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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOCHEMISTRY OF THE FRENCHY INCLINE URANIUM DEPOSIT, SAN MIGUEL COUNTY, COLORADO

By

Alfred T. Miesch

1961

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

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

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Contents

Page

Abstract-- 1

Introduction-- 5

Description and geologic setting of the Frenchy Incline uranium deposit-- 10

Collection of samples--- 16

Composition of the uranium ore-------------------------------- 18

Composition of the unmineralized host rocks------------------- 34

Quantities of extrinsic elements------------------------------ 38

Significance of volume relations between uranium ore and altered sandstone--- 43

Mechanisms of transportation of the elements------------------ 49

- Solution flow--- 49
- Solute diffusion-- 59

Significance of regional variation of composition of uranium deposits in the Salt Wash member of the Morrison formation--- 69

Summary and conclusions--------------------------------------- 92

Acknowledgments--- 104

Literature cited-- 105

Illustrations

Page

Figure 1.--Tectonic sketch map of the Colorado Plateau---------- 11

2.--Geologic map and diagrammatic cross section of the Legin area and vicinity, San Miguel County, Colorado-- 12

3.--Histograms showing concentrations of elements (aluminum through potassium) in drill-core samples from the Frenchy Incline mine area---------- 23

4.--Histograms showing concentrations of elements (silver through chromium) in drill-core samples from the Frenchy Incline mine area----------------- 24

5.--Histograms showing concentrations of elements (copper through nickel) in drill-core samples from the Frenchy Incline mine area----------------- 25

6.--Histograms showing concentrations of elements (lead through uranium) in drill-core samples from the Frenchy Incline mine area----------------- 26

7.--Histograms showing concentrations of elements (vanadium through zirconium) in drill-core samples from the Frenchy Incline mine area---------- 27

8.--Graph showing relation of arithmetic mean: geometric mean ratio to log variance and geometric deviation according to equation of Sichel (1952, p. 275)--------------------------- 30

Page

Figure 9.--Chart showing volume of water passing through a cross-sectional area of 1,000 square feet of sandstone as a function of time and hydraulic gradient, or of time and velocity of flow---------- 54

10.--Chart showing required minimum concentrations of elements in ore solutions of various volumes----- 57

11.--Eh-pH stability fields of iron minerals at various molal concentrations of total sulfur and CO_2-------- 63

12.--Groups of coherent elements in uranium ores from the Salt Wash member of the Morrison formation on the Colorado Plateau---------------------------- 74

13.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of cobalt in uranium deposits in the Salt Wash member of the Morrison formation--- 77

14.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of selenium in uranium deposits in the Salt Wash member of the Morrison formation----------------------------- 78

15.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of zinc in uranium deposits in the Salt Wash member of the Morrison formation---------------------------------- 79

16.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of iron in uranium deposits in the Salt Wash member of the Morrison formation---------------------------------- 80

Page

Figure 17.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of copper in uranium deposits in the Salt Wash member of the Morrison formation---------------------------- 81

18.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of V_2O_5 in uranium deposits in the Salt Wash member of the Morrison formation------------------------- 82

19.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of yttrium in uranium deposits in the Salt Wash member of the Morrison formation---------------------------- 83

20.--Tectonic sketch map of the Colorado Plateau showing concentrations of tuff fragments in sandstone samples from the Salt Wash member of the Morrison formation------------------------- 86

21.--Tectonic sketch map of the Colorado Plateau showing concentrations of heavy minerals in sandstone samples from the Salt Wash member of the Morrison formation------------------------- 88

22.--Tectonic sketch map of the Colorado Plateau showing concentrations of iron in sandstone samples from the Salt Wash member of the Morrison formation-------------------------------- 89

Page

Figure 23.--Tectonic sketch map of the Colorado Plateau showing concentrations of copper in sandstone samples from the Salt Wash member of the Morrison formation-------------------------- 90

24.--Tectonic sketch map of the Colorado Plateau showing concentrations of uranium in sandstone samples from the Salt Wash member of the Morrison formation-------------------------- 91

25.--Chart showing interpretation of the sequence of events in the formation of the Frenchy Incline uranium deposit---------------------------- 103a

Tables

Page

Table 1.--Mean compositions of uranium ore samples from the Frenchy Incline mine and other mines in the Salt Wash member of the Morrison formation---------------- 19

2.--Partial composition of mill-pulp samples of uranium ore from the Frenchy Incline mine-------------------- 20

3.--Mean compositions 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-- 35

4.--Mean composition of drill-core samples of mudstones from the Salt Wash member of the Morrison formation in the Frenchy Incline mine area--------------------- 36

5.--Estimation of quantities of extrinsic elements in the Frenchy Incline uranium deposit------------------ 40

6.--Estimation of restored partial composition of sandstone in the Frenchy Incline mine area----------- 47

7.--Correlation coefficients between logarithms of element concentrations in uranium ore samples from the Salt Wash member of the Morrison formation------- 71

8.--Comparison of quantities of elements in 5,000 tons of average igneous rock and 10,000 tons of uranium ore-- 95

(p. 1 follows)

GEOCHEMISTRY OF THE FRENCHY INCLINE URANIUM DEPOSIT, SAN MIGUEL COUNTY, COLORADO

by

Alfred T. Miesch

Abstract

The Frenchy Incline uranium deposit is in the Salt Wash member of the Morrison formation of Late Jurassic age on the central part of the Colorado Plateau, and consists of sandstone and mudstone that have been impregnated with uranium and vanadium minerals in addition to other constituents. The compositions of the deposit and its host rocks 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 (?), lead, zinc, 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 enriched in other uranium deposits in the Salt Wash member of the Morrison formation on the Colorado Plateau.

Quantitative considerations show that most of the enriched elements in the Frenchy Incline deposit could have been derived from altered sandstone adjacent to the deposit without changing its composition by any detectable amount. However, uranium and probably vanadium were 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.

If the elements were transported to the deposit by flowing ore solutions, the required minimum concentration 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 solution 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.

Probably not all of the elements which are enriched in the deposit were transferred to the site of mineralization by flowing solutions. Thermodynamic considerations suggest that concentration gradients of iron in solution were established in the host sandstone during an early period of relatively stagnant ground-water conditions. Iron and other elements may have been transferred by solute diffusion processes which occurred in response to the concentration gradients.

The regional variations of elements among other uranium deposits in the Salt Wash member point to the sources of these elements in the deposits. It is interpreted that iron, molybdenum, cobalt, nickel, selenium, arsenic, and part of the zinc in the deposits were derived chiefly from tuffaceous materials in or associated with the host sandstone. Some copper, silver, and lead in the deposits may also have been derived from the host sandstone. Additional copper, silver, lead, and part of the zinc were derived from sources external to the Salt Wash member by way of fractures in the salt anticline region of western Colorado and eastern Utah. Vanadium in the deposits may have been derived from heavy minerals in the host sandstone, but not from the altered part of the lens in which the deposit occurs.

Uranium in the Frenchy Incline deposit, and in other deposits in the Salt Wash member, may have been derived from magmatic sources which produced the laccoliths of the La Sal Mountains, from extensive tuffaceous accumulations in the Morrison formation, or from other sources. It is possible that uranium was precipitated from solution on the reduction of uranyl ions by earlier accumulations of pyrite.

An hypothesis of origin for the Frenchy Incline uranium deposit is given which involves at least two stages of mineralization. The hypothesis accounts for the regional distributions of elements in the uranium deposits of the Salt Wash member over the entire Colorado Plateau, and interprets the deposits as having formed from the interaction of dynamic and chemical processes. The dynamic processes controlled hydrologic conditions within the Salt Wash member, and the chemical processes acted in response to changes in these conditions.

Introduction

The problem of the origin of sandstone-type uranium deposits on the Colorado Plateau is a multiple one, involving 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 mechanism of deposition of the elements to form the deposits. Final solutions to all these questions will be necessary before a complete theory of origin for the deposits will gain general acceptance. To date, varying degrees of progress have been made toward the solution of each question, but none has been answered completely. This study has been directed primarily toward determining the source or sources of the elements in the deposits, which may or may not be the same as the source of the fluid which transported the elements. It is not, however, necessary, nor likely, that all the elements 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. In addition, two mechanisms which may have been responsible for transporting elements from their source to the deposit (solution flow and solute diffusion) are discussed.

The chemical compositions of mineralized and unmineralized rocks in and adjacent to the Frenchy Incline uranium deposit, a fairly typical uranium deposit in the Salt Wash member of the

Morrison formation on the Colorado Plateau, are examined and compared with the compositions of other mineralized and unmineralized rocks from the Salt Wash member on other parts of the Plateau. Quantitative studies of the chemical changes which have occurred with ore formation, particularly of the amount of each element added to the sandstone have been made, and, considered in conjunction with other factors, permit speculation regarding possible sources of elements in the deposits.

Other factors which appear to have a direct bearing on the sources of elements in the uranium deposits, and which are considered in this study, are the regional variations in the compositions of the uranium deposits and the unmineralized sandstones in the Salt Wash member of the Morrison formation on the entire Colorado Plateau.

Sandstone-type uranium deposits on the Colorado Plateau consist of sandstone, mudstone, and some 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 evidenced by the fact that layers of mineralized rock commonly cross bedding in the host sandstones which enclose the deposits. The primary ore minerals in the deposits are generally of the low-valent type, consisting of oxides and sulfides containing uranium (IV), vanadium (III and IV), iron (II), and copper (I). A few selenide minerals are present locally. Fragments of plant remains can be observed in most of the deposits, and chemical analyses show organic carbon to be present in essentially all of the ores. Organic carbon and associated H_2S probably served as reducing and precipitating agents. The organic carbon now present is thought to be an excess remaining after oxidization and removal from the ores 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 of the uranium deposits on the Colorado Plateau are directly associated with faults which have clearly undergone pre-ore movement, and the distribution of deposits on the Plateau is not demonstrably 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 sandstone, but the boundaries of other layers sharply 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). Most of the deposits consist of a number of closely spaced ore layers which are commonly several hundred feet across and from less than one up to several feet thick. A large number of the deposits consist of several thousand tons of minable ore, but the total range in size is from less than one ton to more than several million tons.

The uranium deposits on the Colorado Plateau occur mainly in sedimentary units of Late Paleozoic and Mesozoic age, 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 the large majority of the deposits are in the Salt Wash member. Characteristics of sandstone lenses within the Salt Wash member which appear to be typically associated with the occurrence of ore have been tabulated by Weir (1952, p. 26) and include 1) thickness of greater than 40 feet, 2) light brown rather than a 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.

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, a gentle asymmetrical arch underlain by thickened masses of salt derived from 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 $1\frac{1}{2}^{\circ}$ or less. Exposed sedimentary units in the Egnar quadrangle are principally Jurassic and Cretaceous sandstone and shale (fig. 2).

All of 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 and clay. Carbonate forms 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 in color, but the parts of the lens more distant from mineralized rock are reddish brown. Thin mudstone layers adjacent to ore are green colored, but some mudstone in the upper parts of the sandstone lens is reddish brown.

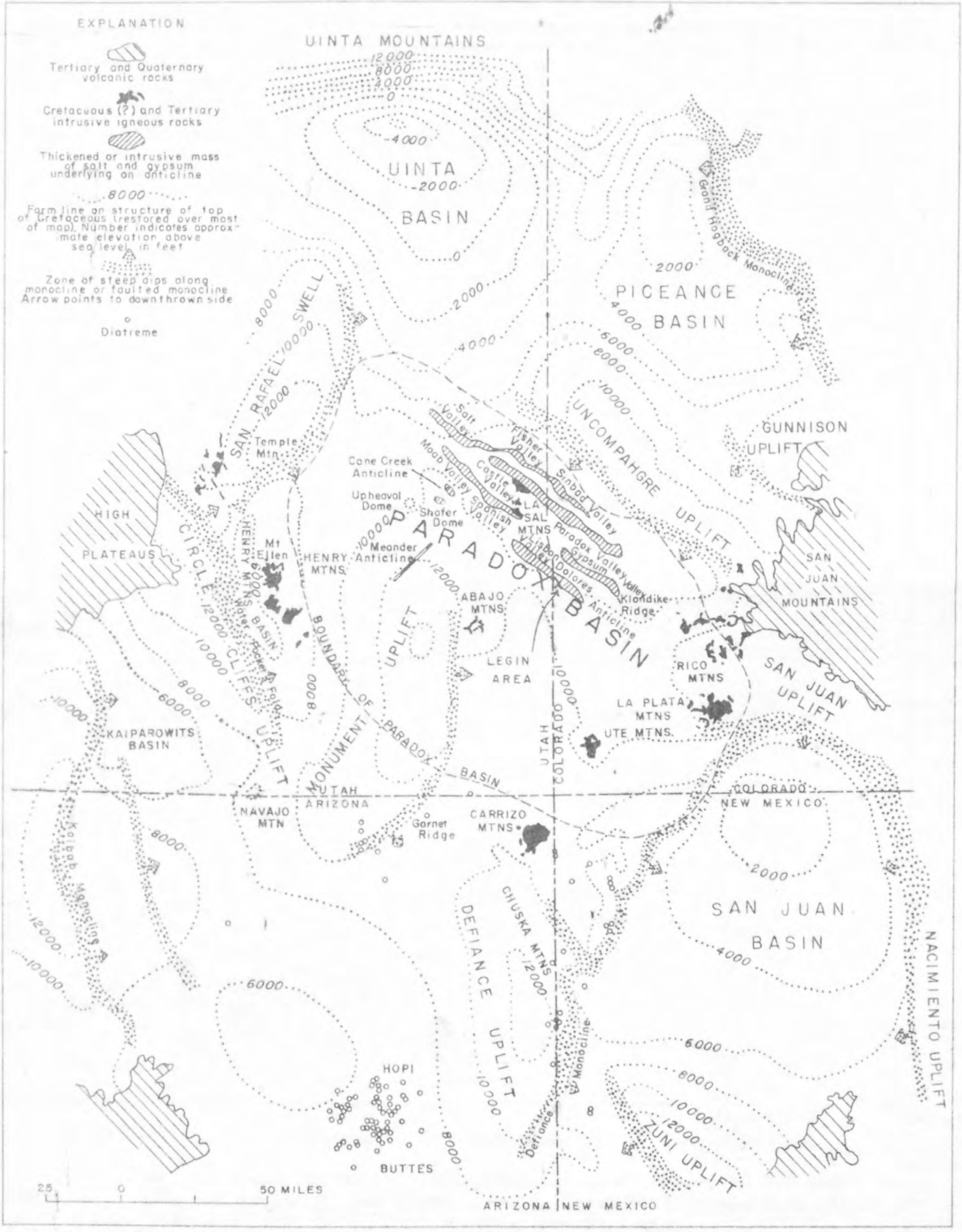
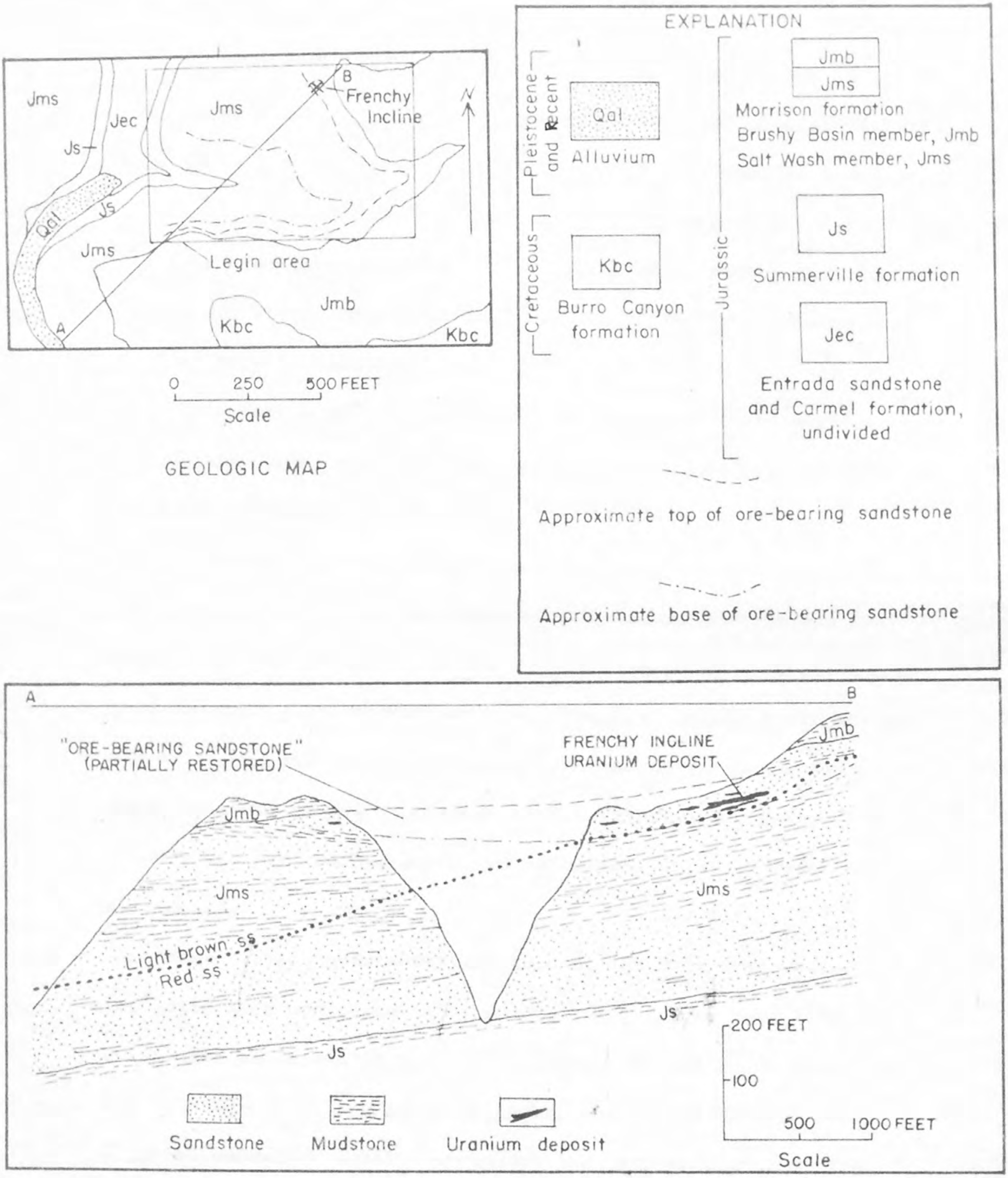


FIGURE 1.--Tectonic sketch map of the Colorado Plateau (after Shoemaker, 1956a)



GEOLOGIC MAP

DIAGRAMMATIC CROSS-SECTION

FIGURE 2.--Geologic map and diagrammatic cross section of the Legin area and vicinity, San Miguel County, Colorado (adapted from Cater, 1955, and Henry Bell, 1952, written communication).

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 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 can be observed, all but the lowermost lenses are light brown in color, and the relations seem to be as shown diagrammatically on the cross section in figure 2. The color difference in the sandstones is due to differences in the colors of the interstitial clay minerals and the iron minerals. In reddish sandstone iron is contained largely in magnetite and hematite, whereas in light-brown sandstone some, and 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, 1952, written communication). The favorable part of the sandstone lens underlies an area of about one-fifth of a square mile and has been penetrated by over 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.

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 Frenchy 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. 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 of the mineralized layers are rich in carbonized stems and leaves of fossil plants. No carbonized logs are present, but one non-uraniferous 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, seven 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 were obtained. The core was split and assayed primarily to determine ore reserves in the deposit. The 45 feet of core were subdivided into 114 individual samples, each about 1 inch in diameter and averaging about 5 inches in 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 spectrographically and by other methods 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. In addition, three horizontal holes were drilled from the mine workings outward for 150 feet; two of the horizontal holes were collared in mineralized layers, but in each of these holes the drill penetrated unmineralized sandstone within 9 feet from the drill collar. None of the horizontal drill holes intersected mineralized rock beyond 9 feet from 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 which penetrated mudstone layers immediately above, within, and immediately 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 1, along with the geometric mean composition of uranium ores from more than 200 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 partially 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 2.

The 114 drill-core samples of mineralized rock were analyzed by a rapid semiquantitative spectrographic method, described by A. T. Myers (1957, written communication) as follows:

"In this procedure a weighed amount of the powdered sample is burned in a controlled d.c. arc and the spectrum recorded on a photographic plate. Selected lines on the resulting plate are visually compared with those of standard spectra prepared in a manner similar to that for the unknowns. The standard spectra were prepared from mixtures of materials containing 68 elements in the following concentrations--10 percent, 4.6, 2.2, 1.0, 0.46, etc. These values were chosen so that the concentrations of the elements decrease from 10 percent to about 0.0001 percent by a factor of the reciprocal of the cube root of 10. This factor provides a geometric concentration series having three members for each order of magnitude and which is consistent with the relation

Table 1 .--Mean compositions of uranium ore samples from the Frenchy Incline mine and other mines in the Salt Wash member of the Morrison formation (in percent).

(1)	(2)	(3)		(4)	(5)	(6)	
	DRILL CORE SAMPLES FROM THE FRENCHY INCLINE MINE					MILL PULP SAMPLES FROM 215 OTHER MINES[6]	
Element[1]	Detection ratio[2]	Geometric mean[3]		Geometric deviation[4]	Arithmetic mean[5]	Geometric mean[3]	
Al	114:114	2.1	$\overset{\times}{\div}$ 1.2	2.1	2.8	2.5	$\overset{\times}{\div}$ 1.1
Fe	114:114	1.1	$\overset{\times}{\div}$ 1.1	1.5	1.2	.87	$\overset{\times}{\div}$ 1.1
Ca	114:114	.95	$\overset{\times}{\div}$ 1.4	4.4	2.9	2.0	$\overset{\times}{\div}$ 1.2
Mg	114:114	.30	$\overset{\times}{\div}$ 1.2	2.2	.42	.76	$\overset{\times}{\div}$ 1.2
Na	65:114	≈.05	---	---	≈.08	.12	$\overset{\times}{\div}$ 1.2
K	89:114	≈.8	---	---	≈1.	≈.6	
Ag	30:114	≈.00003	---	---	≈.00005	≈.00005	
B	31:114	≈.001	---	---	≈.002	≈.002	
Ba	114:114	.055	$\overset{\times}{\div}$ 1.2	2.2	.077	.075	$\overset{\times}{\div}$ 1.2
Be	17:114	≈.00004	---	---	≈.00006	≈.00003	
Co	75:93	.00042	$\overset{\times}{\div}$ 1.2	2.2	.00059	.0012	$\overset{\times}{\div}$ 1.2
Cr	114:114	.0015	$\overset{\times}{\div}$ 1.2	1.8	.0018	.0016	$\overset{\times}{\div}$ 1.1
Cu	114:114	.0093	$\overset{\times}{\div}$ 1.2	1.9	.012	.0090	$\overset{\times}{\div}$ 1.3
Ga	5:114	≈.00006	---	---	≈.00009	≈.00009	
La	1:114	≈.0003	---	---	≈.0005	≈.00004	
Mn	114:114	.028	$\overset{\times}{\div}$ 1.2	2.2	.039	.031	$\overset{\times}{\div}$ 1.1
Mo	64:114	≈.0002	---	---	≈.0003	≈.002	
Ni	112:114	.00091	$\overset{\times}{\div}$ 1.1	1.8	.0011	.0010	$\overset{\times}{\div}$ 1.2
Pb	89:114	.0031	$\overset{\times}{\div}$ 1.6	6.0	.016	.0096	$\overset{\times}{\div}$ 1.2
Sc	0:114	<.0001	---	---	<.0002	≈.0001	
Sr	114:114	.023	$\overset{\times}{\div}$ 1.2	1.8	.028	.012	$\overset{\times}{\div}$ 1.1
Ti	114:114	.055	$\overset{\times}{\div}$ 1.1	1.6	.063	.095	$\overset{\times}{\div}$ 1.1
U	114:114(c)	.084	$\overset{\times}{\div}$ 1.6	6.3	.46	.16	$\overset{\times}{\div}$ 1.2
V	114:114(c)	.49	$\overset{\times}{\div}$ 1.3	3.0	.91	.68	$\overset{\times}{\div}$ 1.1
Y	57:114	≈.0005	---	---	≈.0008	.0015	$\overset{\times}{\div}$ 1.1
Zn	42:114	≈.008	---	---	≈.01	≈.009	
Zr	114:114	.010	$\overset{\times}{\div}$ 1.2	2.3	.015	.021	$\overset{\times}{\div}$ 1.1

[1] Concentrations of all elements except uranium and vanadium were determined by a semiquantitative spectrographic method. Analyst: R.G. Havens, U. S. Geological Survey. Concentrations of uranium and vanadium in drill core samples determined by fluorimetric and wet chemical methods, respectively; data from Henry Bell (1952, written communication). 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 figs. 3-7).

[3] Geometric mean and 99 percent confidence interval.

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

[5] Arithmetic mean computed from geometric mean and geometric deviation by method of Sichel (1952). See figure 8 . Where geometric deviation is unknown the arithmetic mean is considered to be approximately 1.5 times greater than the geometric mean.

[6] See Shoemaker and others (1959, p. 30) for locations of most of the 215 mines.

Table 2. Partial composition of mill-pulp samples of uranium ore from the Frenchy Incline mine (in percent).

Element	Mill-pulp sample [7]		Weighted average
	PMS-79	PMS-80	
As [1]	0.012	0.012	0.012
C (organic) [2]	.23	.20	.22
Hg [3]	<.0001	<.0001	<.0001
P_2O_5 [4]	.052	.052	.052
S [5]	.06	.07	.06
Sb [1]	.0001	<.0001	<.0001
Se [6]	.0008	.0005	.0007

[1] Colorimetric analyses, by H. E. Crowe and J. H. McCarthy, U. S. Geological Survey.

[2] Analyst: Alice Caemmerer, U. S. Geological Survey.

[3] Analyst: J. J. Fahey, U. S. Geological Survey.

[4] Analyst: E. Mallory, U. S. Geological Survey.

[5] Analyst: J. Schuch, U. S. Geological Survey.

[6] Analyst: J. H. McCarthy, U. S. Geological Survey.

[7] Sample PMS-79 was split from 388 tons of uranium ore; sample PMS-80 was split from 282 tons of uranium ore.

between the blackness of the spectral line and the amount of an element present. By means of a comparator showing enlarged adjacent images of the sample spectra and the standard spectra, visual estimates are made of concentrations of the elements in the sample which are then reported as being between two standards in the following manner: X indicating the middle portion (5-2) of an order of magnitude; X+ the higher portion (10-5); and X- the lower (2-1).

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

Thus, 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. 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 (figs. 3 to 7). The fact that only about 60 percent of the reported analytical results fall within the correct class probably has little effect on the mean values, but may cause estimates of deviation from the mean to be somewhat high.

Although 68 elements are looked for in the analytical procedure fewer than 20 are generally detected. The remainder are present in concentrations which 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 (1954, p. 195). Histograms of the analytical data for some elements are truncated at the limits of sensitivity for those elements, indicated by vertical dashed lines on figures 3 to 7.

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 2 years later than the mineralized samples, all spectrographic analyses were made by the same analyst.

Histograms of the analytical data are approximately symmetrical when plotted on logarithmic scales, and the frequency distributions of the original data appear to approximate a lognormal 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 (Fisher, 1950, p. 12) measures than the arithmetic mean

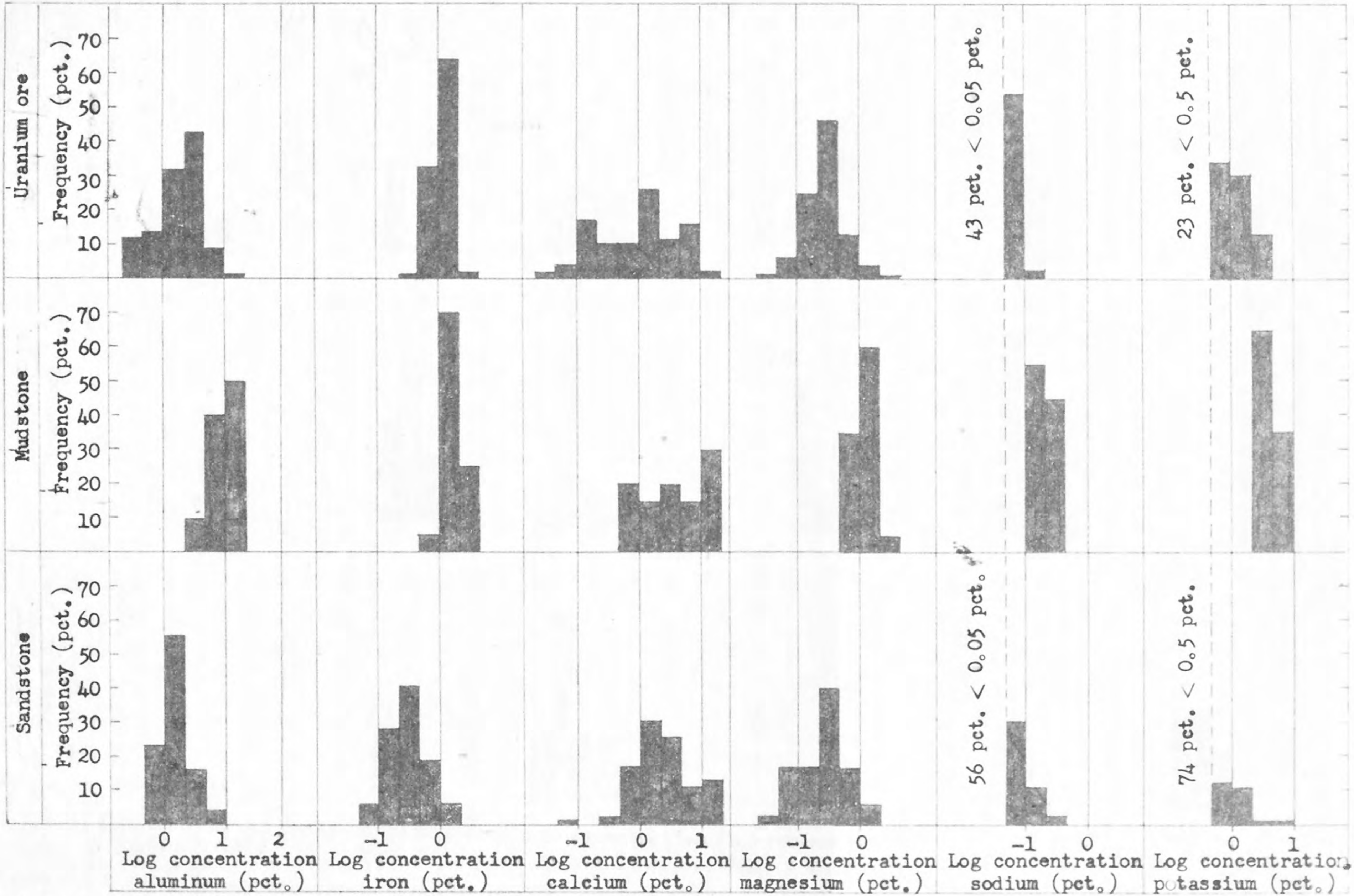


Figure 3 . Histograms showing concentrations of elements (aluminum through potassium) in drill-core samples from the Frenchy Incline mine area (114 samples of uranium ore; 20 samples of mudstone; 85 samples of sandstone).

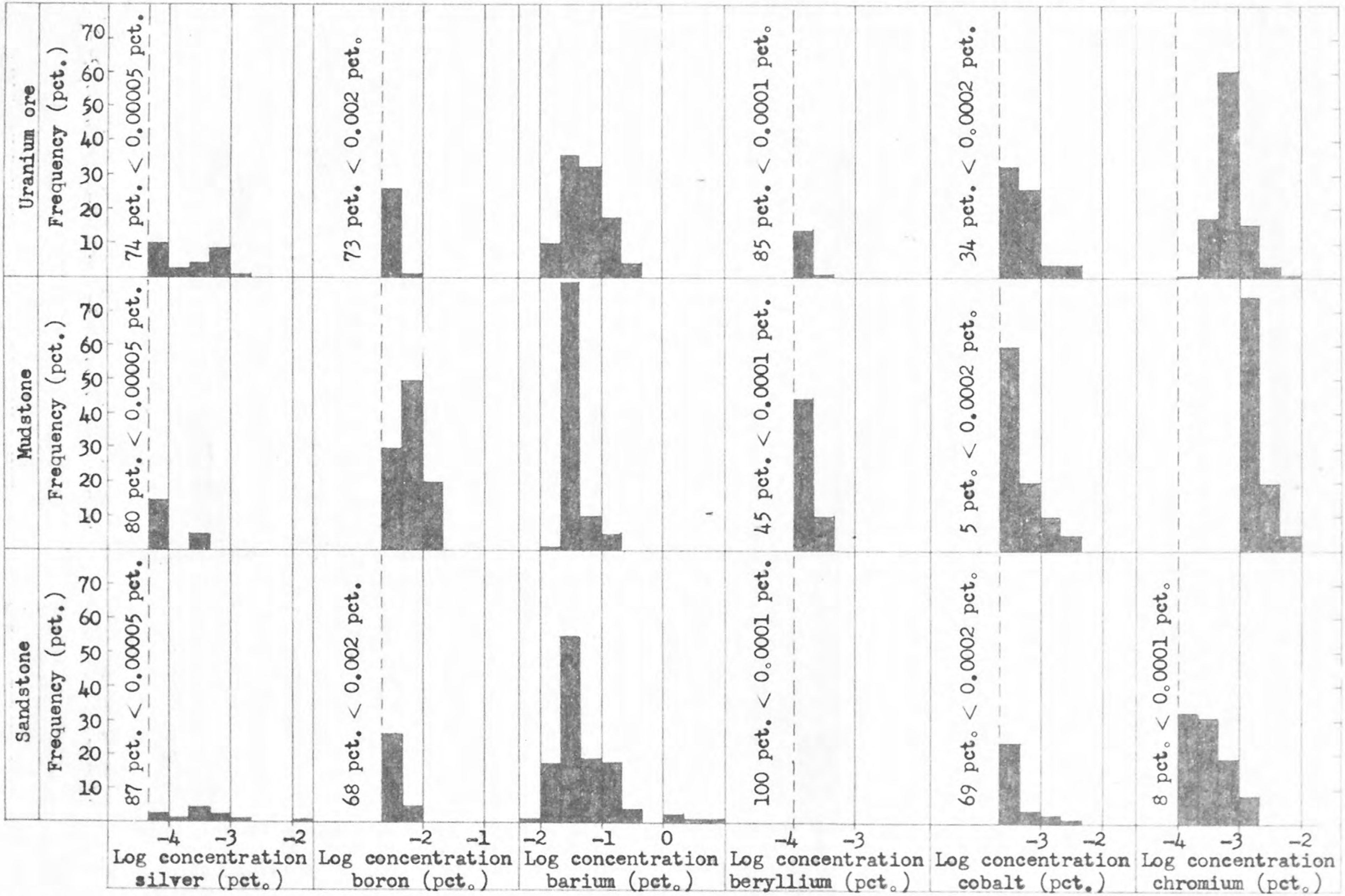


Figure 4. Histograms showing concentrations of elements (silver through chromium) in drill-core samples from the Frenchy Incline mine area (114 samples of uranium ore; 20 samples of mudstone; 85 samples of sandstone).

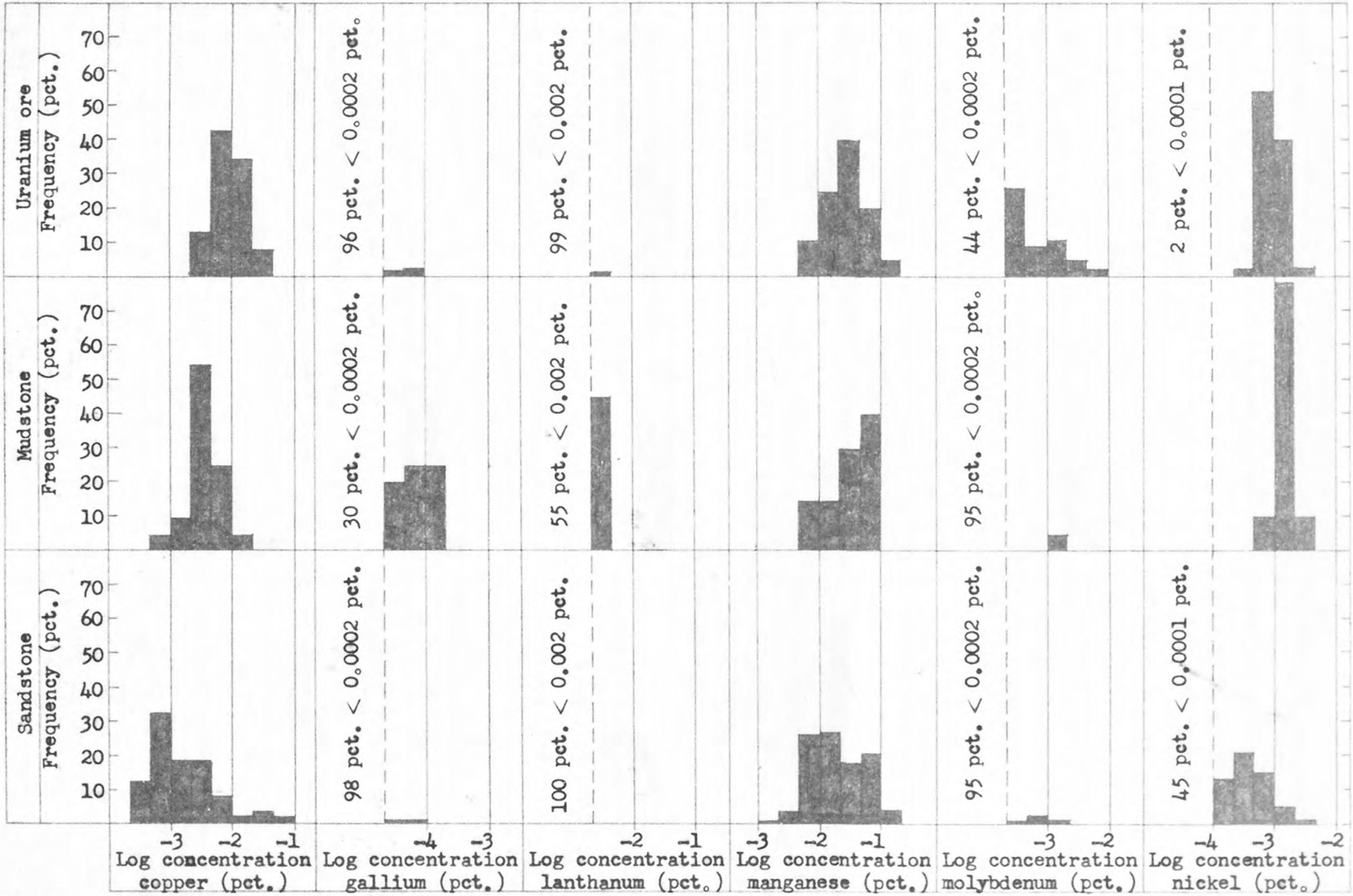


Figure 5. Histograms showing concentrations of elements (copper through nickel) in drill-core samples from the Frenchy Incline mine area (114 samples of uranium ore; 20 samples of mudstone; 85 samples of sandstone).

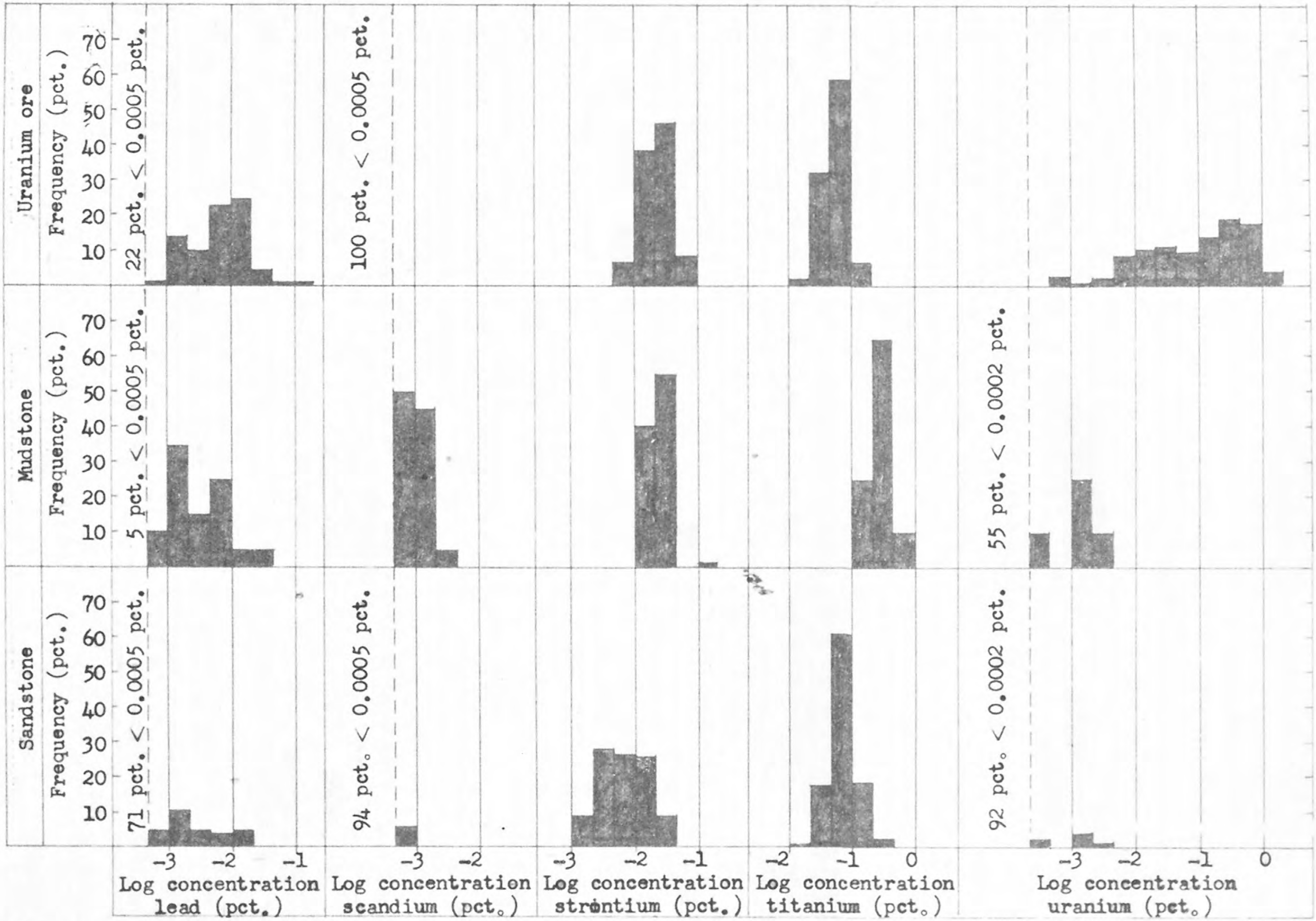


Figure 6. Histograms showing concentrations of elements (lead through uranium) in drill-core samples from the Frenchy Incline mine area (114 samples of uranium ore; 20 samples of mudstone; 85 samples of sandstone).

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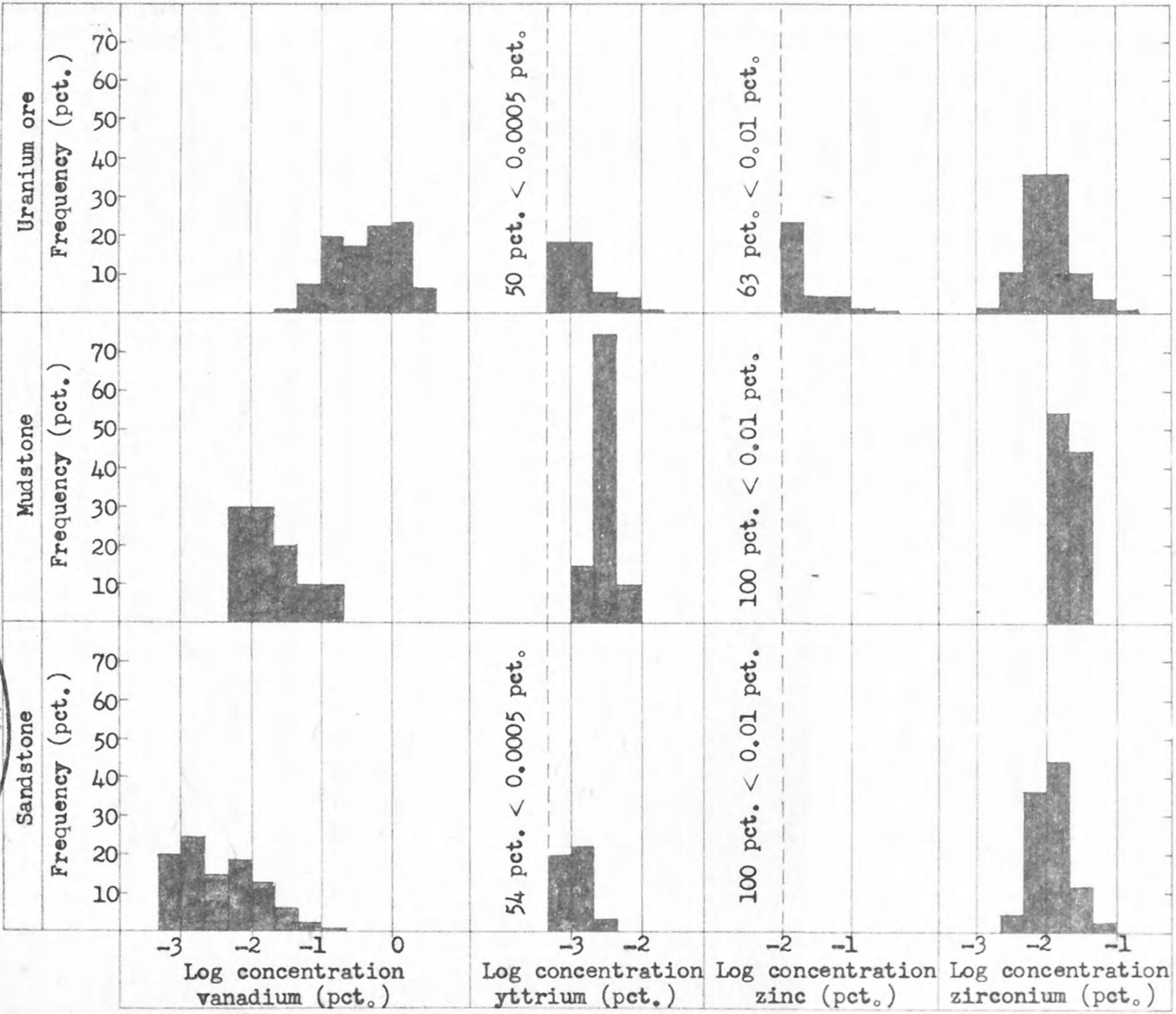

Figure 7. Histograms showing concentrations of elements (vanadium through zirconium) in drill-core samples from the Frenchy Incline mine area (114 samples of uranium ore; 20 samples of mudstone; 85 samples of sandstone).

and standard deviation, respectively. A consistent measure of central tendency is one which tends toward the true mode [~~average value~~] of the population from which the sample is drawn; an efficient statistic is the one which 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:

$$\text{Error of mean log} = \pm \frac{ts}{\sqrt{n-1}}, \quad \text{(Hoel, 1947, p. 144-145)}$$

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 a given number of degrees of freedom. Consequently, the error of the geometric mean (column 3, table 1) is taken as:

$$\text{Error of the geometric mean} = \overset{\times}{\div} \text{antilog} \frac{ts}{\sqrt{n-1}}$$

Although the geometric mean of the analyses, compared to the arithmetic mean, 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, 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, which 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 pointed out that samples from a mine are commonly not representative. Because of this, the true arithmetic mean is estimated better by methods other than dividing the sum of a number of assays by this number. A method proposed by Finney (1941), but developed independently and introduced into the geologic 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 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 of the data, or as a function of the geometric deviation of the data (fig. 8). Various curves are given for various numbers of analyses being studied.

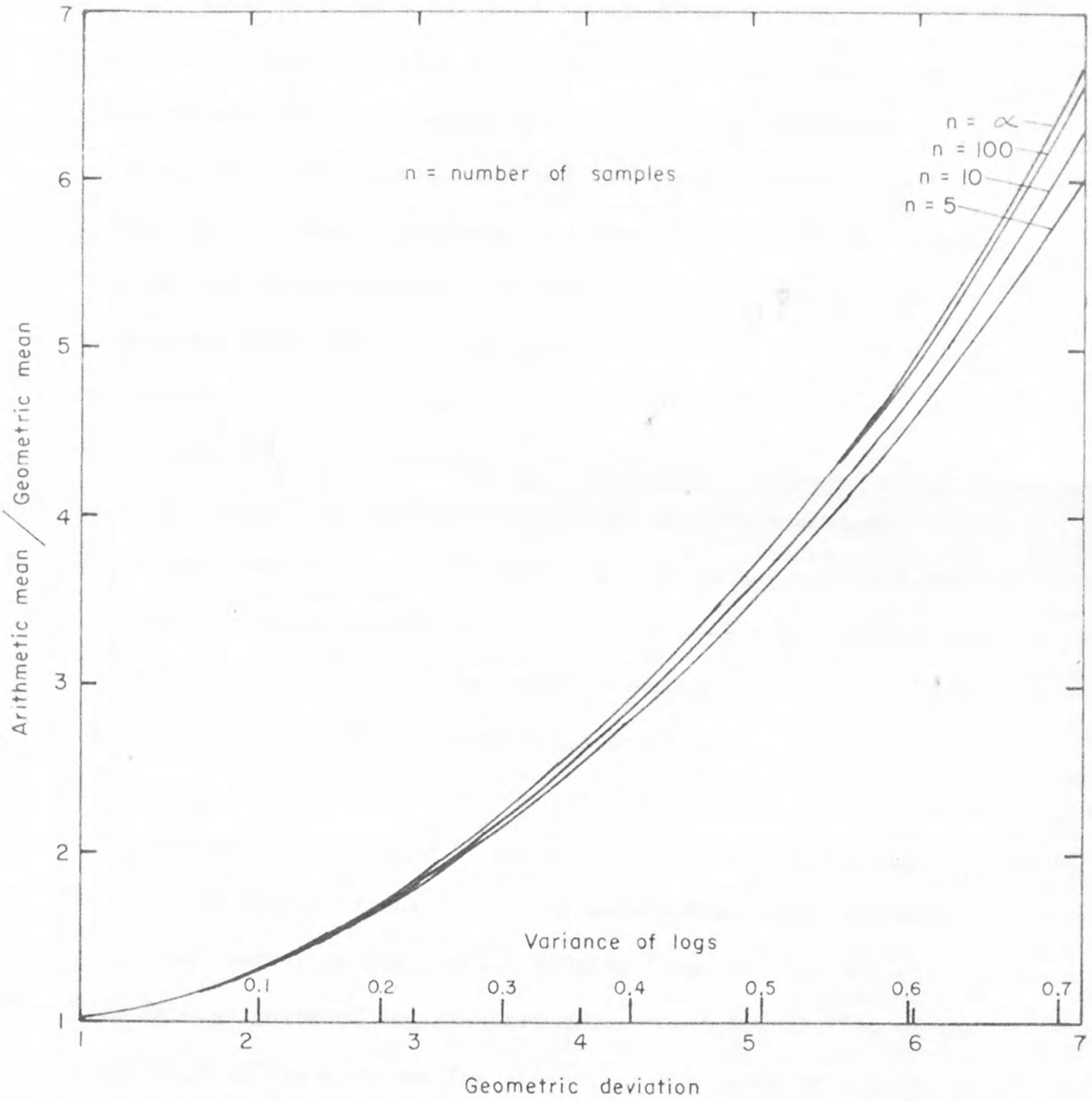

FIGURE 8.--Graph showing relation of arithmetic mean: geometric mean ratio to log variance and geometric deviation according to equation of Sichel (1952, p. 275).

In cases where an element was detected in only a portion of the samples which were analyzed (see Detection ratio, column 2, table 1) geometric and arithmetic means were estimated by approximate methods. Where the element was "not detected" in only a small portion 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, fig. 4). Geometric and arithmetic means, and geometric deviations, were then computed by the same methods used in cases where the element was detected in all the samples analyzed. If the element was not detected in a larger portion of the analyzed samples a second approximate method was used. This method is based on two main 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 (fig. 4), for example, is taken as 0.63 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 figure 4. The figure 0.63 is determined from a table of areas under the normal curve, such as that given by Hoel (1947, p. 243) or Waugh (1943, p. 509). As 74 percent of the area under the frequency curve of concentrations of silver in ore samples (fig. 4) 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 most of the arithmetic means which are known more precisely are about 1.5 times greater than the corresponding geometric means.

In cases where an element is detected in none of the analyzed samples only a maximum estimate of the mean can be given. This maximum is 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 portion 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 data represented on figures 3 to 7.

As an example in reading table 1, the distribution of calcium in uranium ore from the Frenchy Incline deposit may be interpreted as follows. The most characteristic or frequently found 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 $0.95 \div 1.4$ 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 to the geometric mean times the geometric deviation, or 0.95 ÷ 4.4 to 0.95 x 4.4 (0.22 to 4.2 percent). Approximately 95 percent of the concentrations should lie within the range $0.95 \div (4.4)^2$ to $0.95 \times (4.4)^2$, (0.049 to 18.4 percent). According to the computed arithmetic mean, the Frenchy Incline deposit consists of 2.9 percent calcium, and if the deposit is 10,000 tons it contains 10,000 x 0.029 (290) tons of calcium.

In column 6 of table 1 the geometric mean composition of mill-pulp samples of ores from other mines in the Salt Wash member of the Morrison formation is given for comparison purposes. As the mill-pulp samples represent large portions of uranium deposits the arithmetic mean composition of the Frenchy Incline deposit is appropriate for comparing with the geometric mean, or characteristic, composition of ores from other mines. It is apparent that the composition of the Frenchy Incline deposit is not greatly different from that of typical ore from other deposits in the Salt Wash member, except with regard to a few elements, such as lanthanum and molybdenum (table 1). Lanthanum and molybdenum are the only elements whose estimated concentrations in the Frenchy Incline deposit differ from their geometric mean concentrations in ores from other mines by more than a factor of 3.

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 3 and 4, respectively. The statistics were computed and are interpreted in the manner described in the preceeding section.

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 3) 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. The geometric means for most elements are within a factor of 3 (table 3). 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. The large majority of the samples from the Frenchy Incline mine area are light brown in

Table 3.--Mean compositions 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 (in percent).

(1)	(2)	(3)		(4)	(5)	(6)	
	DRILL CORE SAMPLES FROM THE FRENCHY INCLINE MINE AREA					OUTCROP SAMPLES FROM 66 OTHER AREAS[6]	
Element[1]	Detection ratio[2]	Geometric mean[3]		Geometric deviation[4]	Arithmetic mean[5]	Geometric mean[3]	
Al	85:85	1.5	$\overset{x}{\div}$ 1.2	1.8	1.8	1.2	$\overset{x}{\div}$ 1.2
Fe	85:85	.29	$\overset{x}{\div}$ 1.2	2.1	.39	.27	$\overset{x}{\div}$ 1.9
Ca	85:85	2.3	$\overset{x}{\div}$ 1.4	2.9	4.1	2.9	$\overset{x}{\div}$ 1.4
Mg	85:85	.25	$\overset{x}{\div}$ 1.3	2.5	.39	.24	$\overset{x}{\div}$ 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	$\overset{x}{\div}$ 1.4	3.3	.092	.032	$\overset{x}{\div}$ 1.3
Be	0:85	< .00002	---	---	< .00003	---	$\overset{x}{\div}$ 1.3
Co	26:85	≈.0001	---	---	≈.0002	≈.00005	
Cr	78:85	.00028	$\overset{x}{\div}$ 1.3	2.4	.00042	.00086	$\overset{x}{\div}$ 1.3
Cu	85:85	.0016	$\overset{x}{\div}$ 1.4	3.6	.0037	.0017	$\overset{x}{\div}$ 1.3
Ga	2:85	≈.00003	---	---	≈.00005	≈.00007	
La	0:85	< .0003	---	---	< .0005	---	
Mn	85:85	.019	$\overset{x}{\div}$ 1.3	2.8	.032	.022	$\overset{x}{\div}$ 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	$\overset{x}{\div}$ 1.3	2.4	.010	.0057	$\overset{x}{\div}$ 1.2
Ti	85:85	.070	$\overset{x}{\div}$ 1.2	1.7	.083	.053	$\overset{x}{\div}$ 1.2
U	7:85(c)	≈.00006	---	---	≈.00009	.00018	$\overset{x}{\div}$ 1.2
V	85:85	.0036	$\overset{x}{\div}$ 1.5	3.7	.0086	.0012	$\overset{x}{\div}$ 1.3
Y	39:85	≈.0005	---	---	≈.0008	≈.0002	
Zn	0:85	< .002	---	---	< .003	≈.001	
Zr	85:85	.012	$\overset{x}{\div}$ 1.2	1.9	.015	.0089	$\overset{x}{\div}$ 1.3

[1] Concentrations of all elements except uranium were determined by a semiquantitative spectrographic method. Analyst: R.G. Havens, U.S. Geological Survey. Concentrations of uranium in drill core samples determined by chromatographic method. Analyst: C.E. Thompson, U.S. Geological Survey. Concentrations of uranium in outcrop samples determined by fluorimetric method. Analysts: W. Mountjoy and J. Meadows, U. S. Geological 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 figs.3-7)

[3] Geometric mean and 99 percent confidence level.

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

[5] Arithmetic mean computed from geometric mean and geometric deviation by method of Sichel (1952). See figure 8 . Where geometric deviation is unknown the arithmetic mean is considered to be approximately 1.5 times greater than the geometric mean.

[6] Data from W. L. Newman (1958, written communication). See Shoemaker and others, (1959, p. 30) for locations of areas.

Table 4 .--Mean composition of drill-core samples of mudstones from the Salt Wash member of the Morrison formation in the Frenchy Incline mine area (in percent).

(1) Element[1]	(2) Detection ratio[2]	(3) Geometric mean[3]	(4) Geometric deviation[4]	(5) Arithmetic mean[5]
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	.22
K	20:20	4.1 $\overset{\times}{\div}$ 1.3	1.5	4.4
Ag	4:20	≈.00003 ---	---	≈.00005
B	20:20	.0063 $\overset{\times}{\div}$ 1.4	1.7	.0076
Ba	20:20	.036 $\overset{\times}{\div}$ 1.3	1.6	.041
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	.0021
Cu	20:20	.0035 $\overset{\times}{\div}$ 1.6	2.0	.0044
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	.0017
Pb	19:20	.0026 $\overset{\times}{\div}$ 2.2	3.4	.0055
Sc	20:20	.0010 $\overset{\times}{\div}$ 1.4	1.6	.0012
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(c)	≈.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

[1] Concentrations of all elements except uranium were determined by a semiquantitative spectrographic method. Analyst: R.G. Havens, U. S. Geological Survey. Concentrations of uranium determined by a chromatographic method. Analyst: C. E. Thompson, U. S. Geological 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 figures 3-7.

[3] Geometric mean and 99 percent confidence interval.

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

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

color, whereas those from other parts of the Plateau are, in large part, reddish brown, but Newman and Elston (1959, p. 135-136) and Newman (in press) have shown that the colors of sandstone and mudstone from the Salt Wash member in the same area have little relation to their bulk chemical compositions.

The geometric mean concentrations of silver, lead, and vanadium are 3 to 7 times higher in the sandstones from the mine area than in sandstones from other areas, and the geometric mean concentration of uranium in sandstones from the mine area is only one-third as high as the concentration of uranium in sandstones from other areas.

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 3). The Frenchy Incline deposit contains 2.8 percent aluminum (table 1), an amount equivalent to a hypothetical mixture of 89 percent sandstone (containing 1.8 percent aluminum; table 3) and 11 percent mudstone (containing 10.7 percent aluminum; table 4).

Assuming that none of the aluminum was added to the deposit with mineralization the lithologic composition of the deposit is probably close to 89 percent sandstone and 11 percent mudstone, proportions not unreasonable in view of rough visual estimates made in the mine. These proportions 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 estimate of the amount which is intrinsic from the actual amount present. Estimates of extrinsic amounts of elements in the Frenchy Incline deposit are given in table 5. 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 which have only a slightly lower mean concentration in the hypothetical composite (column 2, table 5) than in the uranium ore (column 3, table 5) 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).

It may be seen from table 5 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 essentially all of the lead, zinc, uranium, and vanadium are estimated to be extrinsic. All these elements, except strontium, are major or minor constituents of minerals which are commonly observed in low-valent types of uranium ores in the Salt

Table 5 .--Estimation of quantities of extrinsic elements in the Frenchy Incline uranium deposit.

(1) Element	(2) Concentration (Cm) in hypothetical composite of 89 percent sandstone and 11 percent mudstone(in percent) 1/	(3) Arithmetic mean concentration in uranium ore (in percent) (from table 1)	(4) Amount estimated to be extrinsic in the uranium ore 2/ (percent)	 (grams/10,000 tons)
Al	2.8	2.8	---	---
Fe	.56	1.2	0.6	5.4 x 10^7
Ca	4.5	2.9	---	---
Mg	.49	.42	---	---
Na	≈.08	≈.08	---	---
K	≈.9	≈1.	---	---
Ag	≈.00003	≈.00005	≈.00002	≈2 x 10^3
B	≈.003	≈.002	---	---
Ba	.086	.077	---	---
Be	≈.00002-.00005	≈.00006	---	---
Co	≈.0002	.00059	≈.0004	≈3.6 x 10^4
Cr	.00061	.0018	.0012	1.1 x 10^5
Cu	.0038	.012	.008	7.3 x 10^5
Ga	≈.0001	≈.00009	---	---
La	≈.0003-.0008	≈.0005	---	---
Mn	.033	.039	---	---
Mo	≈.00008	≈.0003	≈.0002	≈2 x 10^4
Ni	≈.0004	.0011	≈.0007	≈6.4 x 10^4
Pb	≈.001	.016	≈.015	≈1.4 x 10^6
Sc	≈.0002	<.0002	---	---
Sr	.012	.028	.016	1.5 x 10^6
Ti	.11	.063	---	---
U	≈.0001	.46	.46	4.2 x 10^7
V	.011	.91	.90	8.2 x 10^7
Y	≈.001	≈.0008	---	---
Zn	<.003	≈.01	≈.01	≈9 x 10^5
Zr	.016	.015	---	---

1/ $Cm = Css + 0.11\,(Cms - Css)$, where Css is the arithmetic mean concentration of the element in the sandstone (table 3) and Cms is the arithmetic mean concentration of the element in the mudstone (table 4).

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

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 abundantly in highly vanadiferous ores in the Entrada sandstone (Botinelly and Fischer, 1959, p. 217-218). 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 200 ores from the Salt Wash (correlation coefficient between logs of analyses equals +0.79) is an indication that silver may be contained largely in copper minerals. In unmineralized sandstone from the Salt Wash 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 5), but this interpretation is subject to some 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 current studies by the writer, but includes also chromium and possibly strontium which are not extrinsic in most other deposits in the Salt Wash. The Frenchy Incline deposit does not contain extrinsic yttrium, an element that 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 deposits (column 4, table 5) is the estimated composition of the intrinsic fraction of the deposit (column 2, table 5). 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 relations 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, principally because of the work of 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. It is likely that the alteration of the sandstone is related, perhaps 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 evidenced by the presence of authigenic pyrite in the altered 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).

It is possible that the alteration of the sandstone and the formation of the ores 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.

Because of the abundance of carbonized fossil plant remains in the altered sandstone it is possible that a moderately reducing environment has existed in the sandstone for long continuous periods of time. Strongly reducing conditions may have been maintained in parts of the sandstone in the more immediate vicinity of carbonized plant remains, as evidenced by the Eh-pH stability relations of the uranium and vanadium minerals (Garrels, 1953 and 1955) deposited near the plant remains.

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 deposit, 10,000 tons in size, 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, or 9×10^{11} grams. If each million tons of sandstone in the area contains 10,000 tons of ore, about 200,000 tons of ore should be present. Total production plus total reserve estimates for the area show 172,000 tons (Henry Bell, 1952, written communication). Therefore, these proportions of altered sandstone and ore are at least approximately correct for the entire Legin area. The volume relationships between altered sandstone and ore in the Legin area are similar to those in other areas near Gateway and Uravan, Colo., which have been studied extensively (J. D. Strobell and others, 1954, written communication).

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 3), 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 5 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, or 9×10^{11} grams, of sandstone in the cylinder of the sandstone which encloses the deposit (table 6). The increase over the present concentrations in the sandstone is less than 4 percent for iron, silver, cobalt, chromium, copper, molybdenum, nickel, strontium, and possibly zinc. The increase in concentration of lead in the sandstone is about 30 percent and is more than 200 percent for vanadium. The increase in the concentration of uranium is more than 50-fold, or 5,000 percent.

Obviously, sandstone in the upper lens of the Salt Wash member in the Legin area, unless it originally contained about 50 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 0.005 percent. Unaltered sandstone samples from the Salt Wash member all contain far less than this amount (Newman, in press). 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.

The restored concentration of vanadium in the altered sandstone is about twice as high as the present concentration (table 6), and amounts to 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 3).

It is doubtful that the cylinder of altered sandstone which 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 which encloses the deposits in the Legin area provided the uranium and vanadium for the deposits in the area. 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. 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 on figure 2 altered sandstone is abundant throughout the Salt Wash member to the southwest of the Legin area. If the total

Table 6 .--Estimation of restored partial composition of sandstone in the Frenchy Incline mine area (in percent).

	(a)	(b)	(b/a)
Element	Present arithmetic mean concentration in sandstone (from table 1)	Restored concentrations of element in sandstone[1]	
Fe	0.39	0.396	1.015
Ag	≈ .00003	≈ .0000302	1.007
Co	≈ .0002	≈ .000204	1.020
Cr	.00042	.000432	1.029
Cu	.0037	.00378	1.022
Mo	≈ .00008	≈ .0000822	1.028
Ni	≈ .0002	≈ .000207	1.035
Pb	≈ .0005	≈ .00066	1.320
Sr	.010	.0102	1.020
U	≈ .00009	.00479	53.
V	.0086	.0177	2.058
Zn	< .003	< .0031	> 1.033

[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 5) were added to 9 x 10^{11} grams of sandstone. This quantity of sandstone, 9 x 10^{11} grams, 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.

uranium and vanadium in the deposits in the Legin area were redistributed through all of the altered sandstone adjacent to the area their concentrations in the sandstone would not be increased by any significant amount.

The volume relations and compositional differences between uranium ore and altered sandstone in the Legin area do indicate, however, that all the extrinsic quantities of elements in the deposits, except those of uranium, vanadium, and lead, could have been derived from altered sandstone in the upper lens of the Salt Wash member which encloses the deposits without the altered sandstone is having had original concentrations of the elements that are significantly greater than those present in unaltered sandstone.

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 may have been 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 5) 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. The assumed absence of diffusion may be correct 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. During periods of greater restriction of solution flow solute diffusion may have been of greater importance.

As the quantities of extrinsic elements in the Frenchy Incline deposit are known (table 5) the required minimum concentrations of the elements in the solutions which transported them to the deposit could be determined if the volumes of the solutions were also known. This information could be of considerable interest in determining other chemical requirements of the solutions, and therefore, possibly their source or origin. Unfortunately, the volume of the ore solution, or solutions, is not known and there is no way known to the writer by which it may be estimated precisely. 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 which are present are most likely post-ore, the result of unloading due to recent erosion. The hydraulic gradient or driving force which caused the solution flow may have simply been 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 had been 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 occurred easily. Soon after the Brushy Basin member began forming, however, areas of discharge must have been few. 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 region (fig. 1), where most of the uranium deposits in the Salt Wash member are located, are in zones on the flanks of the anticlines and have originated with the collapse of their crests due to the mobility of their salt cores, 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 probably restricted to a far lesser extent, and could have been driven 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 approximately. 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. 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:

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

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 the ore solutions probably passed through this entire area. The permeability 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 which 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 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 channel ways were present through which unrestricted discharge could occur. If the Salt Wash aquifer was completely filled and no permeable channel ways 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 on figure 9 are based on Darcy's law and give the volume of water passing through a 1,000 square-foot cross-sectional area of sandstone with a permeability of 0.1 darcy 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

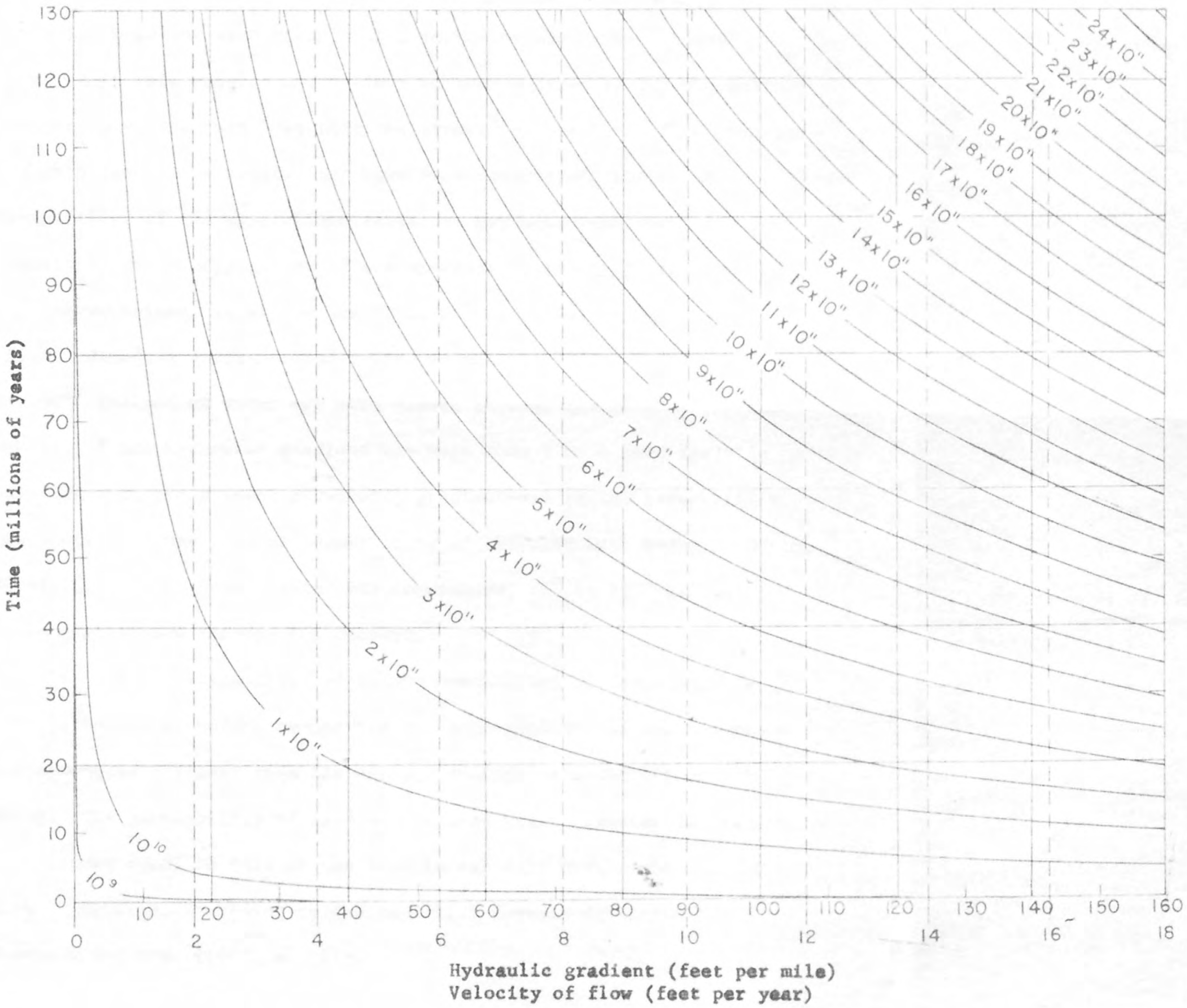

FIGURE 9.--Chart showing the volume of water (in gallons) passing through a cross-sectional area of 1,000 square feet of sandstone as a function of time and hydraulic gradient, or of time and velocity of flow (permeability of sandstone = 0.1 darcy or 1.8 meinzer units; porosity of sandstone = 15 percent).

volumes on figure 9 may be considered as maximum volumes when equating hydraulic gradient with structural gradient or dip. The volumes computed in this problem are maximum volumes because 1) 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 9 that during any period exceeding a few million years, as much as 10^9 to about 3×10^{12} gallons of water may have passed through the Frenchy Incline deposit if the hydraulic gradient was more than 3 or 4 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 same conditions, 10^9 to 10^{12} gallons could have passed through the deposit.

If mineralization occurred before cementation of the sandstone with carbonate 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 (1960, oral communication) the gradients of the streams which deposited the Salt Wash member, judging from channel characteristics and stream gradient relations 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 which may have elapsed between the deposition of the sandstone now forming the deposit and the deposition 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 10 shows the minimum required concentrations of elements in solutions which may have transported them to the Frenchy Incline deposit. The minimum required concentration is, of course, inversely related to the volume of the solution. If uranium, for example, was transported to the deposit by 10^9 to 10^{12} gallons of solution, its concentration in the solution would have necessarily been at least 0.01 to 1 part per million. If the uranium was transported by as much as 3×10^{12} gallons, of solution, however, its concentration in the solution could have been as low as several 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

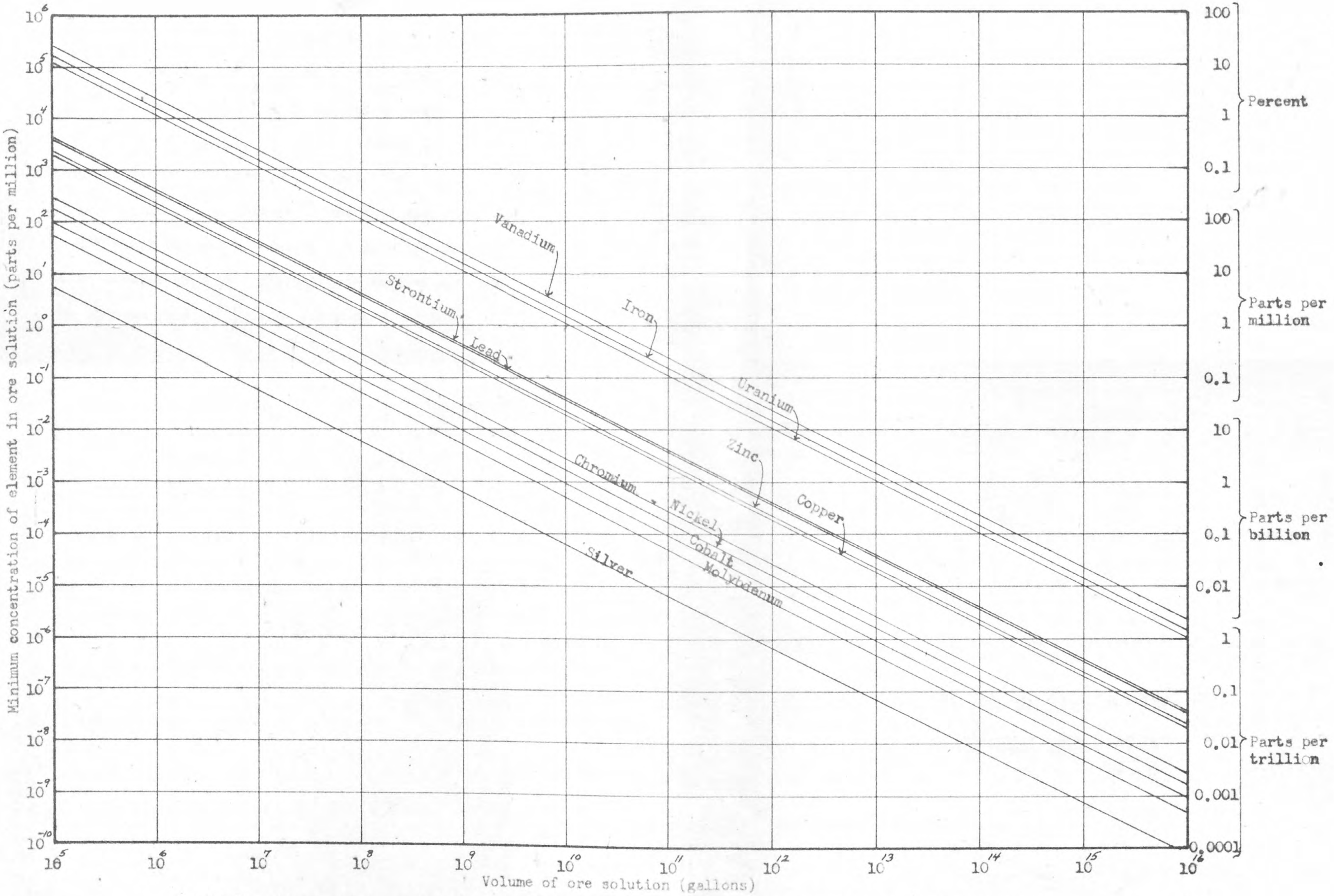

FIGURE 10.--Chart showing required minimum concentrations of elements in ore solutions of various volumes.

mineralization occurred in the 10,000 years following the deposition of the host sandstone (volume of solution = 2 x 10^8 gallons), the concentrations of these elements in the solutions had to be about 100 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 ground waters in the Morrison studied by Phoenix (1959, p. 60-61) the volumes of the solutions must have been equal to or greater than 10^{11} gallons for vanadium and iron, 10^{10} gallons for uranium, and 10^9 gallons for copper and lead.

Solute diffusion

In a previous section it was shown, from compositional and abundance relations between the uranium ore in the Legin 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 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 of sulfur isotopes from sulfide minerals in the deposits by Jensen (1958) 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. As the water saturating the lens became chemically undersaturated, solid phases dissociated to restore equilibrium. 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 has been recognized by Huff and Lesure (1961, written communication) who have observed the occurrence of ore layers which form complete "shells" around pockets of altered sandstone and fossil plant remains. In addition, roll ore bodies, such as those described by Shawe (1956, p. 239), may have formed under stagnant ground-water conditions where diffusion is the only process which can account for the transfer of elements to the ore. Nearly stagnant conditions are implied by Shawe's interpretation that the rolls formed at interfaces between chemically different solutions.

If the chemical environment at the site of mineralization was different from that away from the site of mineralization we may be sure that solute diffusion of some constituents occurred, but the effectiveness of diffusion in transferring constituents from the sandstone to the 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 rate of diffusion, or 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.

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 (written communication, 1961), this environment was also one in which sulfide and sulfate species existed in approximate equilibrium. The Eh-pH conditions of the environment, therefore, were rather restricted. 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 11 Eh-pH stability relations are shown for iron minerals in aqueous solutions containing total sulfur (HSO_4^-, $SO_4^=$, H_2S, HS^-, and $S^=$ species) and total CO_2(H_2CO_3, HCO_3^-, and $CO_3^=$ 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, and 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 11 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 near decaying organic matter according to Hostetler and Garrels (1961, written communication). Along the sulfide-sulfate 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

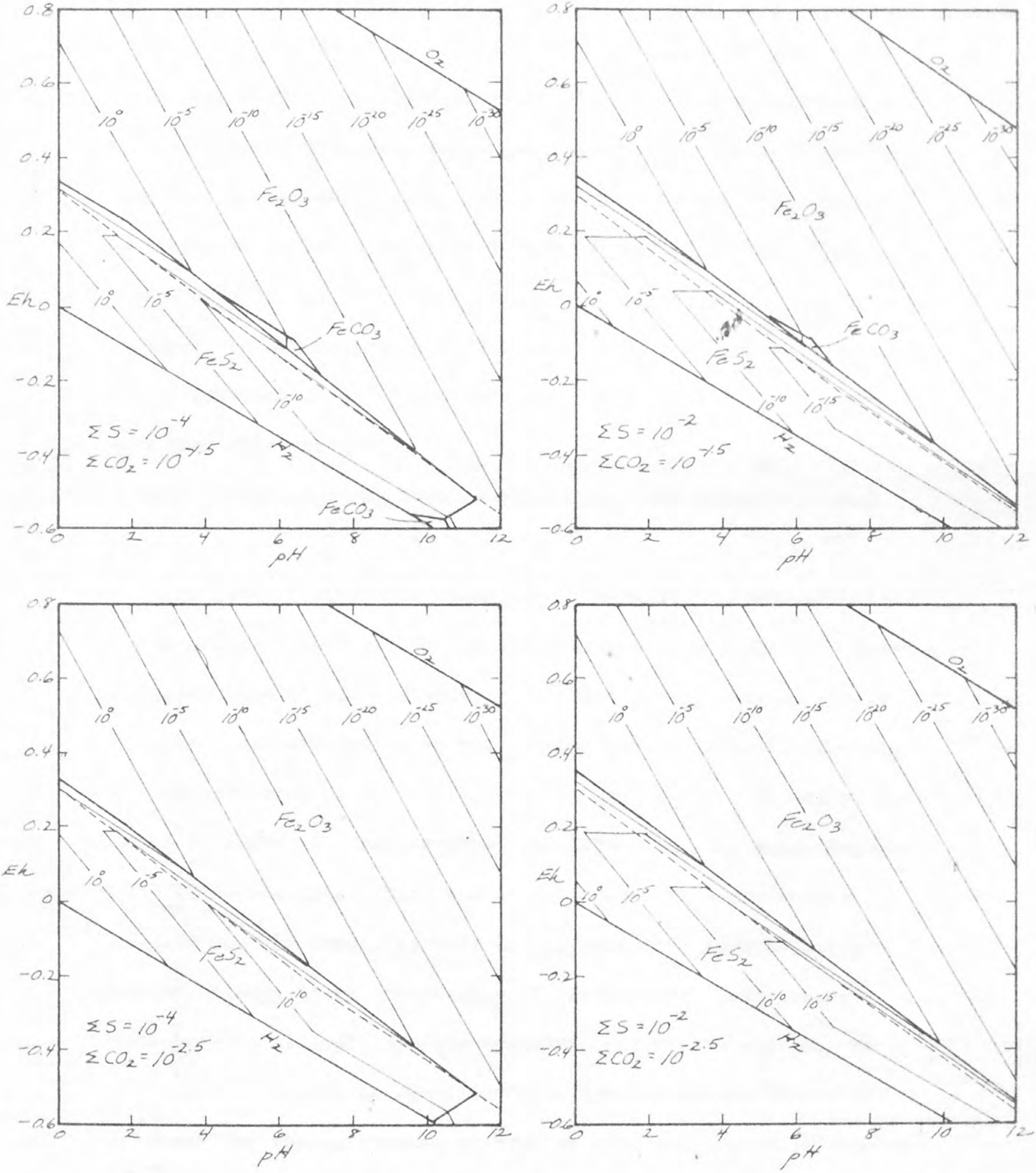

FIGURE 11.--Eh-pH stability fields of iron minerals at various molal concentrations of total sulfur and CO_2. Contours show molal activity of ferrous ion. Dashed line shows equilibrium between sulfide and sulfate species (temperature = 25°C; pressure = 1 atm.).

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) may be computed for certain ideal conditions from a relation given by Garrels and others (1949, p. 1826), but their equation 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:

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

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./cc. for a divalent ion

$A = 2 \times 10^{7}$ sq. cm. (fractional porosity of sandstone, 0.15, times surface area of volume of rock with dimensions 500 x 150 x 2 feet. Actual surface area of the Frenchy Incline ore body is larger 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 which existed was close to 2 sq. cm. per day and the concentration of ferrous ion in solutions saturating the sandstone was about 0.5 parts per million (10^{-5} molal) it may be expected that at least 0.025 equivalents of ferrous iron 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, for 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 5) could have accumulated in about 80 million years, approximately the amount of time between the deposition of the host rock and the structural deformation which occurred in early Tertiary time. If the Salt Wash aquifer was isolated from other permeable units from the time it was covered by the relatively impermeable mudstones of the Brushy Basin member until early Tertiary time, it was saturated with stagnant solutions during this period, and diffusion processes must have operated. Whether they 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 judgments concerning their relative importance, then, must rest on other criteria, in particular, on the structural and hydrologic histories of the sandstone unit in which the Frenchy Incline deposit occurs. 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 volume relations between uranium ore and altered sandstones in the Legin area it is apparent that solution flow was an important process in the transportation of uranium, at least, because uranium was 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.

Significance of regional variation of composition of uranium deposits in the Salt Wash member of the Morrison formation

The regional variations of element concentrations in more than 200 uranium deposits in the Salt Wash were examined in order to determine whether or not they corresponded to the distributions of any known geologic features, such as centers of igneous intrusion, areas of structural uplift or subsidence, or petrographic and chemical features of the host rock. It is thought that 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 that if an element was derived from the host sandstone its distribution in the deposits may correspond partly to its regional distribution in the sandstone.

The compositions of the uranium deposits were determined by semiquantitative spectrographic and chemical analysis of mill-pulp samples, each sample representing at least several tons of mined ore. The mill-pulp samples were collected as a part of a broader study of the uranium deposits on the Plateau; preliminary results of the study and a general description of the samples are given by Shoemaker and others (1959).

Among the uranium deposits in the Salt Wash member certain elements are "geochemically coherent," (Rankama and Sahama, 1950, p. 48) or related in such a way that higher concentrations of one tend to be associated with high concentrations of others. "Geochemical coherency," as used here, does not necessarily imply similarity of chemical behavior, or "chemical coherency" (Rankama and Sahama, 1950, p. 48) in the environment in which the elements are or have been present, but simply that the elements tend to associate themselves with one another. The reasons for the association may be chemical similarities, but it is entirely possible that other reasons for the association may have been important. In fact, some elements may be associated with each other because they behave in distinctly opposite ways in some environments. For example, when uraninite partially replaces pyrite uranium and iron become associated because the iron mineral is soluble and the uranium mineral is not, and because iron is of a more reducing nature than uranium.

Geochemical coherency of minor elements in a group of samples is conveniently measured by the log correlation coefficient (Miesch and Riley, 1961, p. 7); log correlation coefficients between some elements in ores from the Salt Wash member are given in table 7. All these elements, 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. Correlations 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. Statistical problems encountered with 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 encountered in samples taken from a single mining district and from a single mine. High skewness may be partly related to the nature of the analytical error encountered with the spectrographic method, because 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 coherency, 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 be associated.

The antilogarithms of the numbers on which the correlation coefficients in table 7 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 recently by Chayes (1960, p. 4190). However, effects of the constant sum are not examined precisely here because they are necessarily small, owing to the fact that most of the constituents are present in only minor quantities.

Table 7 . Correlation coefficients 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	0.29	-0.17	0.15	0.41	0.13	0.14	0.43	0.00	0.01	0.44	0.21	0.10
Fe		0.11	0.32	0.44	0.12	0.34	0.37	0.25	0.41	0.23	0.28	0.31	0.29
Ag			0.10	0.19	0.79	0.23	0.06	0.71	-0.06	-0.09	0.24	0.01	0.22
As				0.55	0.01	0.44	0.49	0.12	0.45	0.22	-0.08	0.24	0.35
Co					0.16	0.53	0.79	0.24	0.34	0.09	0.04	——	0.31
Cu						0.16	0.08	0.56	0.00	-0.04	0.23	0.04	0.18
Mo							0.49	0.26	0.29	0.06	0.07	0.24	0.21
Ni								0.14	0.30	0.10	0.07	0.27	0.21
Pb									0.04	0.11	0.35	0.07	0.33
Se										0.31	0.07	0.08	0.19
U											0.32	0.18	0.15
V												0.26	0.01
Y													0.22
Zn													

[1] Each coefficient is based on about 200 pairs of analyses.

The geochemical coherency of elements in the uranium deposits is important because it isolates elements which accumulated together, even though they may have responded in different manners to specific chemical and dynamic processes which led to the formation of the deposits. In addition to this, however, the scheme is useful in studying regional variations of the composition of the ores, because elements which have strong geochemical coherency have similar regional variations among the deposits. For example, the regional variation patterns of silver and lead may be expected to be similar to that of copper, because deposits high in copper tend also to be high in the other elements (table 7). Thus, the regional variation patterns of silver and lead need not be determined directly.

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

The correlation coefficients on table 7 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, multiple correlation and regression, and factor analysis, may help unravel some of the complex relations not recognizable by simple correlation methods. However, examination of the correlation coefficients on table 7 shows that the elements may be classed into four groups and several subgroups on the basis of geochemical coherency, according to the scheme shown in figure 12. All elements within a subgroup have at least moderate correlations with every other element in the subgroup.

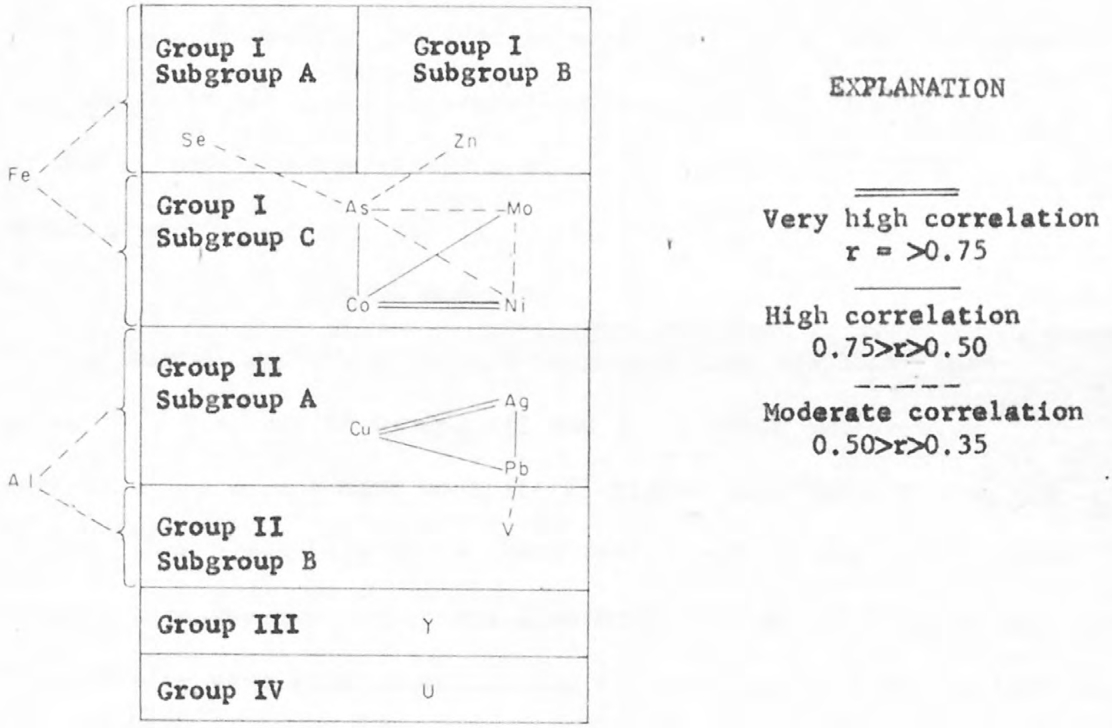

FIGURE 12.--Groups of coherent elements in uranium ores from the Salt Wash member of the Morrison formation on the Colorado Plateau (based on data from table 7).

Elements within a group, but in different subgroups, have 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 I (fig. 12) have moderate or nearly moderate correlations with iron, and none has a significant (99 percent level) correlation with aluminum. All elements in Group II have moderate or nearly moderate correlations with aluminum, and their correlations with iron are lower than moderate. Elements in Groups III and IV, yttrium and uranium respectively, do not have moderate or higher correlations with any of the other elements studied. Examination of the low correlation coefficients, however, suggests that both yttrium and uranium in the deposits have greater affinities for the Group I elements than for the Group II elements.

The compositions of uranium deposits in the Salt Wash member vary widely even for closely spaced deposits in the same mining district, but average compositions of deposits in widely separated areas also vary widely. As the area of interest in the present study is the entire Colorado Plateau, an attempt was made to "smooth out" local variations in compositions in order to reveal 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 (figs. 13-19).

The regional variation pattern for cobalt in uranium deposits in the Salt Wash member (fig. 13) shows that cobalt tends to be more highly concentrated in deposits on the west and northwest parts of the Plateau; geochemically coherent nickel, arsenic, and molybednum must display similar patterns. Similarly, selenium (fig. 14) and zinc (fig. 15) tend to be more highly concentrated in deposits on the west and northwest parts of the Plateau, though zinc also tends to be highly concentrated in deposits in the vicinity of salt anticlines. Iron (fig. 16), as may be expected from its geochemical coherency, also tends to be more highly concentrated in deposits on the west and northwest parts of the Plateau. The distribution of copper in the deposits (fig. 17) 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 region containing these structures. Silver and lead, which are geochemically coherent with copper, undoubtedly have a similar

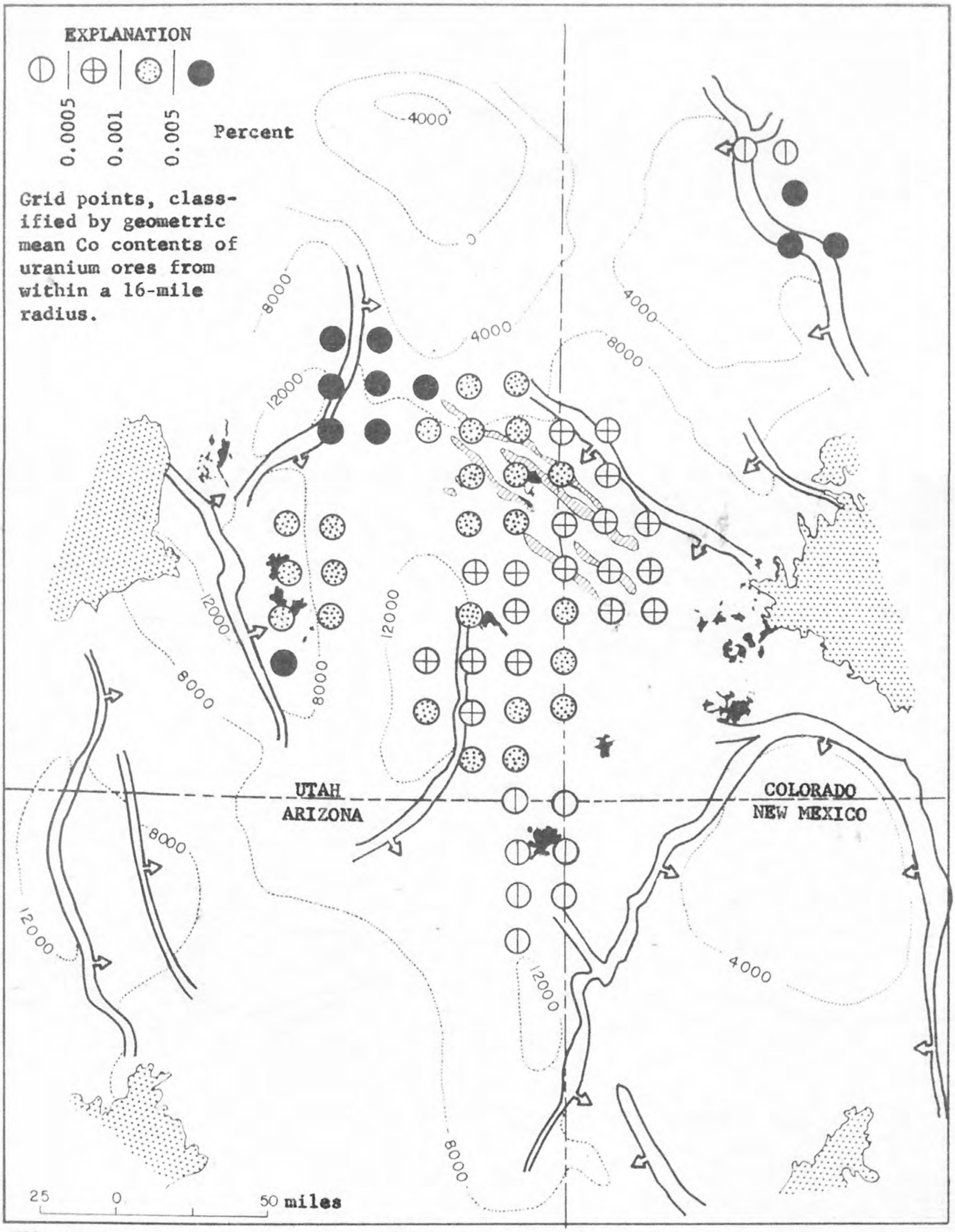

Figure 13.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of cobalt in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

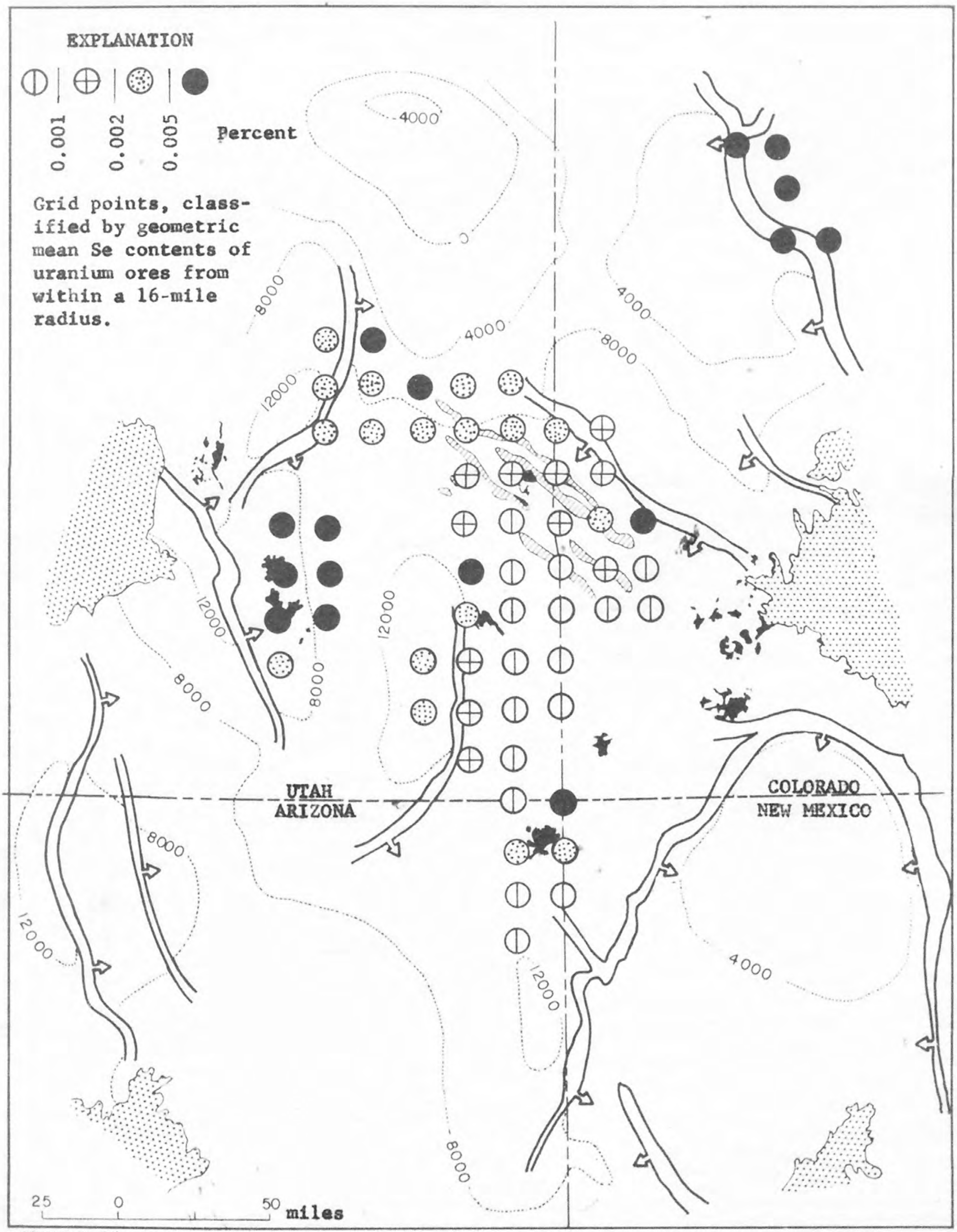

FIGURE 14.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of selenium in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

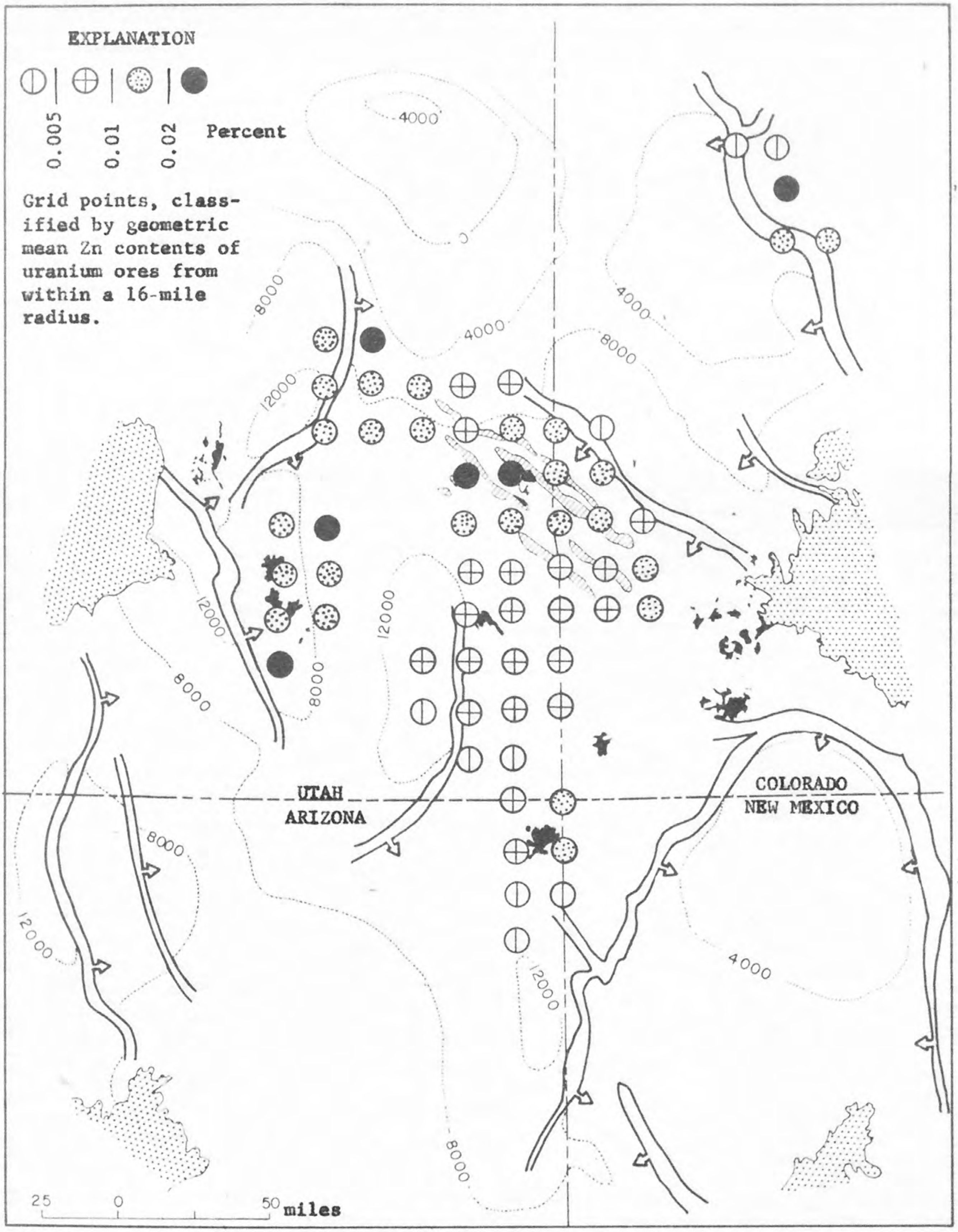

FIGURE 15. Tectonic sketch map of the Colorado Plateau showing mean concentrations of zinc in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

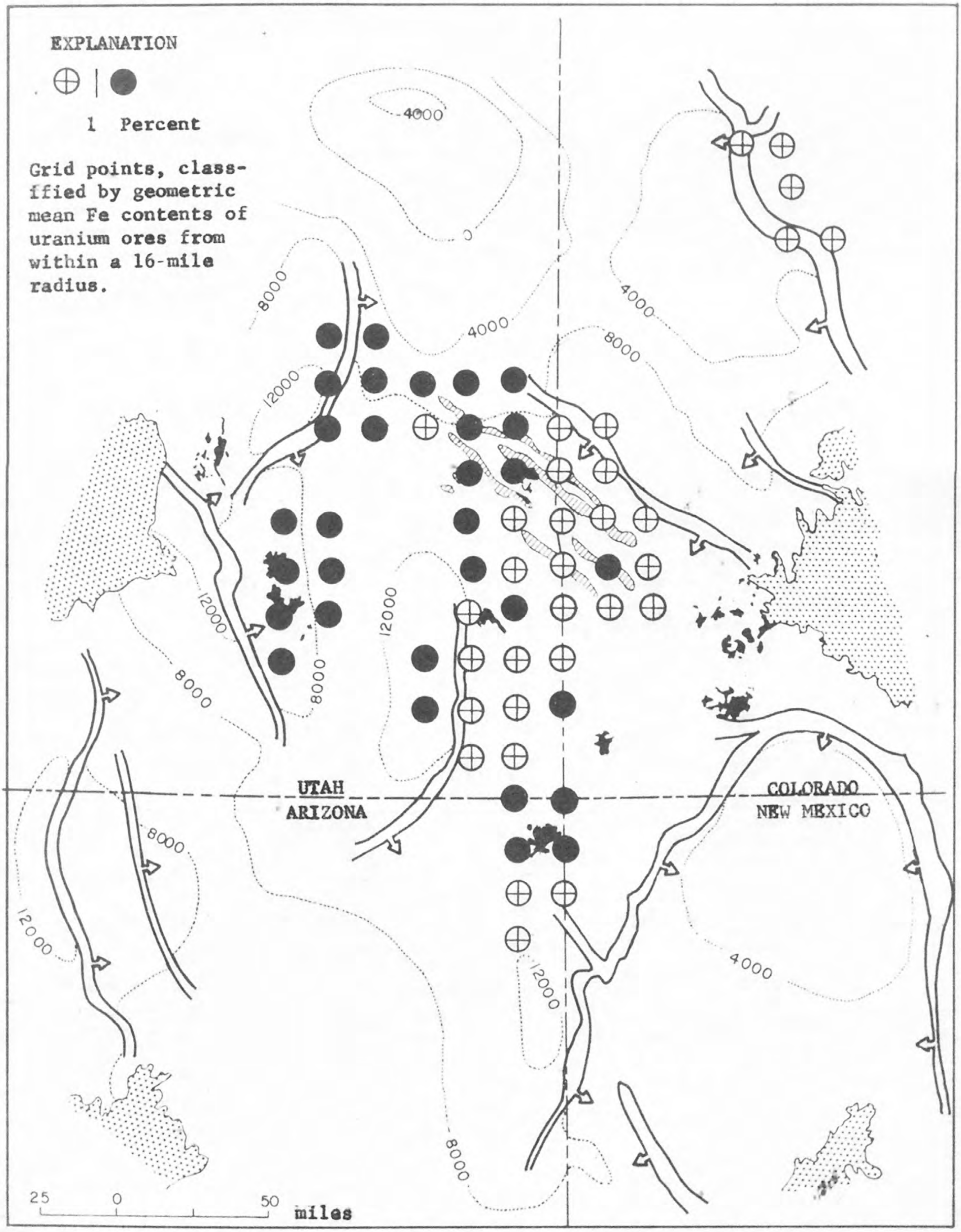

FIGURE 16.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of iron in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

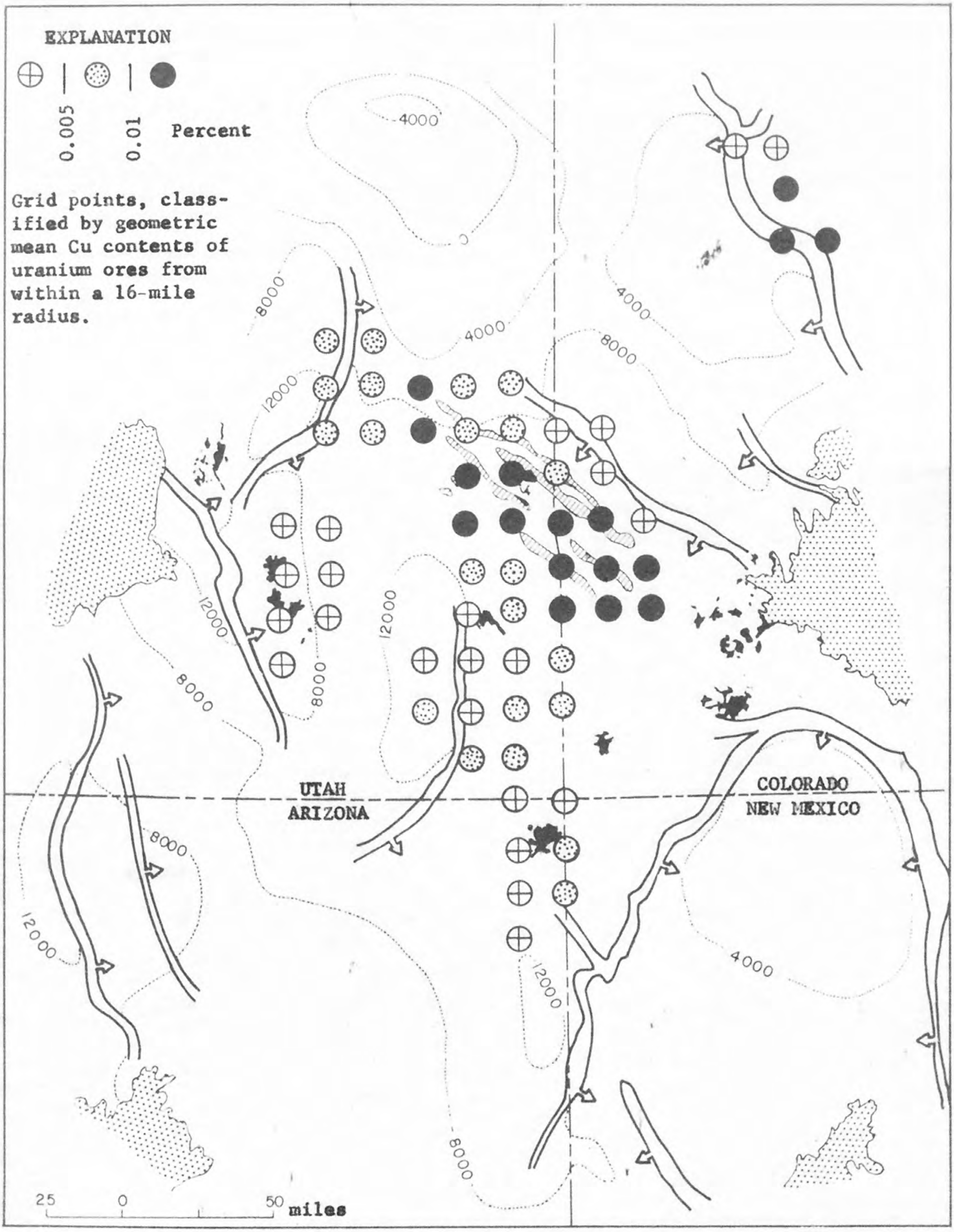

FIGURE 17.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of copper in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

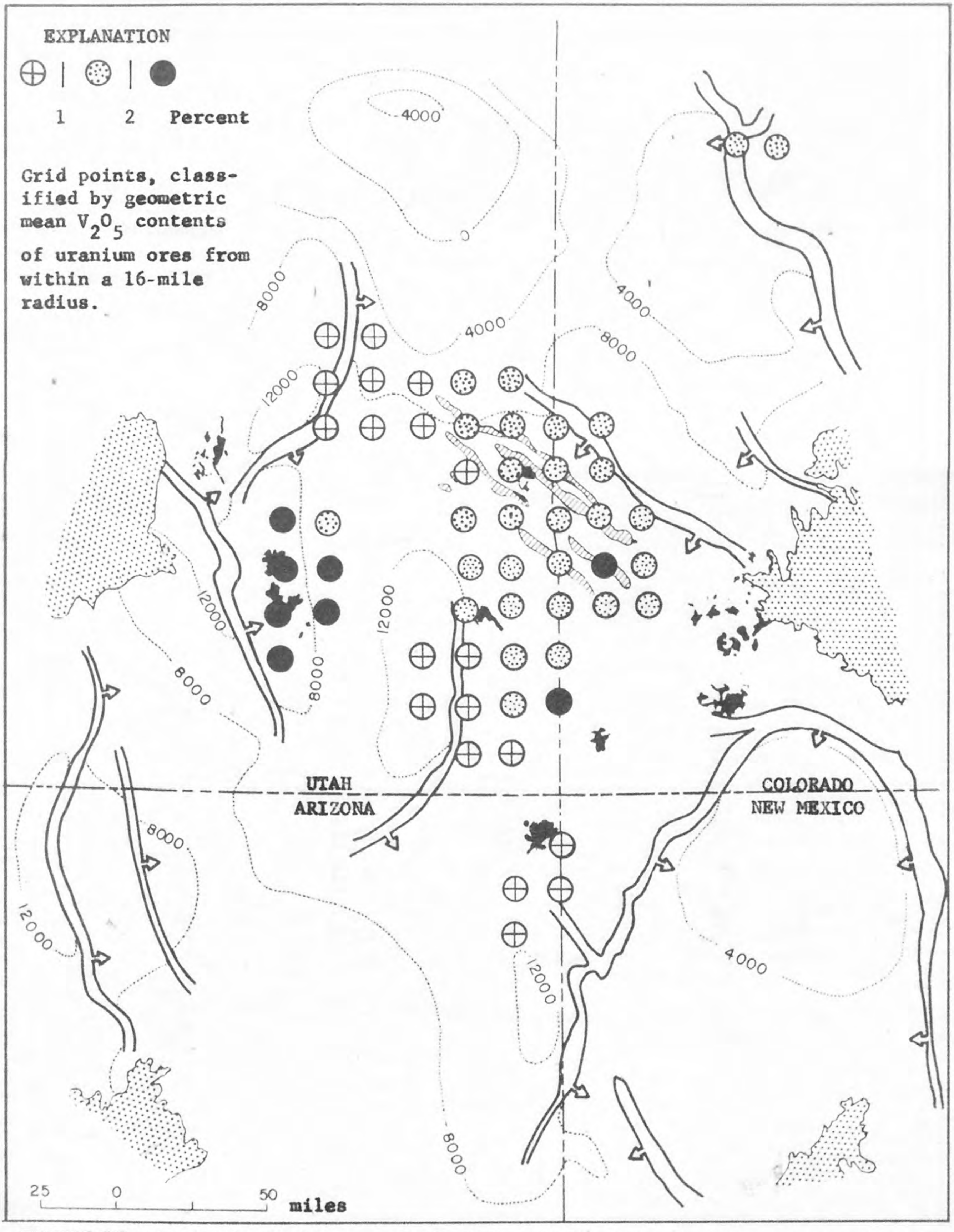

FIGURE 18.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of V_2O_5 in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

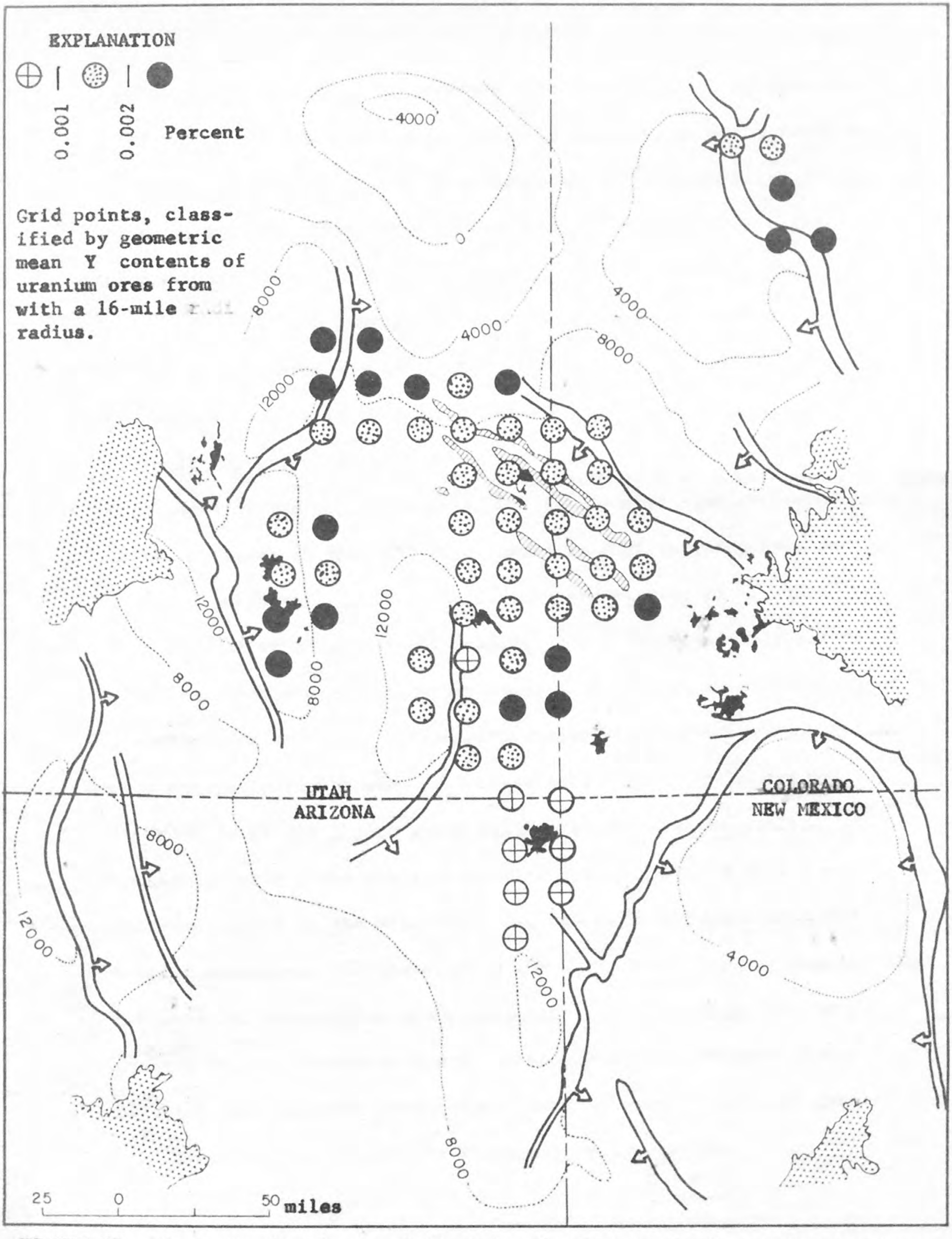

FIGURE 19.--Tectonic sketch map of the Colorado Plateau showing mean concentrations of yttrium in uranium deposits in the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

regional distribution. The regional variation pattern of vanadium (fig. 18) 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 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 yttrium (fig. 19) is more erratic than those of the other elements, but it displays some correspondence to the patterns of the Group I elements in that many deposits on the west and northwest parts of the Plateau are yttrium rich. The regional variation pattern of uranium in the deposits could not be determined because the mill-pulp samples which were studied represent ore shipments which are biased with respect to uranium grade. Commonly, ores were selectively mined and mixed before shipment to the mills in order to attain grades which will yield the highest profit. The optimum uranium grade for a particular ore shipment is 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 to the concentrations of other elements in the ore (table 7; fig. 12), and the concentrations of other elements in the shipments are not generally 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, selenium, zinc, arsenic, molybdenum, cobalt, and nickel tend to be more highly concentrated in deposits to the west and northwest; copper, silver, and lead tend to be high in deposits in the region 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 of the Plateau or to the distribution of broad structural features, except to the salt anticlines. However, it is possible that the patterns do correspond to some other structural or stratigraphic features on the Plateau which have not been represented on the regional variation maps (figs. 13-19), though what these features may be, and their significance, is uncertain.

Each of the three general types of regional variation patterns does correspond at least roughly to the regional variation of some petrographic or chemical feature of the host sandstone. Tuff fragments seem to be more abundant in sandstone from the Salt Wash member on the western parts of the Plateau (fig. 20); this may be a result of 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 the Salt Wash member are suggested by Craig and others (1955, p. 149-151).

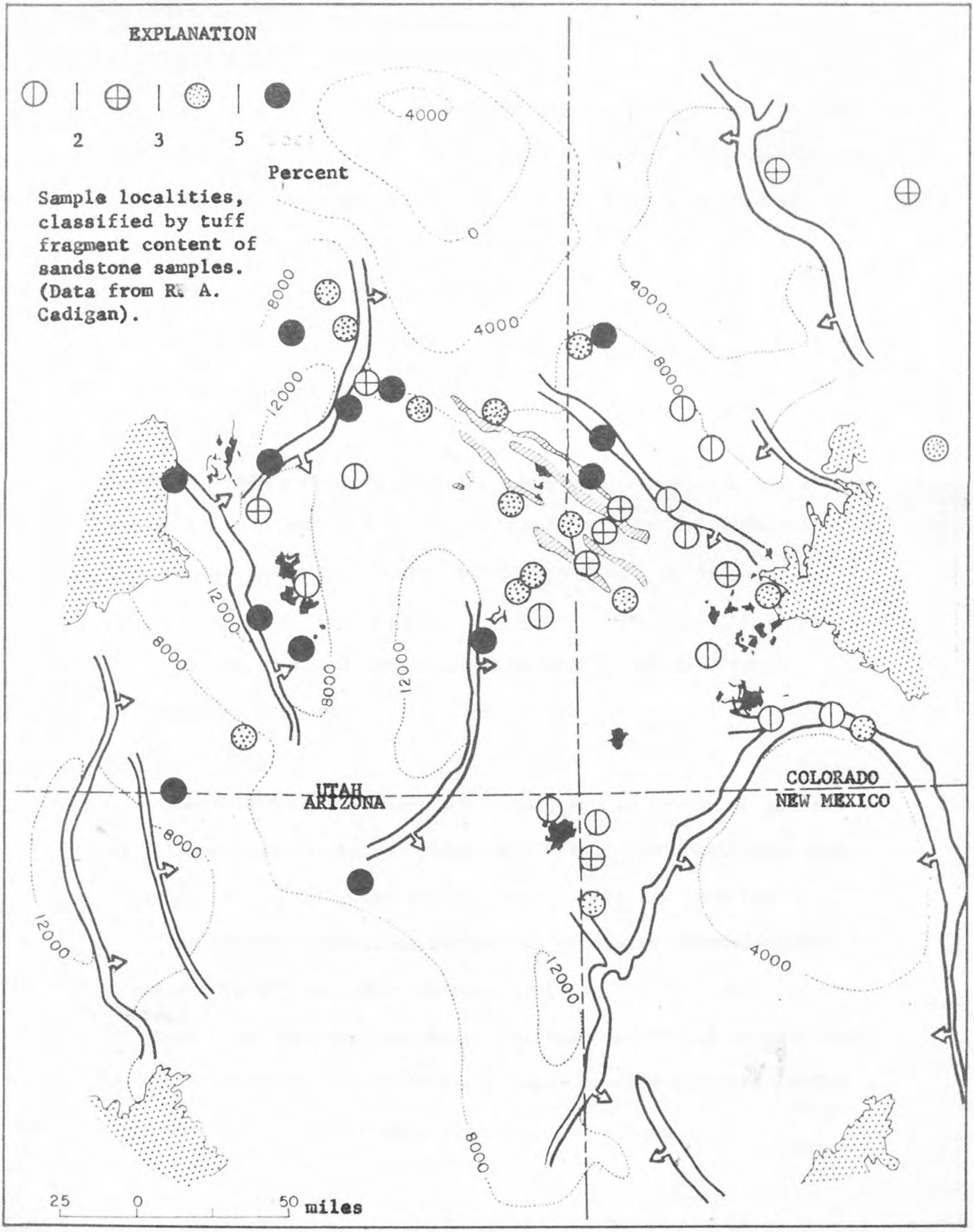

FIGURE 20.--Tectonic sketch map of the Colorado Plateau showing concentrations of tuff fragments in sandstone samples from the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

The regional variation of tuff fragments in sandstone of the Salt Wash member is similar to the regional variation of iron, selenium, zinc, arsenic, molybdenum, cobalt, and nickel in the uranium deposits in the Salt Wash.

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 (fig. 21). 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 (fig. 22).

Unmineralized Salt Wash sandstones in the region of the salt anticlines tend to contain relatively high concentrations of copper (fig. 23) as do Salt Wash uranium deposits in the same region.

The regional variation pattern of uranium in unmineralized sandstone in the Salt Wash is complex (fig. 24), 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).

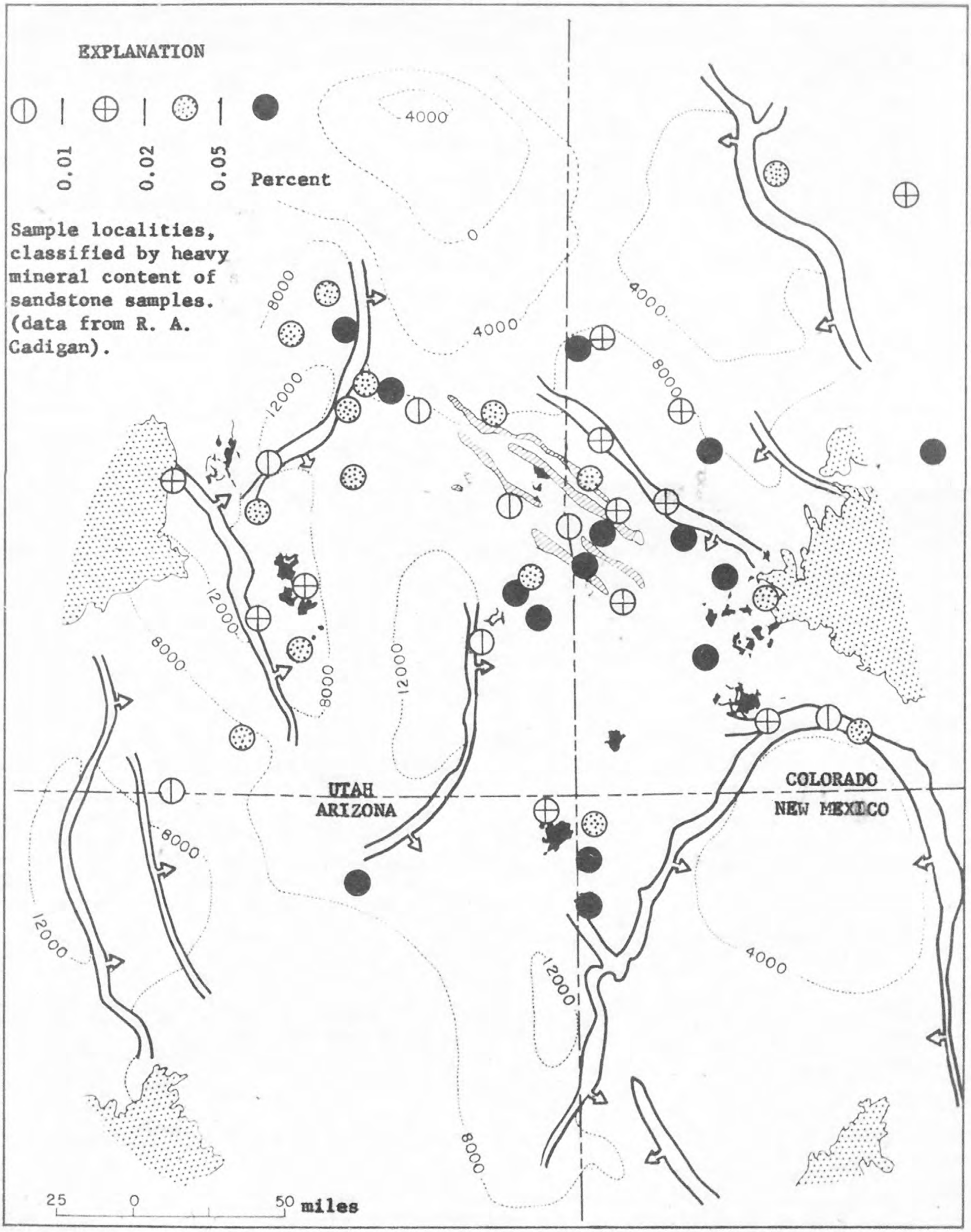

FIGURE 21.--Tectonic sketch map of the Colorado Plateau showing concentrations of heavy minerals (0.044 to 0.062 mm. in diameter) in sandstone samples from the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

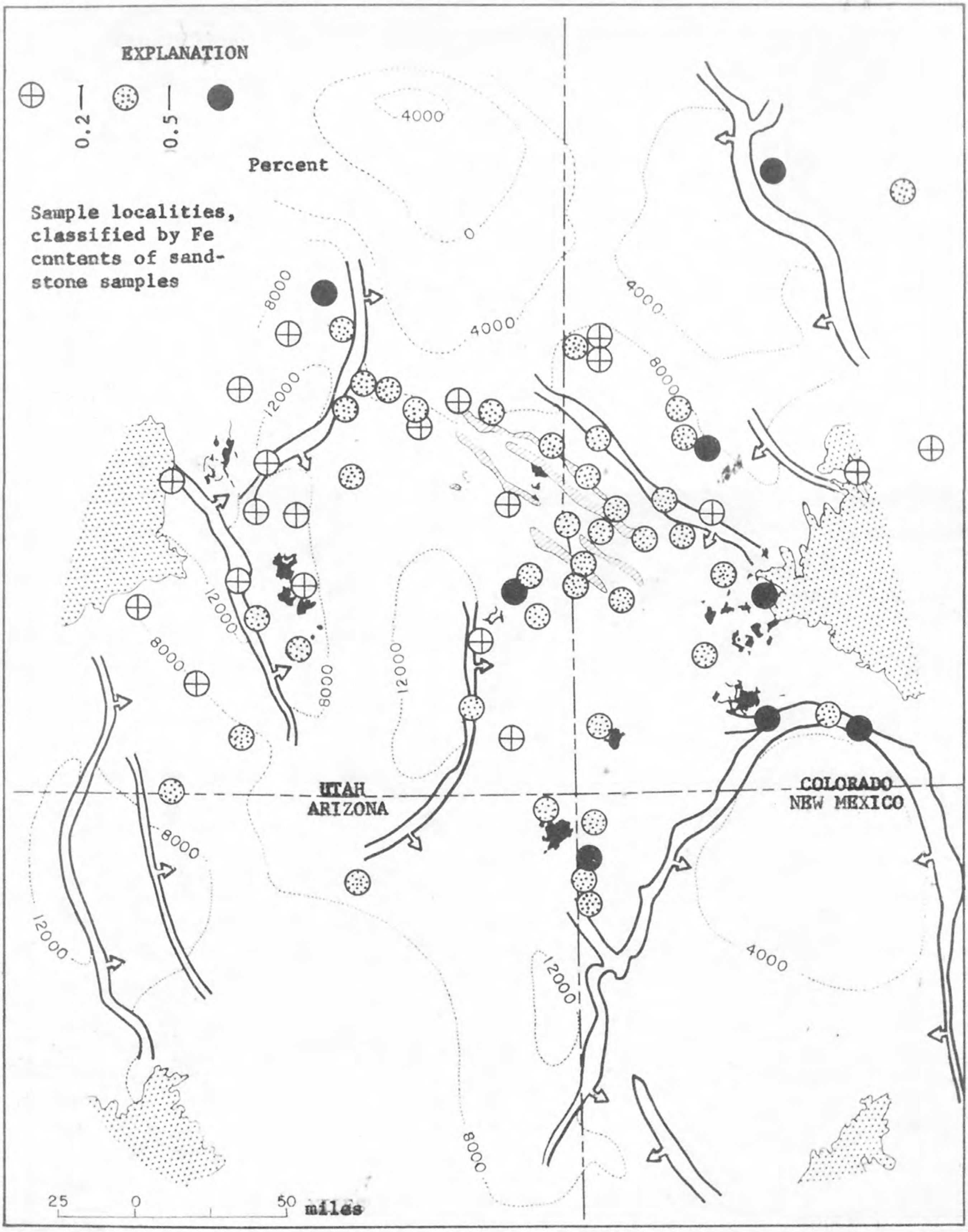

FIGURE 22.--Tectonic sketch map of the Colorado Plateau showing concentrations of iron in sandstone samples from the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

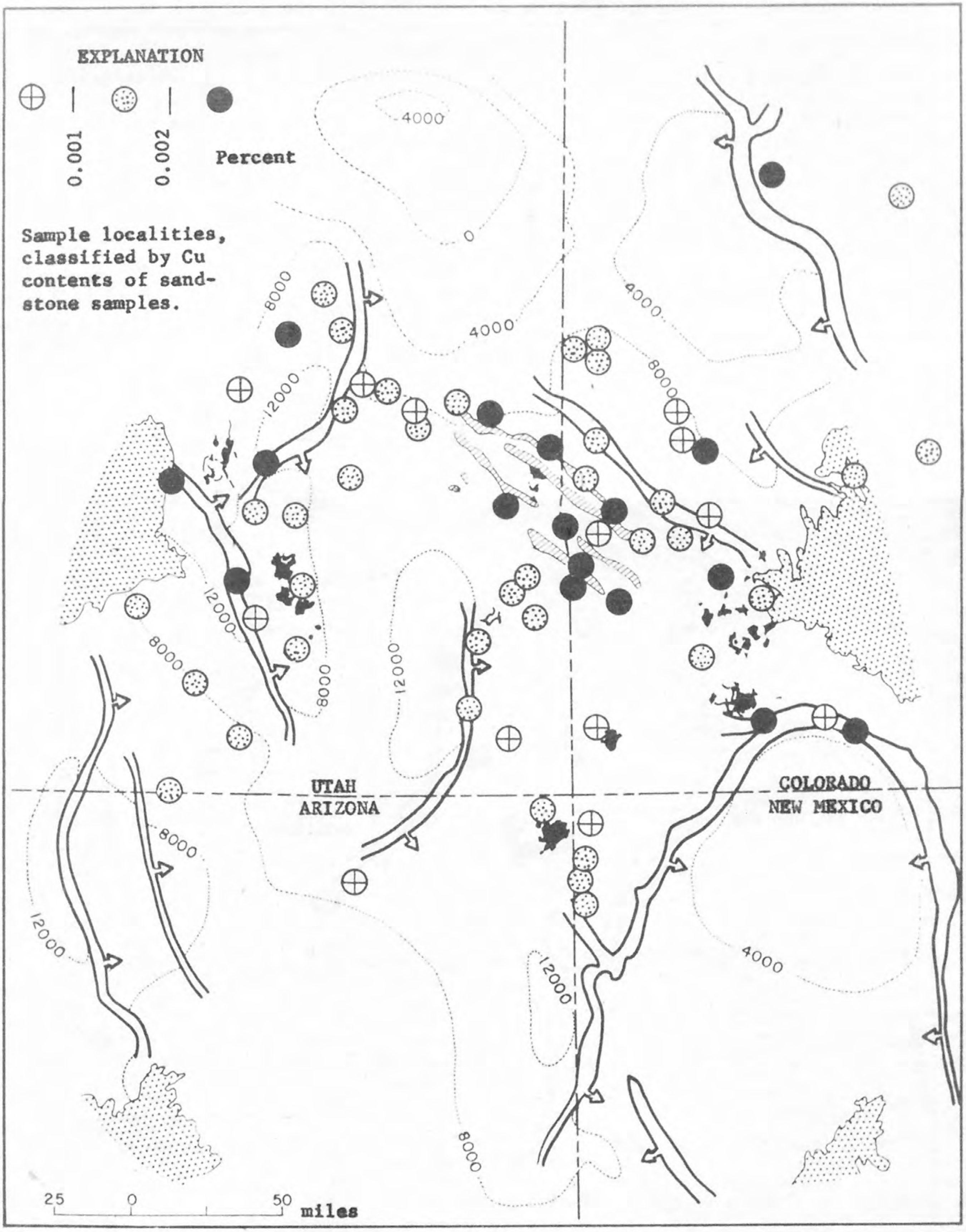

FIGURE 23.--Tectonic sketch map of the Colorado Plateau showing concentrations of copper in sandstone samples from the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

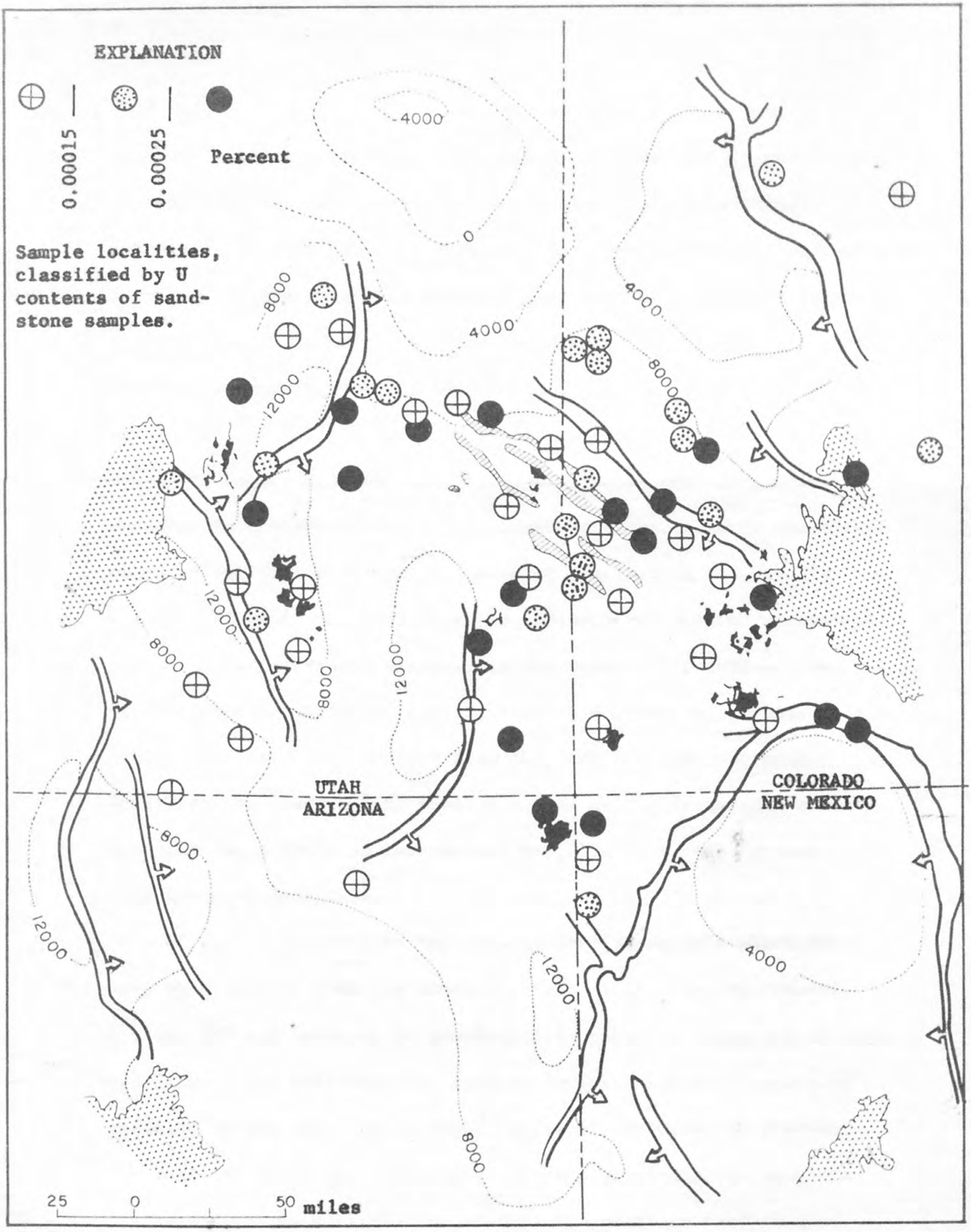

FIGURE 24.--Tectonic sketch map of the Colorado Plateau showing concentrations of uranium in sandstone samples from the Salt Wash member of the Morrison formation (see figure 1 for geologic explanation and names of geologic features).

Summary and conclusions

The elements which are extrinsic or "introduced" in the Frenchy Incline uranium deposit have been determined and the extrinsic quantity of each of these elements in the deposit has been estimated. Knowledge of the extrinsic quantities of elements serves to eliminate the sandstone lens which contains the Frenchy Incline deposit as a possible source for some of the elements. It is concluded that uranium and probably vanadium could not have been derived from the sandstone lens unless the lens originally contained uranium and vanadium in concentration far in excess of those found in unaltered parts of the Salt Wash member. Much of the lead in the deposit may be radiogenic, derived from the radioactive decay of uranium in place. Other extrinsic elements in the deposit, including iron, silver, cobalt, chromium, copper, nickel, molybdenum, strontium, and zinc, could have been derived from the sandstone lens without depleting the sandstone of these elements by any detectable amount. Selenium and arsenic in the deposit may also have been derived from the sandstone lens.

Of the 11 elements in the Frenchy Incline deposit which could have been derived from the sandstone lens, 7 (Fe, Zn, Mo, Co, Ni, Se, and As) are known to be geochemically coherent among all uranium deposits in the Salt Wash and tend to be more highly concentrated in deposits on the west and northwest parts of the Colorado Plateau. The regional variation patterns of these elements in the deposits correspond to the distribution of tuff fragments in sandstone of the Salt Wash member. In addition, the mean concentrations of these elements in altered sandstone in the Legin area tend to be about the same as their mean concentrations in all sandstones in the Salt Wash.

Copper, silver, lead, and vanadium form a second geochemically coherent group of elements in the deposits in the Salt Wash member, but abundance relations in the Legin area show that only copper and silver could have been derived from the sandstone lens without changing the composition of the lens appreciably. The regional variation patterns of copper, silver, and lead, and to a lesser degree zinc, show distinct "highs" over the region of salt anticlines on the Colorado-Utah border. Furthermore, 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 anticline than in deposits more distant from the faults. Thus, the distributions of copper and lead are related to faults associated with the salt anticlines, not only on a broad regional scale, but also on more detailed scales. The regional distribution of copper in the uranium deposits in the Salt Wash corresponds to that in unmineralized sandstone in the Salt Wash.

According to Shawe and others, (1959, p. 411), molybdenum and "some other" trace elements in deposits on the Dolores anticline show no recognizable patterns of distribution relative to the fault zone.

Vanadium, in general, is more highly concentrated in deposits on the eastern part of the Plateau, but deposits in the vicinity of the

Henry Mountains laccoliths are exceptionally vanadium rich. With the exception of 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 sandstone. The mean concentrations of vanadium, silver, and lead in altered sandstone in the Legin area are appreciably higher than their mean concentrations in all Salt Wash sandstones.

Chromium and strontium are not generally extrinsic in uranium deposits in the Salt Wash member but may be extrinsic in the Frenchy Incline deposit. Abundance relations in the Legin area show that extrinsic chromium and strontium in the deposit could have been derived from the sandstone lens which contains the deposit.

From the relations summarized above it is suggested that many of the minor elements (Fe, Mo, Co, Ni, Se, and As) in the Frenchy Incline deposit, and perhaps in most other deposits in the Salt Wash member, were derived mostly from tuffaceous material in or associated with the host sandstone. If the altered sandstone in the lens containing the Frenchy Incline deposit contains only 0.5 percent tuff fragments, about 5,000 tons of tuff fragments are present in the lens within 300 feet of the deposit. If the tuff fragments originally had a minor element content similar to that of the average igneous rock as tabulated by Rankama and Sahama (1950, p. 226), the tuff contained more than sufficient quantities of iron, strontium, chromium, nickel, and cobalt to provide these elements for the ore (table 8). The tuff fragments may also have contained sufficient quantities of

Table 8 . Comparison of quantities of elements in 5,000 tons of average igneous rock and 10,000 tons of uranium ore (in grams).

Element	5,000 tons of average igneous rock [1]	10,000 tons of uranium ore [2]
Fe	225,000,000	54,000,000
Sr	1,350,000	1,500,000
Cr	900,000	110,000
Zn	594,000	≈900,000
Ni	360,000	≈64,000
Co	100,000	≈36,000
Cu	315,000	730,000
Ag	450	≈2,000
Pb	72,000	≈1,400,000
V	675,000	82,000,000
U	18,000	42,000,000

[1] Computed from data given by Rankama and Sahama (1950, p. 226).
[2] From table 5 .

molybdenum, selenium, and arsenic. Waters and Granger (1953, p. 21) have discussed the process whereby minor elements may be released to ground-water solutions during devitrification of volcanic ash. The released elements could have been transferred from the sandstone to the deposit either by flowing solutions or by solute diffusion. As the elements could have been derived from sandstone within a few hundred feet of the deposit diffusion processes may have easily accounted for their transfer.

Copper and silver in the Frenchy Incline deposit may have been derived from the host sandstone, but their regional distribution in the Salt Wash member uranium deposits suggests that they were originally introduced into the Salt Wash member from external sources by way of permeable channel ways 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 region (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 region. Some of the zinc in the Frenchy Incline deposit may have been derived from tuff fragments in the host sandstone near the present deposit, but some also may have been derived from the same source which provided copper, silver, and some of the lead. Zinc, like copper, silver, lead, vanadium, and uranium, could not have been derived solely from 5,000 tons of tuffaceous material equal in composition to the average igneous rock (table 8).

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 distributions of vanadium in the deposits and heavy minerals in the sandstone suggests that vanadium, at least, may have been derived from the heavy minerals. However, it is unlikely that vanadium and uranium were derived from within a few hundred feet of the Frenchy Incline deposit as were, perhaps, many of the other extrinsic elements. Vanadium and uranium may have been derived from altered sandstone which is now present on the south and southwest margin of the Legin area (fig. 2). Because the distance of transport of vanadium and uranium must have been more than a few hundred feet diffusion processes were probably inadequate, and it is likely that the elements were transported to the deposits by flowing solutions. The source of the vanadium in the highly vanadiferous uranium deposits near the Henry Mountains (fig. 18) is unknown. The vanadium in these deposits may have been derived from heavy minerals in the host sandstone, from deep-seated magmatic sources, or from other sources external to the Salt Wash member.

In order to clarify the proposals outlined above and to give the reader a clearer understanding of the possible role of the proposed processes in the history of formation of the Frenchy Incline deposit, the following hypothesis of origin for this deposit is given. Soon after the deposition and burial of the host sandstone lens of the Salt Wash member in the Legin area, enclosed plant remains in the sandstone began a process of decay which led to the formation of H_2S and its ionization products. Production of H_2S caused the precipitation of sulfide minerals containing iron, molybdenum, cobalt, nickel, selenium, arsenic and zinc, in addition to copper, silver and lead. The low Eh environment which must also have been associated with the decaying plant remains probably effected the precipitation of small amounts of uranium and vanadium oxides. If ground-water solutions in the sandstone lens were relatively stagnant the solutions near the plant remains became depleted in these elements and concentration gradients were established in the solutions saturating the lens. Diffusion of elements in solution toward the plant remains began in response to the concentration gradients. As solutions in sandstone relatively distant from the plant remains tended to be depleted in the minor elements because of diffusion, solid phases of the elements in the sandstone tended to dissociate and replenish the solution. Most of the iron, molybdenum, cobalt, nickel, selenium, and arsenic which went into solution were derived from devitrifying tuff fragments. Because of the nearly stagnant conditions, interfaces formed between the chemically different ground-water solutions near and distant from the larger accumulations of plant materials. The interfaces are now marked by the occurrence of roll-type ore bodies. During this early stage in the formation of the deposit most parts of the sandstone lens were altered from red to light-brown through the transformation of hematite to pyrite, though the reducing environment throughout the lens was less pronounced than it was in small areas near the larger accumulations of plant materials.

At a later stage, possibly during early Tertiary time, ground-water flow was accelerated by broad-scale structural deformation of the Colorado Plateau, and solutions bearing copper, silver, lead, and zinc entered the Salt Wash member by way of northwest-trending fractures associated with the salt anticlines. Related solutions deposited silver-bearing copper sulfides in veins in the Wingate sandstone, Burro Canyon formation, Dakota sandstone and other units in the salt anticline region. On entering the Salt Wash member the solutions mingled with ground waters and enriched them in these elements. Copper, silver, lead, and zinc were subsequently precipitated in the sandstone, and this accounts for the relatively high concentrations of copper, at least, in the sandstone in the salt anticline region. Their precipitation may have been caused by a variety of factors such as temperature and pressure changes or reaction with carbonate, sulfate, or other anions in ground waters in the Salt Wash, but also by local concentrations of H_2S or other sulfide species near the localized pockets of decaying plant materials. Thus, although copper, silver, lead, and zinc may have precipitated in widely dispersed amounts throughout the Salt Wash member in the salt anticline region, expecially high concentrations of these elements were superimposed on the local accumulations of sulfides which formed earlier. The solutions bearing these elements may have been derived from magmatic sources which produced the laccolithic bodies in the La Sal Mountains, from evaporite deposits in the Paradox member of the Hermosa formation which underlies the salt anticlines, from bentonitic shales of the Brushy Basin member of the Morrison formation, or from other sources, but because of the spacial distribution of copper vein deposits with regard to the La Sal Mountains (Shoemaker and others, in press) a magmatic source seems most likely.

Uranium and vanadium may have been introduced into the Frenchy Incline deposit during the stage in which copper, silver, lead, and zinc were introduced and by the same solutions, but this is uncertain. If it were proposed that uranium and some lead were derived from deep-seated sources by ascending solutions, as concluded previously by the writer and his associates (Shoemaker and others, in press), the suggestion by Stieff and others (1953, p. 16) that old radiogenic lead derived from depth may be present in some of the deposits could be cited in evidence. A deep-seated source beneath the La Sal Mountains may also account for the high density of deposit spacing in the salt anticline region (Finch, 1955). However, Fischer and Stewart (in press) have shown reasonable evidence, based on data accumulated in numerous field studies in various parts of the United States, that uranium may have been derived from tuffaceous materials which are consistently associated with the deposits. Uranium in the

Frenchy Incline deposit, therefore, may have been derived from extensive tuffaceous accumulations in the Brushy Basin member of the Morrison formation, or from widely dispersed tuffaceous materials in the Salt Wash member. The data presented in this report point out two factors regarding the deposition of uranium in the Frenchy Incline deposit: 1) It is likely that the uranium in the deposit was derived from sources external to the sandstone lens which enclosed the deposit, and 2) ground-water solutions flowing in the Salt Wash member aquifer in response to hydrostatic head resulting only from the dip of the aquifer, for extended periods of time, could have transported a sufficient quantity of uranium to the deposit, even if their uranium content was less than one part per million. The required minimum concentrations of other elements in the solutions are also low, but the regional variation patterns of other elements in the deposits in the Salt Wash, unlike that of uranium, point to their probable sources.

It is likely that vanadium in the Frenchy Incline deposit was also derived from sources external to the sandstone lens which encloses the deposit, and the regional variation pattern of vanadium in Salt Wash uranium deposits indicates that the vanadium may have been derived from heavy minerals in the Salt Wash member. Destruction of heavy minerals has occurred in altered sandstone which is abundant in the vicinity of the Legin area.

The hypothesis outlined above, therefore, involves at least two phases of mineralization, one which led to the accumulation of elements derived from tuffaceous materials and another which caused elements derived from sources external to the Salt Wash member to be superimposed on the earlier accumulations of elements. Uranium and vanadium were deposited after solution flow in the Salt Wash member became appreciable, possibly during the second phase of mineralization, but the present forms of the deposits were established with the first phase of mineralization. Uraniferous roll structures, for example, were formed perhaps by reaction of uranium with pyrite which had accumulated in these structures during periods of relatively stagnant ground-water conditions, when diffusion processes were operating. V. C. Kennedy (1961, oral communication) has found in the Lisbon Valley area, Utah, some roll structures in the Salt Wash which consist largely of ferric oxide and are not detectably uraniferous. C. H. Roach (1961, oral communication) has observed similar structures in the Salt Wash member in Montrose County, Colo. These structures may be products of the early phase of mineralization only, and were not replaced by uranium minerals in any later phase. Also in the Lisbon Valley area, but in the Chinle formation, Kennedy has found roll structures containing uraninite and abundant ferric oxides. This mineral assemblage could have originated on the reduction of uranium by pyrite with the precipitation of oxidized iron and removal of oxidized sulfur as sulfate in ground water.

Vickers (1956, p. 305) has formed pitchblende in the laboratory by reduction of uranium with pyrite. Thermodynamics of the reaction

$$FeS_2 + 7\text{-}1/2UO_2^{++} + 11H_2O = Fe(OH)_3 + 2SO_4^{--} + 19H^+ + 7\text{-}1/2UO_2$$

indicate that at pH conditions near neutral and over wide ranges of sulfate ion concentration, pyrite will precipitate uranyl ion as UO_2 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 because of 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 concentrations, uraninite and ferric hydroxide may still form if the concentration of uranium in solution is more than a few parts per million.

The sequence of events which have led to the accumulation of elements in the Frenchy Incline deposit, as interpreted in the hypothesis given here, is tabulated in figure 25. Examination of this tabulation shows that the deposit is interpreted to have resulted from interaction of dynamic and chemical processes, the dynamic processes controlling hydrologic conditions within the host rock and the chemical processes acting in response to changes in these conditions. Only the principal roles of most elements are shown on figure 25. Iron is neither principally intrinsic nor principally extrinsic in the deposit, but is both in about equal proportions.

(103a follows)

Age	Geologic Event	Hydrologic Conditions	Processes of Diagenesis and Mineralization	Elements accumulated and their Source
Jurassic———?———Cretaceous———?———Tertiary———?—Quaternary		Deposit elevated above ground-water table.	Introduction and removal of soluble cements Decay of plant materials (Conversion of sulfate to sulfide species) Oxidation of low-valent minerals. Redistribution and perhaps some removal of elements with oxidation.	Ca,Mg,Na,K,Mn from ground water (Intrinsic elements) 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.	←?—Alteration of iron minerals by reduction—?→ Solutions entering and leaving Salt Wash member by way of fractures in the Salt anticline region.	(Extrinsic elements) Cu,Ag,Pb,Zn,U?,V? from sources external to the Salt Wash member (e.g., basement rocks, laccoliths, salt plugs, etc.) ←?— U possibly from unknown sources, precipitated by pyrite and carbonized plant remains —?→ ←?— Pb possibly from radioactive decay of uranium in place—?→ ?—V possibly from heavy minerals or other 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 enviroments and concentration gradients within the sandstone. Devitrification and alteration of tuffaceous materials and diffusion. Formation of "roll" structures.	Fe,Co,Ni,Mo,As, Se,Zn,Cr?,Sr? from tuffaceous materials in ss. Cu,Ag,Pb from unknown constituents in ss. (Extrinsic elements)
	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 fm.			Elements contained in detrital minerals and syngenetic precipitates (Si,Al,Fe,Ca,Mg,Na, K,B,Ba,Ga,La,Mn,Sc,Ti,Y,Zr). (Intrinsic elements)

Figure 25. Chart showing interpretation of the sequence of events in the formation of the Frenchy Incline uranium deposit.

103b follows

Isotopic analyses of uranium and lead from the Colorado Plateau uranium deposits have not been successful in determining the time of introduction of uranium with any degree of universal acceptance. This objective may be accomplished in future work. Unless it can be shown by isotopic studies that the uranium in the deposits was introduced either simultaneous with or soon after the deposition of the host sandstone, or prior to the accumulation of pyrite, no adjustment or revision of the hypothesis given here will be required on this basis. In addition to chronological information, isotopic studies may eventually provide conclusive evidence regarding the source of the uranium in the deposits, an important aspect of their origin which, regrettably, is not offered in the hypothesis given here.

103a precedes
104 follows

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