Sources of the elements in the sandstone-type uranium deposits of the Colorado Plateau

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

Trace Elements Investigations Report 629

UNITED STATES DEPARTMENT OF THE INTERIOR
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SOURCES OF THE ELEMENTS IN THE SANDSTONE-TYPE URANIUM DEPOSITS OF THE COLORADO PLATEAU

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

ABSTRACT

Sandstone-type uranium deposits of the Colorado Plateau are epigenetic. Certain elements have been added locally to the sandstone host to form the deposits; the added fraction of each element in the deposits is called extrinsic to distinguish it from the part present in the original unmineralized host. The principal extrinsic components, in their approximate order of abundance, are vanadium, iron, magnesium, uranium, sulfur, arsenic, copper, lead, molybdenum, selenium, cobalt, and nickel.

At least six possible sources for the extrinsic components of the uranium deposits may be considered reasonably likely: 1) the sandstone beds enclosing the uranium deposits, 2) the marine Mancos shale of Cretaceous age, 3) bentonitic shales of Jurassic and Triassic age, 4) petroliferous rocks of Pennsylvanian age, 5) Precambrian crystalline rocks underlying the Colorado Plateau, and 6) magmatic reservoirs of latest Cretaceous or Tertiary age. If the major source of some of the elements is external to the sandstone beds enclosing the deposits, it is likely that several sources have contributed to some if not most of the extrinsic components and that the importance of the various sources differs from one component to the next. Precambrian crystalline rocks are considered the most likely major source of the extrinsic uranium in the deposits.

INTRODUCTION

A broad-scale study of the distribution of elements in the rocks and ores of the Colorado Plateau was initiated by the U. S. Geological Survey in 1951, as a part of a comprehensive investigation of the geology of the uranium deposits and conducted on behalf of the Division of Raw Materials of the U S. Atomic Energy Commission. Results from semiquantitative spectrographic analyses and chemical analyses of approximately 800 samples of rocks and ores form the principal starting point for the discussion set forth here. As study of the distribution of elements is still in progress, the conclusions presented are to some degree preliminary; but completed analysis of the data will not greatly alter the reasoning outlined in this paper.

The purpose of this paper is to examine the relevance of the results of the study of the distribution of elements to the special problem of the source or sources of the elements contained in unusual abundance in the sandstone-type uranium ores. No attempt will be made to review the already voluminous and rapidly expanding literature on the uranium deposits of the Colorado Plateau. The reader is referred to the recent review by McKelvey, Everhart, and Garrels (1955) and to U. S. Geological Survey Professional Paper 300, compiled by L. R. Page, H. E. Stocking, and H. B. Smith (1956), entitled, "Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955."

Two factors that bear on the source of the elements, which will not be discussed, are the structural relations of the uranium deposits and the temperature of deposition of the ore minerals. The structural relations of the ores have been reviewed by Shoemaker (1956C) in a separate report. Evidence on temperature of ore-mineral deposition has been variously interpreted, and most of it is inconclusive. Probably the most significant data are the occurrence of chalcocite-digenite intergrowths in certain ores (Theodore Botinelly, oral communication, 1956) and the very low iron content of the sphalerite (Weeks, Coleman, and Thompson, written communication, 1956) that is a rare constituent of the ores. Present consensus among mineralogists seems to be that the ore minerals were precipitated in the range 100° to 150° C., a range compatible with possible temperatures of the host rocks at the time and at the depth at which mineralization seems to have occurred.

The debt we owe to the analysts, on whose care and skill the success of the study of the distribution of the elements has depended, is evident. Special acknowledgment is due to A. T. Myers and R. G. Havens of the U. S. Geological Survey, who are responsible for the majority of spectrographic determinations incorporated in the reports on which this discussion is based.

GEOLOGIC SETTING OF THE URANIUM DEPOSITS

The Colorado Plateau is an oval region of about 130,000 square miles roughly centered on the cross formed by the boundaries of the four states, Arizona, Colorado, New Mexico, and Utah (fig. 1). The limits of the Colorado Plateau have been defined on the basis of physiographic features (Fenneman, 1931), but it is characterized as well by distinctive structures and an assemblage of sedimentary rocks notable for the high proportion of sandstone and of beds of continental origin. Tectonically, the Colorado Plateau is an island of gentle deformation in a sea of folding, thrusting, and block faulting, bounded on the north and east by the Rocky Mountains and on the west and south by the Basin and Range province. It is essentially a platform underlain by an upheaved block of the earth's crust that is moderately crenulated and warped and tilted to the northeast. A veneer of rocks of Paleozoic and Mesozoic age having an original average thickness of about 10,000 feet is spread upon the dominantly crystalline basement of this platform. Two thick deposits of sedimentary rocks of Tertiary age are also present in downwarps or basins on the northern and eastern sides of the Plateau. Intrusive igneous rocks of probable Cretaceous age and of Tertiary age are widely scattered in laccoliths and diatremes in the central part of the Plateau, and the province is nearly encompassed by extensive fields of volcanics of Tertiary and Quaternary age that overlap its margins. Uranium deposits have been found in many different sedimentary formations and also in igneous rocks, but

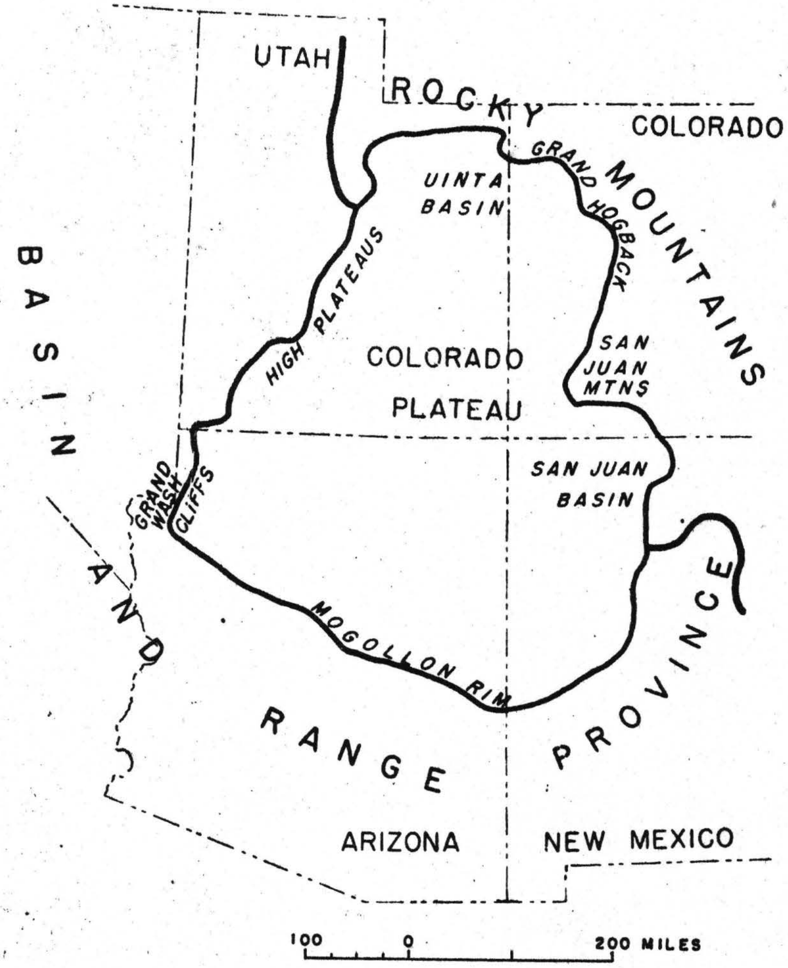

FIGURE 1.--PHYSIOGRAPHIC INDEX MAP OF THE COLORADO PLATEAU, (AFTER FENNEMAN, 1931).

most of the known deposits are in sandstone beds of only a few of the formations (table 1). With regard to uranium deposits, the Colorado Plateau can probably be considered part of a large metallogenic province that includes parts of the adjacent Rocky Mountains and Basin and Range provinces as well.

PHYSICAL CHARACTERISTICS OF THE SANDSTONE-TYPE URANIUM DEPOSITS

Most of the uranium deposits of the Colorado Plateau consist of sandstone and minor amounts of mudstone impregnated with and partly replaced by minerals of uranium, vanadium, and other heavy metals. To this kind of deposit the name sandstone-type uranium deposit has been applied. The ore bodies are generally of tabular form and are roughly parallel to the bedding in the sandstone host, but layers of ore do not coincide with the beds in detail, and locally the margins of ore bodies and of banding within the ore bodies cut sharply across the bedding.

Because the distribution of ore minerals does not follow in detail the lamination of the sedimentary rocks in which the ore is contained, the emplacement of the ore minerals has been interpreted by nearly all geologists to have been later than the deposition of the individual laminae in which the ore minerals are now found. This interpretation has been explicitly stated by Lindgren (1911, p. 568), Coffin, (1921, p. 159 and 176), and later by Fischer (1937, p. 943). The ore deposits are, therefore, conceived as composed of two

Table 1.--Volume of formations, proportion of sandstone, and number of known sandstone-type uranium deposits in the principal geologic units of the Colorado Plateau from the Cutler formation (Permian) to the Dakota sandstone (Cretaceous).

System	Geologic unit	Volume cubic miles 1/	Percent sandstone 1/	Volume of sandstone cubic miles	number of known uranium deposits 2/
Cretaceous	Dakota sandstone	1,440	70	980	17
	Lower Cretaceous rocks	800	20	180	9
Jurassic	Morrison formation				
	Brushy Basin member	3,200	14	450	30
	Westwater Canyon member	1,000	60	600	20
	Recapture member	1,300	65	850	6
	Salt Wash member	2,500	58	1,450	1,900
	Bluff sandstone	300	98	290	0 3/
	Cow Springs sandstone	2,500	98	2,450	0 3/
	Summerville formation	1,700	55	940	7
	Entrada sandstone	3,800	98	3,700	29
	Carmel formation	2,800	60	1,700	0 3/
	Navajo sandstone	11,000	100	11,000	2
	Kayenta formation	1,100	90	990	7
Triassic	Wingate sandstone	3,000	100	3,000	7
	Chinle 4/ formation	16,000	40	6,400	165
	Shinarump member	1,000	90	900	423
	Moenkopi formation	10,000	50	5,000	4
Permian	Cutler formation	6,000	70	4,300	49

1/ Volume of formations within the limits of the Colorado Plateau (fig. 1). Calculated from isopach maps drawn on the basis of unpublished stratigraphic sections on file with the Geological Survey and partly on the basis of data by McKee (1951). Percent sandstone is from an average of randomly selected published and unpublished stratigraphic sections.

2/ Number of known deposits as of January 1955. Deposits tabulated from compilations used in preparation of maps showing distribution of uranium depositions (Shoemaker and Luedke, unpublished data: Finch, 1955).

3/ In construction of the scatter diagram shown in figure 4 a value of 0.5 has been arbitrarily assigned for the number of known deposits.

4/ Exclusive of Shinarump member.

fundamental parts: 1) a mass of sediment or rock formed prior to emplacement of the ore minerals, and 2) minerals carrying the bulk of the ore elements and other associated minerals introduced or formed in the mass of sediment or rock that today constitutes the ore deposit. The first part may be thought of as the indigenous or intrinsic part of the ore deposits, corresponding approximately in composition to the rocks that would have occupied the space of the ore deposits had mineralization never occurred. The second part, introduced during mineralization, may be thought of as foreign or extrinsic to the individual rock masses that constitute the deposits. It is the latter or extrinsic part that is the subject of this paper.

EXTRINSIC PART OF THE URANIUM DEPOSITS

The extrinsic part of a typical sandstone-type uranium deposit consists of many elements in addition to uranium and vanadium. The most direct method of determining what elements are likely to be present in the extrinsic parts of uranium deposits is to compare the composition of the deposits with the composition of the unmineralized host sandstone (table 2). Table 2 shows some of the elements that are believed to be present in the extrinsic part of sandstone-type uranium deposits in the Salt Wash member of the Morrison formation of Jurassic age, one of the principal ore-bearing sedimentary units, and the ratio of the average abundance of each element in the uranium deposits to its average abundance in unmineralized sandstone in the Salt Wash. The ratios are based on analyses of samples of ore from

Table 2.--Principal elements contained in the extrinsic part of sandstone-type uranium deposits in the Salt Wash member of the Morrison formation of Jurassic age.

Element	Abundance ratio[1/]
Uranium	>1,000
Vanadium	500
Cobalt	~20
Nickel	~20
Arsenic	>17
Lead	>9
Yttrium	~8
Copper	7
Selenium	>6
Molybdenum	>3
Iron	3.7
Magnesium	3.0
Sulfur	Not estimated

1/ Ratio of estimated geometric mean concentration in uranium ores to estimated geometric mean concentration in unmineralized sandstones, based mainly on semiquantitative spectrographic determinations. Because the log standard deviation of the concentration of each element in the samples of ore studied is similar to the log standard deviation of the concentration of the same element in the unmineralized sandstones, this ratio is nearly identical with the ratio of the estimated arithmetic means (abundances).

about 200 uranium deposits and on analyses of about 100 samples of unmineralized sandstone. The elements uranium, vanadium, cobalt, nickel, copper, arsenic, selenium, yttrium, molybdenum, lead, iron, and magnesium are known to be significantly more abundant in the average ore from the Morrison than in average unmineralized sandstone in the Salt Wash. The abundance ratios range from about 3 in the case of magnesium to more than 1,000 in the case of uranium. A closely similar group of elements is present in the extrinsic part of sandstone-type uranium deposits in Triassic and other formations on the Colorado Plateau.

Some elements contained in the extrinsic part of the uranium ores are present in much greater average amounts than other elements in the extrinsic part, and the order of abundance of the various extrinsic constituents is, therefore, different from the order of abundance ratios for each constituent given in table 2. The approximate order of abundance of the principal extrinsic constituents of ores in the Salt Wash member of the Morrison formation is as follows: vanadium, iron, magnesium, uranium, sulfur, arsenic, copper, lead, molybdenum, selenium, cobalt, and nickel.

It is important to note that all elements believed to be present in the extrinsic part of sandstone-type uranium deposits are also present in the host sandstones. Thus no element is likely to be contained entirely in the extrinsic part of a sandstone-type uranium deposit. Even the elements uranium and vanadium that are contained very largely in the extrinsic part, are also present in small amounts in the sedimentary detritus contained in the deposits. All elements shown in table 2 are partly indigenous or intrinsic in the sedimentary host and partly extrinsic. The intrinsic or "background" fraction of uranium and vanadium is very small in average ore from the Morrison formation, but the intrinsic fraction of an element such as copper is appreciable. More than half of the magnesium and iron in average ore from the Morrison is believed to be an indigenous part of the sedimentary material in the deposits.

The sandstones of the Salt Wash member of the Morrison formation have an arithmetic mean content of about 20 ppm (parts per million) vanadium and about 1 ppm uranium. A cylinder of average unmineralized sandstone from the Salt Wash 50 feet high and 2,000 feet in diameter contains enough uranium and vanadium to form a 5,000-ton ore body with an average grade of 0.30 percent uranium and 4.5 percent vanadium.

The amount of other metals contained in such a cylinder of sandstone is greatly in excess of that required to form a 5,000-ton ore body with the average composition of the ore from the Morrison. Because the ore deposits are only a very small fraction of the total amount of sandstone in the Salt Wash, the amount of uranium and vanadium in the unmineralized sandstone of the Salt Wash member vastly exceeds the amount of uranium and vanadium contained in the ores. If, for example, 100,000,000 tons of material containing 0.30 percent uranium were uniformly mixed with the volume of sandstone present in the Salt Wash on the Colorado Plateau, the average uranium content of the sandstones would be raised less than 0.02 ppm. This small difference could not be demonstrated with acceptable confidence by any practicable system of sampling.

From the point of view of availability, it is possible that the extrinsic fraction of all elements known to be present in the extrinsic part of the sandstone-type uranium deposits could have been derived from the unmineralized sandstones enclosing the deposits. There is an indigenous supply of all elements in unmineralized sandstones of the Morrison formation that is more than adequate to furnish the amounts of the various metals contained in ore from the Morrison.

HOST SANDSTONES AS POSSIBLE SOURCES OF EXTRINSIC CONSTITUENTS

The possibility that the unmineralized sandstones were the source of the extrinsic constituents in the ores from the Morrison formation is suggested to some extent by the observed distribution of vanadium and copper in samples of unmineralized sandstones from the Salt Wash member (figs. 2 and 3). The principal areas in which the unmineralized sandstones contain more-than-average vanadium include a region of closely spaced uranium deposits in Colorado, referred to as the Uravan mineral belt by Fischer and Hilpert (1952), and at least a part of a region of closely spaced uranium deposits in northeastern Arizona near the Four Corners (fig. 2). This distribution might be interpreted as indicating that ore deposits are most numerous where the initial supply of intrinsic vanadium was highest. Alternatively, the areas of high vanadium might also be interpreted as broad halos of very weakly mineralized sandstone surrounding the districts with numerous ore deposits. It is not known, in other words, which is cause and which is effect.

Similarly, the distribution of copper in unmineralized sandstone of the Salt Wash member seems to be related in a general way to the distribution of copper in uranium ores from the Salt Wash. In an area on the Utah-Colorado border in which the unmineralized sandstones contain more-than-average amounts of copper, the uranium deposits in the Salt Wash contain more-than-average copper (cf. figs. 3 and 7). Again, it is not known which is cause and which is effect.

If the enclosing sandstones are the source of some of the metals contained in the uranium deposits, part of these metals might have been derived from heavy detrital minerals in the sandstones. Shawe (1956) finds that, in the southern part of the Uravan mineral belt in Colorado, the opaque heavy minerals, chiefly oxides of iron and

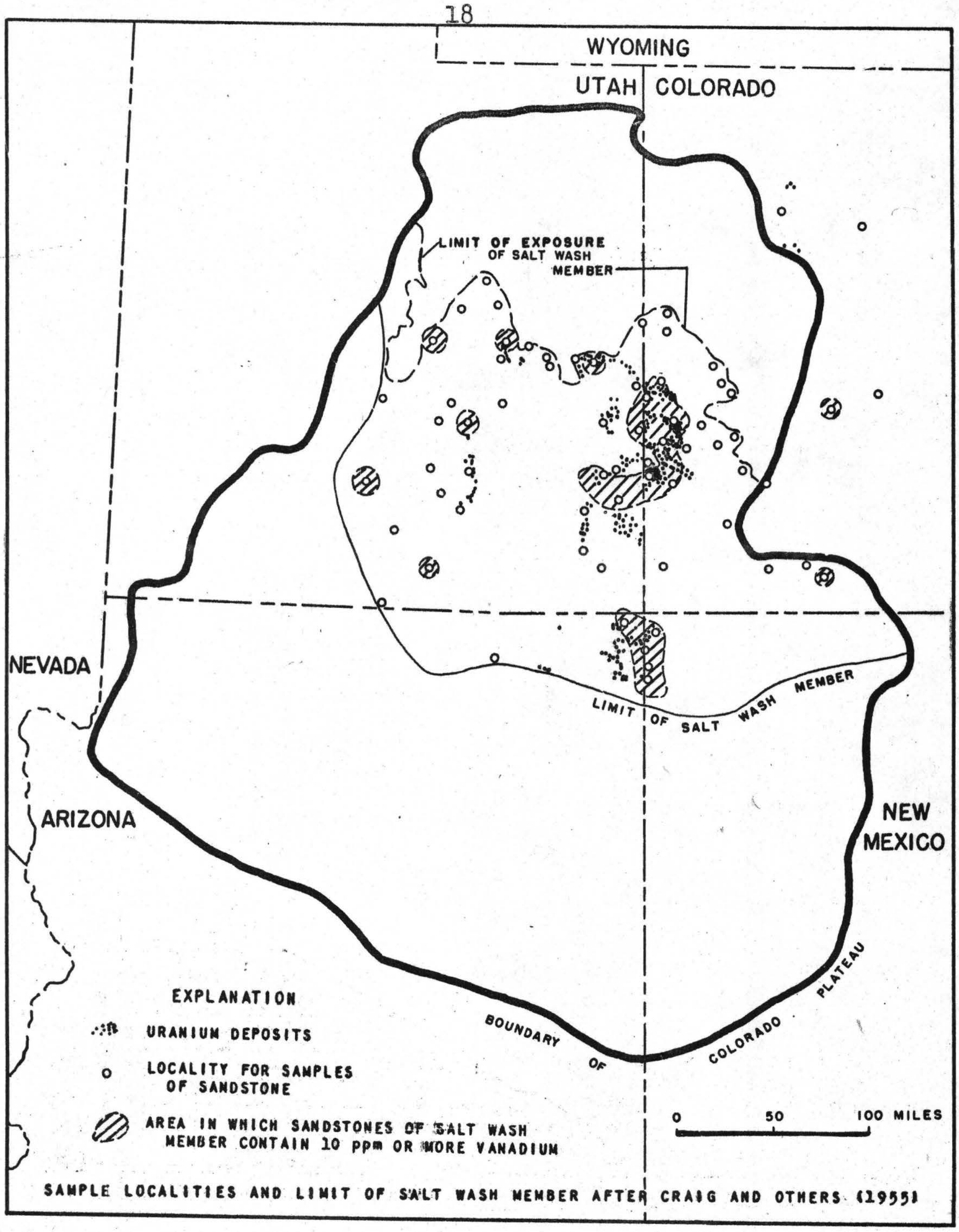

FIGURE 2.--MAP OF THE COLORADO PLATEAU SHOWING DISTRIBUTION OF URANIUM DEPOSITS IN THE SALT WASH MEMBER OF THE MORRISON FORMATION AND AREAS IN WHICH UNMINERALIZED SANDSTONES OF THE SALT WASH CONTAIN 10 PPM OR MORE VANADIUM.

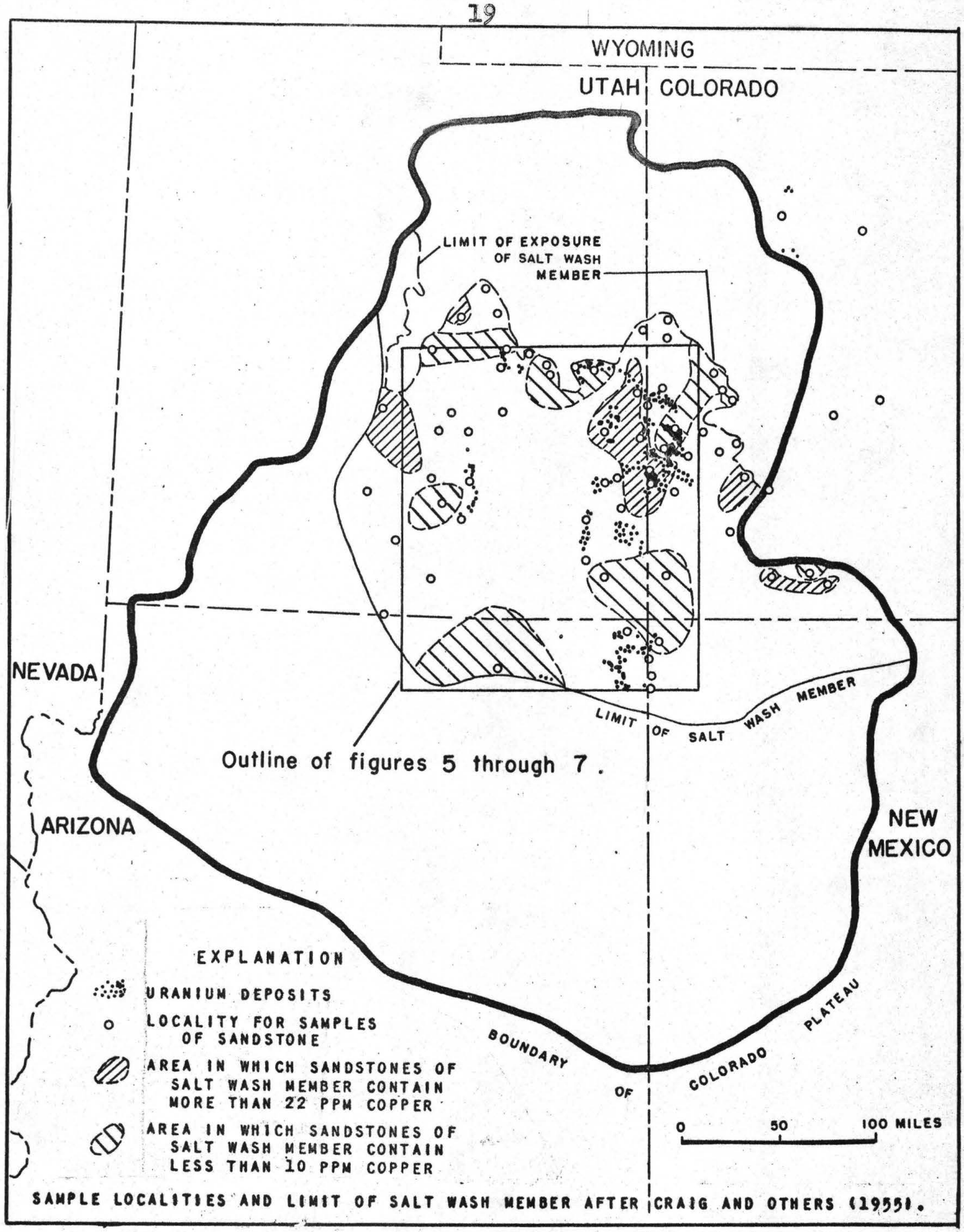

FIGURE 3.--MAP OF THE COLORADO PLATEAU SHOWING DISTRIBUTION OF URANIUM DEPOSITS IN THE SALT WASH MEMBER OF THE MORRISON FORMATION AND THE DISTRIBUTION OF COPPER IN UNMINERALIIZED SANDSTONES OF THE SALT WASH.

titanium, have been destroyed or altered in altered sandstone adjacent to uranium deposits. Analysis of heavy minerals from the sandstones of the Salt Wash member shows that the heavy minerals have a high content of many, but not all, of the elements found in the extrinsic part of the uranium deposits. Placer titanium deposits composed of unusual concentrations of heavy minerals occur in sandstones of Late Cretaceous age in the Colorado Plateau and Rocky Mountains and are not only markedly uraniferous but also have a content of some other heavy metals comparable to the sandstone-type uranium deposits (Murphy and Houston, 1955; Allen, 1956; Chenoweth, 1956).

There is, on the other hand, no correlation between the abundance of ore elements in the unmineralized sandstones of the various formations on the Colorado Plateau and the frequency of occurrence of uranium deposits in the sandstones. Figure 4 is a scatter diagram showing the relation between the estimated abundance of vanadium and the number of known ore deposits per 1,000 cubic miles of sandstone in all of the principal sandstone-bearing formations for which we have analytical data. The various formations are scattered essentially at random on the diagram. The sandstones of some formations, like the Moenkopi formation of Triassic age, have a relatively high average content of vanadium but very few known uranium-vanadium ore deposits. The sandstones in the Salt Wash member of the Morrison formation of Jurassic age, which contain the largest number of known uranium-vanadium deposits, have an average vanadium

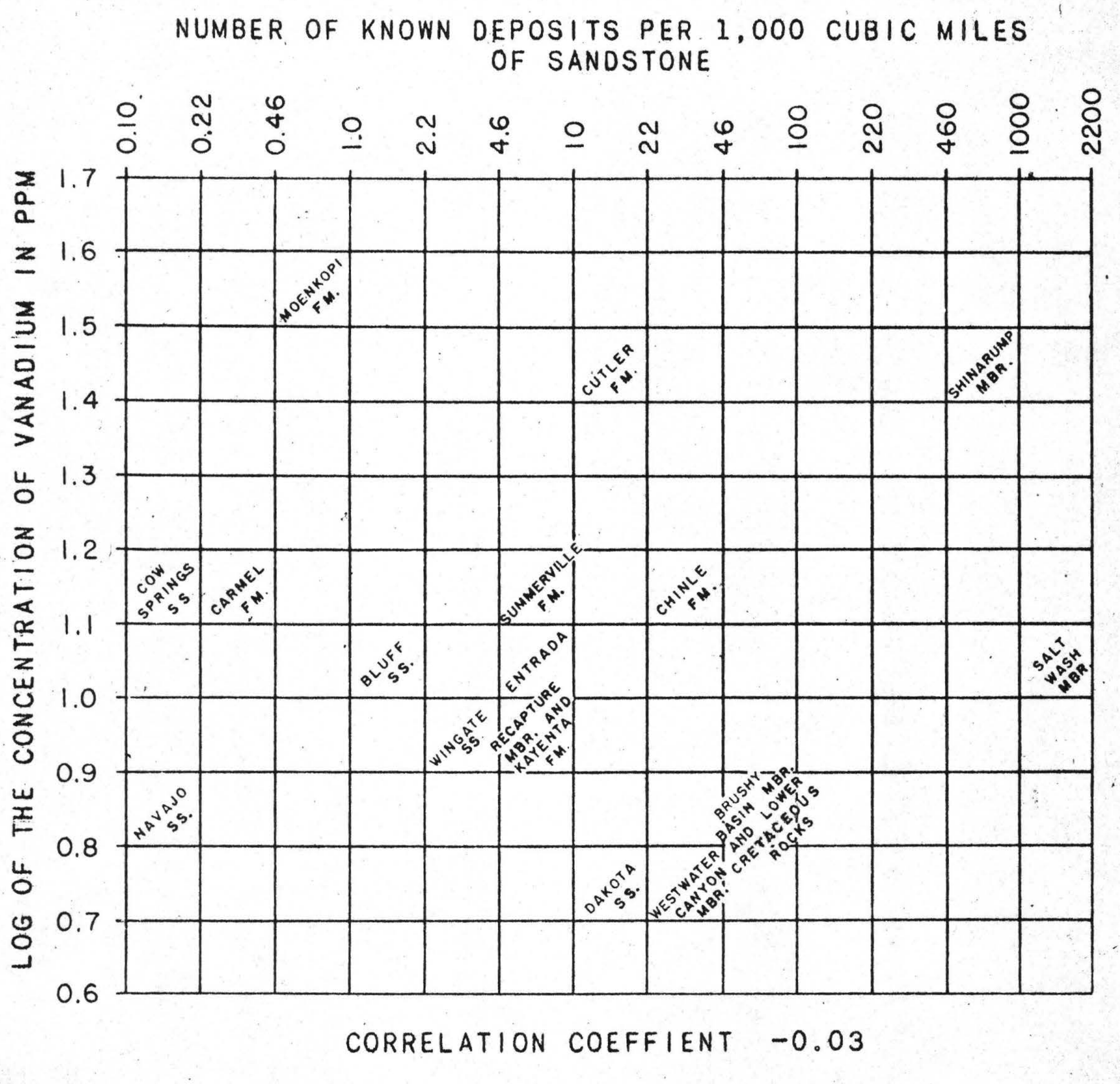

FIGURE 4.--SCATTER DIAGRAM SHOWING THE CORRELATION BETWEEN THE NUMBER OF KNOWN URANIUM DEPOSITS PER 1,000 CUBIC MILES OF SANDSTONE AND THE ESTIMATED GEOMETRIC MEAN CONCENTRATION OF VANADIUM IN LATE PALEOZOIC AND MESOZOIC SANDSTONES OF THE COLORADO PLATEAU.

content close to the median of other sandstones on the Colorado Plateau. The abundance of vanadium in sandstones of the Shinarump member of the Chinle formation of Triassic age is relatively high compared with other Colorado Plateau sandstones, as is shown on the diagram, yet the average vanadium content of uranium ores from the Shinarump is considerably lower than the average vanadium content of uranium ores in the Salt Wash.

The estimated arithmetic mean content of some of the elements in unmineralized sandstone in the Salt Wash can be compared with estimated means in average sandstone published by Rankama and Sahama (1950) in table 3. Most of the means in sandstone in the Salt Wash are surprisingly close to the means given by Rankama and Sahama. The close matches of uranium and vanadium are probably fortuitous. It is clear, however, that the sandstones in the Salt Wash are not unusually rich in most of the elements that make up the extrinsic fraction of the ores, and, in particular, that the uranium and vanadium content of sandstones in the Salt Wash is not abnormal. This is true regardless of whether the uranium deposits are included in proportion to their weight in the estimated averages. The occurrence of uranium-vanadium ore deposits in the sandstone in the Salt Wash cannot be ascribed to an unusual content of the ore metals in the bulk sandstones.

Table 3.--Estimated average concentration of elements in sandstone of the Salt Wash member of the Morrison formation and in "average" sandstone. (Concentration given in arithmetic mean parts per million.)

Element	Sandstone of the Salt Wash 1/	Average 2/ sandstone
Si	>100,000	367,500
Al	15,000	25,300
Fe	3,000	9,900
Mg	4,000	7,100
Ca	70,000	39,500
Na	2,000	3,300
K	~4,000	11,000
Ti	600	960
Zr	150	Not given
Mn	400	Trace
Ba	600	170
Sr	70	<26
Cu	20	34 3/
Cr	9	68 - 200
V	18	20
Co	~1	0
Ni	~1	2 - 8
Ag	~0.5	0.44
Y	~3	1.6
B	10	9 - 31
Yb	~0.5	Not given
U	1.2 4/	1.2

1/ Estimates based mainly on semiquantitative spectrographic analyses of 96 samples of sandstone.

2/ Rankama, Kalervo, and Sahama, Th. G., 1950, Geochemistry: Univ. of Chicago Press, table 5.52, p. 226.

3/ Clarke, F. W., 1924, Data of Geochemistry: U. S. Geol. Survey Bull. 770, p. 509 (Cu recalculated from CuO).

4/ Estimate based on fluorimetric analyses of 23 samples of sandstone.

EVIDENCE FOR EXTERNAL SOURCES OF THE EXTRINSIC CONSTITUENTS

Let us consider the possibility or likelihood that the extrinsic constituents of the sandstone-type uranium deposits have been derived in part from sources external to the sandstones in which the ores occur. One of the more important lines of evidence bearing on the origin of the sandstone-type uranium ores is provided by efforts of Stieff, Stern, and Milkey (1953) to date the period of mineralization by means of lead-uranium ratios. Their work indicates that mineralization occurred long after the accumulation of the principal host strata, and that mineralization occurred, moreover, at about the same time in formations of both Triassic and Jurassic age.

The processes of mineralization almost certainly involved circulation of solutions, and circulation of solutions long after the accumulation of the sandstones probably required the entry and discharge of water or other solvents from the mineralized beds. The occurrence of uranium deposits in many different formations suggests, by itself, that mineralizing solutions may have crossed formational boundaries, and rare deposits of uranium and associated metals along faults and pipe-like collapse features (Shoemaker, 1956A; Keys and White, 1956) shows that the metals have definitely been transported across beds at least locally.

Perhaps the most suggestive evidence that some extrinsic constituents of the sandstone-type uranium deposits have been derived from sources external to the enclosing sandstones is the regional pattern of distribution of certain elements in uranium ores in different formations (figs. 5, 6, and 7). Figure 5 illustrates the distribution of nickel in ores from both the Morrison formation and sandstones of Triassic age in the central part of the Colorado Plateau. The actual content of nickel varies somewhat erratically from deposit to deposit, but it can be seen from the figure that the content of nickel in the uranium ores tends to increase from southeast to northwest. Uranium deposits in the Morrison formation and rocks of Triassic age are interspersed in the area shown, and the regional variation of nickel seems to be independent of the stratigraphic position of the ores. A similar pattern was found for cobalt and a somewhat similar distribution was obtained for molybdenum.

A different pattern was observed in the case of the distribution of lead in the sandstone-type uranium ores (fig. 6), but again the distribution seems to be largely independent of the stratigraphic position of the ores. Most of the deposits containing higher-than-average concentrations of lead occur within a region of salt anticlines. A second area in which the deposits tend to have higher-than-average amounts of lead occurs between the Henry and Abajo Mountains of Utah. Zinc, silver, and copper have similar patterns of distribution (fig. 7). The distribution of copper is different from that of lead, zinc, and silver, however, in one important respect. The copper content tends to be high in the salt-anticline area and in the area between the Henry and Abajo Mountains as in the case of the other three metals, but in the area between the mountains the

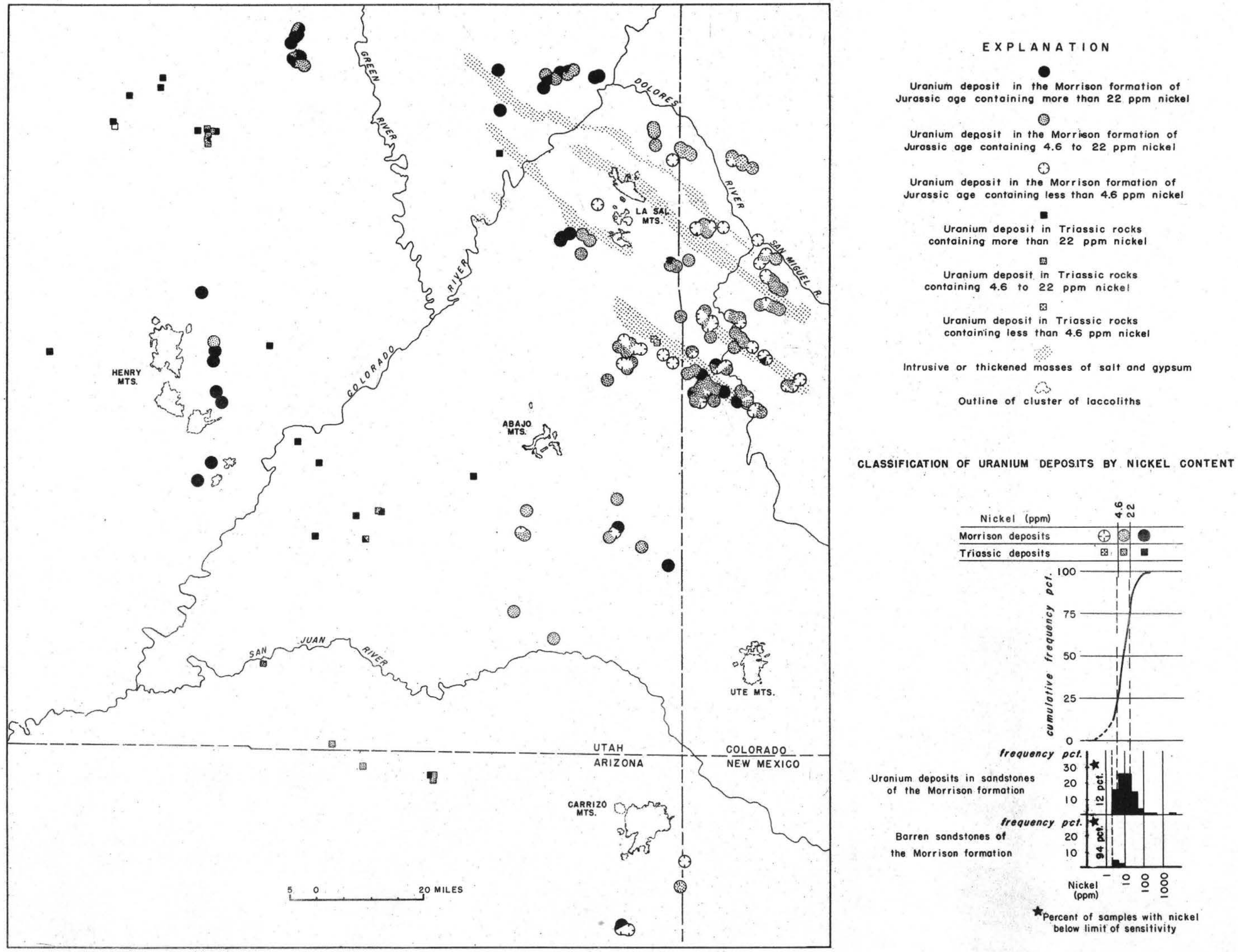

Figure 5.--MAP OF PART OF THE COLORADO PLATEAU SHOWING THE DISTRIBUTION OF NICKEL IN URANIUM DEPOSITS

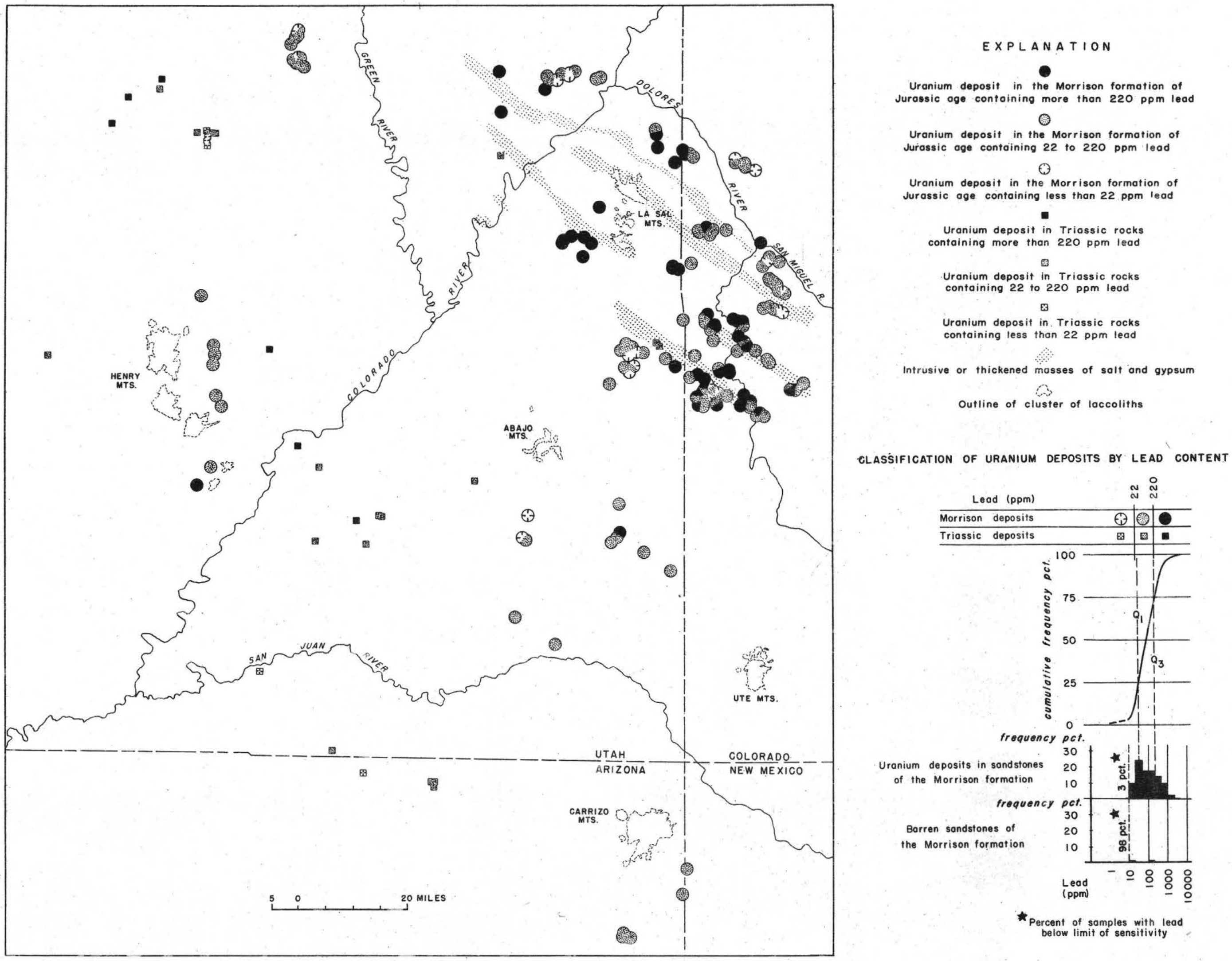

Figure 6.--MAP OF PART OF THE COLORADO PLATEAU SHOWING THE DISTRIBUTION OF LEAD IN URANIUM DEPOSITS

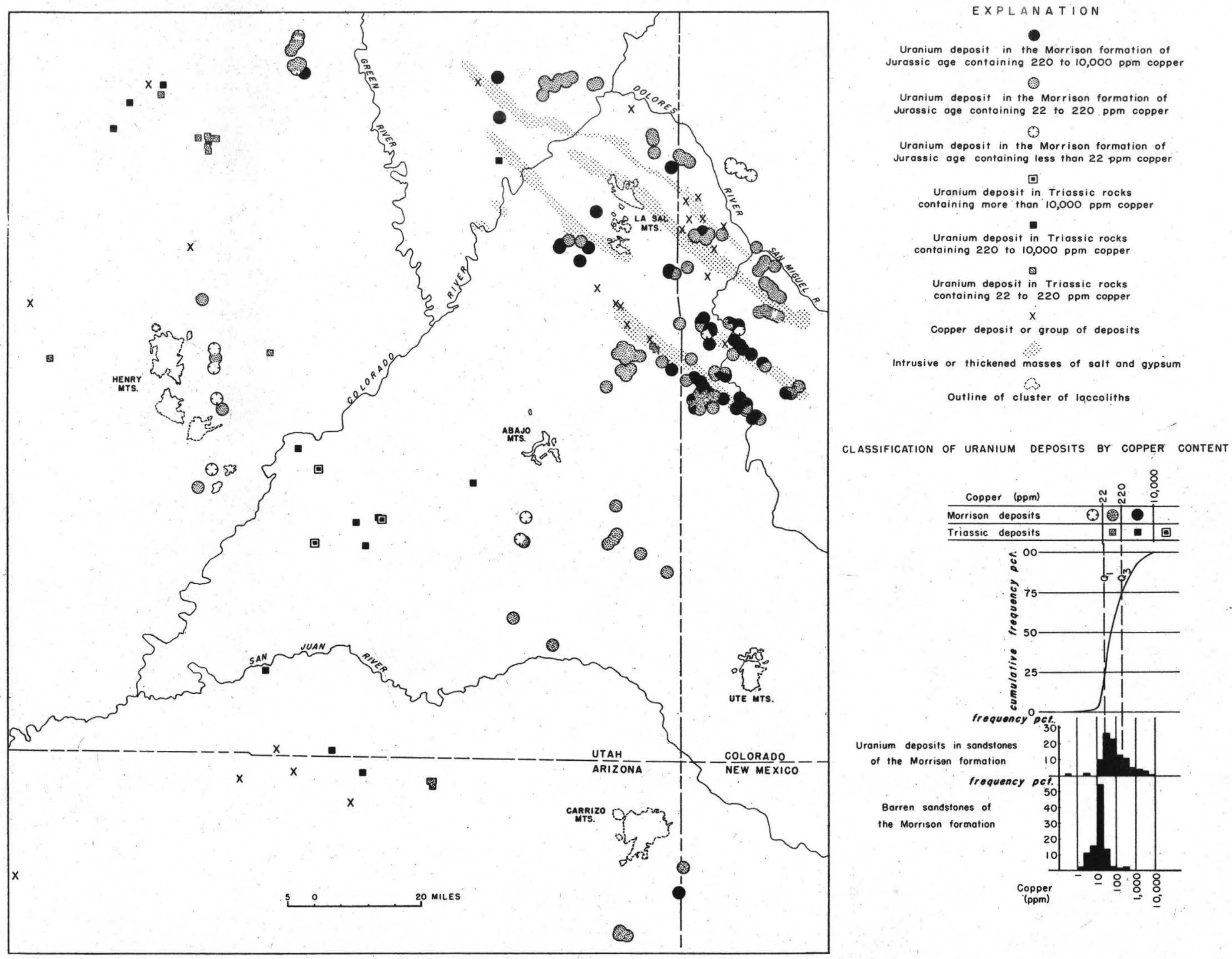

Figure 7.--MAP OF PART OF THE COLORADO PLATEAU SHOWING THE DISTRIBUTION OF COPPER IN URANIUM DEPOSITS AND LOCATION OF COPPER DEPOSITS

copper content of the uranium ores is much higher than in ores anywhere else in the central part of the Colorado Plateau. The deposits with exceptionally high copper content are all in one sedimentary unit, the Shinarump member of the Chinle formation.

With the exception of copper and vanadium, the extrinsic constituents of uranium deposits in the central Colorado Plateau thus seem to have a regional distribution that is independent of stratigraphic position of the ores. Essentially the same suite of elements is present in the extrinsic part of the ores found in both sandstones of Triassic age and the Morrison formation of Jurassic age, and the range of abundance of the extrinsic constituents is about the same. Within a given formation the abundance of individual extrinsic constituents in the ores varies by a factor of 100 to 1,000. Where ores are present in more than one formation within a relatively small district (for example, between the Abajo and La Sal Mountains, figs. 5, 6, and 7), on the other hand, the composition of the extrinsic part of the ores in different formations tends to be similar. These relations suggest that some factor or factors external to the individual formations but common to both have influenced the composition of the ores. One of these factors may have been the source of the extrinsic constituents.

It is not necessary to believe that all the extrinsic constituents of the sandstone-type uranium ores had the same source. If source is a major factor in governing the regional distribution of extrinsic constituents in the ores, it is entirely possible, if not likely, that the source of the nickel-cobalt-molybdenum group of elements, for example, was different from the source of the copper-lead-zinc-silver group of elements. There are, furthermore, good reasons to believe that the source of each element is actually manifold or multiple. Whatever the source of the mineralizing solutions, they probably reacted to some degree and exchanged elements with all the rocks they traversed from the original source of the solutions to the site of deposition of the ore. If the main source of some of the elements is external to the sandstone beds enclosing the deposits, it is likely that several sources have contributed to some if not most of the extrinsic constituents, and that the importance of the various sources differs from one element to the next. The evidence for each element should be judged independently. Copper and vanadium, for example, might be judged to come mainly from the sandstones, but this would not necessarily indicate the principal source of the uranium or other extrinsic constituents.

The most likely external sources of extrinsic constituents in the uranium deposits can be classed into two groups: 1) supergene sources, or sources that overlie the ore-bearing beds and from which the metals would have been transported by downward migration of ore-forming solutions, and 2) hypogene sources, or sources that underlie the ore-bearing beds and from which the metals would have been transported by upward migration of ore-forming solutions.

POSSIBLE SUPERGENE SOURCES OF EXTRINSIC CONSTITUENTS

As possible supergene sources of the extrinsic constituents of the uranium ores the Mancos shale (Cretaceous), or the marine waters in which the Mancos shale was deposited, and bentonitic or tuffaceous shales of both the Brushy Basin member of the Morrison formation (Jurassic) and the Chinle formation (Triassic) have been suggested (Gruner, 1954; Koeberlin, 1938; Proctor, 1953, p. 138-142). Deposition of the Mancos shale took place during the first large invasion of the sea over the greater part of the Colorado Plateau after a long history of dominantly continental sedimentation. The extent to which this marine invasion influenced the composition and circulation of ground water in the underlying continental beds is not known. (See Kelley 1955, p. 101-102.) The capacity of sea water to supply the known extrinsic constituents of the Colorado Plateau sandstone-type uranium deposits seems to be demonstrated by the relatively high concentrations of nearly all these elements in marine phosphorites (McKelvey, Swanson, and Sheldon, 1953). Bentonite beds are rather common in the Mancos shale, and it is also possible that the volcanic ash now transformed to bentonite constitutes a potential source of some of the extrinsic constituents. The Mancos shale is moderately seleniferous and supports a variety of selenium-bearing plants (Trelease and Beath, 1949, p. 73). The upper part of the Mancos of the central part of the Colorado Plateau is equivalent to the Sharon Springs member of the Pierre shale of the Great Plains region (Cobban and Reeside, 1952, chart 10b), a unit that has some lithologic similarities to parts of the Mancos and which has been found to be markedly uraniferous in places (Tourtelot, 1956).

The evidence against the Mancos shale or Mancos sea as a source of the elements in the uranium deposits is largely non-chemical. The principal objection would seem to be that the main ore-bearing beds are everywhere separated stratigraphically from the Mancos by widespread thick units of shale of low permeability, whereas Cretaceous sandstone beds that directly underlie the Mancos shale are generally not mineralized. If the Mancos shale is the source of some of the extrinsic constituents of the uranium deposits, it is strange that the immediately underlying sandstones of Cretaceous age and sandstone strata within the Mancos, which are lithologically similar in many respects to the ore-bearing beds of Jurassic and Triassic age, are not more widely mineralized.

Stratigraphically nearer sources of the extrinsic elements are suggested by the work of Waters and Granger (1953) who pointed out that the Brushy Basin member of the Morrison formation, which in most places immediately overlies the ore-bearing Salt Wash member, and the lower part of the Chinle formation, which immediately overlies the ore-bearing Shinarump member, are both rich in fine-grained volcanic detritus now altered to bentonite. The hypothesis of downward leaching of metals from tuffs, though rejected by Waters and Granger (1953), has been applied by Denson and Gill (1956) to account for the uraniferous lignite deposits of eastern Montana and the Dakotas, and by Love (1952) to the uranium deposits at Pumpkin Buttes, Wyoming. The rocks of the Morrison formation have been found to be abnormally rich in selenium by Trelease and Beath (1949), p. 69-70), who (p. 94) postulated volcanic detritus as the source of the selenium.

Studies by D. A. Phoenix (written communication, 1955) of sandstone lenses in the base of the Brushy Basin member of the Morrison formation suggest that locally the distribution of uranium deposits in sandstones of the underlying Salt Wash member may be related to the occurrence of basal sandstone and conglomerate lenses in the Brushy Basin. A possible control of the uranium deposits by overlying rocks may be indicated. Very recently a uranium deposit has been discovered in a 1-foot thick carbonaceous siltstone bed in a bentonitic sequence in the middle of the Brushy Basin member in the Green River desert area of Utah. According to H. S. Johnson (oral communication) this bed can be traced about 3,000 feet along the outcrop and is markedly uraniferous throughout its extent. This deposit might represent an original syngenetic concentration of uranium. In addition to uranium, the mineralized bed contains more molybdenum and cerium-group rare earths than ordinary siltstone of the Morrison formation.

Just as in the case of the Mancos shale, however, sandstone beds within the tuffaceous shale of the Morrison and Chinle formations might be expected to contain the highest proportion of uranium deposits, if the tuffaceous shales were the source of the extrinsic constituents, but such sandstone beds are only rarely mineralized. A further objection to the shales as sources would be the greater difficulty in accounting for the regional patterns of element distribution (figs. 5, 6, and 7), which seem to be independent of the stratigraphic position of the deposits, if the extrinsic elements in the deposits of each of the two main producing groups of beds were derived from two independent units of tuffaceous shale. It should also be noted that normal felsic volcanic material that is enriched in uranium (Adams, 1954; Larsen and others, 1956), and probably also in molybdenum and lead, and therefore a likely source of these three elements, tends to be impoverished in vanadium, nickel, and cobalt, which are generally concentrated in mafic volcanic rocks (Nockolds and Allen, 1953 and 1954). Thus the volcanic detritus is not a particularly likely source of the entire suite of extrinsic elements unless both mafic and felsic volcanics are represented in the tuffs. With the one notable exception, unusual quantities of most of the elements that are typically extrinsic in the uranium ores are not known to be present in the bentonitic sequences of the Morrison and Chinle. Further data on this point, however, are desirable.

EVIDENCE FOR UPWARD MIGRATION OF URANIUM ORE-FORMING SOLUTIONS

An alternative explanation for the localization of most of the sandstone-type uranium deposits beneath thick sections of bentonitic shales would be that the bentonitic shales formed relatively impermeable barriers for the upward migration of the ore-forming solutions. In this connection, it is important to note that in the main area of uranium production from the Salt Wash member of the Morrison formation the bentonitic shale members of the older Chinle formation are very thin or absent (fig. 8). Thus the Salt Wash is most intensively mineralized where the Chinle formation, which underlies the Salt Wash at depth, would present the least barrier to rising solutions.

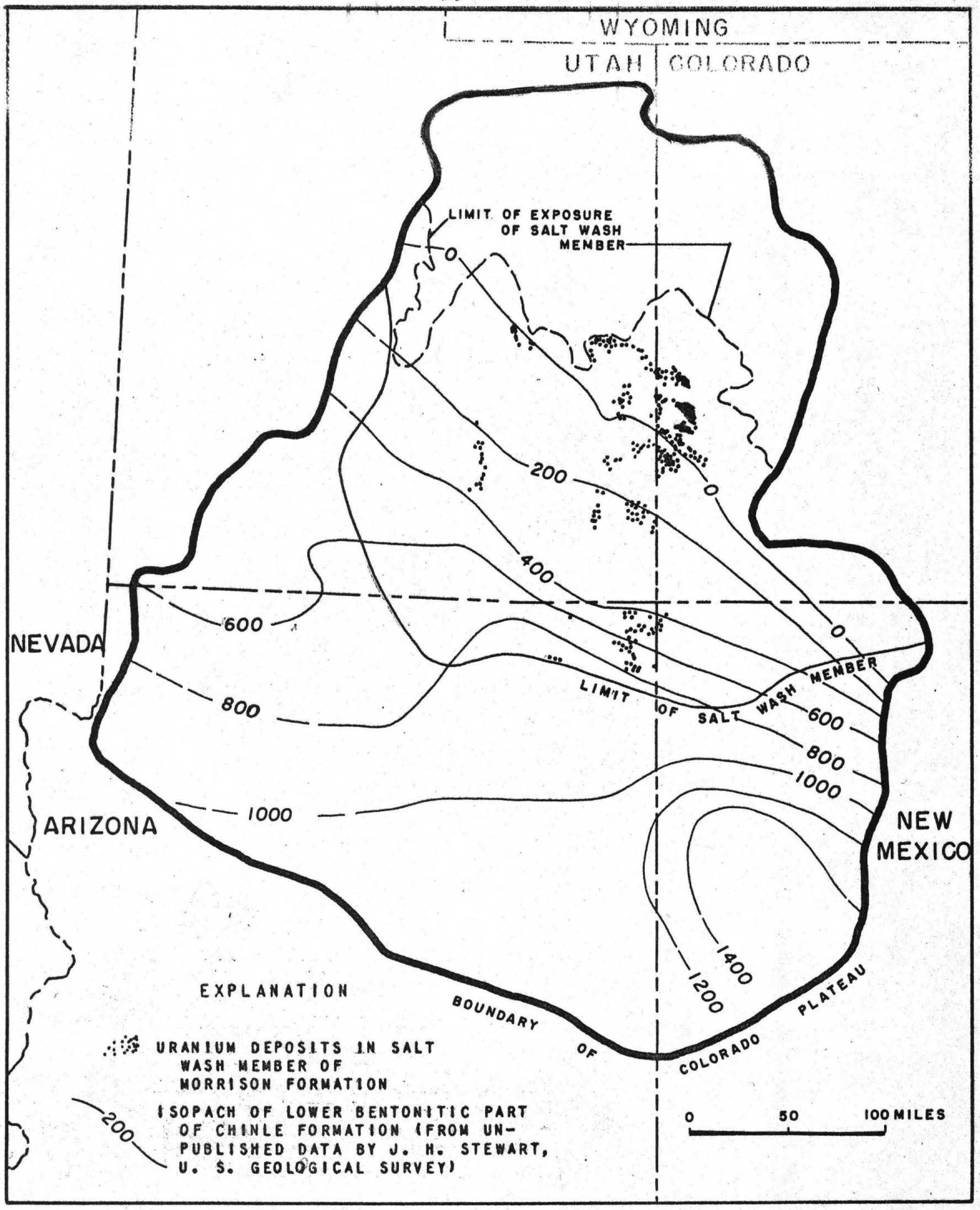

FIGURE 8.--MAP OF COLORADO PLATEAU SHOWING THICKNESS OF LOWER BENTONITIC PART OF CHINLE FORMATION AND DISTRIBUTION OF URANIUM DEPOSITS IN THE SALT WASH MEMBER OF THE MORRISON FORMATION.

Further evidence for the upward migration of uranium ore-forming solutions is provided by the relation between the uranium deposits and copper deposits in the vicinity of the Uravan mineral belt. Most of the copper deposits in this area lie in an arcuate zone or belt between the Uravan mineral belt and the La Sal Mountains of Utah (fig. 9). Both simple vein deposits along faults and disseminated copper deposits occur in this copper belt. It has been suggested that the copper deposits are unrelated to the uranium deposits by Fischer (1936, p. 572 and 598), who believed the vein copper deposits to be of hydrothermal origin. However, with the exception of vanadium, the copper deposits contain essentially the same suite of extrinsic elements as the uranium deposits in the Morrison formation in the nearby Uravan mineral belt (table 4). Some, but not all, of the copper deposits contain extrinsic uranium. Among deposits north of Paradox Valley (fig. 9), no sharp dividing line can be drawn on the basis of metal content between slightly uraniferous copper deposits on the one hand and cupriferous uranium-vanadium deposits on the other. Both types of deposits have similar relations to faults and a similar distribution with respect to intrusive salt masses (Shoemaker, 1956a). Finally, the isotopic composition of a sample of lead extracted from galena from one of the vein copper deposits near Paradox Valley is similar to abnormal galena leads obtained from the sandstone-type uranium deposits (Lorin R. Stieff, written communication).

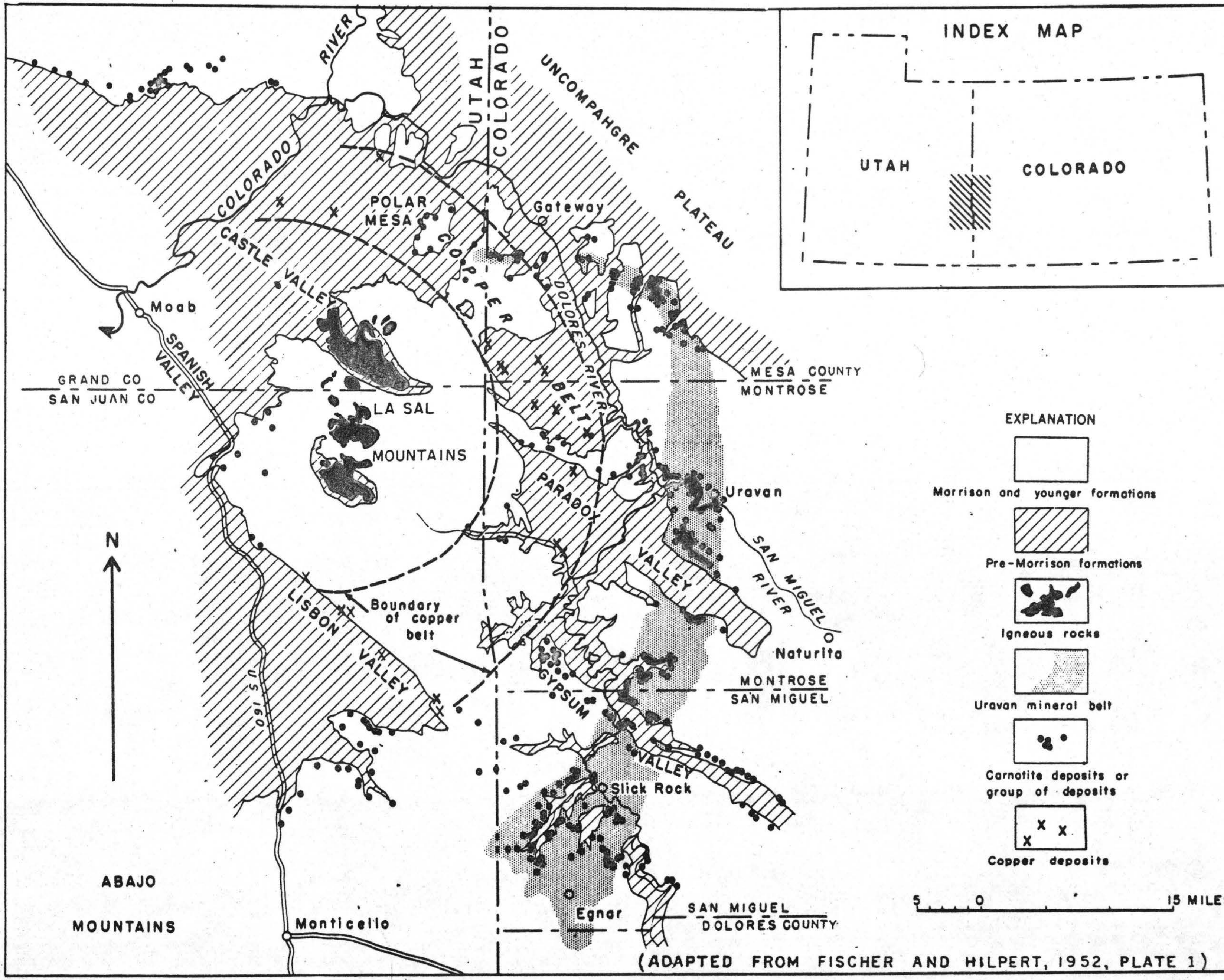

Figure 9.--MAP OF PART OF COLORADO AND UTAH SHOWING THE DISTRIBUTION OF COPPER DEPOSITS AND DISTRIBUTION OF URANIUM DEPOSITS IN THE MORRISON FORMATION.

Table 4.--Fluorimetric and semiquantitative spectrographic analyses of selected vein and fault-controlled copper deposits in the Wingate sandstone of Triassic age near the Uravan mineral belt, Colorado (in percent).

Element	Cliff Dweller mine 1/	Copper Rivet mine 1/	Pyramid group 2/	Average uranium ore from the Salt Wash member of the Morrison formation
U	<0.001 3/	0.004 3/	0.007 3/	0.X
V	<0.001	<0.001	0.00X	X.0
Co	0.000X	<0.0005	0.0X	0.00X
Ni	0.000X	0.000X	0.00X	0.00X
As	<0.1	X.	X.	0.0X
Pb	0.0X	0.0X	0.0X	0.00X
Cu	X.	XX.	XX.	0.00X
Mo	0.0X	0.0X	0.0X	0.00X

1/ Spectrographic analysis by P. J. Dunton, U. S. Geological Survey.

2/ Spectrographic analysis by R. G. Havens, U. S. Geological Survey.

3/ Fluorimetric analysis by R. DuFour, J. Wahlberg, J. Meadows, and W. Montjoy, U. S. Geological Survey.

In the vein copper deposits, most of which are localized in the massive Wingate sandstone of Triassic age, there seems to be a distinct tendency for the ore to occur near the base of the sandstone just above fine-grained sandstones and mudstones of the underlying Chinle formation. This relation suggests that the mineralizing solutions rose along the faults cutting the Chinle and deposited the ore where they first came in contact with the openly fractured

Wingate sandstone, which is the preferred host of the vein copper deposits. As shown by the composition of the vein deposits (table 4) these solutions evidently carried most of the elements that make up the extrinsic part of the sandstone-type uranium deposits, including uranium.

Most of the copper deposits are in beds of Triassic or older age, whereas most of the uranium deposits in the Uravan mineral belt are in the uppermost sandstone stratum of the Salt Wash member of the Morrison formation of Jurassic age. In the area between the zone of copper deposits and the Uravan mineral belt there are a number of sandstone-type uranium deposits containing significant amounts of copper. Most of these deposits are in the lower sandstones of the Salt Wash. These relations suggest a regional and also a crude vertical overlapping zonation of copper and uranium. If this is not merely a fortuitous arrangement of mineral deposits, it suggests that the mineralizing solutions or copper- and uranium-bearing emanations may have migrated vertically and possibly also eastward in the vicinity of the Uravan mineral belt, depositing most of the copper first and most of the uranium later.

A further point of evidence on the upward migration of solutions is provided by the distribution of gypsum in sandstones in the Salt Wash in eastern Paradox Valley within the Uravan mineral belt. Near the center of eastern Paradox Valley, the Salt Wash rests with sedimentary contact on the intrusive evaporite core of the Paradox Valley salt anticline. The upper part of the salt intrusion is capped by a thick mass of gypsum. The sandstones of the Salt Wash, where the Salt Wash rests directly on the gypsum cap, contain abundant gypsum in the form of veinlets and as an interstitial cement. Away from the salt core, the gypsum content of the sandstones decreases rapidly (Donald P. Elston and Theodore Botinelly, written communication). Two elements, bismuth and indium, which are closely associated with the gypsum, have been detected in sandstones of the Salt Wash in and on the edge of Paradox Valley, but these two elements have not been detected in any of our other samples of sandstone from the Colorado Plateau. The inference seems good that the source of the gypsum and the two elements, bismuth and indium, is the underlying salt intrusion and that the gypsum has been transported into the sandstone by upward migrating solutions.

POSSIBLE HYPOGENE SOURCES OF EXTRINSIC CONSTITUENTS

Among the possible hypogene sources of the extrinsic constituents of the uranium ores, the one that is suggested by the regional distribution of the elements in the uranium deposits is the series of salt, gypsum, petroliferous shale, and sandstone beds of the Paradox member of the Hermosa formation of Pennsylvanian age forming the cores of the salt anticlines. Copper, lead, silver, and zinc each tend to be high in the uranium ores in an area that is partially coincident with the region of the salt structures. The significance of this relation is not known, but the occurrence of copper, lead, and zinc sulfides, as well as iron and manganese sulfides and several arsenic minerals in the cap rock of some Texas and Louisiana salt domes (Hanna and Wolf, 1934; Barnes, 1933), supports the belief that some of each of these elements in the sandstone-type uranium deposits could have been derived from the evaporites of Pennsylvanian age or from rocks interbedded with the evaporites. Study of gamma-ray logs of about a dozen deep holes drilled in the intrusive cores of the salt anticlines reveals that the salt has uniformly very low radioactivity, except where potash salts are present, but the beds interstratified with the salt, chiefly black carbonaceous or petroliferous shales, commonly show more-than-normal radioactivity. Away from the intrusive masses the black shales can be correlated over wide areas by radioactivity logs (Wengerd and Strickland, 1954, p. 2186). Uranium concentrated in the black shales may very likely be the principal parent of helium in gas produced from the Hermosa formation in southeastern Utah (Anderson and Hinson, 1951, p. 120-121).

The possibility that part of the uranium and some of the other extrinsic elements in the uranium ores may have come from petroliferous shale interbedded with the evaporites is further substantiated by the studies of Erickson, Myers, and Horr (1954), who found that the suite of elements contained in detectable quantities in crude oils and asphalts from various parts of the United States includes nearly all the extrinsic constituents detectable spectrographically in the sandstone-type uranium deposits of the Colorado Plateau. Hydrocarbons that have been found in both large and small quantities in some of the uranium deposits (Hess, 1922; Kerr and Kelly, 1956) may very likely have been derived in part from petroliferous shale beds in the Pennsylvanian system. If the ore-forming solutions came in part from below the ore-bearing formations it seems highly probable that at least a very small part of the extrinsic elements in the uranium deposits that contain hydrocarbons was introduced from the same source as the hydrocarbons. The Pennsylvanian system, on the other hand, can hardly be recommended as a source of elements in the southwestern part of the Colorado Plateau where evaporites and petroliferous beds are not present in the Pennsylvanian system or rocks of Pennsylvanian age are entirely missing.

Possible sources of uranium below the Pennsylvanian Hermosa formation are also suggested by the distribution of helium-bearing gases on the Colorado Plateau (fig. 10). The concentrations of helium in some of the natural gases from the Colorado Plateau are among the highest in the United States (Anderson and Hinson, 1951). Some of the gases high in helium occur in the Morrison and Chinle formations, the principal hosts of the uranium deposits, but others occur at considerable depth in limestone and dolomite limestone beds of Mississippian or Devonian age. Pronounced gamma-ray anomalies have also been observed on well logs of this stratigraphic interval, one estimated for the writers by Carl M. Bunker of the Geological Survey to represent approximately 0.01 percent equivalent uranium. These might be syngenetic occurrences of uranium or epigenetic deposits of uranium or other radioactive elements.

Several broad lines of evidence suggest a possible genetic relationship between the sandstone-type uranium deposits and the laccolithic intrusions of the central part of the Colorado Plateau.

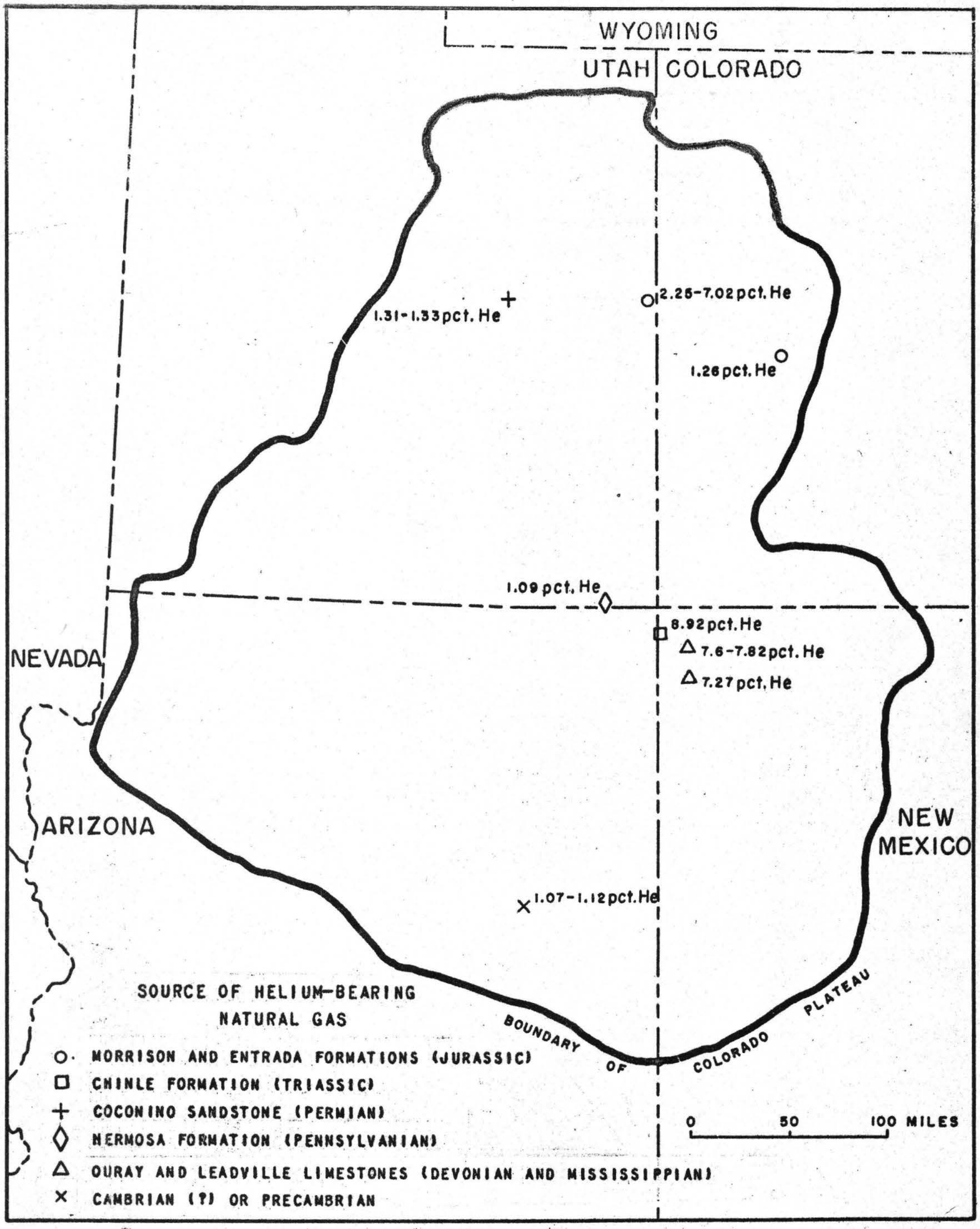

FIGURE 10.--MAP OF THE COLORADO PLATEAU SHOWING LOCALITIES FROM WHICH NATURAL GAS CONTAINING MORE THAN 1 PERCENT HELIUM HAS BEEN OBTAINED.

The laccoliths are in clusters that underlie small isolated mountain groups scattered through the same region in which most of the productive uranium deposits are found (figs. 5, 6, and 7). The age of the laccoliths is not well established, but some evidence based on the occurrence of coarse igneous detritus in beds of latest Cretaceous age on the east side of the Colorado Plateau suggests that some of the laccoliths of the central Colorado Plateau are of latest Cretaceous age (Eckel, 1949, p. 42,; Shoemaker, 1954, p. 63; Kelley, 1955, p. 56). At least some igneous activity on the east side of the Colorado Plateau in latest Cretaceous time is indicated, and the lead-uranium age determinations of the sandstone-type uranium ores indicate a comparable age for most of the uranium deposits. There is a broad spatial association of the uranium deposits with the laccoliths and a possible correspondence in age. The close association between igneous intrusions and uranium deposits in the Front Range of Colorado (Phair, 1952; Sims and Tooker, 1956), with which some of the Colorado Plateau uranium deposits are approximately contemporaneous (Stieff and Stern, 1952, p. 708), lends some weight to the suggestion of a genetic relation between the uranium deposits and igneous activity on the Colorado Plateau. Some auriferous vein deposits in the laccolithic complex of the La Plata Mountains in southwestern Colorado contain noteworthy amounts of vanadium (Eckel, 1949, p. 61), and some are radioactive.

Geochemical studies in the Ute Mountains of southwestern Colorado conducted in connection with our distribution-of-elements investigation have shown that the suite of minor elements transported during deuteric and later alteration of the igneous rocks includes nearly all the extrinsic elements found in small uranium deposits along faults adjacent to the mountains. Solutions probably connected with igneous activity in the laccolithic mountains are, therefore, potential sources of some of the extrinsic elements of the uranium deposits.

The distribution of copper and uranium deposits on the east side of the La Sal Mountains of Utah (fig. 9) can be interpreted to indicate that the apparent rough zonal relation is focused around the La Sal igneous center. Copper deposits and pyritic veins, some carrying a small amount of gold, occur in parts of the La Sal igneous complex. A few of these deposits contain a small amount of introduced uranium. Similar zonal relations have not been found around the other laccolithic mountains, with the possible exception of the Ute Mountains, however, and neither the general distribution of uranium deposits nor the distribution of extrinsic elements in the uranium deposits can at the present time be shown to be definitely related to the distribution of the laccolithic intrusions.

Despite the broad association between the uranium deposits and the laccolithic intrusions, the sum of evidence does not seem to indicate any direct relation between the most of the sandstone-type uranium deposits and the exposed laccolithic rocks. Judging from the estimates given by Hunt (1954, p. 144) for the Henry Mountains, the total volume of igneous material that can be inferred to be intruded in each laccolithic mountain group is only a few tens of cubic miles at the most. The sedimentary rocks enclosing the laccoliths only rarely are visibly metamorphosed more than a few inches from the igneous contacts, which suggests that no great amount of solution was given off from the intrusions. Had the mineralizing solutions been derived from the known intrusions, the solutions, in order to reach the sites of many of the deposits, would have had to travel tens of miles along the beds across whatever regional structures may have been formed at the time of mineralization. If the uranium deposits are related to the magmas that formed the laccoliths, they are probably more directly related to some broad and perhaps deeply buried reservoir or reservoirs of which the laccoliths are only relatively small offshoots. It is also possible that the laccoliths merely influenced the pressure and temperature of solutions already present in the sedimentary rocks (Donald G. Wyant, written communication, 1953).

Probably the most suggestive evidence on the source of any single element is afforded by the studies of Stieff and Stern (1954; 1956) on the isotopic composition of galena and other lead-mineral leads from the Colorado Plateau. These studies indicate that the sandstone-type uranium deposits contain at least two generations of radiogenic lead: original (or old) radiogenic lead deposited with the uranium, and radiogenic lead formed after deposition by the decay of the uranium. The original radiogenic lead formed in an environment with an unusually high abundance of uranium; it has an estimated age of about 800 million years, which places its ultimate source in Precambrian rocks (L. R. Stieff and T. W. Stern, written communication). Because some lead minerals have been found to contain a high proportion of this old radiogenic lead (L. R. Stieff and T. W. Stern, written communication), it seems likely that the old radiogenic lead has been transported directly from its Precambrian source to the site of the sandstone-type uranium deposits without going through any intermediate steps, such as a sedimentary cycle, in which a large proportion of common lead would tend to be mixed either mechanically or chemically with the old radiogenic lead. In addition, leads extracted from galena from vein deposits in Tertiary volcanic rocks in the San Juan Mountains, just east of the Colorado Plateau (fig. 1), contain a small but significant amount of apparently the same old radiogenic lead. An immediate source in Precambrian rocks of the old radiogenic lead and presumably at least part of the uranium with which it is associated in the sandstone-type uranium deposits thus seems to be indicated. This evidence does not necessarily indicate anything about the source of the remainder of the lead (common lead), which constitutes the major part of the lead in most of the sandstone-type uranium deposits, or of the other extrinsic elements; but, if the conclusions of Stieff and Stern are correct, part of some of the other extrinsic elements may possibly have had the same source as the old radiogenic lead and the uranium from which it probably was derived.

SUMMARY AND CONCLUSIONS

By way of summary, the following hypothesis of the origin of most of the sandstone-type uranium deposits on the Colorado Plateau is proposed. Heated solutions, either derived from a magma reservoir or reservoirs present under the Colorado Plateau in latest Cretaceous time or driven off from solid rocks during a regional increase in the thermal gradient associated with magmatic activity, rose through the crust along many separate channelways. These solutions probably reacted chemically and thermally with the rocks through which they passed, exchanging elements and cooling as they migrated toward the surface. On reaching the permeable beds in the sedimentary layer of Paleozoic and Mesozoic age that covers most of the Colorado Plateau, the solutions spread widely and probably mingled with fluids already present in the sedimentary layer. Some materials of hypogene origin may even have reached the surface and been discharged.

If this picture is in the main or in part correct, in particular, if the mineralizing solutions crossed formational boundaries, the various metals in the extrinsic part of sandstone-type uranium ores probably have diverse sources, and some, if not most, of the individual metals probably have multiple sources. Uranium, for example, has probably been derived mainly from the Precambrian basement, and a small fraction may have been derived from rocks of Pennsylvanian age. Copper may have been derived partly from magmatic or Precambrian sources, partly from salt intrusions, and partly from the sandstones that enclose the uranium deposits. Vanadium could perhaps be an element that was derived mainly from the sandstones enclosing the uranium deposits. Part of the selenium in the uranium deposits in the Morrison formation may have come from seleniferous bentonites adjacent to the ore-bearing sandstone beds or from volcanic detritus in the ore-bearing sandstones themselves.

Finally, it should be emphasized that all the uranium deposits on the Colorado Plateau are almost certainly not of the same origin. Some uranium deposits, such as at Marysvale, Utah (Walker and Osterwald, 1956), and in the Hopi Buttes of Arizona (Shoemaker, 1956B), are directly related to igneous rocks. Some deposits in sandstone beds of Tertiary age (Grutt and Whalen, 1955, p. 127-128), and in coals of Cretaceous age (Vine, 1956) may well have been derived by the leaching of uranium from tuffaceous sediments. And some uranium deposits, such as the radioactive titaniferous sandstones, are truly syngenetic.

LITERATURE CITED

Adams, J. A. S., 1954, Uranium and thorium contents of volcanic rocks, in Faul, Henry, ed. Nuclear Geology: P. 89-98, New York, John Wiley and Sons, Inc.

Allen, J. E., 1956, Titaniferous Cretaceous beach placer in McKinley County, New Mexico (abstract): Geol. Soc. America, Rocky Mountain section official program, p. 9.

Anderson, C. C., and Hinson, H. H., 1951, Helium-bearing natural gases of the United States--analyses and analytical methods: U. S. Bur. Mines Bull. 486, 141 p.

Barnes, V. E., 1933, Metallic minerals in anhydrite cap rock, Winnfield salt dome, Louisiana: Am. Mineralogist, v. 18, p. 335-340.

Chenoweth, W. L., 1956, Radioactive titaniferous heavy-mineral deposits in the San Juan basin, New Mexico and Colorado (abstract): Geol. Soc. America, Rocky Mountain section official program, p. 12.

Clarke, F. W., 1924, The data of geochemistry: U. S. Geol. Survey Bull. 770, 841 p.

Cobban, W. A., and Reeside, J. B., Jr., 1952, Correlation of the Cretaceous formations of the western interior of the United States: Geol. Soc. America Bull., v. 63, p. 1011-1043.

Coffin, R. C., 1921, Radium, uranium, and vanadium deposits of southwestern Colorado: Colo. Geol. Survey Bull. 16, 231 p.

Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L., Mullens, T. E., and Weir, G. W., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U. S. Geol. Survey Bull. 1009-E, p. 125-168.

Denson, N. M., and Gill, J. R., 1956, Uranium-bearing lignite and its relation to volcanic tuffs in eastern Montana and North and South Dakota: U. S. Geol. Survey Prof. Paper 300, p. 413-418.

Eckel, E. C., with sections by J. S. Williams, F. W. Galbraith, and others, 1949, Geology and ore deposits of the La Plata district, Colorado: U. S. Geol. Survey Prof. Paper 219, 179 p.

Erickson, R. L., Myers, A. T., and Horr, C. A., 1954, Association of uranium and other metals with crude oil, asphalt, and petroliferous rock: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 2200-2218.

Fenneman, N. M., 1931, Physiography of western United States: 534 p. New York, McGraw-Hill Book Co., Inc.

Finch, W. I., 1955, Preliminary geologic map showing the distribution of uranium deposits and principal ore-bearing formations of the Colorado Plateau region: U. S. Geol. Survey Min. Inv. Field Studies Map MF 16.

Fischer, R. P., 1936, Peculiar hydrothermal copper-bearing veins of the northeastern Colorado Plateau: Econ. Geology, v. 31, p. 571-599.

____________1937, Sedimentary deposits of copper, vanadium-uranium, and silver in southwestern United States: Econ. Geology, v. 32, p. 906-951.

Fischer, R. P., and Hilpert, L. S., 1952, Geology of the Uravan mineral belt: U. S. Geol. Survey Bull. 988-A, p. 1-13.

Gruner, J. W., 1954, The origin of the uranium deposits of the Colorado Plateau and adjacent regions: Mines Mag. (Denver), v. 44, p. 53-56.

Grutt, E. W., Jr., and Whalen, J. F., 1955, Uranium in northern Colorado and southern Wyoming, in Guidebook to the geology of northwest Colorado: Intermountain Assoc. Petroleum Geologists and Rocky Mountain Assoc. Geologists, p. 126-129.

Hanna, M. A., and Wolf, A. G., 1934, Texas and Louisiana salt-dome cap-rock minerals: Am. Assoc. Petroleum Geologists Bull., v. 18, p. 215-225.

Hess, F. L., 1922, Uranium-bearing asphaltite sediments of Utah: Eng. and Min. Jour. Press, v. 114, p. 272-276.

Hunt, C. B., assisted by Paul Averitt and R. L. Miller, 1954, Geology and geography of the Henry Mountains region, Utah: U. S. Geol. Survey Prof. Paper 228, 234 p.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. New Mexico Pub. in Geology, no. 5, 120 p.,Albuquerque, N. Mex. Univ. N. Mex. Press.

Kerr, P. F., and Kelly, D. R., 1956, Urano-organic ores of the San Rafael Swell, Utah: Econ. Geology, v. 51, p. 386-391. [Discussion]

Keys, W. S., and White, R. L., 1956, Investigation of the Temple Mountain collapse and associated features, San Rafael Swell, Emery County, Utah: U. S. Geol. Survey Prof. Paper 300, p. 285-298.

Koeberlin, F. R., 1938, Sedimentary copper, vanadium-uranium, and silver in southwestern United States: Econ. Geology, v. 33, p. 458-461. (Discussion of paper by R. P. Fischer, 1937, same journal, v. 32, p. 906-951.)

Larsen, E. S., Jr., Phair, George, Gottfried, David, and Smith, W. L., 1956, Uranium in magmatic differentiation: U. S. Geol. Survey Prof. Paper 300, p. 65-74.

Lindgren, Waldemar, 1911, Copper, silver, lead, vanadium, and uranium ores in sandstone and shale: Econ. Geology, v. 6, p. 568-581.

Love, J. D., 1952, Preliminary report on uranium deposits in the Pumpkin Buttes area, Powder River basin, Wyoming: U. S. Geol. Survey Circ. 176, 37 p.

McKee, E. D., 1951, Sedimentary basins of Arizona and adjoining areas: Geol. Soc. America Bull., v. 62, p. 451-506.

McKelvey, V. E., Everhart, D. L., and Garrels, R. M., 1955, Origin of uranium deposits: Soc. Econ. Geologists, 50th Anniversary volume, 1905-1955, Part I, p. 464-533.

McKelvey, V. E., Swanson, R. W., and Sheldon, R. P., 1953, The Permian phosphorite deposits of western United States: 19th Internat. Geol. Cong. Comptes Rendus, v. 11, p. 45-64.

Murphy, J. F., and Houston, R. S., 1955, Titanium-bearing black sand deposits of Wyoming: Wyoming Geol. Assoc., 10th Ann. Field Conference Guidebook, p. 190-196.

Nockolds, S. R., and Allen, R., 1953, The geochemistry of some igneous rock series: Geochim. et Cosmochim. Acta, v. 4, no. 3, p. 105-142.

__________ 1954, The geochemistry of some igneous rock series, pt. 2: Geochim. et Cosmochim. Acta, v. 5, no. 6, p. 245-285.

Page, L. R., Stocking, H. E., and Smith, H. B., (Compilers), 1956, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955: U. S. Geol. Survey Prof. Paper 300, 739 p., U. S. Government Printing Office, Washington, D. C.

Phair, George, 1952, Radioactive Tertiary porphyries in the Central City district, Colorado, and their bearing upon pitchblende deposition: U. S. Geol. Survey TEI-247, 53 p. issued by U. S. Atomic Energy Comm., Tech. Inf. Service Extension, Oak Ridge.

Proctor, P. D., 1953, Geology of the Silver Reef (Harrisburg) mining district, Washington County, Utah: Utah Geol. and Mineralog. Survey Bull. 44, 169 p.

Rankama, Kalervo, and Sahama, Th. G., 1950, Geochemistry: 912 p., Chicago, Univ. of Chicago Press.

Shawe, D. R., 1956, Significance of roll ore bodies in genesis of uranium-vanadium deposits on the Colorado Plateau: U. S. Geol. Survey Prof. Paper 300, p. 239-241.

Shoemaker, E. M., 1954, Structural features of southeastern Utah and adjacent parts of Colorado, New Mexico, and Arizona: Utah Geol. Soc., Guidebook to the geology of Utah, no. 9, p. 48-69.

__________1956a, Geology of the Roc Creek quadrangle, Colorado: U. S. Geol. Survey Geol. Quadrangle Map 83.

__________1956b, Occurrence of uranium in diatremes on the Navajo and Hopi Reservations, Arizona, New Mexico, and Utah: U. S. Geol. Survey Prof. Paper 300, p. 179-185.

__________1956c, Structural features of the central Colorado Plateau and their relation to uranium deposits: U. S. Geol. Survey Prof. Paper 300, p. 155-170.

Sims, P. K., and Tooker, E. W., 1956, Pitchblende deposits in the Central City district and adjoining areas, Gilpin and Clear Creek Counties, Colorado: U. S. Geol. Survey Prof. Paper 300, p. 105-111.

Stieff, L. R., and Stern, T. W., 1952, Identification and lead-uranium ages of massive uraninites from the Shinarump conglomerate, Utah: Science, v. 115, p. 706-708.

__________1954, Original radiogenic lead, an additional correction for lead-uranium and lead-lead age calculations (abs.): Geol. Soc. America Bull., v. 65, p. 1308.

__________1956, Interpretation of the discordant age sequence of uranium ores: U. S. Geol. Survey Prof. Paper 300, p. 549-555.

Stieff, L. R., Stern, T. W., and Milkey, R. G., 1953, A preliminary determination of the age of some uranium ores of the Colorado Plateau by the lead-uranium method: U. S. Geol. Survey Circ. 271, 19 p.

Tourtelot, H. A., 1956, Radioactivity and uranium content of some Cretaceous shales, central Great Plains: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 62-82.

Trelease, S. F., and Beath, O. A., 1949, Selenium; its geological occurrence and its biological effects in relation to botany, chemistry, agriculture, nutrition, and medicine: 292 p., Burlington, Vt., The Champlain Printers.

Vine, J. D., 1956, Uranium-bearing coal in the United States: U. S. Geol. Survey Prof. Paper 300, p. 405-411.

Walker, G. W., and Osterwald, F. W., 1956, Relation of secondary uranium minerals to pitchblende-bearing veins at Marysvale, Piute County, Utah: U. S. Geol. Survey Prof. Paper 300, p. 123-129.

Waters, A. C., and Granger, H. C., 1953, Volcanic debris in uraniferous sandstones, and its possible bearing on the origin and precipitation of uranium: U. S. Geol. Survey Circ. 224, 26 p.

Wengerd, S. A., and Strickland, J. W., 1954, Pennsylvanian stratigraphy of Paradox Salt Basin, Four Corners region, Colorado and Utah: Am Assoc. Petroleum Geologists Bull., 38, p. 2157-2199.