

# Geochemical Distribution of Some Metals in the Moenkopi Formation and Related Strata, Colorado Plateau Region

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By ROBERT A. CADIGAN

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*A study of the concentrations of metals, their  
covariance, and geochemical associations  
in members and sedimentary rock facies  
of the Moenkopi Formation and  
related lithologic units*



UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

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Library of Congress catalog-card No. 74-179646

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For sale by the Superintendent of Documents, U.S. Government Printing Office  
Washington, D.C. 20402 - Price 35 cents (paper cover)  
Stock Number 2401-1197

## CONTENTS

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	Page
Abstract .....	1
Introduction .....	2
Purpose and scope of investigation.....	2
Geographic and geologic setting.....	3
Previous work .....	4
Acknowledgments .....	4
Stratigraphy .....	4
Petrology .....	9
Observations .....	9
Interpretations .....	10
Geochemical studies .....	12
Sampling and analytical methods .....	12
Elements studied .....	16
Statistical analysis .....	16
Stratigraphic comparisons .....	18
Facies comparisons .....	28
Geochemical association of the metals.....	30
Textural and compositional comparisons.....	36
Locality comparisons .....	43
Gold .....	48
Summary and conclusions .....	50
References cited .....	55

## ILLUSTRATIONS

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	Page
FIGURE 1. Map showing location of Colorado Plateau region.....	3
2. East-west cross section across the Colorado Plateau region, illustrating typical facies and member relationships in the Moenkopi Formation .....	8
3-5. Probability graphs of the log distributions of:	
3. Ca, Fe, Mg, Ti, Ba, and Mn.....	19
4. Sr, Zr, V, Cr, Cu, and Cu(A).....	20
5. Y, Pb, Ni, Co, Ag(A), and Hg(A).....	21
6. Probability graph of the highly truncated log distributions of Be and Au(A) .....	22
7-9. Graphs showing:	
7. Mean abundance of 20 metals in the Moenkopi For- mation .....	23
8. Comparison of metal content of some members with average metal content of the entire formation.....	25
9. Comparison of metal content of rocks from different facies with average metal content of the entire formation .....	29

	Page
FIGURE 10. Diagrammatic illustration of significant positive associations of metals in the Moenkopi Formation.....	35
11. Graph showing comparison of metal content of groups of samples having different textures with average metal content of the entire formation.....	38
12. Graph showing comparison of metal content of four metal-enriched mudstones with average metal content of six siltstones .....	44
13. Map showing sample localities having the largest average number of high metal values per sample.....	49

## TABLES

	Page
TABLE 1. Generalized chart showing nomenclature of the Moenkopi Formation and lithologically related strata in different parts of the Colorado Plateau region.....	5
2. The locations, names, and lithologic characteristics of the members of the Moenkopi Formation and of lithologically related formations .....	6
3. Summary of higher-than-average amounts of rock components contributed to the Moenkopi Formation by the four general source areas, and the interpreted source terranes in order of influence on the derived sediments.....	12
4. Index of sample localities, number of samples, and units sampled in the Moenkopi Formation and lithologically related strata .....	13
5. Metals looked for, lower detection limits, and percent of samples for which numerical values were obtained.....	17
6. Selected measures of central tendency and dispersion computed for the log distributions of the 20 metals used in the Moenkopi study .....	22
7. Sensings of comparisons of metal values in the different groups of samples with the formation geometric means as illustrated in figures 8 and 9.....	30
8. Nonparametric association coefficients measuring relative correlation between each possible pair of metals.....	32
9. Metal content of randomly selected samples of very coarse, coarse, medium, fine, and very fine grained sandstones from the Moenkopi Formation .....	37
10. Metal content of randomly selected samples of siltstones, claystones, and calcareous siltstones, limestones, and dolomites from the Moenkopi Formation .....	41
11. Metal content of Moenkopi Formation mudstone samples collected from rocks underlying uranium deposits in the Chinle Formation .....	43
12. Distribution by locality of the 32 highest values for each of the 20 metals used in the present study, and additional valid values available for La, Mo, Nb, Sn, and Zn.....	45
13. Localities that contain the 16 highest values per sample, and 16 highest secondary metals ratios .....	48

# GEOCHEMICAL DISTRIBUTION OF SOME METALS IN THE MOENKOPI FORMATION AND RELATED STRATA, COLORADO PLATEAU REGION

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By ROBERT A. CADIGAN

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## ABSTRACT

Major factors that affect the metal content of rocks constituting the Triassic(?) and Lower and Middle(?) Triassic Moenkopi Formation and lithologically related Permian and Triassic strata in the Colorado Plateau region are sediment source, texture, and nearness to channels of movement of mineralizing solutions. Significant positive and negative coefficients of association show that the primary relationship that controls the abundance of the different groups of metals is the proportion of marine source components and interstitial calcareous cement to detritus from terrestrial source areas.

The Moenkopi is a typical red-bed formation and forms the basal unit of the Triassic. It is unconformable with underlying Permian formations and with the overlying Chinle Formation. A geochemical study of the occurrences of Ca, Fe, Mg, Ti, Ba, Mn, Sr, Zr, V, Cr, Cu, Y, Pb, Ni, Ag, Hg, Au, and Be in the Moenkopi suggests that average metal content varies significantly among its stratigraphic members. Ti, V, Cr, Y, Ni, and Au vary in amount inversely with grain size; Ba varies in amount directly with grain size. Rocks from marine or marginal marine environments are very high in Ca, Sr, and Mg, and very low in Ba, Zr, Ti, V, Ni, Fe, Cr, Mn, and Co. Published reports of metal content of siltstone and sandstone formations in general indicate that, in comparison, the Moenkopi is deficient in average content of most metals but is richer in Cr, Co, and Au.

The metals Fe, V, Cu, Co, Ti, Cr, Y, and Ni have a highly significant degree of positive mutual association; Mg, Sr, Pb, Hg, and Ca do not have significant positive associations with specific metals. The highly significant negative associations are Ca with Ba, Ti, Cr, and Ni; Ag with Ba, Zr, and Pb; Hg with Y, Pb, and Ni; and Sr with Zr.

In the Moenkopi Formation, metals that occur chiefly with the heavy mineral fraction of detritus from terrestrial sources are Fe, Ti, Mn, Zr, V, Cr, Cu, Y, Ni, Au, and Be. Metals that occur chiefly in marine carbonate rocks and siltstones and marginal marine evaporites are Ca and Hg. Metals that occur in different modes and in significant proportions in both marine and terrestrial sediments are Mg, Sr, and Pb. Ba occurs almost exclusively in terrestrial sedimentary rocks in an interstitial cement, barite, which competes with and apparently replaces the Ca-bearing cement, calcite.

Gold was detected in one-third of the samples studied. Highest average gold content (0.09 parts per million) is in the enriched mudstones at the top of the formation. Highest proportions of samples that contain detectable gold occur in the north-central and northeastern parts of the Colorado Plateau region. Lowest proportions are in the salt anticline area of southeastern Utah and southwestern Colorado.

Mudstones at the Chinle-Moenkopi contact are, in many localities, highly enriched in Cu, Y, Be, Sr, Ni, Co, V, Ti, Fe, Pb, and Au. The enriched mudstones commonly occur below known uranium ore deposits in the Chinle Formation, suggesting that in areas of unknown uranium ore potential, Moenkopi mudstones at the upper contact may prove useful in geochemical prospecting.

Sixteen areas of anomalously high metal values were delineated on the basis of the average number of high (upper 10 percent) metal values per sample. These areas are recommended for further study or exploration.

## INTRODUCTION

Metal content varies within the Triassic Moenkopi Formation and related strata in the Colorado Plateau region in response to many factors. These factors are sedimentary texture, original mineral composition including both detritus and cements, sources of sediment, nearness to zones of introduced minerals, diagenesis, and tectonic and geographic environments of erosion, transportation, and deposition. The Moenkopi, a typical red-bed formation whose common facies is a relatively well sorted coarse siltstone interbedded with very fine grained sandstone, is unique in the sense that it is composed of strata whose environments of deposition ranged from continental alluvial to marine (including that of evaporites) and it contains more than average trace amounts of gold.

## PURPOSE AND SCOPE OF INVESTIGATION

The investigation is part of a study of the distribution of trace metals in sedimentary rock formations of the Colorado Plateau. Background values for 20 metals (counting spectrographic and atomic-absorption Cu determinations as two different metals) were determined for the Moenkopi as a whole, for individual members of the formation, for lithologically related Permian and Triassic strata, for certain textural and compositional rock types, and for rocks close to known stratified sandstone uranium ore deposits. Metal geochemical associations were assigned on the basis of statistically significant covariation, and geologic interpretations of the covariation were made in terms of source and mode of occurrence. Areas of anomalously high metal values were delineated and recommended for further study or exploration.

**GEOGRAPHIC AND GEOLOGIC SETTING**

The Colorado Plateau region comprises western Colorado, the northwest quarter of New Mexico, and most of the east half of Utah and north half of Arizona (fig. 1).



FIGURE 1.—Location of Colorado Plateau region (shaded).

Rocks exposed in the Colorado Plateau region range in age from Precambrian to Holocene. Newman (1962, figs. 42–68) showed isopach and outcrop maps of many stratigraphic units ranging in age from the Precambrian through the Tertiary. Rocks of

Mesozoic age, the most widely exposed rocks in the Plateau region, are dominantly terrestrial quartzitic-feldspathic-tuffaceous clastic rocks interlayered with minor marginal marine and marine rocks. In four-fifths of the region, the sedimentary beds are flat lying or gently warped. The dominant structures are salt-cored anticlines, sharp monoclinal folds, and structures formed by laccoliths, volcanic flows, and plugs.

The arid climate and resulting lack of vegetation yield excellent rock exposures in the steep-walled canyons or wide valleys of the major streams and in the slopes of the valleys, washes, canyons, and arroyos of the minor and intermittent streams.

#### PREVIOUS WORK

The distribution of elements in Colorado Plateau rocks was studied by Shoemaker, Miesch, Newman, and Riley (1959) with special emphasis on the contained uranium deposits. That study resulted from the intense economic and academic interest in uranium occurrences during the 1950's and the ready availability of much geochemical data. Additional results were reported by Newman (1962) and Miesch (1963) and geochemical relationships of copper, vanadium, and uranium in uranium deposits and their host rocks were summarized by Fischer and Stewart (1961).

#### ACKNOWLEDGMENTS

Most of the rock samples used in the investigation were collected by J. H. Stewart, F. G. Poole, and me. Additional samples were supplied by W. L. Newman, E. M. Shoemaker, and others.

"Wet" analyses for gold, silver, copper, and mercury were done under the supervision of G. H. VanSickle. Silver and copper analyses were done by A. J. Toevs and Lucy Dickson. Mercury analyses were done by W. W. Janes. Six-step spectrographic analyses for 32 metals were done by J. L. Finley. Mrs. Laurette Bates assisted with data cards, tables, and illustrations.

#### STRATIGRAPHY

In the Colorado Plateau region the Moenkopi Formation of Triassic(?) and Early and Middle(?) Triassic age is the basal Triassic formation. It overlies unconformably several Permian formations and is overlain unconformably by the Chinle Formation of Late Triassic age. The nomenclature and regional relationships of the Moenkopi are summarized in table 1. Detailed stratigraphic relations of the Moenkopi Formation have been reported by Stewart, Poole, and Wilson (1971).

TABLE 1.—Generalized chart showing nomenclature of the Moenkopi Formation and lithologically related strata in different parts of the Colorado Plateau region

	Northern Arizona, eastern Arizona, southern Utah, western Utah	San Rafael Swell, <sup>1</sup> east-central Utah	Northern Utah to northwestern Colorado		Southwestern Colorado, southeastern Utah	Western New Mexico
Triassic	Chinle Formation	Chinle Formation	Chinle Formation		Chinle Formation	Chinle Formation
	Moenkopi Formation	Moenkopi Formation	Mahogany, Thaynes, and Woodside Formations	Moenkopi Formation  State Bridge Forma- tion	Moenkopi Formation	Moenkopi Formation
Permian	( <sup>2</sup> )	( <sup>2</sup> )			( <sup>2</sup> )	( <sup>2</sup> )
	Kaibab Limestone	Coconino Sandstone	Park City Formation	Weber Sand- stone	Cutler Formation	San Andres Limestone

<sup>1</sup> Use of Coconino in San Rafael Swell uncertain.<sup>2</sup> No deposition in this area.

The Moenkopi Formation is a typical red-bed unit such as those that characterize upper Paleozoic and lower and middle Mesozoic strata in the Colorado Plateau region. The Moenkopi is exposed in many localities throughout the west two-thirds of the region. It ranges in thickness from at least 2,000 feet on the west border of the region to less than 10 feet in the eastern part, where it is barely recognizable as Moenkopi. The basal Triassic formations, including the Moenkopi, are shown on the isopach map by McKee and others (1959, pl. 9, fig. 1).

The Moenkopi consists of numerous members, none of which extends throughout the entire depositional area of the formation. The names, locations, and lithologic characteristics of the mem-

TABLE 2.—*The locations, names, and lithologic characteristics of the members of the Moenkopi Formation and of lithologically related formations*

Location	Name	Lithologic characteristics
<b>Members of the Moenkopi Formation</b>		
Southwestern Utah, northwestern Arizona, and southeastern Nevada.	Upper red .....	Red siltstone and sandstone.
	Shnabkaib .....	White gypsum, gray limestone (marine), red siltstone, and sandstone.
	Middle red .....	Red siltstone and sandstone.
	Virgin Limestone .....	Gray limestone and siltstone (marine).
	Lower red .....	Red siltstone and sandstone.
	Timpoweap .....	Red siltstone, gray limestone (marine) and light-gray chert pebble conglomerate.
North-central and eastern Arizona.	Holbrook .....	Reddish-brown sandstone and siltstone.
	Moqui .....	Reddish-brown siltstone and sandstone, minor white gypsum.
	Wupatki .....	Reddish-brown siltstone and sandstone, lower "massive" sandstone bed.
Western New Mexico .....	Undifferentiated .....	Red siltstone and sandstone.
Southeastern Utah .....	Cliff-forming .....	Reddish-brown and grayish-red siltstone and sandstone.
	Upper slope-forming .....	Grayish-red and reddish-brown siltstone and sandstone.
	Ledge-forming .....	Red siltstone and sandstone.
	Sinbad Limestone .....	Yellowish-gray limestone (marine).
	Lower slope-forming .....	Grayish-red, yellowish-gray, and light- greenish-gray siltstone and sandstone.
	Hoskinnini .....	Reddish-brown siltstone and sandstone containing fine to coarse sand grains.
Eastern Utah, western Colorado (salt anticline area).	Pariott .....	Red-brown, purplish-brown, orange, and red sandstone, siltstone, and clayey mudstone.
	Sewemup .....	Reddish-brown and grayish-red siltstone and sandstone.
	Ali Baba .....	Red conglomeratic sandstone and red sandstone and siltstone.
	Tenderfoot .....	Reddish-brown siltstone and sandstone, local red arkosic conglomerate, white gypsum.
	Undifferentiated .....	Red siltstone and sandstone.
Northern Utah and Utah- Colorado border area.		
<b>Lithologically related formations</b>		
Northeastern Utah (west Uinta Mountains).	Mahogany .....	Red siltstone and sandstone.
	Thaynes .....	Brownish-gray limestone (marine).
	Woodside .....	Red siltstone and sandstone.
Northwestern Colorado .....	State Bridge:	
	Upper member .....	Red siltstone and sandstone.
	South Canyon Creek Member. <sup>1</sup>	Limestone.
	Lower member <sup>1</sup> .....	Red siltstone and sandstone.

<sup>1</sup> Considered to be of Permian age and therefore older than Moenkopi strata in the Colorado Plateau region. The upper member of the State Bridge Formation is considered to be Triassic and Permian age.

bers are outlined in table 2. Rocks described as siltstone and sandstone, the dominant lithology of the formation, are generally thin-bedded poorly resistant interbedded coarse siltstone and very fine grained sandstone. Formations in northeastern Utah (west Uinta Mountains) and northwestern Colorado that are similar to and considered to be, at least in part, stratigraphically equivalent to the Moenkopi Formation are also shown in table 2. They are certainly the same lithologically.

The sediments may be divided into three general facies: (1) a marginal marine and alluvial red and gray coarse siltstone and very fine to fine-grained sandstone facies, which includes all undifferentiated red beds, all the informal red and gray members, the Moqui, Wupatki, Pariott, Sewemup, and Ali Baba Members of the Moenkopi, the upper and lower members of the State Bridge Formation, and the Mahogany and Woodside Formations; (2) an alluvial relatively coarse sandstone facies, represented by parts of the Tenderfoot, Holbrook, and Hoskinnini Members of the Moenkopi; and (3) a limestone and evaporite facies, composed of the marine Virgin and Sinbad Limestone Members, the marginal marine Timpoweap (limestone and conglomerate) Member, the marine to marginal marine Shnabkaib (gypsum and limestone) Member, the marine South Canyon Creek Member of the State Bridge Formation (limestone), the scattered gypsum beds (mostly in the basal strata) of the Moenkopi, and the marine Thaynes (limestone) Formation.

Typical facies and member relations in the Moenkopi Formation are illustrated in figure 2, which is based on four stratigraphic sections measured and described by Stewart, Poole, and Wilson (1971): the Kanarraville, Capitol Wash, and North Sixshooter Peak sections in Utah, and the Paradox Valley section in Colorado. Marine and marginal marine facies in the form of limestone and gypsum beds are common on the west side of the area of deposition, but these thin and disappear to the east. Coarse chert pebbles probably derived from west-central Arizona form the limestone-cemented conglomerate of the Timpoweap Member in the west.

The siltstone and sandstone facies is dominant and is characterized by an overall reddish-brown color. The strata of this facies are typically flat bedded with some small-scale crossbedding, and they weather to slopes covered with platy fragments. Ripple-marked bedding surfaces are common. Strata associated with gypsum commonly exhibit contorted bedding.

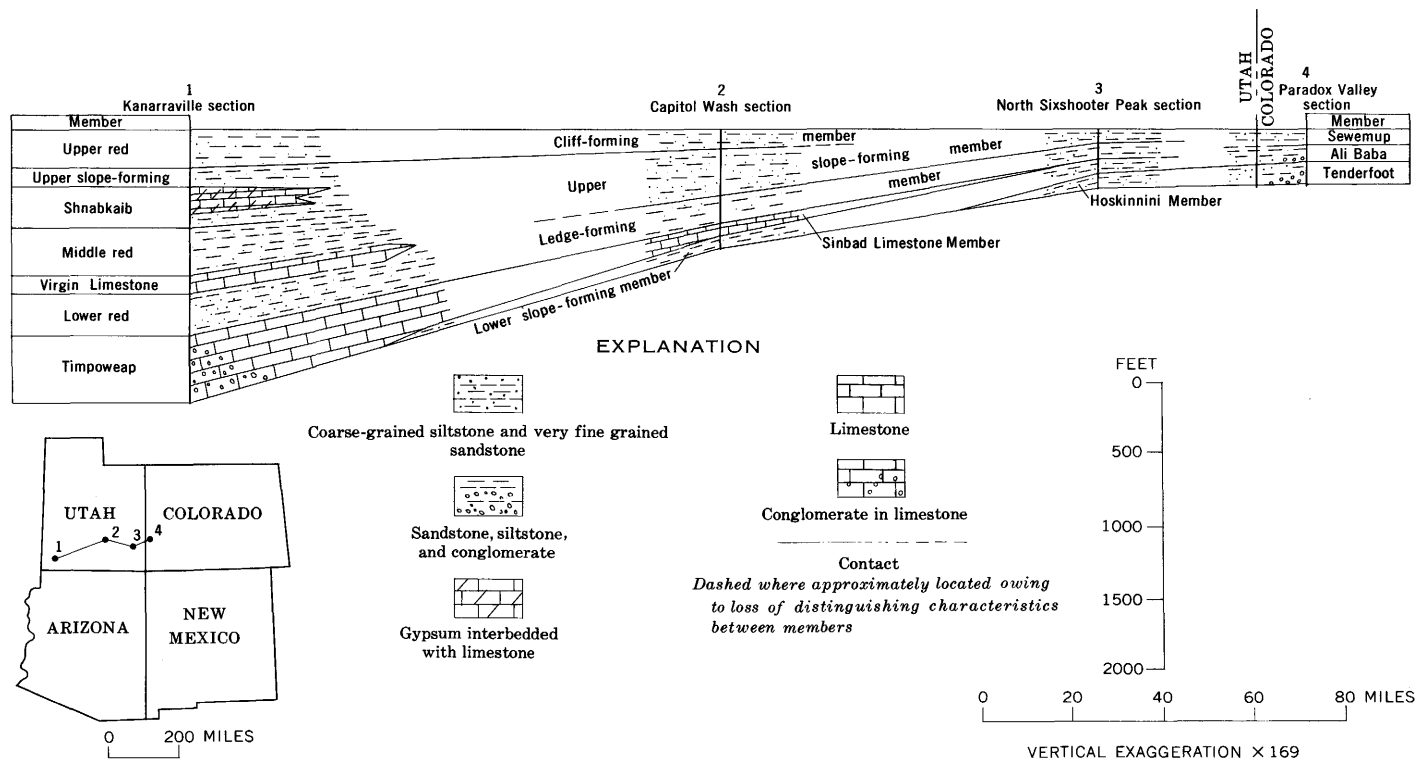


FIGURE 2.—East-west cross section across the Colorado Plateau region, illustrating typical facies and member relationships in the Moenkopi Formation. Data from Stewart, Poole, and Wilson (1971).

## PETROLOGY OBSERVATIONS

The rocks of the Moenkopi and contiguous formations of similar lithology are classified on the basis of present mineral composition as varieties of orthoquartzite, arkose, graywacke, limestone, dolomite, and gypsum. The major detrital components are grains of quartz, chert, chalcedony, albite, oligoclase, orthoclase, and sanidine(?), and fragments of quartzite, probable silicified limestone, granite, altered silicified devitrified tuff, and felsite. The most abundant accessory minerals are flakes of biotite, muscovite, and chlorite, and grains of zircon, tourmaline, garnet, staurolite, rutile, apatite, magnetite, ilmenite, leucoxene, and altered amphibole.

Illite is the dominant clay mineral; kaolinite and chlorite are generally minor, but each is dominant in some strata. Combinations of illite, montmorillonite, and chlorite-illite with mixed-layer montmorillonite also occur. Some of the clay minerals were derived from the source areas, and some were derived by alteration from other detrital minerals. All clay minerals observed were recrystallized during diagenesis.

The major nondetrital mineral components present as cements are calcite, dolomite, gypsum, barite, authigenic quartz as overgrowths on quartz grains, anatase, and authigenic orthoclase as overgrowths on detrital particles of orthoclase. Iron oxides, as finely crystalline alteration products either alone or mixed with clay, also act as cements.

Diagenesis altered the composition of the original sediment. Most affected were feldspars, biotite and other heavy minerals, volcanic ash, tuff, and pumice fragments, and detrital clays. Feldspars show evidence of replacement by carbonates and clay minerals; biotite was altered to chlorite, chloritic clay, and iron oxides; other original detrital mafic minerals, such as pyroxenes, amphiboles, and ilmenite, were mostly altered to metallic oxides and hydrous aluminum silicates (clay minerals); volcanic ash was altered to montmorillonite, much of which in turn was then altered to chloritic and illitic clays; and tuff and pumice fragments were devitrified and then either silicified or altered to clay minerals. Most siliceous orthoquartzite and chloritic graywacke in the Moenkopi are more the products of diagenesis than of tectonic environment. The petrology of the Moenkopi and lithologically related strata is discussed in detail in another report (Cadigan, 1971).

Sandstones of the Moenkopi and related strata are generally very fine grained and moderately sorted with slightly positively

skewed and moderately peaked grain-size distributions.<sup>1</sup> The siltstones are generally coarse grained and are moderately to poorly sorted with slightly positively skewed and moderately peaked grain-size distributions. The claystones are coarse grained and poorly sorted, with negatively skewed and flattened (negatively peaked) grain-size distributions.

Source areas for the Moenkopi and related sediments included the Uncompahgre highland area of southwestern and west-central Colorado (Baker and others, 1933, p. 975) and a continuous positive area that is now the Basin and Range province of southern Arizona and southern New Mexico (McKee and others, 1959, pl. 9, fig. 1). Streams transported sediment from these sources (McKee, 1954) across the northwestward-sloping area of deposition and on toward the marginal marine and marine environments to the west.

Local feldspar-rich sediments suggest the presence of a major source of feldspar in the Uncompahgre highland, and minor sources of feldspar in southeastern Arizona and southwestern New Mexico. The major source of silicified-rock fragments appears to have been in southern New Mexico, with a minor source in southern Arizona. A major source of biotite and chlorite appears to have been the Uncompahgre highland in western Colorado.

#### INTERPRETATIONS

The Moenkopi Formation shows regional variations in composition, grain size, and thickness that are significant both statistically and geologically. Proportions of certain minerals show individual regional gradients with highs near related source areas; measures of grain-size distribution yield regional trends related to direction of sediment movement; and thickness variations yield trends related to slope of the depositional surface.

Regional trends of grain-size distribution measures show that from southeast to northwest, the grain size, skewness, and peakedness decrease and the degree of sorting increases; these trends suggest that the direction of sediment movement was northwestward.

The Moenkopi Formation was deposited on a partly eroded plain

<sup>1</sup> For the convenience of the reader, the grain-size distribution measures are briefly reviewed: the range of particle sizes in a sediment forms what is called a size distribution. Good sorting indicates a small range of particle sizes; poor sorting indicates the opposite. If the sediment is uniformly sorted, the particle-size distribution is called normal. A lack of sorting uniformity results in a size distribution that is nonsymmetrical (skewed and (or) peaked). Positive skewness indicates a disproportionately large range of finer sizes compared with the range of coarser sizes; negative skewness indicates the opposite. Positive peakedness indicates a disproportionately large amount of particles in the middle of the size range; negative peakedness indicates a disproportionately large amount of particles in both the fine and the coarse ends of the size range.

which subsided at a low to moderate rate. The source areas underwent tectonic uplift at a low to very low rate. Sediments that were eroded from the weathered sources were mostly silt, clay, and very fine sand. Erosion and deposition took place in a warm arid climate that produced oxidized sediments and evaporite basins. In the present study, interpretations of tectonic uplift and subsidence were made largely according to the system described in a previous report (Cadigan, 1961) and especially from the relationships apparent in figure 11 of that report.

Decreases in the rate of source-area uplift at times reduced the supply of detritus, and this reduction, combined with the effects of a continuous rate of subsidence of the area of deposition, permitted invasion into eastern alluvial areas by marine environments from the west. Toward the end of Moenkopi deposition, the rate of source-area uplift slowly increased, and the resulting increased flow of detritus caused the retreat of the marine environment westward beyond the borders of the Colorado Plateau region.

The energy level<sup>2</sup> in the environment of deposition of the Moenkopi generally was low, but locally it varied from low to high. Conglomerates present in the basal strata—the Tenderfoot, Ali Baba, and Timpoweap Members as well as the higher Holbrook Member—testify to the occasional presence of high energy levels in the marginal parts of the area of deposition adjacent to source areas.

All source areas produced detritus containing quartz, feldspar, mica, volcanic igneous, metamorphic, and sedimentary rock fragments, but the proportions of these types of fragments varied greatly from one area to another. From evidence supplied by trend-surface analyses, certain terranes are proposed as being dominant in certain source areas, as listed in table 3. The weathering in the source areas prior to erosion presumably altered the surface of the source rocks. Detritus from the weathered surfaces was deposited and subjected to further change during diagenesis. The terranes listed in table 3 are suggested as the source rocks of the Moenkopi sediments with the realization that other rocks, for example sodic andesite (in the southwestern source), also may have been present. As a result of the combined effects of weathering and diagenesis, andesite might yield few identifying stable detrital minerals.

The four interpreted source areas are the Uncompahgre highland in southwestern Colorado; a southwestern source, part of the

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<sup>2</sup> Energy level refers to the rate at which geologic processes operate in a system of erosion, transportation, and deposition. This is an extension of the "energy concept" of Gilbert (1914).

Basin and Range province of New Mexico; a southern source, part of the Basin and Range province of southwestern New Mexico and southeastern Arizona; and a southeastern source in south-central Arizona. The last three were probably more or less physically continuous areas.

TABLE 3.—*Summary of higher-than-average amounts of rock components contributed to the Moenkopi Formation by the four general source areas, and the interpreted source terranes in order of influence on the derived sediments*

[X indicates higher-than-average amount of rock components contributed to the Moenkopi Formation]

Source areas	Uncompahgre highland	Southwestern	Southern	Southeastern
Rock component				
Quartz .....	X	-----	X	-----
All rock fragments	X	X	-----	X
Feldspar .....	X	X	-----	-----
Mica flakes .....	X	X	-----	-----
Volcanic detritus ...	X	-----	X	-----
Heavy minerals ....	X	-----	X	X
Siliceous rock fragments.	-----	X	-----	X
Terrane				
Dominant.....	Granite.....	Siliceous sedimentary rocks.	Quartzite.....	Metamorphic rocks.
Intermediate.....	Metamorphic rocks.	None evident.....	None evident.	Siliceous sedimentary rocks.
Minor.....	Arkose; rhyolite.	Granite; andesite?	Rhyolite.....	None evident.

## GEOCHEMICAL STUDIES

### SAMPLING AND ANALYTICAL METHODS

The rock samples used for this study were selected as representative of the outcrops from which they were taken. Weathered surfaces were removed and a 2- to 3-pound sample was taken from an area less than 1 foot square. In thick stratigraphic sections, samples were selected at predetermined intervals along a line perpendicular to the outcrop of the beds. In well-exposed sections consisting of different members, at least three samples were taken from each member. Some samples were taken in the Moenkopi near uranium ore deposits in the overlying Chinle Formation. A total of 323 samples was collected from 76 localities (table 4). The number of samples collected at each locality ranged from one to 18. To eliminate clusters of data points, some closely spaced localities were combined in the previously published petrology study, reduc-

ing the total sample localities to 65. (See sample locality map, pl. 1, in Cadigan, 1971.)

TABLE 4.—*Index of sample localities, number of samples, and units sampled in the Moenkopi Formation and lithologically related strata*

[Number refers to locality number on published map (Cadigan, 1971, pl. 1). All members sampled are of Moenkopi and related strata. Those preceded by asterisk (\*) are State Bridge Formation]

No.	Sample locality		Number of samples	Members sampled
	Area	Long W. Lat N.		
Arizona				
1	Black Creek .....	109.23° 35.33°	3	Undifferentiated.
5	Hunters Point .....	109.13° 35.60°	2	Do.
9	St. Johns "A" .....	109.37° 34.43°	2	Do.
			3	Holbrook.
10	Black Point .....	111.27° 35.73°	1	Moqui.
			2	Wupatki.
12	Sunset Mountain .....	110.90° 34.87°	3	Holbrook.
15	Big Canyon .....	111.55° 36.15°	2	Moqui.
			3	Wupatki.
60	Holbrook .....	110.16° 34.88°	2	Holbrook.
			1	Moqui.
			1	Wupatki.
70	Winslow .....	110.83° 35.08°	4	Holbrook.
81	Shinumo Altar .....	111.72° 36.44°	2	Undifferentiated.
			2	Lower massive sandstone.
210	14 miles west of Navajo Bridge ...	111.82° 36.70°	2	Upper red.
			2	Shnabkaib.
			1	Lower red.
211	Kato Sells 2 .....	109.86° 36.93°	2	Upper slope-forming.
400	Hoskinnini Mesa .....	110.40° 36.85°	2	Hoskinnini.
			1	Upper slope-forming.
401	Nokai Dome .....	110.40° 36.93°	1	Do.
Colorado				
3	Sheephorn Creek .....	106.52° 39.91°	1	*Upper.
			1	*South Canyon Creek.
4	South Canyon Creek .....	107.43° 39.56°	1	*Upper.
			1	*Lower
8	Gateway (The Palisade) .....	108.99° 38.68°	2	Ali Baba.
			4	Tenderfoot.
15	Paradox Valley .....	108.85° 38.35°	1	Sewemup.
			14	Ali Baba.
			3	Tenderfoot.
18	Meeker .....	107.80° 39.97°	3	*Upper
			1	*Lower.
139	Gore Pass .....	106.58° 40.16°	1	*Undifferentiated.
186	Main Elk Creek .....	107.59° 39.63°	1	*Upper.
188	Skull Creek .....	108.68° 40.33°	2	Undifferentiated.
189	Deer Creek .....	106.54° 40.20°	1	*Do.
400	Sinbad Valley .....	108.97° 38.52°	1	Pariott.
			3	Sewemup.
			6	Ali Baba.
			7	Tenderfoot.
Nevada				
1	Horse Spring Valley .....	114.13° 36.36°	2	Upper red.
			1	Middle red.
New Mexico				
1	Chavez-Prewitt "A" .....	108.06° 35.32°	3	Undifferentiated.
3	Fort Wingate "A" .....	108.57° 35.48°	2	Do.
16	Riley .....	107.21° 34.38°	3	Do.
20	Mesa Gallina .....	107.24° 34.67°	3	Do.
Utah				
6	Muddy River .....	110.97° 38.57°	1	Cliff-forming.
			1	Upper slope-forming.
			1	Ledge-forming.
			1	Lower slope-forming.
7	Straight Wash .....	110.52° 38.78°	1	Upper slope-forming.
			1	Lower slope-forming.
8	Temple Mountain .....	110.67° 38.68°	1	Upper slope-forming.
			2	Ledge-forming.
			1	Sinbad.
			3	Lower slope-forming.
9	Poison Spring Wash (Buckacre Point).	110.40° 38.10°	1	Upper slope-forming.
			2	Ledge-forming.
			2	Lower slope-forming.

TABLE 4.—*Index of sample localities, number of samples, and units sampled in the Moenkopi Formation and lithologically related strata—Continued*

No.	Sample locality		Number of samples	Members sampled
	Area	Long W. Lat N.		
Utah—Continued				
10	Horse Canyon (Lampstand Draw, Long Canyon).	111.22° 37.95°	1 2 1	Upper slope-forming. Ledge-forming. Sinbad.
11	Muley Twist .....	111.03° 37.83°	1 2 2	Lower slope-forming. Cliff-forming. Upper slope-forming.
14	Silver Falls .....	111.15° 37.74°	2 1 4 3	Ledge-forming. Cliff-forming. Upper slope-forming. Ledge-forming.
18	Richardson Amphitheater .....	109.32° 38.78°	1 2 2	Sewemup. Ali Baba. Tenderfoot.
22	Kanarraville "A" .....	113.20° 37.50°	2 1 1	Upper red. Lower red. Timpoweap.
25	Bears Ears .....	109.87° 37.64°	2 2 4	Ledge-forming. Lower slope-forming. Hoskinnini.
26	Bridger Jack Mesa .....	109.68° 37.97°	3	Do.
27	Comb Wash .....	109.65° 37.32°	2	Do.
28	Cottonwood Creek .....	109.68° 37.77°	4	Do.
29	Hite .....	110.43° 37.78°	6 2	Upper slope-forming. Ledge-forming.
30	Jacobs Chair .....	110.23° 37.73°	1 2 3	Upper slope-forming. Ledge-forming. Hoskinnini.
32	Lockhart Canyon .....	109.68° 38.35°	1 1 1 3	Upper slope-forming. Ledge-forming. Lower slope-forming. Hoskinnini.
33	Milk Ranch Point .....	109.68° 37.61°	3	Do.
34	Monitor Butte .....	110.43° 37.23°	3 1	Ledge-forming. Hoskinnini.
35	North Sixshooter Peak .....	109.66° 38.15°	1 1 1 2	Upper slope-forming. Ledge-forming. Lower slope-forming. Hoskinnini.
36	Poncho House .....	109.75° 37.12°	1 1	Lower slope-forming. Hoskinnini.
38	Steer Mesa .....	110.00° 38.42°	2 4	Lower slope-forming. Hoskinnini.
41	Vernal .....	109.48° 40.60°	2	Undifferentiated.
43	Chimney Rock .....	111.30° 38.33°	1 1 2	Upper slope-forming. Ledge-forming. Sinbad.
45	Leeds .....	113.35° 37.20°	1	Lower slope-forming.
47	St. George "A" .....	113.67° 37.05°	2 3 5 2 2	Upper red. Do. Shnabkaib. Middle red. Virgin.
49	Clay Hills Pass .....	110.31° 37.44°	6 3 1 1 4	Lower red. Upper slope-forming. Ledge-forming. Lower slope-forming. Hoskinnini.
64	Pleasant Creek (Miners Mountain).	111.20° 38.17°	2 3 4 1	Upper slope-forming. Ledge-forming. Sinbad. Lower slope-forming.
160	Torrey .....	111.39° 38.35°	1	Upper red.
173	Clay Gulch .....	110.40° 37.34°	1 2	Ledge-forming. Hoskinnini.
200	Happy Jack area .....	110.27° 37.74°	2	Upper slope-forming.
248	Clay Hills Crossing .....	110.40° 37.30°	3	Hoskinnini.
286	Cedar City .....	113.07° 37.72°	1	Upper red.
300	Dynamite Point .....	110.53° 39.05°	2	Upper slope-forming.
304	Virgin .....	113.12° 37.25°	1	Upper red.
305	The Peaks .....	111.17° 37.87°	1 1 1 1	Cliff-forming. Ledge-forming. Sinbad. Lower slope-forming.
307	Farm Creek .....	110.72° 40.38°	1 4	Mahogany Formation. Thaynes Formation.
309	Deer Flat (Hide-out mine) .....	110.02° 37.66°	4	Upper slope-forming.
310	Mineral Canyon .....	109.92° 38.55°	3	Do.

TABLE 4.—*Index of sample localities, number of samples, and units sampled in the Moenkopi Formation and lithologically related strata—Continued*

No.	Sample locality			Number of samples	Members sampled
	Area	Long	W. Lat N.		
Utah—Continued					
312	3 miles south of Kanab .....	112.55°	37.00°	2	Upper red.
313	Red House Cliffs (Midway section).	110.27°	37.43°	1	Upper slope-forming.
				1	Ledge-forming.
				1	Lower slope-forming.
315	Red House Cliffs (North section).	110.23°	37.45°	2	Hoskinnini.
				3	Do.
319	Bicknell .....	111.53°	38.33°	1	Upper red.
323	Oljato Trading Post .....	110.26°	37.05°	1	Undifferentiated.
325	Moab .....	109.60°	38.62°	1	Pariott.
				2	Sewemup.
				3	Ali Baba.
				2	Tenderfoot.
326	Junction Butte .....	109.83°	38.33°	3	Hoskinnini.
400	Frey Canyon .....	110.14°	37.63°	4	Upper slope-forming.
401	Shinarump No. 1 mine .....	109.71°	38.68°	1	Sewemup.
402	Castle Valley .....	109.40°	38.66°	1	Mottled zone.
				1	Pariott.
				1	Sewemup.
				2	Ali Baba.
				1	Tenderfoot.

Chemical analyses were performed using a six-step spectrographic method slightly modified from the three-step technique described by Myers, Havens, and Dunton (1961). Smaller quantities of gold and silver can be detected by the atomic-absorption methods than by the six-step spectrographic method. Detection of copper is about the same with both methods; duplication provided an opportunity to make a statistical comparison between the two methods for copper. Analysis for gold was also done using an atomic-absorption technique. Silver and copper analyses were duplicated with an atomic-absorption technique described by Huffman, Mensik, and Rader (1966) and Huffman (1968). Mercury, not included among the elements determined in the six-step spectrographic method, was determined utilizing a large-volume atomic-absorption technique described by Vaughn (1967).

Uranium was not sought by chemical analysis because previous work with similar samples indicated that detectable amounts of uranium were present only in well-mineralized rock, suggesting that few if any of the samples in this study would be found to contain detectable uranium. All samples, however, were scanned with a scintillation counter for evidence of radioactivity above background. None was detected.

Values for copper, silver, gold, and mercury determined by atomic absorption are identified in this report by modifying the element symbols to Cu(A), Ag(A), Au(A), and Hg(A). Unmodified symbols indicate values determined by spectrographic method; for example, Cu, Fe, and Ni. Cu and Cu(A) are treated as two different elements throughout the rest of the report.

Ag(A) values, according to G. H. VanSickle (written and oral

commun., 1968), tend to be high when Ca values are high, but this seems to be a result of the effect of calcite on the atomic-absorption method used for Ag(A) rather than a valid geochemical correlation.

#### ELEMENTS STUDIED

Table 5 lists the metals looked for in the samples, their lower limits of detection, and the percentage of samples for which numerical values were obtained for each element. The lower detection limit is the minimum amount of a particular element that can be detected with a particular method. The upper detection limit is the maximum amount that can be discerned before saturation of the discriminating element occurs. Numerical values are those that range between (and include) the detection limits. Frequency distributions containing some values that lie outside the detection limits are called censored distributions (Cohen, 1959, 1961; Miesch, 1967).

This study is based on determinations of the 20 elements listed in the first half of table 5. Distributions of 18 of these elements are sufficiently uncensored for purposes of a statistical study. Au(A) and Be, despite severe censoring of their distributions, are included in this study because of the current interest in their modes of occurrence as well as their economic importance. It is, of course, important to emphasize the tentativeness of any conclusions suggested by the Au(A) and Be data calculations. The 16 elements listed in the second half of table 5 were not included in the statistical study because of the small percentage of samples from which numerical values for these elements were obtained.

#### STATISTICAL ANALYSIS

To utilize as many of the available analytical data as possible, values which fell below the lower limits of detection were arbitrarily assigned a value equal to one-half of the lower detection limit value. This was also done to avoid using zero values, which are probably incorrect. For example, the lower detection limit of yttrium is 10 ppm (parts per million). Thus, values reported as less than 10 ppm were assigned a value of 5 ppm. Similarly for high determinations, calcium values reported as greater than 10 percent were arbitrarily assigned the value of 20 percent—twice the upper limit of detection.

Numerical values were transformed to logarithms essentially for purposes of calculating statistical measures as discussed in a previous report (Cadigan, 1969). The statistical analysis of the data is similar to that used by Miesch and Riley (1961) and Miesch

TABLE 5.—*Metals looked for, lower detection limits, and percent of samples for which numerical values were obtained*

[Six-step spectrographic analyses were done by J. L. Finley. Atomic-absorption analyses for Cu(A) and Ag(A) were done by A. J. Toevs and Lucy Dickson; and atomic-absorption analyses for Hg(A), by W. W. Janes]

Metal	Symbol used in report	Lower detection limit (ppm)	Percent of samples for which numerical values were obtained
Elements used in statistical study because of high percentage of samples for which numerical values were obtained			
Calcium <sup>1</sup>	Ca	50	98
Iron	Fe	10	100
Magnesium	Mg	50	100
Titanium	Ti	2	100
Barium	Ba	2	100
Manganese	Mn	1	100
Strontium	Sr	5	100
Zirconium	Zr	10	96
Vanadium	V	7	97
Chromium	Cr	1	99
Copper	Cu(A)	10	65
Copper	Cu	1	99
Yttrium	Y	10	74
Lead	Pb	10	83
Nickel	Ni	3	92
Cobalt	Co	3	77
Beryllium	Be	1	4
Silver	Ag(A)	.2	96
Mercury	Hg(A)	.01	98
Gold	Au(A)	.02	32
Elements looked for but not used in statistical study because of small percentage of samples for which numerical values were obtained			
Gold	Au	20	0
Silver	Ag	1	1
Lanthanum	La	30	5
Molybdenum	Mo	3	2
Tungsten	W	100	0
Zinc	Zn	200	1
Arsenic	As	2,000	0
Bismuth	Bi	10	0
Cadmium	Cd	50	0
Antimony	Sb	200	0
Tin	Sn	10	1
Tellurium	Te	2,000	0
Tantalum	Ta	200	0
Platinum	Pt	50	0
Palladium	Pd	2	0
Niobium	Nb	3	1

<sup>1</sup> Six calcium determinations were greater than 10 percent, the upper detection limit.

(1967). Measures of average concentration are the geometric mean (the antilog of the log distribution mean) and the median. Analytical data were punched on cards, and computations of means, standard deviations, and cumulative frequencies were performed by electronic computer.

Some miscellaneous computational tasks were done by direct entry into a smaller computer. Logs to the base  $x$  (Cadigan, 1969) used in the study are derived from the formula

$$\log_x N = \left( \frac{N}{0.003125} \right)^{\frac{1}{\log_{10} 2}}$$

The following paragraphs discuss statistical properties of the element distributions. Readers with no interest in such a discussion may skip to the section entitled "Stratigraphic Comparisons" without much loss of continuity.

A test for normality utilizing chi-square at the 95-percent significance level showed that statistical distributions approach log normal for 13 of the 20 metals studied and depart significantly from log normal for five of the metals (Ni, Sr, Mg, Ba, and Cr). Probability graphs of the 18 log distributions are shown in figures 3, 4, and 5. As is conventional, the divergence from a straight line exhibited in the percentiles below 10 and above 90 were discounted in the log normality test. Probability graphs of the Au(A) and Be are shown in figure 6. Table 6 lists selected measures of central tendency and dispersion for the log distributions.

Figure 7 graphically presents at log scale the relative abundance of the 20 metals, the detection limit, the range of geometric mean, and the rank of the metals in order of abundance. These average values are based on the 323 samples of Moenkopi and were used as the standard against which average values of certain stratigraphic units, textural rock types, and compositional rock types within the Moenkopi Formation were compared.

The range-of-mean interval, a graphic indication of relative dispersion, is of similar width for most of the 20 metals. This reflects the similarity of log standard deviations and standard errors of the mean listed in table 6.

#### STRATIGRAPHIC COMPARISONS

Figure 8 illustrates the relative amounts of metal content in some members of the Moenkopi Formation compared with the abundance of the same 20 metals in the formation as a whole.

Figure 8, column A, shows the formation averages (geometric means) as a graphic standard. From a statistical geochemical

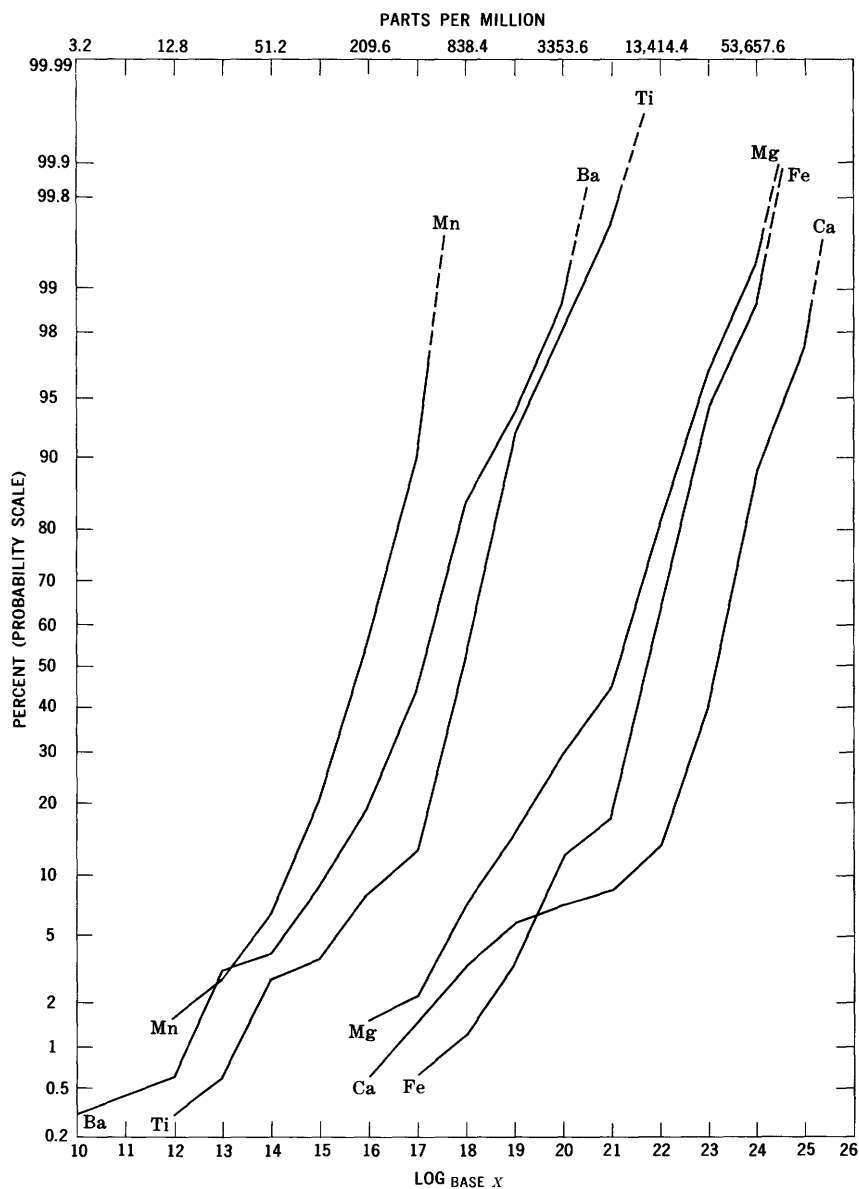


FIGURE 3.—Log distributions of Ca, Fe, Mg, Ti, Ba, and Mn. Dashed line segments indicate extrapolation.

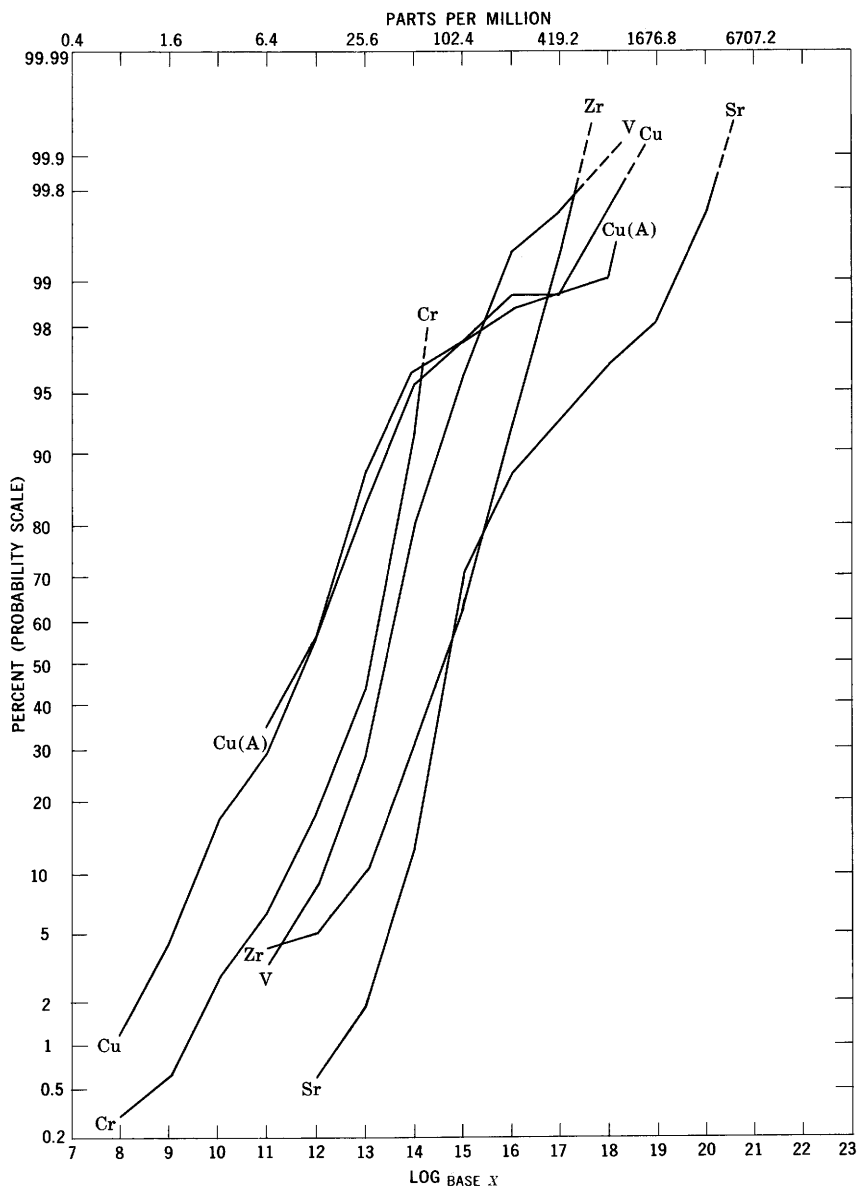


FIGURE 4.—Log distributions of Sr, Zr, V, Cr, Cu, and Cu(A). Dashed line segments indicate extrapolation.

viewpoint, these averages based on all samples collected are arbitrary estimates of the true formation abundances. The graphs in the other columns are intended to show the metal content of different stratigraphic members in terms of the average metal content of the entire formation more readily than could be seen from a comparison of figures in parts per million. Thus, for

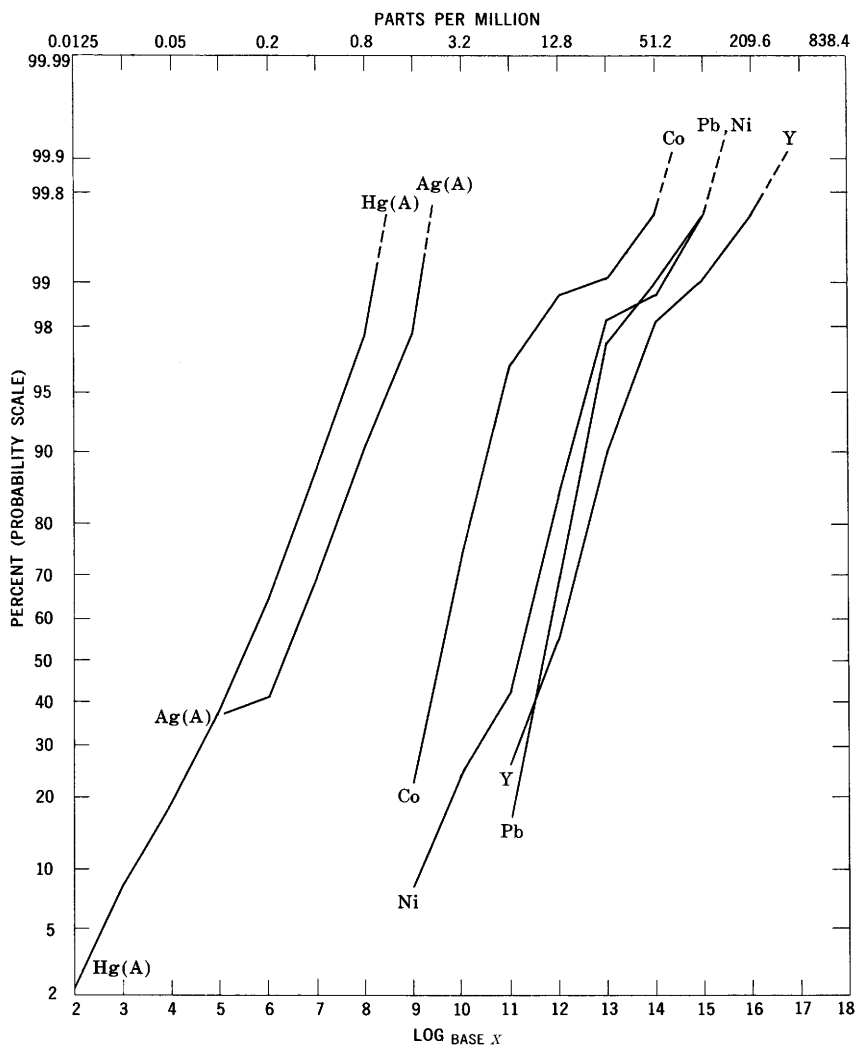


FIGURE 5.—Log distributions of Y, Pb, Ni, Co, Ag(A), and Hg(A). Dashed line segments indicate extrapolation.

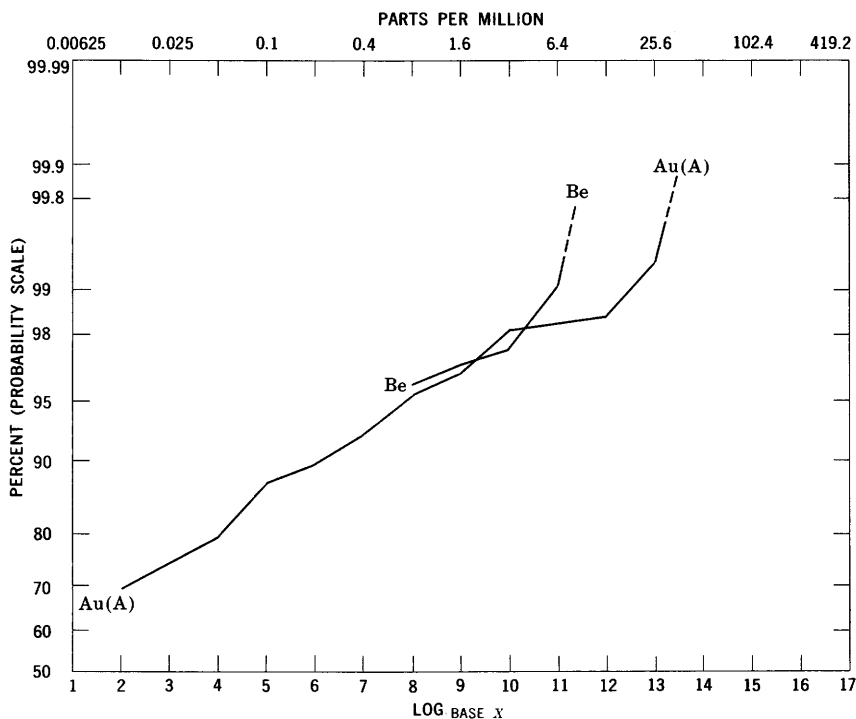


FIGURE 6.—Highly truncated log distributions of Be and Au(A). Dashed line segments indicate extrapolation.

TABLE 6.—Selected measures of central tendency and dispersion computed for the log distributions of the 20 metals used in the Moenkopi study

[Metal symbols accompanied by "A" indicate analyses by atomic-absorption method]

Metal	Logarithmic measures <sup>1</sup>			Arithmetic measures, in parts per million <sup>2</sup>		
	Standard deviation	Mean	Standard error of mean	Geometric mean	Median	Expected range of geometric mean at 95-percent significance level
Ca .....	1.582	22.749	0.0880	22,000	29,000	20,000-25,000
Fe .....	1.163	21.437	.0647	8,900	11,000	8,100-9,700
Mg .....	1.565	20.641	.0871	5,100	7,000	4,500-5,800
Ti .....	1.207	17.891	.0672	760	790	690-830
Ba .....	1.552	16.998	.0864	410	440	360-460
Mn .....	1.114	15.997	.0620	190	180	170-210
Sr .....	1.275	14.996	.0709	100	81	91-110
Zr .....	1.360	14.575	.0757	76	78	69-85
V .....	1.129	13.265	.0628	31	34	28-34
Cr .....	1.114	12.793	.0620	22	27	20-24
Cu(A) .....	1.356	11.985	.0754	12	10	11-14
Cu .....	1.602	11.626	.0891	10	11	9-11
Y .....	.945	11.813	.0526	11	11	10-12
Pb .....	.676	11.730	.0376	11	10	10-11
Ni .....	1.057	10.948	.0588	6.2	7.1	5.6-6.7
Co .....	1.028	10.246	.0572	3.8	2.3	3.5-4.1
Be .....	.539	7.414	.0300	.53	Unknown	0.51-0.56
Ag(A) .....	1.244	6.370	.0692	.26	.25	0.24-0.28
Hg(A) .....	1.535	5.393	.0854	.13	.13	0.12-0.15
Au(A) .....	1.209	2.333	.0673	.016	Unknown	0.014-0.017

<sup>1</sup> Logarithms to base  $x$  (Cadigan, 1969).

<sup>2</sup> Rounded to two significant figures.

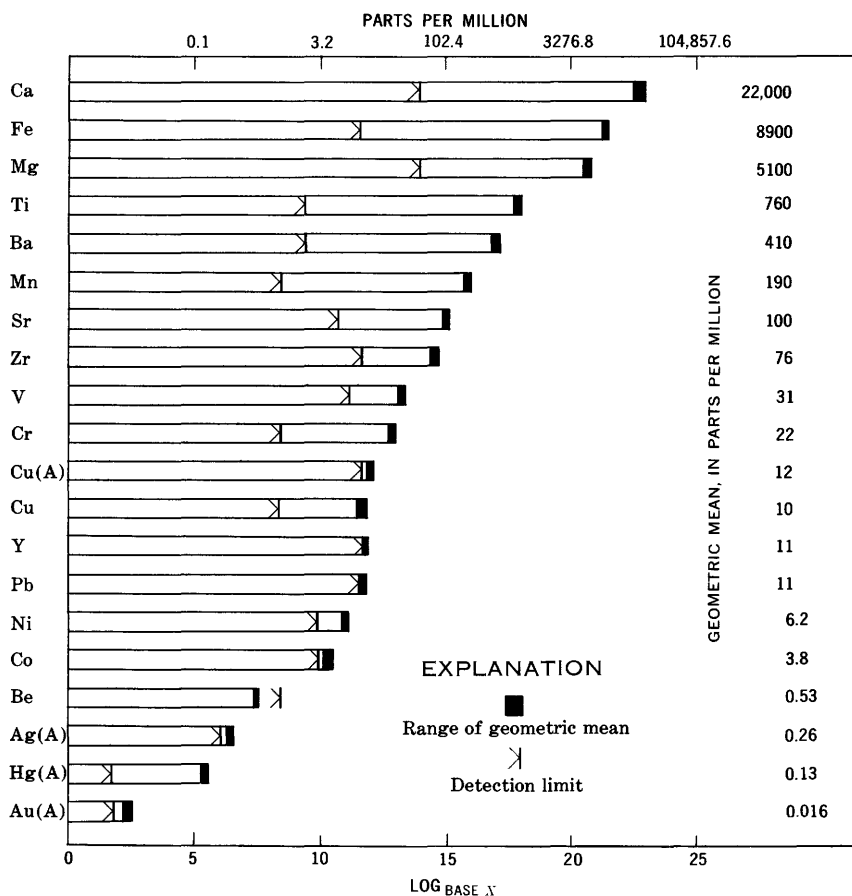
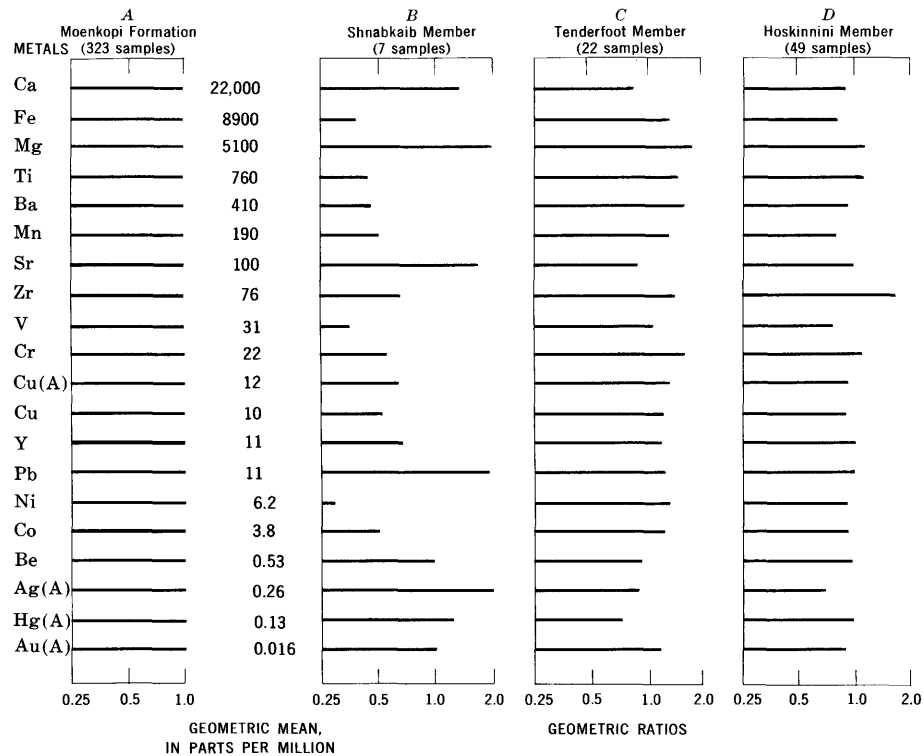


FIGURE 7.—Mean abundance of 20 metals in the Moenkopi Formation, limits of detection, and range of geometric means. Units of horizontal scale are logarithmic (base 10). Metals are arranged from top to bottom in order of decreasing abundance.

example, in column A, the horizontal bars representing the standard values of Ca and Pb are of the same length and each represents the abundance of its respective element; the bar for Ca represents its geometric mean, 22,000 ppm, whereas the bar for Pb represents its geometric mean, 11 ppm. The respective lengths of the bars for Ca and Pb in column B indicate that Ca in the Shnabkaib Member is about 1.4 times as abundant as Ca in the entire formation, whereas Pb in the Shnabkaib is nearly two times as abundant as the formational abundance of Pb. The horizontal scale is graduated geometrically to indicate 0.25, 0.5, 1.0, 2.0, and, for some members, 4.0 times the formation geometric mean.



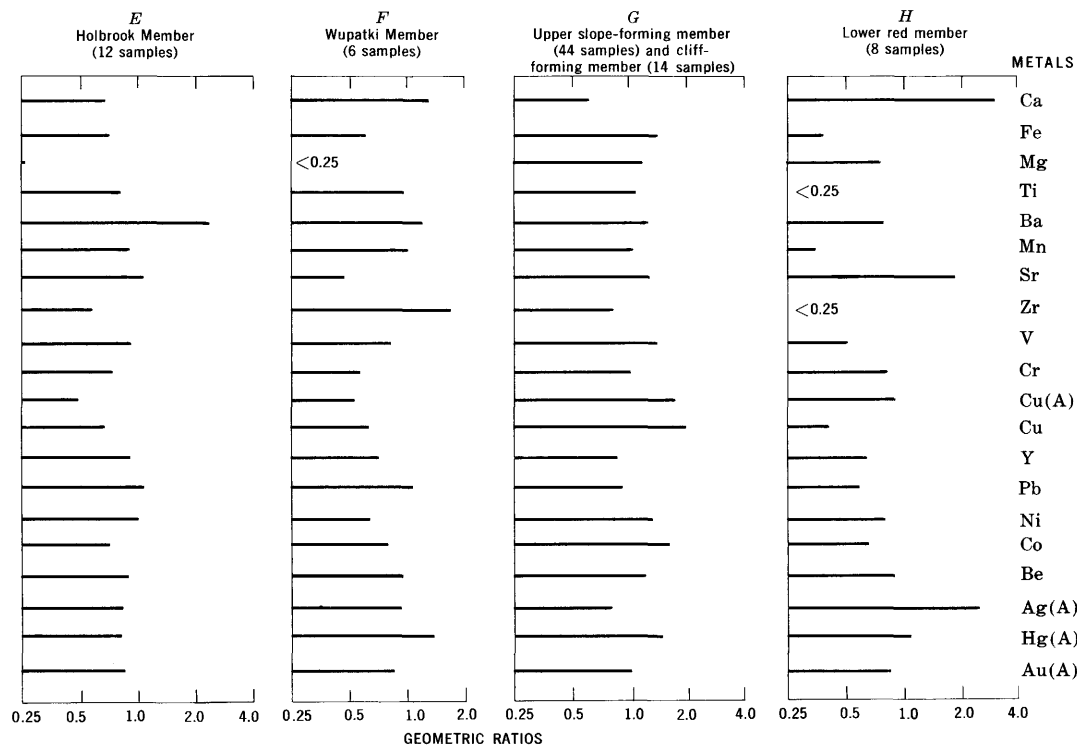


FIGURE 8.—Comparison of metal content of some members of the Moenkopi Formation with average metal content of the entire formation. All values compared are geometric means. Horizontal scale indicates proportion, or geometric ratio, in terms of the standard, column A.

The Shnabkaib Member (fig. 8, col. *B*) is a marginal marine evaporite sedimentary unit containing gypsum, limestone, and limy siltstone. Compared with the formation mean, the Shnabkaib contains on the average much more Ca, Mg, Sr, Pb, and Ag(A), but it contains less than half as much Fe, Ti, Ba, V, and Ni, and much less of almost all the other metals.

The Tenderfoot Member (fig. 8, col. *C*) is an arkosic continental alluvial sedimentary unit in western Colorado and eastern Utah and was probably derived from the Uncompahgre highland source area in western Colorado. Of the 20 geometric means, 15 are higher than the formation means. Using unadjusted chi-square, we found this number of differences to be statistically significant at the 95-percent confidence level. Thus, a comment that the Tenderfoot has a significantly higher metal content than the formation as a whole refers to the fact that a significant number (15 or more) of geometric means for the Tenderfoot are higher than the comparable formation geometric means. Differences between comparable geometric means for individual metals are sometimes described in terms of magnitude. An order of magnitude difference would indicate that one of two geometric means being compared is two times, or more, larger than the other. The simple terms "higher" or "lower" describe general differences of less than an order of magnitude between compared geometric mean values. The individual metal geometric means in the Tenderfoot do not vary nearly as much from corresponding formation means as do those of the Shnabkaib. Au(A) content in the Tenderfoot is slightly higher than the formation mean.

The Hoskinnini Member (fig. 8, col. *D*), although correlated with the Tenderfoot Member (Stewart, 1959) because both occupy similar positions in the stratigraphic column in adjacent areas, has significantly lower metal content than the Tenderfoot and than the formation as a whole. Individual metals in all three—Hoskinnini Member, Tenderfoot Member, and the formation as a whole—however, are present in quantities of the same order of magnitude. Au(A) content in the Hoskinnini is slightly lower than the formation mean.

The Holbrook Member (fig. 8, col. *E*), a sandstone-siltstone unit with conspicuous sandstone beds, and the Wupatki Member (fig. 8, col. *F*), a siltstone-sandstone unit also with conspicuous sandstone beds, in north-central Arizona were probably derived from sources in southwestern New Mexico and southeastern Arizona. Both are generally lower in metal content than the formation, the Holbrook significantly so. Particularly noticeable is the low Mg content of

both members. It is about one-fourth the formation geometric mean. Cu(A) for the two members is about half the formation mean, but Au(A) is only slightly lower. Sr in the Wupatki Member is lower by an order of magnitude than the formation mean.

The low Mg values probably reflect the lower proportions of mica and chlorite in these rocks as compared with those derived from Uncompahgre highland sources (p. 10).

The upper slope-forming member and the overlying but not everywhere distinguishable cliff-forming member (fig. 8, col. *G*), the uppermost members of the Moenkopi in southeastern and eastern Utah, are examples of the typical red siltstone-sandstone facies and represent a low-energy alluvial-plain environment of deposition. They were derived from generally the same sources as the Tenderfoot and Hoskinnini Members. Their content of metals is significantly higher than the formation mean, and Cu is more than twice as abundant. Other conspicuously high value metals are Cu(A), Co, Hg(A), and V. The abundance of Cu and other metals is probably not related to source or depositional environment because in the Tenderfoot Member, which is similar to the upper slope-forming and cliff-forming members in terms of source, Cu is only slightly above the formation mean. The high Cu content in the upper slope-forming and cliff-forming members may be related to the uranium deposits that occur in some localities at or just above the Moenkopi-Chinle contact. More evidence of this possible relationship is considered later in the report (p. 40). Au(A) content is about the same as the formation mean.

The lower red member (fig. 8, col. *H*) (red calcareous coarse siltstone, very fine grained sandstone, and limestone) in southwestern Utah, southeastern Nevada, and northwestern Arizona is thought to be marginal marine in origin. Detrital sediment was probably derived from source areas in southern Arizona. Compared with the formation mean, the average metal content is significantly lower in the lower red member; Ca, Sr, and Ag(A) are much higher; Ti and Zr, which are strongly related to terrestrial detritus, are lower by two orders of magnitude; and Au(A) is slightly lower.

In summary, figure 8 illustrates differences among the geometric means for the formation and the individual members that can be attributed to the effects of specific geologic variables related to provenance. The significant and order-of-magnitude differences between geometric means of the formation and those of the Shnabkaib and lower red members (fig. 8, cols. *B* and *H*) reflect major

variation in source. The principal source of metals of the two members was the sea by way of the complex of marine environments of deposition, characterized by high Ca, Sr, Mg, Pb, and Ag(A). (Ag(A) values, however, may be analytically dependent on Ca values, as discussed on p. 15.) The low Fe, Ti, Mn, Zr, and V geometric means are an indication that terrestrial sources supplied only a minor proportion of the sediment and metal content of these members.

Variation in metal content resulting from differences between terrestrial sources is illustrated by the significant, but less than order-of-magnitude, differences between the Hoskinnini and Tenderfoot Members, which variation suggests minor differences between two similar terrestrial sources. On the other hand, the significant and, for some metals, order-of-magnitude differences between the Tenderfoot and the Holbrook and Wupatki Members (for example, the deficiencies of Mg, Fe, Cr, Cu, and Cu(A) in the Holbrook and Wupatki) reflect major differences between terrestrial sources.

A third type of variation results from the effect of an extrinsic source and is represented by the contrast between the higher amounts of Cu, Cu(A), and Hg(A) in the upper slope-forming and cliff-forming members as compared with the Tenderfoot and Hoskinnini Members. The increases of metal abundances in the upper slope-forming and cliff-forming members are the effects of interstratal solutions acting as a supplementary extrinsic source of metals.

Other variables whose effects are not demonstrable in figure 8 but which no doubt control to some extent the variation of metal content in Moenkopi rocks are the process of diagenesis (which, however, is thought to be a regional constant), particle size, and particle composition, a function of particle size, diagenesis, and source.

Although none of the members of the Moenkopi is composed of particles of only one size classification, members can be grouped into facies according to general differences in texture and composition (p. 7).

#### FACIES COMPARISONS

Rock facies are defined for purposes of this report as certain combinations of particle size and mineral composition. The three major facies are (1) siltstone-sandstone facies—the dominant Moenkopi rock type; (2) sandstone facies—represented by samples from the Holbrook, Hoskinnini, and Tenderfoot Members of

the Moenkopi; and (3) limestone-evaporite facies—represented by samples from the Timpoweap, Virgin, Sinbad, and Shnabkaib Members of the Moenkopi and Thaynes Formations. Differences in metal content among the three facies are shown graphically in figure 9. Unity, or the standard of comparison, is once again the formation geometric mean (fig. 8, col. A).

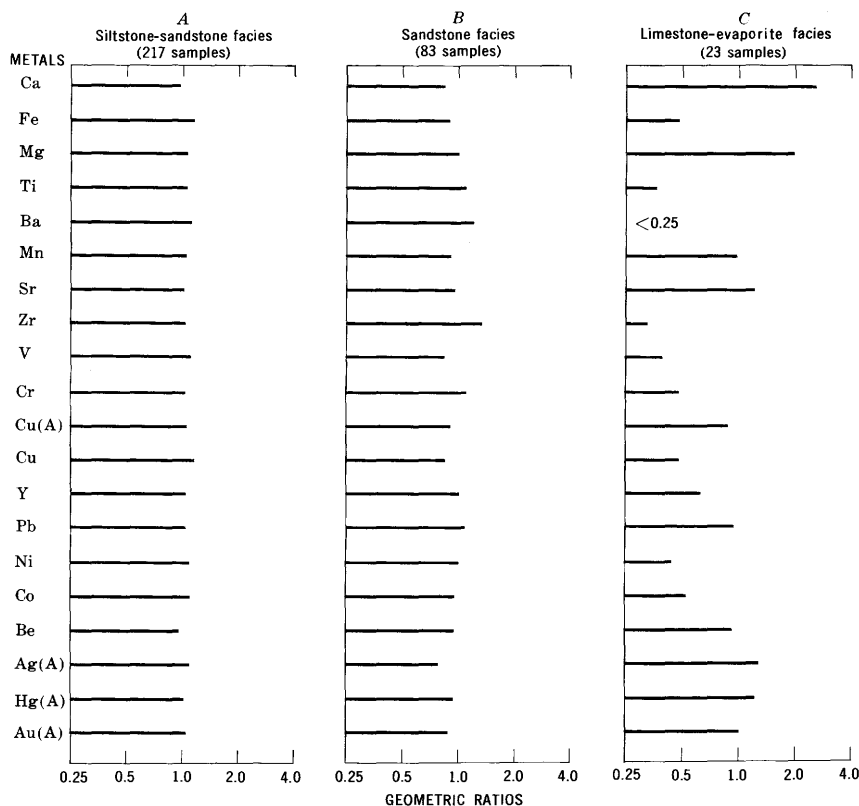


FIGURE 9.—Comparison of metal content of rocks from different facies with average metal content of the entire formation as shown in figure 8, column A. All values compared are geometric means.

The siltstone-sandstone facies (fig. 9, col. A), partly because it is represented by 65 percent of the total samples collected from the Moenkopi, shows no order-of-magnitude differences from the formation mean; it does, however, show statistically significant slightly higher mean metal content than the formation.

The sandstone facies (fig. 9, col. B) shows no significant differences, but it does show a generally lower mean metal content than the formation.

The limestone-evaporite facies (fig. 9, col. *C*) shows the greatest differences compared with the formation means. Ca and Mg are at least twice as high, and Fe, Ti, Zr, V, Cr, Cu, and Ni are only about half as high as the formation geometric means, a repetition of the proportions observed for the marine members illustrated in figure 8. This facies is dominantly marine in origin. The siltstone-sandstone and sandstone facies are composed dominantly of terrestrial sediments.

Au(A) geometric means for the siltstone-sandstone and limestone-evaporite facies are about the same as the formation mean. The Au(A) mean for the sandstone facies is slightly lower.

#### GEOCHEMICAL ASSOCIATION OF THE METALS

The 10 comparative graphs in figures 8 and 9 were used to investigate element covariation in the Moenkopi Formation. Each metal value on each graph was compared with the formation mean, and the result of the comparison was "sensed" as "plus," "minus," or "equal." Using this technique, the  $10 \times 20$  matrix in table 7 was prepared. The matrix consists of plus (+), minus (-), and zero (0) symbols which describe a nonparametric relationship

TABLE 7.—*Sensings of comparisons of metal values in the different groups of samples with the formation geometric means as illustrated in figures 8 and 9*

[Explanation of symbols: +, more than the formation mean; -, less than the formation mean; 0, equal to the formation mean. (A) following metal symbol indicates analysis by atomic-absorption method]

	Figure 8—							Figure 9—		
	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>	<i>H</i>	<i>A</i>	<i>B</i>	<i>C</i>
Ca.....	+	-	-	-	+	-	+	-	-	+
Fe.....	-	+	-	-	-	+	-	+	-	-
Mg.....	+	+	+	-	-	+	-	-	0	+
Ti.....	-	+	+	-	-	+	-	+	+	-
Ba.....	-	+	-	+	+	+	-	+	+	-
Mn.....	-	+	-	-	+	+	-	+	-	-
Sr.....	+	-	-	+	-	+	+	0	-	+
Zr.....	-	+	+	-	+	-	-	+	+	-
V.....	-	+	-	-	-	+	-	+	-	-
Cr.....	-	+	+	-	-	+	-	+	+	-
Cu(A).....	-	+	-	-	-	+	-	+	-	-
Cu.....	-	+	-	-	-	+	-	+	-	-
Y.....	-	+	-	-	-	-	-	+	+	-
Pb.....	+	+	+	+	+	-	-	-	+	-
Ni.....	-	+	-	+	-	+	-	+	+	-
Co.....	-	+	-	-	-	+	-	+	-	-
Be.....	-	-	-	-	-	+	-	-	-	-
Ag(A).....	+	-	-	-	-	-	+	+	-	+
Hg(A).....	+	-	+	-	+	+	+	+	-	+
Au(A).....	0	+	-	-	-	+	-	+	-	+

between the geometric mean for each metal in each of the 10 subdivisions and the formation geometric mean for that metal. Nonparametric relationship as used here means one which is not defined by numerical measurements. Nonparametric statistics have been described by Siegel (1956).

The sensings in the matrix for each metal were then compared with the sensings for every other metal. The number of agreements was divided by 10, and the result was labeled the coefficient of association. For example, the sensings of Ca and Fe agree in three of the 10 columns; the coefficient of association is three-tenths, or 0.3. The sensings of Sr and Zr agree in none of the columns, but for figure 9, column A, they are 0 and + respectively. The 0 used to indicate equality with the formation mean is, for convenience, assigned a value of one-half, so the coefficient of association for Sr and Zr becomes five-hundredths, or 0.05.

Table 8 shows the calculated nonparametric association coefficients. The statistical significance of such coefficients as these has not been previously established. The metal abundances originally compared are means rather than individual sample values, which has the effect of lowering the probability of significantly high association coefficients occurring by chance.

To establish a basis for defining significance limits, an experiment was done using 200 random single sensings to produce a 10 x 20 matrix similar to that shown in table 7. The sensings were obtained by assigning "plus" to even random numbers and "minus" to odd numbers. Theoretical coefficients were then computed. The resulting normal distribution of coefficients, with its mean at 0.5 by definition, was analyzed using probability paper. The significance levels estimated from the random distribution are as follows:

<i>Association coefficient</i>	<i>Significance level</i>
0.65.....	.90
.71.....	.95
.77.....	.98
.82.....	.99

On the basis of this estimate of significance and considering that means were used as already mentioned, coefficients of 0.80 or higher and 0.20 or lower in table 8 were assumed to be very highly significant, meaning that the probability is less than 0.01 that a coefficient of 0.80 or greater or 0.20 or less can occur by chance. Coefficients greater than 0.50 indicated positive relationships, and coefficients less than 0.50 indicate negative relationships.

Of the 67 significant coefficients of association listed in table 8, 56 are positive and only 11 are negative. Significant coefficients



for the elements Ca, Ag(A), Hg(A), and Sr are mostly negative. Discussion of geologic factors responsible for significant associations, both positive and negative, suggested by the coefficients in table 8, is based on previously reported petrologic relationships (Cadigan, 1971).

Proportions of major components of sedimentary rocks—for example, nondetrital minerals and detrital minerals—tend to be negatively related to each other; as one increases in proportion the other decreases. Statistically, this is referred to as the relation of components of a constant sum (Chayes, 1960). Of the metals in this study, only Ca could be classified as a major component; it is a constituent of calcite, gypsum, and dolomite, the most abundant cementing minerals in the Moenkopi. The other metals are, volumetrically, considerably less abundant and may be considered, for purposes of this report, as minor rock components, without inherent direct negative associations.

The significant negative correlations around Ca—Ti, Cr, Ni, and Ba—probably reflect indirectly the negative relationship between proportion of cement and proportion of detritus. Cr and Ni are assigned generally to the detrital fraction and specifically to the heavy mineral fraction which is concentrated chiefly in the very fine sand-sized or very coarse silt-sized particles.

Thus as Ca-bearing cements increase, the proportion of Ti-, Cr-, and Ni-bearing detritus decreases. Ba, on the other hand, occurs chiefly in barite, an interstitial cementing mineral. Petrographic relations suggest that barite replaces calcite in sandstones; thus the Ca-to-Ba negative correlation supports the petrographic interpretation and suggests that such replacement occurs only in detrital rocks and in proportion to the amount of detritus present.

The significant negative associations around Ag(A)—Ba, Zr, and Pb—are not discussed in this report because of the unreliability of the Ag(A) analytical results from samples that contain high proportions of calcite.

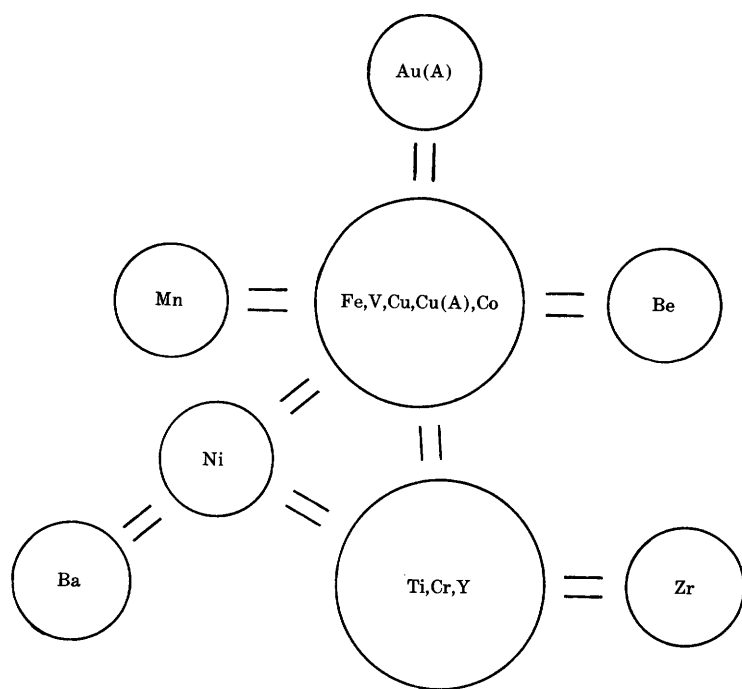
The significant negative associations around Hg(A)—Y, Pb, and Ni—are also suggestive of a negative relationship between nondetrital and detrital components. Hg(A) has a high positive but nonsignificant correlation with Ca which, together with abundances shown in figures 8 and 9, indicates that Hg(A) is more abundant in highly calcareous rocks than in detrital rocks. Rankama and Sahama (1950) noted that in a marine environment, clay minerals tend to concentrate Hg(A). This tendency would explain the preference of Hg(A) for both the clayey and the

calcareous marine sediments. Another association, illustrated in figure 8, column *G*, is that Hg(A) values are high in many samples collected near uranium deposits. Thus the high Hg(A) mean for the upper slope-forming and cliff-forming members is probably the effect of the presence of the uranium deposits and associated mineralizing solution activity at the top of the members in some localities.

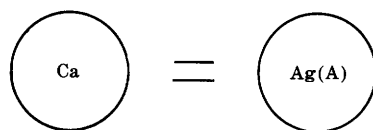
The negative association between Sr and Zr in light of the almost significant negative relationships of Sr to Ti, Cr, Pb, and Y seems at first glance to be another detrital-to-nondetrital relationship. Strangely, however, Sr, although noticeably high in marine and marginal marine sediments, shows only a random association with Ca in table 8. According to Rankama and Sahama (1950), Sr occurs most commonly as a sulfate in sedimentary rocks and may occur as a residual after the removal of aragonite or calcite by solution action. Evidence of such removal is present in crumpled, distorted clayey and fine siltstone strata in the Moenkopi. Sr, then, is not associated either positively or negatively with Ca cements. It has a sharp negative association with Zr and therefore with the heavy-mineral-bearing very fine sand and very coarse silt fraction. Sr thus is believed to occur in marginal marine evaporites and also in the clay and fine silt facies of terrestrial sedimentary rocks, both of which, in terms of proportions, would bear negative relationships to the Zr-bearing sand fractions.

Low coefficients of association (0.35 to 0.65) between any two metals that have strong mineralogic associations may be explained in terms of multiple modes of occurrence. For example, Ca and Mg are associated in cement-forming carbonate minerals, but Mg also occurs in certain detrital minerals that do not contain Ca, including the micas, their alteration product chlorite, and some of the quantitatively significant clay minerals. Thus, although Mg and Ca show strong positive association in the marine and marginal marine rocks (fig. 8, cols. *B* and *C*), the association is negative in terrestrial sediments (fig. 8, cols. *C*, *E*, *F*, and *G*).

Figure 10 illustrates the significant positive associations among 20 metals based on the coefficients shown in table 7. The largest group of interassociated metals comprises Fe, V, Cu, Cu(A), Co, Ti, Cr, Y, and Ni. These metals are subdivided as shown because other individual metals are associated separately in occurrence with the two major subgroups. Ni is associated with both subgroups and with Ba, which in turn is associated with no other metal. Au(A), Be, and Mn each appear to be associated individually with metals of the upper subgroup, and Zr is associated



ASSOCIATED METALS



PROBABLY ARTIFICIALLY ASSOCIATED METALS



UNASSOCIATED METALS

FIGURE 10.—Significant positive associations of metals in the Moenkopi Formation.

with metals of the lower subgroup. The grouping suggests that, in Moenkopi Formation rocks, Zr, Ti, Cr, and Y are principally detrital-controlled metals, and Fe, V, Cu, Cu(A), Co, Ni, Be, Au(A), and Mn are detrital- and solution-controlled metals.

Four metals, Mg, Sr, Pb, and Hg(A), show no significant positive associations. If the Ca-to-Ag relationship is manmade, then Ca also belongs down in the bottom row of circles in figure 10 as a metal lacking positive associations.

The apparently isolated significant positive association between Ba and Ni is not really isolated. High coefficients of association (0.70) suggest strong positive relationships between Ba and Fe, Ti, Mn, Zr, V, Cr, Y, and Co, which includes all the metals except Cu and Cu(A) to which Ni is significantly positively related.

Fe occurs commonly as a red oxide—an almost universal alteration product and rock-coloring pigment in the Moenkopi—and suggests itself as a metal very likely to be taken into solution by and redeposited from interstratal solutions. The significant positive associations with other metals, such as Cr, Y, and Ti, and through them with detrital-carried Zr suggest, however, that Fe and associated soluble metal ions do not migrate far from their original point of deposition. In other words, the red beds of the Moenkopi are colored by oxidized Fe from their contained Fe-bearing detritus.

Pb shows no significant positive associations possibly because of its multiple modes of occurrence. According to Rankama and Sahama (1950), Pb is high in granitic source rocks, easily removed in solution, subject to precipitation in alluvial environments, and, in sea water, concentrated in clays and in sulfate evaporites. Potentially, then, Pb could be present in detrital rock fragments, in interstitial precipitated minerals in terrestrial rocks, and in marine mudstones and in marginal marine evaporites, which, barring the possibility of contamination, may account for its relatively consistent abundance in most Moenkopi rocks.

#### TEXTURAL AND COMPOSITIONAL COMPARISONS

Possible relations between texture and metal content of sandstones, siltstones, mudstones, claystones, and limestones were investigated using sets of samples randomly selected from those for which textural data were available (Cadigan, 1971). Sample data are listed in table 9.

The metal content of six very coarse and coarse-grained sandstones and the geometric mean for each metal are shown in the first half of table 9. Grain size (median) and sorting (phi stand-

TABLE 9.—*Metal content (in parts per million) of randomly selected samples of very coarse, coarse, medium, fine, and very fine grained sandstones from Moenkopi Formation*

[Samples are listed in order of decreasing grain size from left to right. Geometric mean values are italicized for contrast. Values in parentheses are below detection levels; see discussion on p. 16. Analyses were by six-step spectrographic method, by J. L. Finley, except that analyses of the following were by atomic-absorption method: Cu(A) and Ag(A), by A. J. Toevs and Lucy Dickson; Hg(A), by W. W. Janes. Standard deviation and median grain diameter pertain to the phi grain-size distribution]

Very coarse and coarse grained sandstones							
Standard deviation (phi)	3.02	2.80	2.83	1.80	2.13	1.80	Geo-metric mean
Median grain diameter (mm)	1.55	1.30	1.18	0.97	0.64	0.53	
Field No.	L2617	L4763	L4764	L2545	L2629	L2627	
Laboratory No. (AA-)	B999	D080	D081	B982	B005	B003	
Ca	10,000	7,000	1,000	70,000	15,000	30,000	<i>15,780</i>
Fe	20,000	15,000	10,000	5,000	15,000	15,000	<i>12,250</i>
Mg	5,000	5,000	5,000	1,500	10,000	20,000	<i>5,785</i>
Ti	700	700	700	200	700	500	<i>537</i>
Ba	3,000	1,500	3,000	700	700	700	<i>1,291</i>
Mn	150	200	50	200	300	300	<i>173</i>
Sr	300	70	70	100	70	70	<i>95</i>
Zr	50	70	70	30	70	30	<i>50</i>
V	50	30	30	20	50	20	<i>31</i>
Cr	30	20	20	20	15	30	<i>22</i>
Cu(A)	12	12	12	25	15	32	<i>17</i>
Cu	5	5	7	2	5	3	<i>41</i>
Y	15	(5)	(5)	10	10	(5)	<i>76</i>
Pb	20	10	10	10	10	10	<i>11</i>
Ni	7	7	7	3	5	3	<i>50</i>
Co	5	7	5	(1.5)	7	5	<i>4.6</i>
Be	1.0	(.5)	(.5)	(.5)	(.5)	(.5)	<i>.56</i>
Ag(A)	.3	(.1)	(.1)	.4	.25	(.1)	<i>.18</i>
Hg(A)	.03	(.005)	.025	.06	.20	.05	<i>.036</i>
Au(A)	.02	(.01)	(.01)	(.01)	(.01)	(.01)	<i>.011</i>
Medium, fine, and very fine grained sandstones							
Standard deviation (phi)	1.96	2.16	1.73	2.08	1.76	1.65	Geo-metric mean
Median grain diameter (mm)	0.38	0.31	0.24	0.17	0.12	0.084	
Field No.	L2612	L3718	L1636	L1352	L1993	L3198	
Laboratory No. (AA-)	B994	D067	B845	B835	B910	D053	
Ca	10,000	15,000	50,000	30,000	30,000	10,000	<i>20178</i>
Fe	20,000	10,000	7,000	2,000	10,000	7,000	<i>7,622</i>
Mg	5,000	500	15,000	7,000	2,000	2,000	<i>3,188</i>
Ti	1,500	700	1,000	500	700	1,000	<i>846</i>
Ba	1,000	500	200	700	1,500	700	<i>647</i>
Mn	200	150	150	100	300	200	<i>173</i>
Sr	100	70	100	70	2,000	30	<i>120</i>
Zr	150	150	50	30	150	150	<i>96</i>
V	30	30	50	70	30	30	<i>38</i>
Cr	50	20	30	20	30	30	<i>29</i>
Cu(A)	27	12	60	125	(5)	42	<i>28</i>
Cu	10	7	15	70	10	5	<i>12</i>
Y	30	15	10	(5)	10	10	<i>11</i>
Pb	20	15	(5)	(5)	10	10	<i>10</i>
Ni	5	10	5	3	7	5	<i>5.5</i>
Co	7	10	(1.5)	(1.5)	3	3	<i>3.4</i>
Be	(.5)	(.5)	(.5)	(.5)	(.5)	(.5)	<i>.5</i>
Ag(A)	.25	.60	(.1)	.45	.35	.35	<i>.31</i>
Hg(A)	.16	.06	.40	.50	.09	.30	<i>.19</i>
Au(A)	.02	(.2)	(.01)	(.01)	.3	.01	<i>.015</i>

ard deviation) are given for each sample. Figure 11, column A, shows the comparison of the geometric means of the six samples with the geometric means of the Moenkopi as a whole. Major (order-of-magnitude) differences are those of the relatively high

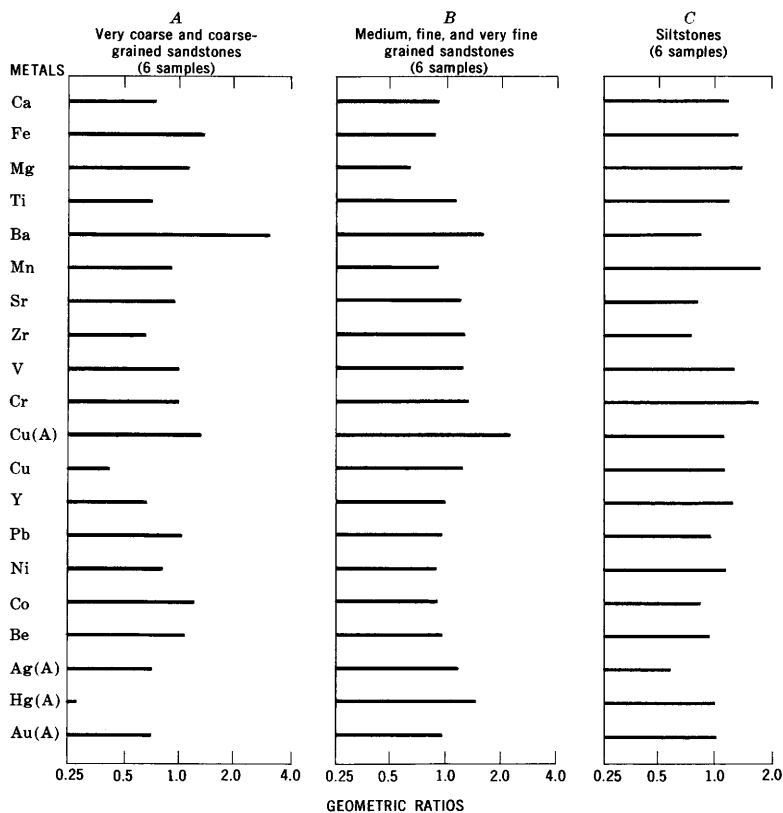
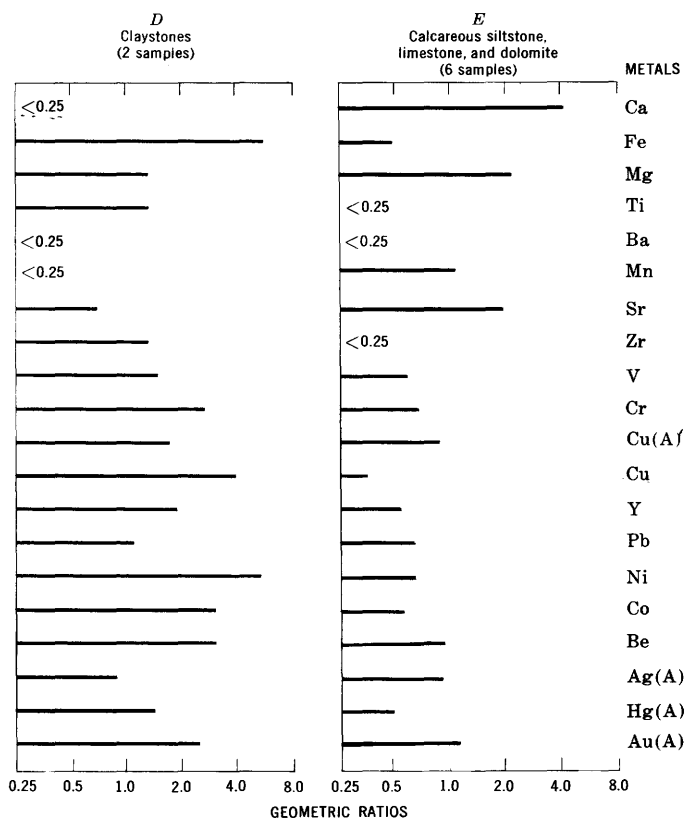


FIGURE 11.—Comparison of metal content of groups of samples having formation as shown in figure 8, column A. All

Ba and the relatively low Hg(A) in the coarse-grained fraction of the formation. Cu is low and Cu(A) is high, suggesting that results of the two analytical methods are not comparable for very coarse and coarse-grained sandstone.

The second half of table 9 lists the metal content of six medium, fine, and very fine grained sandstones. Figure 11, column B, shows the comparison of their geometric means to the formation as a whole; Cu(A) is an order of magnitude higher. Hg(A) and Cu are higher and Mg and Ba are notably lower in column B than in column A of figure 11.

Means for 14 of the 20 metals are higher in the medium, fine, and very fine grained sandstones than in the coarse-grained sandstones. Ten of these metals exceed the formation mean, compared with only eight of the metals in the coarser sandstones. These general increases in metal content are compatible with the petro-



different textures with average metal content of the entire values compared are geometric means.

graphic evidence that the fine and very fine sand sizes contain larger proportions of heavy minerals than do the coarser sizes.

Table 10 lists the metal content of six siltstones, ranging from coarse to very fine grained. Figure 11, column C, shows the comparison of their geometric means with the formation means. As in the medium to very fine grained sandstones (table 9), the metal content compared with the formation mean metal content shows no order-of-magnitude differences; 12 metals are higher and eight are lower. Mn and Cr are conspicuously higher. Mn is almost twice as high in the siltstones as it is in the two groups of sandstones.

Table 10 also lists the metal content of two claystones, and figure 11, column D, shows the comparison of their log means with the formation means. Several metals are higher—Cr, Cu, Co, Be, and Au(A) by one order of magnitude and Fe and Ni by

two orders of magnitude. Ca, Ba, and Mn are lower by two orders of magnitude.

A comparison of columns *A*, *B*, *C*, and *D* of figure 11 indicates that with decreasing grain size, Ti, V, Cr, Y, Ni, and Au show a persistent increase, Ba shows a persistent decrease, and Ca shows a small increase from column *A* through column *C* and an abrupt decrease in column *D*. Pb remains relatively constant.

Table 10 also lists the metal content of six samples of calcareous siltstone, limestone, and dolomite ranging in soluble carbonates from 50 to 97 percent. The metals Ti, Ba, Sr, Zr, V, and Cr decrease as the amount of soluble carbonates increases. A comparison of chemically determined percent solubles with spectrographically determined Ca and Mg shows poor correlation; in sample L3145, for example, spectrographically determined Ca, Mg, and Fe as carbonates would account for only 40 percent of the acid solubles. Figure 11, column *E*, shows the comparison of the geometric mean metal values of the carbonate rocks with the formation geometric means. Not surprisingly, Ca, Mg, and Sr are much higher, Mg and Ca by one and two orders of magnitude, respectively. Ti, Ba, Zr, Fe, Cu, and Hg(A) are low by one or more orders of magnitude. The carbonate rocks, compared with the formation as a whole, are significantly lower in metals.

Mudstones (poorly sorted siltstones and claystones) from the top of the Moenkopi in localities where uranium deposits are found in overlying rocks of the Chinle Formation vary widely in metal content. Table 11 lists the metal content in the only samples available from such rocks. These are compared in figure 12 with ordinary siltstones (from table 10 and fig. 11, col. *C*).

Metals that are one or more orders of magnitude more abundant in the mudstones than in siltstones, in order of decreasing differences from the siltstone means, are Cu, Cu(A), Y, Be, Sr, Ni, Co, Au(A), V, Ti, Fe, and Pb. Metals that are relatively low in amount are Ca, Mn, and Ag(A). Cu, specifically, is more than 30 times higher than both the siltstone average (fig. 12, col. *A*) and the formation average (fig. 8, col. *A*). Au(A) is more than five times as high as the formation average. The value of Ca is less than one thirty-second of the formation mean; the value of Mn is about one-fourth the formation mean. The high metal values are undoubtedly related both to rocks with higher-than-average heavy mineral content (note: Zr, Cr, and Ti) and to the overlying uranium deposits. The high Cu, Cu(A), Y, Sr, Ni, Co, Be, and Au(A) probably represent enrichment by metal-bearing solutions moving along the Chinle-Moenkopi contact.

TABLE 10.—*Metal content (in parts per million) of randomly selected samples of siltstones, claystones, and calcareous siltstones, limestones, and dolomites from the Moenkopi Formation*

[Samples are listed in order of decreasing grain size from left to right. Geometric mean values are italicized for contrast. Values in parentheses are below detection levels; values in brackets are above the upper detection limits; see discussion on p. 16. Analyses were by six-step spectrographic method, by J. L. Finley, except that analyses of the following were by atomic-absorption method: Cu(A) and Ag(A), by A. J. Toevs and Lucy Dickson; Hg(A), by W. W. Janes. Standard deviation and median grain size pertain to the phi grain-size distribution].

	Siltstones						Geometric mean
Standard deviation.....	2.19	1.78	1.57	2.16	2.67	1.96	
Median grain diameter (mm).....	0.062	0.044	0.030	0.022	0.013	0.0043	
Percent acid solubles.....							
Field No. ....	L1969	L1777	L2626	L1645	L1843	L1876	
Laboratory No. (AA-).....	B902	B876	D002	B854	B886	B897	
Ca.....	20,000	30,000	30,000	30,000	20,000	30,000	<i>26,207</i>
Fe.....	5,000	10,000	10,000	15,000	20,000	20,000	<i>12,009</i>
Mg.....	700	5,000	15,000	20,000	10,000	15,000	<i>7,349</i>
Ti.....	700	700	1,500	700	1,500	700	<i>902</i>
Ba.....	300	1,000	300	500	200	200	<i>349</i>
Mn.....	150	300	300	700	200	700	<i>331</i>
Sr.....	50	70	70	70	100	150	<i>80</i>
Zr.....	200	150	15	50	50	30	<i>57</i>
V.....	30	30	30	30	70	70	<i>40</i>
Cr.....	30	30	50	20	70	50	<i>38</i>
Cu(A).....	(.5)	25	18	25	30	(.5)	<i>14</i>
Cu.....	2	20	7	20	20	15	<i>11</i>
Y.....	15	15	10	15	15	15	<i>14</i>
Pb.....	10	10	10	(.5)	20	15	<i>10</i>
Ni.....	3	5	7	5	15	15	<i>7.0</i>
Co.....	(1.5)	(1.5)	3	3	7	7	<i>3.2</i>
Be.....	(.5)	(.5)	(.5)	(.5)	(.5)	(.5)	<i>.5</i>
Ag(A).....	(.1)	.35	.40	(.1)	(.1)	(.1)	<i>.15</i>
Hg(A).....	.10	.08	.05	.24	.26	.16	<i>.13</i>
Au(A).....	(.01)	.02	(.01)	.03	.03	(.01)	<i>.016</i>

TABLE 10.—*Metal content (in parts per million) of randomly selected samples of siltstones, claystones, and calcareous siltstones, limestones, and dolomites from the Moenkopi Formation—Continued*

	Claystones			Calcareous siltstones, limestones, and dolomites							
Standard deviation	2.20	2.08	Geometric mean								Geometric mean
Median grain diameter (mm)	0.004	0.0023									
Percent acid solubles											
Field No.	L2057	L1755		50.7	62.7	82.2	87.5	93.1	97.1		
Laboratory No. (AA-)	B918	B873	L2157 B933	L4776 D093	L2303 B954	L2150 B3932	L3152 B030	L3145 B025			
Ca	3,000	1,000	1,752	70,000	200,000	200,000	50,000	50,000	70,000	88,790	
Fe	30,000	70,000	45,825	7,000	3,000	2,000	3,000	3,000	7,000	4,283	
Mg	3,000	15,000	6,708	7,000	2,000	2,000	30,000	30,000	70,000	10,992	
Ti	2,000	2,000	2,000	700	700	300	50	50	50	162	
Ba	300	15	67	500	300	70	30	15	15	64	
Mn	70	30	46	500	300	200	100	70	300	199	
Sr	70	70	70	1,500	500	300	150	50	30	192	
Zr	70	150	102	70	20	30	(5)	(5)	(5)	13	
V	70	30	46	100	70	10	10	7	7	18	
Cr	50	70	59	30	50	10	50	5	3	16	
Cu(A)	25	20	22	(5)	25	27	(5)	22	(5)	11	
Cu	30	50	59	50	2	3	3	1	2	5.5	
Y	30	15	21	15	(5)	(5)	(5)	(5)	(5)	6.0	
Pb	15	10	12	(5)	(5)	30	(5)	(5)	(5)	6.7	
Ni	50	20	52	10	5	(1.5)	7	(1.5)	5	4.0	
Co	15	10	12	3	3	(1.5)	3	(1.5)	(1.5)	2.1	
Be	1.0	3.0	1.7	(.5)	(.5)	(.5)	(.5)	(.5)	(.5)	.5	
Ag (A)	.55	(.1)	.23	.6	.45	.55	(.1)	(.1)	(.1)	.28	
Hg (A)	.30	.12	.19	.14	(.005)	.10	.20	.12	.04	.064	
Au (A)	.20	(.01)	.04	(.01)	(.01)	(.01)	.02	.02	.06	.017	

TABLE 11.—*Metal content (in parts per million) of Moenkopi Formation mudstone samples collected from rocks underlying uranium deposits in the Chinle Formation*

[Samples are listed in order of decreasing grain size from left to right. Geometric mean values are italicized for contrast. Values in parentheses are below detection levels listed on p. 16. Analyses were by six-step spectrographic method, by J. L. Finley, except that analyses of the following were by atomic-absorption method: Cu(A) and Ag(A), by A. J. Toevs and Lucy Dickson; Hg(A), by W. W. Janes]

Standard deviation	2.33	1.97	2.24	2.11	Geometric mean
Median grain diameter (mm)	0.013	0.013	0.005	0.0036	
Sample No	L1813	L1814	L1826	L1827	
Ca	700	1,000	500	300	<i>569</i>
Fe	70,000	20,000	50,000	15,000	<i>32,010</i>
Mg	3,000	3,000	5,000	5,000	<i>3,873</i>
Ti	2,000	3,000	2,000	3,000	<i>2,449</i>
Ba	500	500	300	300	<i>387</i>
Mn	70	100	300	30	<i>89</i>
Sr	500	500	1,000	700	<i>647</i>
Zr	100	150	100	100	<i>111</i>
V	150	100	100	150	<i>122</i>
Cr	70	70	70	70	<i>70</i>
Cu(A)	250	1,100	950	35	<i>309</i>
Cu	200	700	700	200	<i>374</i>
Y	30	70	70	500	<i>93</i>
Pb	30	50	15	15	<i>24</i>
Ni	30	70	100	20	<i>45</i>
Co	10	100	70	3	<i>21</i>
Be	7	5	7	3	<i>5.2</i>
Ag(A)	(.1)	(.1)	(.1)	(.1)	<i>.1</i>
Hg(A)	.30	.55	.20	.11	<i>.25</i>
Au(A)	.06	.10	.46	.02	<i>.09</i>

## LOCALITY COMPARISONS

In order to select the localities that yielded samples with the highest proportion of high metal values, data on metal content of the 323 samples from the Moenkopi and related strata at 76 (reduced by "declustering" to 64) localities were sorted to obtain the sample localities containing the 32 highest values for each metal. Only analytically determined numerical values were used (for example, 30 values for Au(A) and 13 for Be). Adding available values for La, Mo, Nb, Sn, and W, not used previously in the study, the total number of values used in locality comparisons was 647. This number represents the approximate upper 10 per cent of values; it was chosen arbitrarily to reduce the values to be considered to a manageable number.

Using the number of high metal values found at each locality and the number of samples collected at each locality, it was possible to calculate the average number of high metal values per sample for each locality. These averages are shown as "values per sample" in table 12. Taking locality 60 in Arizona as an example, the four samples collected at this locality contain one

of the 32 high values for each of the metals Ca, Fe, Cr, Cu(A), Cu, Y, Pb, Co and Ag(A) and two of the high values for Mn and Ba. Dividing the total of 13 high values by the number of samples (four) yields the average number of high "values per sample," 3.25.

To refine the "values per sample" result, the metals were divided into "primary" metals, including Ca through Zr (see table 12) and "secondary" metals, V through Zn. This division was a rough device to remove the effects of (1) carbonate and sulfate-bearing minerals and (2) some metals strongly related to detrital heavy-

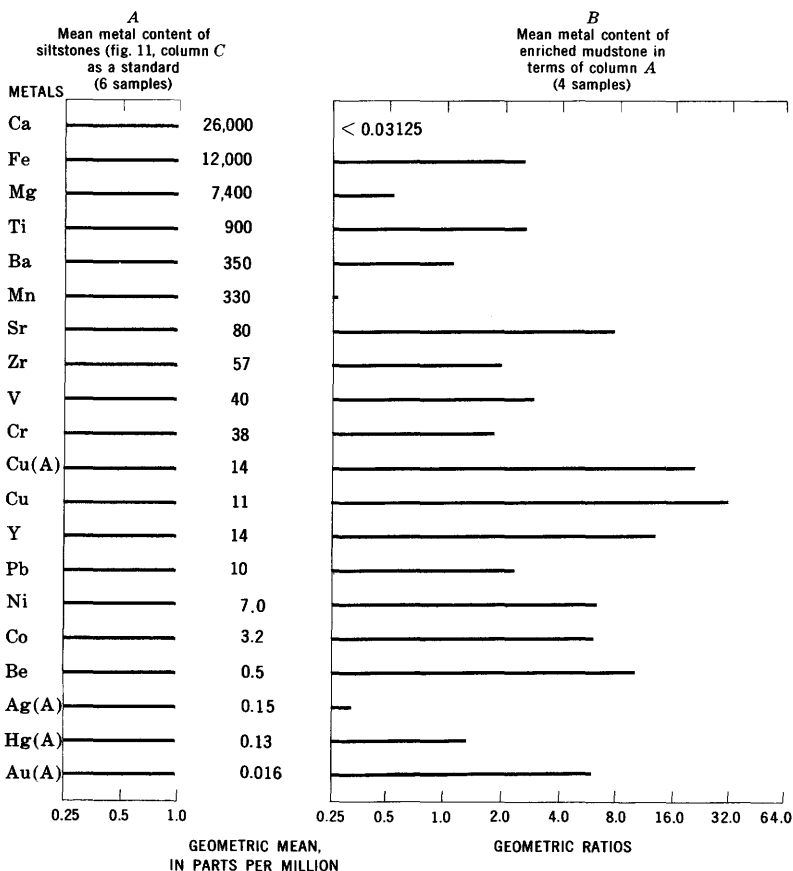


FIGURE 12.—Comparison of metal content of four metal-enriched mudstones with average metal content of the six siltstones of table 10 and figure 11, column C. All values compared are geometric means. A, Mean metal content of siltstones, table 10, used as a standard of comparison; B, mean metal content of metal-enriched mudstones, in terms of column A.

TABLE 12.—*Distribution by locality of the 32 highest values for each of the 20 metals used in the present study, and additional valid values available for La, Mo, Nb, Sn, and Zn*

[Leaders (....) in figure columns indicate an absence of high values of the metal in samples collected at the locality]

State.....	Arizona												Colorado									
Locality Nos. in table 4....	1	5	9	10	12	15	60	70	81	210	211	400 401 2	3	4	8	15	18	139 189 2	186	188	400	
Number of samples.....	3	2	5	3	3	5	4	4	4	5	4	2	2	2	6	18	4	2	1	2	17	
Primary sedimentary rock metals																						
Ca.....		1		1			1				1							1		1	1	
Fe.....			1				1								4		3					
Mg.....																	8				1	
Ti.....			1										1				3			1	2	
Mn.....						1		2	1				1				3				3	
Ba.....			1		1	1		2	1		1				1		5				1	
Sr.....								2								1					2	
Zr.....	1					1				1			1	1	1					1	1	
Secondary sedimentary rock metals																						
V.....										1	1					2					2	
Cr.....							1								1	2	1			1	2	
Cu(A).....							1		2	1	1	1			2						1	
Cu.....							1					1									3	
Y.....			2				1						1	1	1	1				1	1	
Pb.....					1		1								4						2	
Ni.....			1										1			2	1				3	
Co.....			1		1		1									1		1			1	
Be.....			1									1			1	1				1		
Ag (A).....				1			1						1			2				1	1	
Hg (A).....				1							3	1	1					1			1	
Au(A).....			1											1	1		1		1		1	
La.....															1	1				1		
Mo.....																						
Nb.....																						
Sn.....																						
Zn.....																						
Values per sample.....	0.0	0.5	2.2	1.67	1.0	0.2	3.25	1.0	0.5	0.6	1.75	2.0	3.5	1.5	3.0	1.89	0.75	1.5	1.0	4.0	1.71	
Secondary ratio.....	0	0	1.40	1.00	0.33	0	1.75	0	0.50	0.40	1.25	2.00	2.0	1.00	1.83	0.66	0.75	1.00	1.00	2.50	1.06	



State-----	Utah—Continued																					
Locality Nos. in table 4.	33	34 173 248	35	36	38	41	43 160	45	47	49 313 315	64	286	300	304	307	309 400	310	312	319	323	325 401	402
Number of samples.	3	10	5	2	6	2	6	2	18	17	10	1	2	1	5	8	3	2	1	1	9	5
Primary sedimentary rock metals—Continued																						
Ca-----		1					1		9		3				2		1	1				
Fe-----		1		2			1		1		2	2				3	2				1	
Mg-----							3		6		4						1					
Ti-----		2		2		1			1		2	2				4	1				1	
Mn-----		1					1	1	2		2				3			1	1		1	
Ba-----		1		2					2		1										2	1
Sr-----		1							6		4	5			1	4					1	1
Zr-----	1		2						2						1						3	1
Secondary sedimentary rock metals—Continued																						
V-----	1	1		2					2	3	2					4					2	1
Cr-----	1			2					2	1	1					4	2				1	
Cu(A)-----		2					1		1	2	6					3					1	1
Cu-----	1	1							3	3	1					4	3		1		1	
Y-----		3			1					1	2					4					3	
Pb-----	1	1		2			1		2	2	1				1	3					1	2
Ni-----		1			2				2							4	2				3	1
Co-----		1		3					1	1	1		1			3	2				1	
Be-----	1	1														4	1				1	
Ag(A)-----					1	1		1	8						2	1					2	1
Hg(A)-----	5		1				1		1	5	3					1					1	
Au(A)-----		1							2	1		1			2	2		1				
La-----	1	1								1						4	1				1	
Mo-----									1							2						
Nb-----				3																		
Sn-----																					1	
Zn-----																1						
Values per sample--	1.0	1.0	4.60	1.50	3.50	1.00	1.5	1.0	2.89	1.82	3.5	1.0	0.5	0.0	2.4	6.88	5.33	1.5	2.0	0.0	3.11	1.5
Secondary ratio----	0.67	0.90	3.00	0.50	2.67	0.50	0.50	0.50	1.28	1.29	1.70	1.00	0.50	0	1.00	5.50	3.67	0.5	1.0	0	2.11	1.2

mineral suites, and to obtain a ratio weighted in favor of the higher values of rarer metals. This ratio, designated the "secondary ratio" (table 12) was computed using only the secondary metals and the number of samples. In the example of locality 60, there are seven "secondary" metals, which divided by the number of samples (four) yields a "secondary ratio" of 1.75.

The calculations of the "values per sample" and the "secondary ratio" were made to obtain numerical measures which can be used to rank the sample localities in terms of high metal occurrence. In table 13, the 16 localities (upper quartile) with the highest

TABLE 13.—*Localities that contain the 16 highest values per sample, and 16 highest secondary metals ratios*

[Localities are listed in approximate order of highest to lowest ratios. Locality names and numbers (in parentheses) are those listed in table 4]

Localities that contain 16 highest values per sample	Localities that contain 16 highest secondary ratios
*Deer Flat, Utah (309)	*Deer Flat, Utah (309)
**Mineral Canyon, Utah (310)	**Mineral Canyon, Utah (310)
North Sixshooter Peak, Utah (35)	North Sixshooter Peak, Utah (35)
Skull Creek, Colo. (188)	Steer Mesa, Utah (38)
Steer Mesa, Utah (38)	Skull Creek, Colo. (188)
Pleasant Creek, Utah (64)	**Silver Falls, Utah (14)
Sheephorn Creek, Colo. (3)	**Shinarump No. 1 mine, Utah (401)
Holbrook, Ariz. (60)	Sheephorn Creek, Colo. (3)
*Shinarump No. 1 mine, Utah (401)	**Nokai Dome, Ariz. (401)
Lockhart Canyon, Utah (32)	Lockhart Canyon, Utah (32)
St. George "A," Utah (47)	Gateway (The Palisade), Colo. (8)
Horse Spring Valley, Nev. (1)	Holbrook, Ariz. (60)
**Silver Falls, Utah (14)	Pleasant Creek, Utah (64)
Farm Creek, Utah (307)	Hite, Utah (29)
Hite, Utah (29)	Comb Wash, Utah (27)
Kanarraville "A," Utah (22)	Horse Spring Valley, Nev. (1)

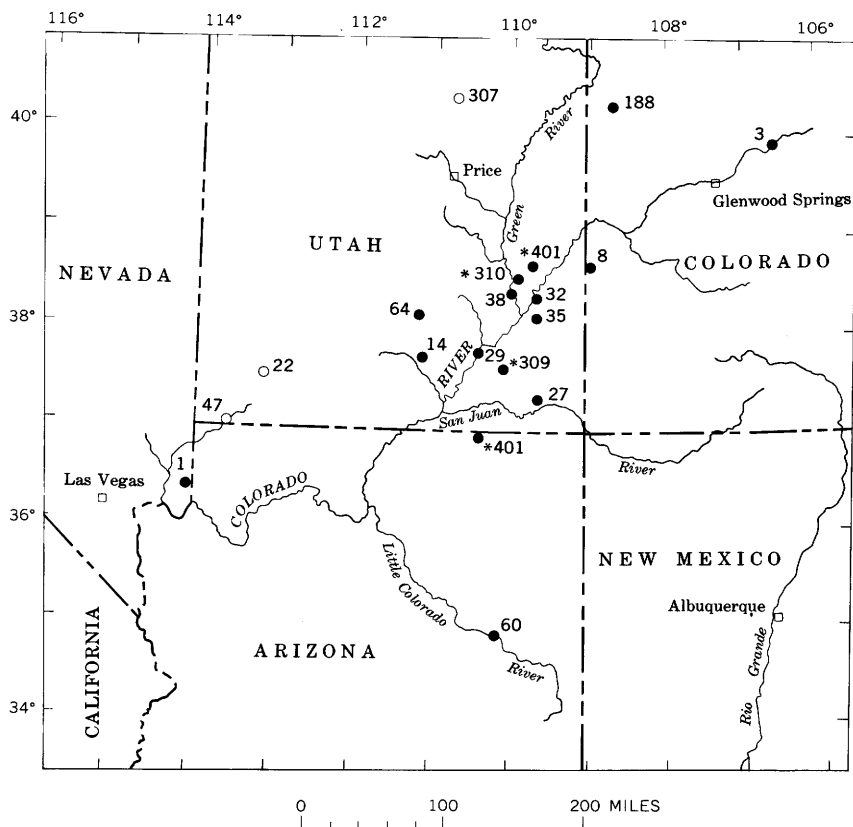
\*Mine nearby.

\*\*Mining activity in area.

"value per sample" measures and with the highest "secondary ratio" measures are listed separately and in order of decreasing amounts. The secondary metals list contains three localities different from the total metals list. All 20 localities are shown in figure 13.

#### GOLD

Surprisingly, 101 samples from the Moenkopi Formation contain Au(A) detectable at the 0.02-ppm detection level. The Tenderfoot Member is slightly high in Au(A), and the Hoskinnini, Holbrook, and Wupatki Members and lower red member are slightly low. Au(A) is definitely high in the metal-enriched mudstones below the Chinle-Moenkopi contact and in some localities



## EXPLANATION

○  
Sample locality having one of 16 highest  
metal values per sample

*Based on primary plus secondary sedimentary-rock-metals content (tables 12 and 13)*

22  
Sample locality number, by State

\*  
Known uranium deposits in close vicinity

●  
Sample locality having one of 16 highest  
metal secondary ratios

*Based on secondary sedimentary-rock-metals content (tables 12 and 13)*

*With the exception of localities 8 (Colorado), 27 (Utah), and 401 (Arizona), these are also sample localities having one of 16 highest metal values per sample*

FIGURE 13.—Sample localities having the largest average number of high metal values per sample. Data from tables 12 and 13. Sample locality numbers are those listed in table 4.

below known uranium deposits. It is high in claystones and low in coarse sandstones. Au(A) was found to have a significant positive geochemical association with Fe, Cu, Cu(A), V, and Co in Moenkopi rocks (fig. 10). The highest detected amount of

Au(A), 0.70 ppm, is in a limestone (Thaynes Formation) sample from Farm Creek, Utah (locality 307). Because of the highly censored nature of the Au distribution, I could not compute statistical measures that would show the full range of variation in Au values among different members, facies, and textures.

A chi-square test of the regional distribution of the samples containing detectable Au(A) using a previously described method (Cadigan, 1962) and seven arbitrarily selected areas yielded a probability of randomness of less than 0.01, an indication that the regional distribution of Au(A) in the Moenkopi is not random. The main source of deviations from randomness resulted from a deficiency of Au(A) in the salt anticline area in the southeastern Utah-southwestern Colorado border area and an excess of Au(A) in the area including the southern and southeastern flanks of the Uinta Mountains uplift and associated structures in northeastern Utah and northwestern Colorado.

### SUMMARY AND CONCLUSIONS

The Moenkopi Formation of Triassic(?) and Early and Middle Triassic age and contiguous lithologically related strata constitute one of the red-bed units of the Colorado Plateau region. The Moenkopi is the basal unit of the Triassic stratigraphic sequence in the west two-thirds of the region. Unconformities are present at the lower contacts with several different Permian formations and at its upper contact with the Chinle Formation.

The Moenkopi was deposited on a slowly subsiding plain within environments which ranged from alluvial on the east to marine on the west. Tectonic activity in the source areas, the Uncompahgre highland of Colorado, and highlands in southern Arizona and New Mexico ranged from quiescence to slow uplift. Minor volcanic activity occurred in the western Uncompahgre highland and in highlands in what is now the southern Arizona-New Mexico border area.

Lack of sediment from the source areas during periods of quiescence allowed marine environments to migrate eastward across the subsiding plain into the central parts of the region. The marine invasions are marked by the presence of marine clastic limestones and by marginal marine gypsum evaporite deposits, particularly in the western part of the region.

The Moenkopi is composed of sediments eroded from relatively low-lying weathered terranes of granitic, low-grade metamorphic, sedimentary, and minor volcanic rocks, and of marginal marine gypsum deposits and marine limestones. Diagenetic changes oc-

curred which probably further altered many of the detrital minerals, particularly the feldspars and the ferromagnesian "heavy" minerals. Most of the clays are recrystallized and represent the combined products of alteration in the source area and post-depositional diagenesis.

The Moenkopi has been divided into numerous members, none of which is recognized as extending throughout the region. Each seems to be related to a specific source area or to an interval of marine or marginal marine deposition. The members are generally conformable.

The analytical data for this study were obtained from 323 rock samples from 64 localities. Data were sought on 33 metals. Analyses were done by the six-step spectrographic method for 32 of the metals and by atomic-absorption methods for four of the metals—gold, silver, copper, and mercury. Sufficient valid data for statistical analysis were obtained for only 18 metals (counting spectrographic and atomic-absorption analyses for copper as two different metals). Gold and beryllium data are severely censored and most of the samples contain amounts below the level of detection, but, because of special interest in these metals, they are considered in addition to the other 18 metals in the statistical study.

The 20 sets of metal values used in the study are, in order of geometric mean abundance in the Moenkopi Formation as a whole, Ca, Fe, Mg, Ti, Ba, Mn, Sr, Zr, V, Cr, Cu(A), Cu, Y, Pb, Ni, Co, Be, Ag(A), Hg(A), and Au(A).

The statistical distributions of 13 metal values are essentially log normal and five (Ni, Sr, Mg, Ba, and Cr) are not. Pb, Be, and Y distributions exhibit the lowest variances, and Zr, Cu(A), Cu, Hg(A), Ca, Mg, and Ba, the highest.

Metal content in the Moenkopi and related lithologic units varies significantly, mainly because of the difference in source of rock components. Largest differences observed are between units derived predominantly from a marine source (the sea) and units derived predominantly from terrestrial sources. Metal content of the marine and marginal marine members of the Moenkopi (the Shnabkaib, Virgin, Sinbad, Timpoweap, and lower red) and of the Thaynes Formation, compared with geometric means of metals in the Moenkopi Formation as a whole, is markedly and significantly low. The characteristic exceptions are much higher values for Ca, Mg, and Sr. Individual metals that are lower in marine rocks by approximately an order of magnitude

are Fe, Ti, Ba, Mn, Zr, V, Cr, Ni, and Co. These metals are derived chiefly from terrestrial sources.

The next lower order of differences in metal content among members was related to different terrestrial sources. These differences were observed specifically between the Tenderfoot Member and the Holbrook and Wupatki Members and between the Tenderfoot and Hoskinnini Members.

The Tenderfoot Member, a continental alluvial arkosic lithologic unit, was derived from the western slope of the Uncompahgre highland in western Colorado. The Holbrook and Wupatki Members are continental alluvial units derived from the southern highland sources of Arizona and New Mexico. The metal content of the Tenderfoot is conspicuously and significantly higher than that of the other two members. Mg is higher in the Tenderfoot by more than two orders of magnitude, an indication of a major difference in composition between the two terrestrial source areas.

The Hoskinnini Member, also a continental alluvial arkosic unit, was derived from sources in southwestern Colorado and northern Arizona. Compared with the Tenderfoot Member, it is significantly lower in metal content, but abundances of individual metals for both units fall into the same order of magnitude. Differences are attributed to minor differences between similar sources. Compared with the formation geometric means, the Hoskinnini is slightly but significantly lower and the Holbrook and Wupatki are markedly and significantly lower in metal content. The Tenderfoot is slightly but significantly higher.

A third order of differences in metal content among the units was related to metal contributions by interstratal solutions. These differences were observed specifically in comparisons of the geometric mean metal values of the upper slope-forming and cliff-forming members with those of the Moenkopi as a whole, and with the Tenderfoot and Hoskinnini Members. The upper slope-forming and cliff-forming members were derived from the same sources as the Tenderfoot and Hoskinnini; they are significantly higher in metal content than both the formation as a whole and the Hoskinnini. They are not significantly higher in metal content than the Tenderfoot, but they are conspicuously higher in specific metals that are related to ore deposits in the overlying Chinle Formation. The metals with higher-than-expected abundances are: Cu(A), Cu, Co, Hg(A), V, and Sr. Increments of these metals were contributed to the upper strata of the upper slope-forming and cliff-forming members by solutions migrating

along the overlying unconformity between the Moenkopi and Chinle Formations.

A fourth order of difference is that which occurs within the units and which is attributed to variation in facies. Facies are defined in terms of a combination of particle size and composition. Comparisons were made among the siltstone-sandstone facies (the dominant one), the sandstone facies, the limestone-evaporite facies, and the Moenkopi and related lithologic units as a whole. The siltstone-sandstone facies is significantly higher in metal content than all the units as a whole, and higher but not significantly so than the other two facies. No magnitude differences exist for individual metal abundances among all the units as a whole, the sandstone-siltstone facies, and the sandstone facies. Magnitude differences in metal content between the limestone-evaporite facies and the other facies occur, but they are differences related to the marine source of the limestone-evaporite facies rather than to variation in only particle size and composition.

Comparisons among four groups of samples, representing coarse sandstones, fine sandstones, siltstones, and claystones, show decreases in Ba with decrease in grain size, and gradational increases in Ti, V, Cr, Y, Ni, and Au. The gradational increases are the result of increasing proportions of heavy minerals which, in the Moenkopi, show greatest concentration in the very fine sand and very coarse silt sizes. In a suite of rocks composed of 50–97 percent carbonates, Sr, Ti, Ba, Zr, V, and Cr decrease in quantity as percent carbonates increase. Mg shows an increasing trend; Ca values should show an increasing trend, but they do not because proportions exceed the discriminating capability of the analytical method. Y, Pb, Be, Au, Ni, and Co were present in quantities too close to their detection level to show any trend.

Coefficients of association computed for all possible pairs of the 20 metals studied contain 11 significant negative coefficients and 56 significant positive ones. The negative associations around the metals Ca, Ag(A), Hg(A), and Sr are related directly or indirectly to a major negative relationship of proportion of marine sediments to proportion of terrestrial sediments.

The significant positive coefficients come from 14 metals which form a positively associated group: Fe, V, Cu, Cu(A), Co, Ti, Cr, Y, Ni, Ba, Zr, Mn, Be, and Au(A); these, with the exception of Ba, are related directly or indirectly to sediments derived from terrestrial sources. All were probably contained in the original detrital heavy minerals. Mg, Sr, Pb, Hg(A), and possibly Ca form

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the 1990s, the number of people in the UK who are employed in the public sector has increased by 1.5 million, from 2.5 million in 1980 to 4 million in 1995. The public sector has become a major employer in the UK, and its growth has been a key factor in the overall growth of the economy.

The public sector has also become a major provider of social services, and its growth has been a key factor in the overall growth of the economy. The public sector has become a major employer in the UK, and its growth has been a key factor in the overall growth of the economy.

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