposits in the Legin area, are small compared with the quantities of the same elements in the altered sandstone adjacent to the deposits. The elements could have been derived from the altered sandstone without the sandstone having lost more than a few percent of its original minor element content. Uranium, vanadium, and lead, however, are important exceptions. Much of the lead may have originated by radioactive decay of uranium in the deposit, but uranium and probably vanadium must have been derived from sources external to the altered part of the sandstone lens in which the uranium deposits occur. Copper, silver, lead, and zinc in the deposits, because of their regional variation pattern and occurrence in vein-type deposits (point 3 above), are interpreted to have been derived, at least partly, from sources external to the Salt Wash Member. Uranium, vanadium, copper, silver, lead, and zinc, therefore, must have been transported to the uranium deposits by flowing ore solutions.

6. The history of tectonics and sedimentation of the Colorado Plateau is indicative of at least three major periods of different hydrologic conditions within the Salt Wash Member: (a) an early period extending from the time the Salt Wash Member host rock was deposited until it was covered by the overlying mudstones of the Brushy Basin Member, (b) an intermediate period extending from the deposition of the Brushy Basin Member until structural deformation in Late Cretaceous or early Tertiary time, and (c) a later period from Late Cretaceous or early Tertiary time until the present. The early period may have been about 10,000 years in duration and was one of relatively rapid ground-water movement. The intermediate period

was one of relative stagnation, and during the later period groundwater flow was accelerated.

7. It has been shown that during periods of stagnation, steep concentration gradients of iron in solution may arise in the vicinity of decaying plant remains. Diffusion of iron and perhaps other elements toward the plant remain will occur in response to the gradients. The amount of material that can be diffused for a given distance per unit time cannot be estimated precisely. Some ore rolls in the Salt Wash Member have been interpreted as products of diffusion.

8. If the concentrations of uranium and vanadium in the solution or solutions which transported them were a few parts per million or less and the hydraulic gradient causing the solution flow was less than the present structural gradient in the Legin area, the time required to transport these elements is far in excess of the time interval from the deposition of the host rock to the advent of relatively stagnant ground water condition. Uranium and vanadium were probably transported and deposited during or after Late Cretaceous or early Tertiary time. The transportation and deposition of copper, silver, lead, and zinc in the uranium deposits probably also occurred after Late Cretaceous or early Tertiary time, as these elements were being deposited in veins stratigraphically higher and lower than the Morrison Formation.

From the points outlined above it is suggested that many of the minor elements (Fe, Mo, Ni, As, Co, Se, and Y) in the uranium deposits in the Salt Wash Member of the Morrison Formation may have been derived largely from tuffaceous materials in the Salt Wash Member. Such a source would account for the distributions of these elements in the deposits. Deposits on the western parts of the Plateau contain more of the elements because the sandstones there contain more tuff.

If the altered sandstone in the lens containing the ore in the Legin area contains 4 percent tuffaceous materials (Cadigan and Miesch, 1958, p. 149), about 40,000 tons of tuffaceous materials are present in the lens within 300 feet of the Frenchy Incline deposit. Although it is unlikely that the bulk chemical composition of the tuff was equivalent to that of the average igneous rock as tabulated by Rankama and Sahama (1950, p. 226), it is possible that the relative concentrations of elements in the tuff and this hypothetical average rock were roughly similar. If this were the case, it is apparent from the data in table 8, from the abundance viewpoint only, that the tuffaceous materials could supply the required amounts of the iron, nickel, and cobalt to the Frenchy Incline deposit more easily than they could supply such elements as copper, silver, lead, vanadium, and uranium. Waters and Granger (1953, p. 21) have discussed the process whereby

Table 8.—*Comparison of abundances of elements in average igneous rock with those in uranium ore composing the Frenchy Incline deposit*

Element	Abundances (in grams)			Element	Abundances (in grams)		
	a 40,000 tons of average igneous rock [1]	*b* Extrinsic fraction of 10,000 tons of uranium ore in Frenchy Incline deposit [2]	*a*:*b* Abundance ratio		*a* 40,000 tons of average igneous rock [1]	*b* Extrinsic fraction of 10,000 tons of uranium ore in Frenchy Incline deposit [2]	*a*:*b* Abundance ratio
Cr	7,200,000	110,000	65	Cu	2,520,000	640,000	3.9
Ni	2,880,000	≈64,000	45	Ag	3,600	≈2,000	1.8
Fe	1,800,000,000	54,000,000	33	Pb	576,000	730,000	.79
Co	800,000	≈36,000	22	V	5,400,000	100,000,000	.054
Sr	10,800,000	1,400,000	7.7	U	144,000	16,000,000	.0090
Zn	4,752,000	≈900,000	5.3				

[1] Computed from data given by Rankama and Sahama (1950, p. 226).

[2] From table 6, footnote 2.

minor elements may be released to ground-water solutions during devitrification of volcanic ash.

Distribution patterns, regional and local, of copper, silver, and lead in the Salt Wash uranium deposits suggest that the elements were introduced into the Salt Wash Member largely from external sources by way of permeable channelways provided by fractures on the flanks of salt anticlines. Copper and silver in the uranium deposits, therefore, may be genetically related to fracture controlled deposits of these elements in the salt anticline area (Fischer, 1936, p. 573). Lead may have been similarly introduced, but much of the lead in the deposits is radiogenic and originated in place after the introduction of uranium.

The regional variation pattern of zinc shows features common to those of iron and associated elements but is also similar to those of copper, silver, and lead in that zinc is high in deposits in the salt anticline area. Some of the zinc in the Frenchy Incline deposit may have been derived from tuff fragments in the host sandstone near the present deposit (table 8), but some also may have been derived from the same source which provided copper, silver, and some of the lead.

The source of vanadium and uranium in the Frenchy Incline deposit and in other deposits in the Salt Wash Member is more questionable, but the rough correspondence of the distribution of vanadium in the deposits and heavy minerals in the sandstone suggests that vanadium, at least, may have been derived from the heavy minerals. This source was first suggested by Shawe and others (1959, p. 413–414). However, it is unlikely that vanadium and uranium were derived solely from within a few hundred feet of the Frenchy Incline deposit as were, perhaps, many of the other extrinsic elements. Vanadium and uranium in the Frenchy Incline deposit may have been derived from altered sandstone which is now present on the south and southwest margin of the Legin area (fig. 4). However, other possible sources of uranium and vanadium, such as the Brushy Basin Member of the Morrison Formation, deep-seated magmas, and laccolithic intrusions, cannot be excluded.

If certain elements in the uranium deposits were transported only up to a few hundred feet, solute diffusion could have been the main transporting mechanism for these elements. The occurrence of roll structures in the deposits suggests that diffusion processes may have occurred. They are interpreted as having formed at interfaces between chemically different solutions. However, uranium, copper, silver, lead, zinc, and probably vanadium are interpreted to have been brought to the deposits from sources beyond the limit over which diffusion may operate effectively and probably were transported mainly by flowing solutions. It is possible that the rolls, which contain all of these elements, were formed by diffusion occurring within a flowing solution. However, certain difficulties arise from this hypothesis. One such problem is that a flowing solution might flush out a precipitating agent such as H_2S in solution faster than it can be generated by anerobic bacteria, thereby homogenizing the ground-water environment so that chemical reactions which could produce ore minerals do not occur. Another objection is that the configurations of some rolls are difficult to explain as having originated in a flowing solution. Finally, stable solution interfaces suggested by the sharp boundaries of most rolls probably could not be maintained over any considerable time in a flowing solution. However, in a solution flowing at a rate of less than 18 feet per year (fig. 6) the effects of diffusion processes may not be obliterated by the flow because the rate of diffusion in this case is likely to be comparable to the rate of flow, depending of course on the particular ion and its concentration in the solution.

Alternatively, if ground water within the Salt Wash Member was stagnant or nearly so from the time the unit was covered by the Brushy Basin Member until structural deformation occurred in Late Cretaceous or early Tertiary time, there is little reason to believe that diffusion and accumulation of elements near pockets of decaying plant materials did not occur during this time. Consequently, some of the elements in the present uranium deposits may have accumulated largely by diffusion processes prior to the accumulation of elements brought by flowing solutions (Miesch, 1961, p. 290). Rolls composed mainly of pyrite in sandstone possibly formed with diffusion and were later replaced by uranium and vanadium minerals, accompanied by the introduction of copper, silver, lead, and zinc. Thus, the uranium deposits could have formed during multiple stages. Evidence for this is found in the existence of virtually nonuraniferous iron oxide rolls in the Salt Wash Member in the Bull Canyon mining area, Montrose County, Colo., (C. H. Roach, 1961, oral communication) and in the Lisbon Valley area, Utah, (Kennedy, 1961, p. 95–96). These rolls could be products of the earlier stage of mineralization only and were not replaced by uranium minerals during a later stage. The iron oxides may have formed with near-surface oxidation of pyrite. Relatively few of the uranium deposits in the Salt Wash Member remain unoxidized, but some of those in the Chinle Formation in the Lisbon Valley area contain uraninite with abundant ferric oxides (V. C. Kennedy, oral communication, 1961). This mineral assemblage could have originated on the reduction of uranium by iron and sulfur from rapidly dissociating pyrite, with the precipitation of oxidized iron and removal of oxidized sulfur as sulfate in migrating ground water. The rapid dissociation of pyrite might have been brought about by a change in chemical environment due to acceleration of ground-water flow and flushing out of sulfide species that previously were present in the ground water. Thermodynamics of the reaction $FeS_2 + 7\frac{1}{2}UO_2^{+2} + 11H_2O = Fe(OH)_3 + 2SO_4^{-2} + 19H^{+1} + 7\frac{1}{2}UO_2$ indicate that at pH conditions near neutral and over wide ranges of sulfate ion concentration, the presence of pyrite can lead to the precipitation of uranyl ion as UO_2 (uraninite) with the conversion of pyrite to ferric hydroxide, even if the concentration of uranyl ion is a few parts per billion or less. The presence of carbonate will inhibit this reaction through the formation of the uranyl dicarbonate and tricarbonate complexes, but at a pH of about 9, and over wide ranges of possible sulfate and carbonate ion concentrations, uraninite and ferric hydroxide may still form if the concentration of uranium in solution is more than a few parts per million.

Laboratory evidence for the precipitation of uraninite by iron and sulfur from pyrite has been found by Rafalsky (1958, p. 441).

At least two other points regarding the formation of roll structures in uranium deposits must be considered. Both points may detract from the multiple stage hypothesis. Rolls are common on the Colorado Plateau only in vanadiferous uranium deposits and are defined megascopically largely by vanadium minerals, mostly vanadium clays. However, we cannot be as confident that vanadium was brought to the uranium deposits from a great distance as we can be certain that uranium was brought from a distance. The possibility that vanadium minerals accumulated early in the deposits, along with pyrite and some other constituents, cannot be excluded. Vanadium may have played some part in the precipitation of uranium in roll structures. The second point that may detract from the multiple stage hypothesis is that numerous microscopic studies, though providing evidence of early pyrite in the ores, have not, to my knowledge, shown clear evidence for the suggested process of uranium reduction and precipitation by iron and sulfur from pyrite.

STUDIES OF URANIUM DEPOSITS IN THE CHINLE FORMATION AND OTHER FORMATIONS ON THE COLORADO PLATEAU

Studies of uranium ores from formations other than the Morrison are not completed, but sufficient data have been examined to provide a general account of compositions and regional variations in composition of the ores. Actually, clustering of known uranium deposits in other formations into relatively small areas precludes meaningful studies of the broad regional compositional variations within any one of the units separately. Only small areas can be studied and compared with one another.

For example, known uranium deposits in the Shinarump Member of the Chinle Formation of Late Triassic age are mostly on the central and southern parts of the Monument Uplift, and those in the Moss Back Member of the Chinle are mostly in the northwestern quarter of the Paradox Basin (fig. 1). The deposits in the Moss Back Member at Temple Mountain, Utah, are chemically distinct from other deposits in the Moss Back and are regarded as a separate group in compositional studies. Deposits in other members of the Chinle Formation are widely scattered over the Colorado Plateau, but there is a cluster of these deposits along the Little Colorado River in northeastern Arizona, south of the Kaiparowits basin (fig. 1).

Uranium deposits in several other stratigraphic units occur in clusters in northwest New Mexico. These units include the Westwater Canyon Sandstone Member of the Morrison Formation, the Dakota Sandstone of Cretaceous age, and the Todilto Limestone of Late Jurassic age. A few deposits occur in the Abo Formation of Early Permian age and in the Recapture and Brushy Basin Members of the Morrison Formation.

A few uranium deposits in other units occur in widely separated areas. These include deposits in the Entrada Sandstone near the westernmost edge of the San Juan Mountains and northeast of the Uncompahgre Uplift, near Rifle, Colo., deposits in the Uinta Formation of Eocene age in the Uinta Basin, deposits in the Summerville Formation in Gypsum Valley, and in the Hermosa Formation near Klondike Ridge on the southeast margin of the salt anticline area (fig. 1).

Observations of the compositions and compositional variations of uranium deposits in the Chinle Formation that appear especially pertinent to interpretations in this report are: (1) Host rocks of uranium deposits in the Chinle Formation, unlike those in the Salt Wash Member of the Morrison Formation, are lithologically heterogeneous (Finch, 1959, p. 157), and the deposits are highly variable in chemical composition relative to deposits in the Salt Wash Member. (2) Members of the Chinle immediately above the Shinarump southwest of the Paradox Basin are especially rich in tuffaceous materials (Stewart and others, 1959, p. 523). Uranium deposits in the Chinle Formation, especially those in the Shinarump Member, tend to be richer in minor element content than those in the Salt Wash Member of the Morrison Formation. (3) Uranium deposits in the Shinarump Member of the Chinle in the White Canyon area of the western part of the Monument Uplift are notably rich in copper and silver. Abundant fractures, unreported from this area, have been observed in the salt anticline area where the copper and silver-rich deposits in the Salt Wash Member are located. No fracture-controlled vein-type copper deposits have been found in the White Canyon area, although they have been found in the salt anticline area. (4) Most ores from the Chinle Formation, especially those from the Shinarump Member in the White Canyon area, are low in vanadium content. Ores from the Moss Back Member at Temple Mountain, however, contain more vanadium than other ores from the Chinle.

Uranium deposits in the Moss Back Member of the Chinle Formation at Temple Mountain are a unique group not only compositionally but structurally as well. They are associated with abundant fracturing, and vein-type copper deposits are abundant in the same area. However, the uranium ores are clearly copper-poor. The inorganic fractions of the ores are grossly similar to those from the Salt Wash Member of the Morrison Formation, but some ores contain notable concentrations of organic carbon of disputed origin.

Most of the ores from uranium deposits in northwestern New Mexico tend to be poor in minor element content. Ores from several deposits in the Abo Formation, however, are rich in most minor elements, compared with deposits in other stratigraphic units on the plateau.

Ores from deposits in the Entrada Sandstone on the eastern part of the Colorado Plateau tend to contain a little more vanadium than those from the Salt Wash Member of the Morrison Formation but are distinctly poor in uranium grade. Some of these deposits contain high local concentrations of such elements as chromium, selenium, and lead, but these metals are not sought in the mining operations and generally are not included with mined ore.

From examination of the regional variation in composition of uranium deposits in all ore-bearing formations on the Colorado Plateau, including the Salt Wash Member of the Morrison Formation (pl. 1), it is found that the elements may be classified into 5 groups:

(1) Co, Ni, Y, Mo, As, Sb, and Fe: These elements tend to be most highly concentrated in uranium deposits on the western part of the Colorado Plateau, generally regardless of the stratigraphic units in which they occur. (2) Ag and Pb: These elements tend to be highly concentrated in uranium deposits in scattered areas on the western part of the plateau and in the salt anticline area of western Colorado and eastern Utah. (3) Cu and Zn: These elements are highly concentrated in deposits in most areas on the western part of the plateau and also in the salt anticline area. (4) Se: Selenium is highly concentrated in scattered areas throughout the plateau; the distribution of selenium is not similar to that of any other element studied. (5) V: Vanadium increases in abundance in uranium deposits from west to east across the entire plateau, regardless of the stratigraphic units in which the deposits occur. An exception to this general trend occurs in an area extending east of the Henry Mountains north to Temple Mountain, on the western part of the plateau; ores from this area are vanadium-rich.

Interpretations of the causes of these regional variation patterns are withheld until current studies are completed. However, most of the minor elements that appear to be associated with tuffaceous materials in uranium deposits in the Salt Wash Member of the Morrison Formation are similarly associated with tuff in deposits in other units. Selenium appears to be an exception. Arkosic units such as the Shinarump Member of the Chinle Formation and the Abo Formation contain copper-rich deposits. This has been found to be true in a much broader group of deposits reported on by Fischer and Stewart (1961). With the possible exceptions of uranium deposits in fractured rocks near Temple Mountain, Utah, and some deposits in Lisbon Valley, Utah, studied by Kennedy (1961, p. 146), none of the deposits display evidence of having received extrinsic elements from sources external to their host rock units.

SUMMARY AND CONCLUSIONS

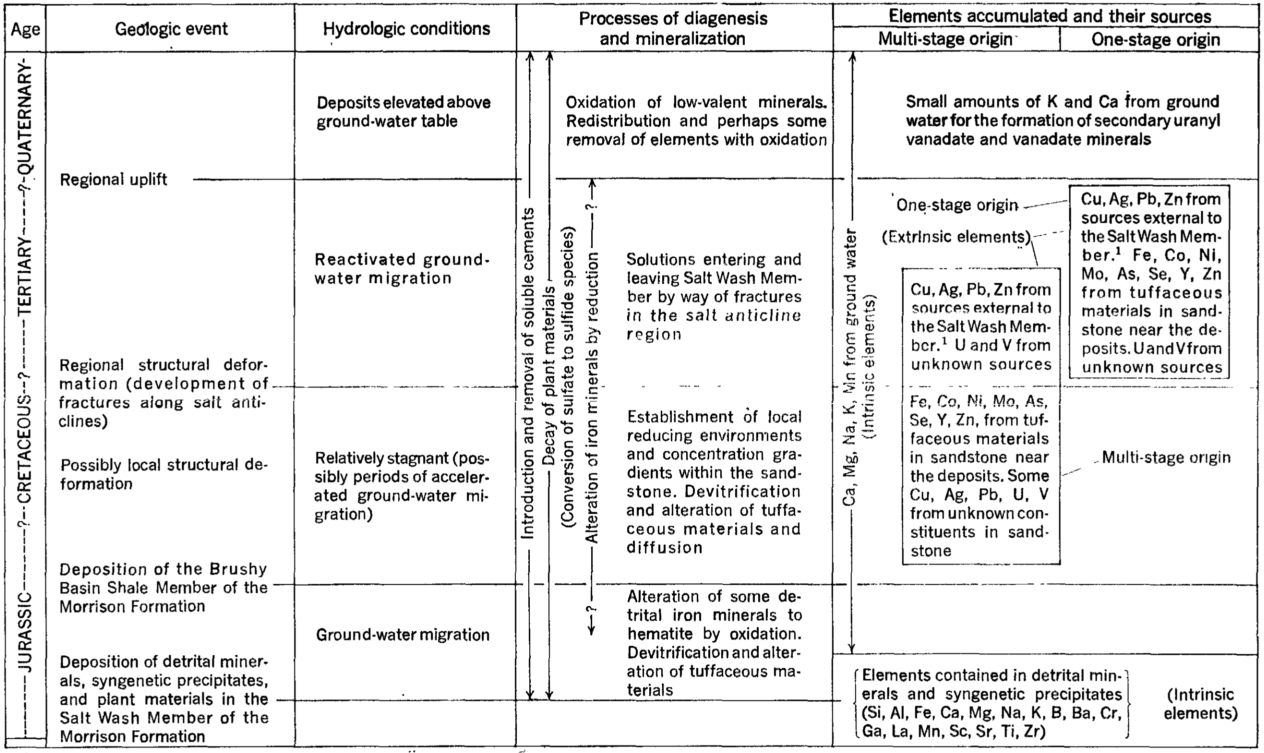
Studies of the regional variation and geochemical coherence of extrinsic elements in uranium deposits in the Salt Wash Member of the Morrison Formation indicate that some of the elements (Fe, Co, Ni, Mo, As, Se, and Y) may have been derived mainly from tuffaceous materials in the host rocks. Other elements (Cu, Ag, and Pb) may have been derived mainly from sources external to the Salt Wash Member in the salt anticline area of western Colorado and eastern Utah, but some of the lead is of radiogenic origin, derived from the decay of uranium in place. Zinc appears to have been derived from both sources. Uranium and probably vanadium in the Frenchy Incline deposit were derived from sources outside the altered part of the sandstone lens in which the deposit occurs. The elements derived from tuffaceous materials could have come from the altered sandstone lens.

Uranium deposits in the Salt Wash Member could have formed entirely during a period when ground-water solutions were migrating through the sandstone, most likely after regional deformation in Late Cretaceous or early Tertiary time. Alternatively, they could have formed partly during an early period of relatively stagnant hydrologic conditions and partly during later ground-water migration. Both hypotheses pose difficulties.

A summary of major events in the geologic history of the Salt Wash Member on the Colorado Plateau is given in figure 9. These geologic events controlled hydrologic conditions within the Salt Wash, and hydrologic conditions, in turn, determined the processes of diagenesis and mineralization that occurred. The last two columns in figure 9 indicate when various elements may have accumulated in the uranium deposits, according to two hypotheses. Further evaluation and comparison of these hypotheses must come from additional field and geochemical investigations. According to the one stage hypothesis of origin, solutions bearing Cu, Ag, Pb, and Zn were brought to the Salt Wash Member from external sources by way of fractures in the salt anticline area, during a period of ground-water migration. The solutions may also have carried uranium and vanadium, but these elements could also have been leached from rocks within the Salt Wash as the solutions migrated through it or could have been transported separately. Other elements, including Fe, Co, Ni, Mo, As, Se, Y, and some Zn, were leached from tuffaceous materials in the sandstone.

According to the multiple stage hypothesis of origin, Fe, Co, Ni, Mo, As, Se, Y, and some Zn (possibly also some Cu, Ag, Pb, U, and V) accumulated in the deposits during an early stage of relatively stagnant ground-water conditions by processes of solute diffusion. Roll structures, defined largely by concentrations of pyrite, originated in the ore bodies during this time. After structural deformation of the Salt Wash Member and acceleration of ground-water migration, solutions bearing Cu, Ag, Pb, and Zn entered the Salt Wash, and deposits of these elements were superimposed on the earlier accumulations of elements. Uranium and vanadium may have been brought by the same solutions carrying Cu, Ag, Pb, and Zn but may also have been transported separately. Roll structures containing uranium and vanadium minerals may have formed from the precipitation of these elements in the earlier pyrite rolls.

Studies of the distribution of elements in uranium deposits in stratigraphic units other than the Salt Wash Member of the Morrison Formation have not been completed, but evidence thus far accumulated suggests that elements associated with tuffaceous materials



Age	Geologic event	Hydrologic conditions	Processes of diagenesis and mineralization	Elements accumulated and their sources: Multi-stage origin	Elements accumulated and their sources: One-stage origin
JURASSIC------?--CRETACEOUS--?------TERTIARY-----?-QUATERNARY-		Deposits elevated above ground-water table	Oxidation of low-valent minerals. Redistribution and perhaps some removal of elements with oxidation	Small amounts of K and Ca from ground water for the formation of secondary uranyl vanadate and vanadate minerals	
	Regional uplift				
		Reactivated ground-water migration	Solutions entering and leaving Salt Wash Member by way of fractures *in the salt anticline region*	One-stage origin (Extrinsic elements) Cu, Ag, Pb, Zn from sources external to the Salt Wash Member.[1] U and V from unknown sources	Cu, Ag, Pb, Zn from sources external to the Salt Wash Member.[1] Fe, Co, Ni, Mo, As, Se, Y, Zn from tuffaceous materials in sandstone near the deposits. U and V from unknown sources
	Regional structural deformation (development of fractures along salt anticlines)				
	Possibly local structural deformation	Relatively stagnant (possibly periods of accelerated ground-water migration)	Establishment of local reducing environments and concentration gradients within the sandstone. Devitrification and alteration of tuffaceous materials and diffusion	Fe, Co, Ni, Mo, As, Se, Y, Zn, from tuffaceous materials in sandstone near the deposits. Some Cu, Ag, Pb, U, V from unknown constituents in sandstone	Multi-stage origin
	Deposition of the Brushy Basin Shale Member of the Morrison Formation				
		Ground-water migration	Alteration of some detrital iron minerals to hematite by oxidation. Devitrification and alteration of tuffaceous materials		
	Deposition of detrital minerals, syngenetic precipitates, and plant materials in the Salt Wash Member of the Morrison Formation			Elements contained in detrital minerals and syngenetic precipitates (Si, Al, Fe, Ca, Mg, Na, K, B, Ba, Cr, Ga, La, Mn, Sc, Sr, Ti, Zr)	(Intrinsic elements)

[1]For example, basement rocks, laccoliths, salt plugs, and others, by way of fractures

FIGURE 9.—Interpretation of the sequence of events in the formation of uranium deposits in the Salt Wash Member of the Morrison Formation.

in the Salt Wash are also associated with these materials in other units. No evidence has been found except in small areas that deposits in other units received extrinsic elements from sources external to their host rocks.

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