Geochemical Anomalies and Alteration in the Moenkopi Formation, Skull Creek, Moffat County, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 761

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By R. A. CADIGAN

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Geologic and geochemical reconnaissance of a formation and an area containing significantly higher background metal values than are commonly found elsewhere in the Colorado Plateau region

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GEOCHEMICAL ANOMALIES AND ALTERATION IN THE MOENKOPI FORMATION AT SKULL CREEK, MOFFAT COUNTY, COLORADO

By Robert A. Cadigan

ABSTRACT

The Moenkopi Formation of Triassic age exposed in the scarp encircling Skull Creek anticline in Moffat County, Colo., contains a thick altered layer of greenish-gray siltstone which is overlain by reddish-brown siltstone in most localities. Metal content of both the red and the altered rocks in the Skull Creek area is significantly higher than the geometric mean of metal content of Moenkopi strata in the Colorado Plateau region as a whole.

A very thin zone of enrichment at the upper contact of the green altered rock with the overlying red rock contains anomalous amounts of copper (100–5,000 parts per million) and other metals. Samples from the enriched zone are at least four times higher than the Moenkopi averages in contents of vanadium, chromium, copper, nickel, cobalt, silver, lanthanum, and boron.

Mercury is present in anomalously high amounts (geometric mean of all analyses, 2 ppm; maximum, >10 ppm) in the altered Moenkopi exposed in the southeastern erosion scarp area, the only area where the Moenkopi is completely altered. No enriched zone was found there.

Other anomalous occurrences of mineralization and alteration include a copper-uranium deposit in the base of the Jurassic Curtis Formation, conspicuous alteration in the Triassic Gartra Member of the Chinle, sulfide minerals containing anomalous amounts of arsenic, lead, and zinc in the top of the Pennsylvanian and Permian Weber Sandstone and in joints in the Triassic and Jurassic Glen Canyon Sandstone and the Chinle Formation, and anomalously high values of chromium, vanadium, gold, and silver at one locality in the Gartra Member.

Factor analysis of measurements of metal content of the enrichment zone suggests two major events: (1) Invasion of the rocks by metal-bearing solutions and alteration of part of the Moenkopi, and (2) an interaction at the contact between the red rocks which represent an oxidized environment and the green rocks which represent an invading reducing environment. This interaction results in a thin zone of enrichment of leached and redeposited metals—mercury, copper, silver, uranium, and gold—at the geochemical interface.

The area is recommended for further geochemical exploration.

INTRODUCTION

During investigation of the distribution of metallic elements in the Moenkopi Formation in the Colorado Plateau region (Cadigan, 1971a), anomalous concentrations of some metals, particularly copper and mercury, were found in samples from the Skull Creek anticline in the extreme northwestern part of Colorado. Field studies and further sampling in 1969–70 established the presence of geochemical anomalies in the area as a whole, of which the most conspicuous was a copper anomaly associated with bodies of pale-greenish-gray rocks within the normally red strata of the Moenkopi in the scarp surrounding the anticline. The metal anomalies and abnormal color relationships suggest epigenetic alteration of the formation in this area.

Skull Creek anticline (fig. 1) is in the northern part of the Colorado Plateau region, north of the settlement of Skull Creek, Colo. The area is shown on the U.S. Geological Survey's 7½-minute quadrangle maps, Lazy Y Point and Skull Creek, Colo., and occupies all of T. 4 N., R. 101 W., and parts of adjacent townships. It is approximately 11 miles (18 kilometers) northeast of the Rangely oil field. Unimproved roads, passable only in dry weather, lead into the central part of the anticline from U.S. Highway 40. Four-wheel-drive vehicles are recommended for off-highway use in the area.

GEOLOGY

STRATIGRAPHY

Rocks exposed in Skull Creek anticline range in age from Pennsylvanian to Cretaceous. Table 1 summarizes the stratigraphic column. Thickness and descriptive data are adapted from Thomas, McCann, and Raman (1945); those data for the Moenkopi Formation are somewhat modified on the basis of the

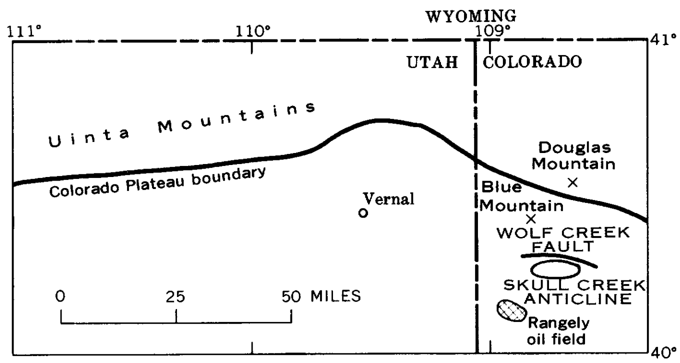


Figure 1.—Index map of the northern part of the Colorado Plateau region.

work by Schell and Yochelson (1966), who redefined the contact between the Moenkopi and Park City Formations, and by F. G. Poole (oral and written commun., 1969), who described and measured a section through the Moenkopi at Skull Creek.

The uppermost unit of the Park City Formation is exposed in the base of the southern scarp face west of Miller Creek water gap where the upper contact crosses the section line between secs. 28 and 29, T. 4 N., R. 101 W. This unit is a limestone 4 inches (10 centimeters) thick which lies at the top of the tawny beds of Schell and Yochelson (1966) and which is overlain by reddish-brown siltstone strata assigned to the Moenkopi Formation. Light-colored strata above this contact are related to color changes within the Moenkopi Formation.

The base of the Moenkopi is covered by alluvial wash in most of the anticline area, but the rest of the formation is well exposed. The upper contact of the Moenkopi with the Gartra Member of the Chinle Formation is marked by the conspicuous coarse-grained, resistant, ledge-forming sandstone strata of the Gartra. The Moenkopi contains some resistant, thin calcareous very fine grained sandstone beds, but poorly resistant, coarse-grained siltstone strata predominate, as suggested by the exposures shown in figure 2.

STRUCTURE

Skull Creek anticline is an asymmetrical structural feature—almost monoclinal—on the southeastern flank of the Uinta Mountains structural system (Ritzma, 1956). Its southern limb dips more steeply (20°–45°) than the northern limb (2°–5°). The anticlinal axis arcs from a west-east orientation to a northwest-southeast orientation in the area of the study with the concave side of the axis to the south. This arc produces a structural feature which has been called Skull Creek dome (Rocky Mountain Association of Petroleum Geologists, 1941).

The Skull Creek anticline is an excellent example of a breached anticline. Throughout an area (fig. 3) 12 miles (19 km) long and 6 miles (10 km) wide, it has been eroded down to the Weber Sandstone which forms a broad slightly to moderately dissected domed surface. An erosional scarp which has a perimeter of approximately 30 miles (48 km) and which encircles the exposed Weber Sandstone is cut in the Park City,

TABLE 1.—*Stratigraphic units present in the Skull Creek anticline area*

Period and unit	Thickness (ft)	General description
Cretaceous:		
Mancos Shale	5,000	Gray to black carbonaceous marine siltstone with minor calcareous beds and lenticular sandstone strata.
Frontier Sandstone Member	300	Thick- and thin-bedded gray sandstone interbedded with gray to black carbonaceous siltstone.
Mowry Member	50	Hard dark-gray to black siliceous shale weathering to light ash-gray chips.
Dakota Sandstone	50	Resistant thick-bedded brownish-gray-weathering sandstone; characteristically forms prominent massive beds.
Burro Canyon(?) Formation	50	Green to varigated gray-green and purple siltstone upper unit and a thick-bedded light-gray conglomeratic sandstone lower unit.
Jurassic:		
Morrison Formation	675	Variegated green-gray, and maroon siltstone upper part, and a thick crossbedded, fine-grained, white sandstone lower part.
Curtis Formation	115	Thin-bedded gray shale, platy glauconitic brownish-gray very fine grained sandstone; abundant *Belemnite* fragments.
Entrada Sandstone	175	Massive thick-bedded light-gray very fine to fine-grained sandstone; forms high rounded cliffs: glauconite in upper part.
Carmel(?) Formation	25	Pinches out in area; reddish-brown silty sandstone.
Jurassic and Triassic:		
Glen Canyon Sandstone [1]	540	Spectacularly crossbedded massive thick-bedded fine-grained sandstone; forms high, bare dome-shaped buttes.
Triassic:		
Chinle Formation	250	Red calcareous siltstone, very fine grained red sandstone and lime-pellet conglomerate.
Gartra Member	20	Basal conglomerate of the Chinle, white conspicuous ledge, medium-grained conglomeratic sandstone; hematite-impregnated.
Moenkopi Formation	525	Reddish-brown to grayish-green regularly bedded micaceous coarse siltstone and very fine grained sandstone; red color absent locally.
Permian:		
Park City Formation	220	Grayish-orange and yellowish-brown siltstone (the tawny beds of Schell and Yochelson, 1966) underlain by gray very fine grained calcareous sandstone.
Permian and Pennsylvanian:		
Weber Sandstone	975	Massive crossbedded thick-bedded gray fine-grained sandstone; forms steep-walled canyons, rocky tree-covered slopes.

[1] Called the Navajo Sandstone by Thomas, McCann, and Raman (1945); renamed by Poole and Stewart (1964) on the basis of regional stratigraphic relationships.

FIGURE 2.—Interior valley of the Skull Creek breached anticline, viewed northwestward. Jcu, basal sandstone of Curtis Formation; Je, Entrada Sandstone; JTRg, Glen Canyon Sandstone; TRc, Chinle Formation; TRm, Moenkopi Formation; Ppc, Park City Formation; PIPw, Weber Sandstone. White strata in the left foreground and in the distant scarp are altered rocks in the Moenkopi Formation. Skull Creek is in the center foreground in the arroyo which is cut in thick valley alluvium. The Carmel(?) Formation, which occurs discontinuously between the Entrada and Glen Canyon Sandstones, was observed in lenses as much as 10 feet thick in two exposures in the south scarp. Neither exposure is visible in this photograph.

Moenkopi, and Chinle Formations, and in the rim-forming Glen Canyon Sandstone. Succeeding concentric hogbacks which are present only on the southern steeply dipping limb are (1) the Entrada Sandstone rimmed by the resistant basal sandstone of the Curtis Formation, (2) the persistent ledge-forming Dakota Sandstone, and (3) the Frontier Sandstone Member of the Mancos Shale.

The east-striking Wolf Creek fault (fig. 1), a steeply dipping thrust fault related to the Uinta Mountains structural complex, borders the northern limb of the anticline (W. R. Hansen, oral commun., 1970). Numerous fault and joint systems striking generally from north to east may be observed within the anticline, but only minor displacement is evident. Displacement of hogback ridges south of Miller Creek water gap, apparent in aerial photographs, suggests the presence of an important fault occurring in conjunction with a sharp fold. Some fault traces in the western part of the anticline converge on a broad center near Red Wash water gap; this convergence suggests fracturing in response to localized stress. Major open faults, some of which are shown in figure 3, and major systems of parallel joints trending between northeast and east cut the Weber Sandstone in the core of the anticline. Erosion along the northeast-trending zones of weakness has produced fairly straight narrow deep box canyons in the Weber Sandstone and in the rocks forming the south slope of the southern limb of the anticline. All drainage from the anticline is to the south. Subsequent interior drainage parallels the scarp surrounding the core, particularly on the southern and eastern edges where deposits of reddish-brown alluvial sediment and loess up to 30 feet in thickness are deeply incised. The alluvial fill extends southward through the three major water gaps in the southern scarp, Skull Creek, Miller Creek, and Red Wash, and into the flatlands south of the anticline.

MINERAL OCCURRENCES AND MINING ACTIVITY

The Skull Creek anticline area and the region to the north have been prospected extensively since the 1870's and have been the source of some mineral production. The Douglas Mountain district that is approximately 20 miles north of the Skull Creek area has a record of some copper and silver ore production (200 ± tons) from 1873 to 1947 (Vanderwilt, 1947, p. 144). Records in the Moffat County Clerk's office describe a considerable amount of prospecting and claim staking in the Blue Mountain area between Skull Creek and Douglas Mountain from 1870 until much of the Blue Mountain area was incorporated into the Dinosaur National Monument in 1938.

During the early 1900's, high-grade radium ore was mined from the base of the Curtis Formation in the south limb of the Skull Creek anticline (N½ sec. 35, T. 4 N., R. 101 W.; fig. 3). The deposit was mined for vanadium from 1917 to 1920 and finally, for uranium in the 1950's. According to Isachsen (1955), the ore occurred in carbonized plant-bearing mudstone and

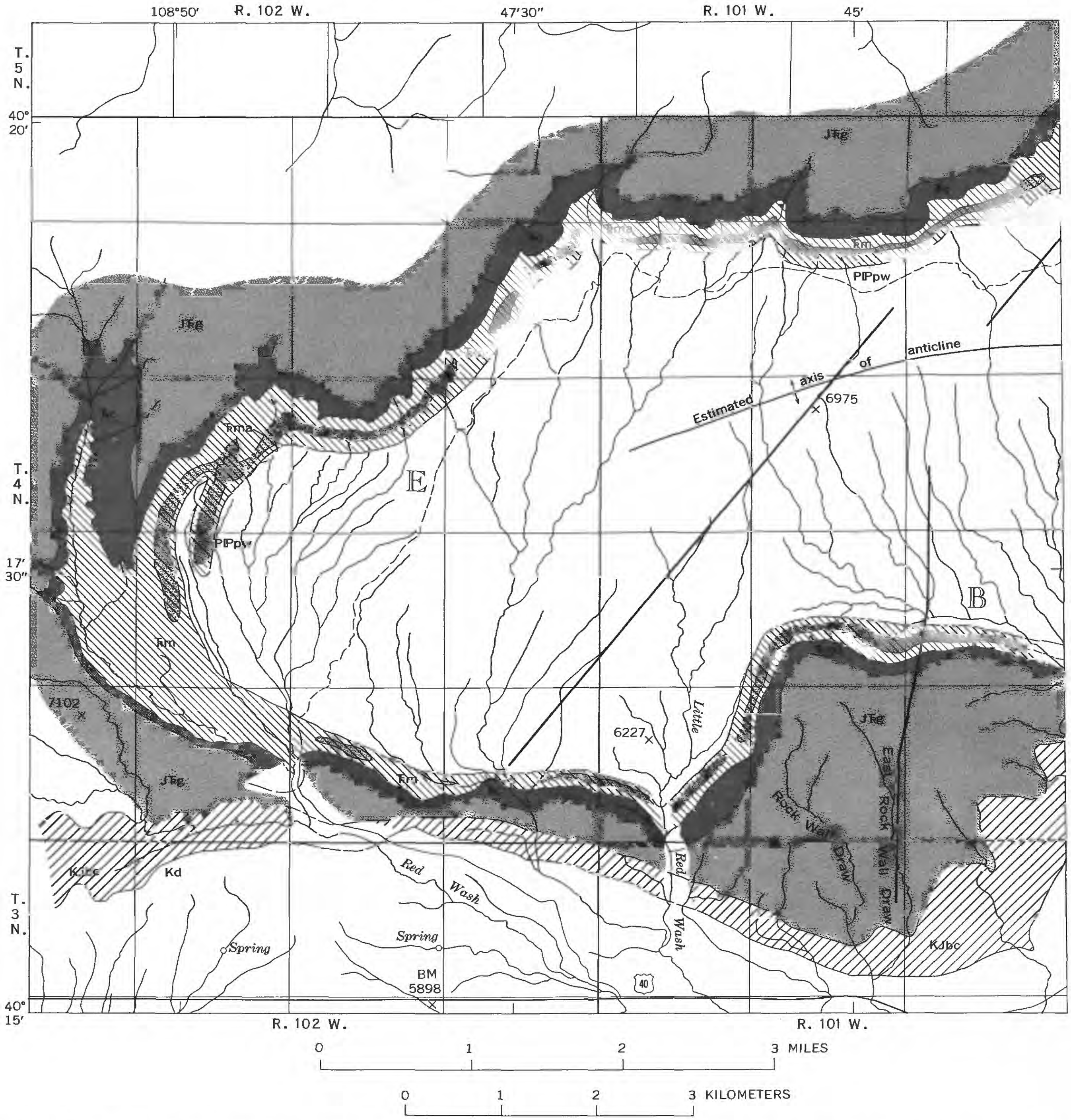
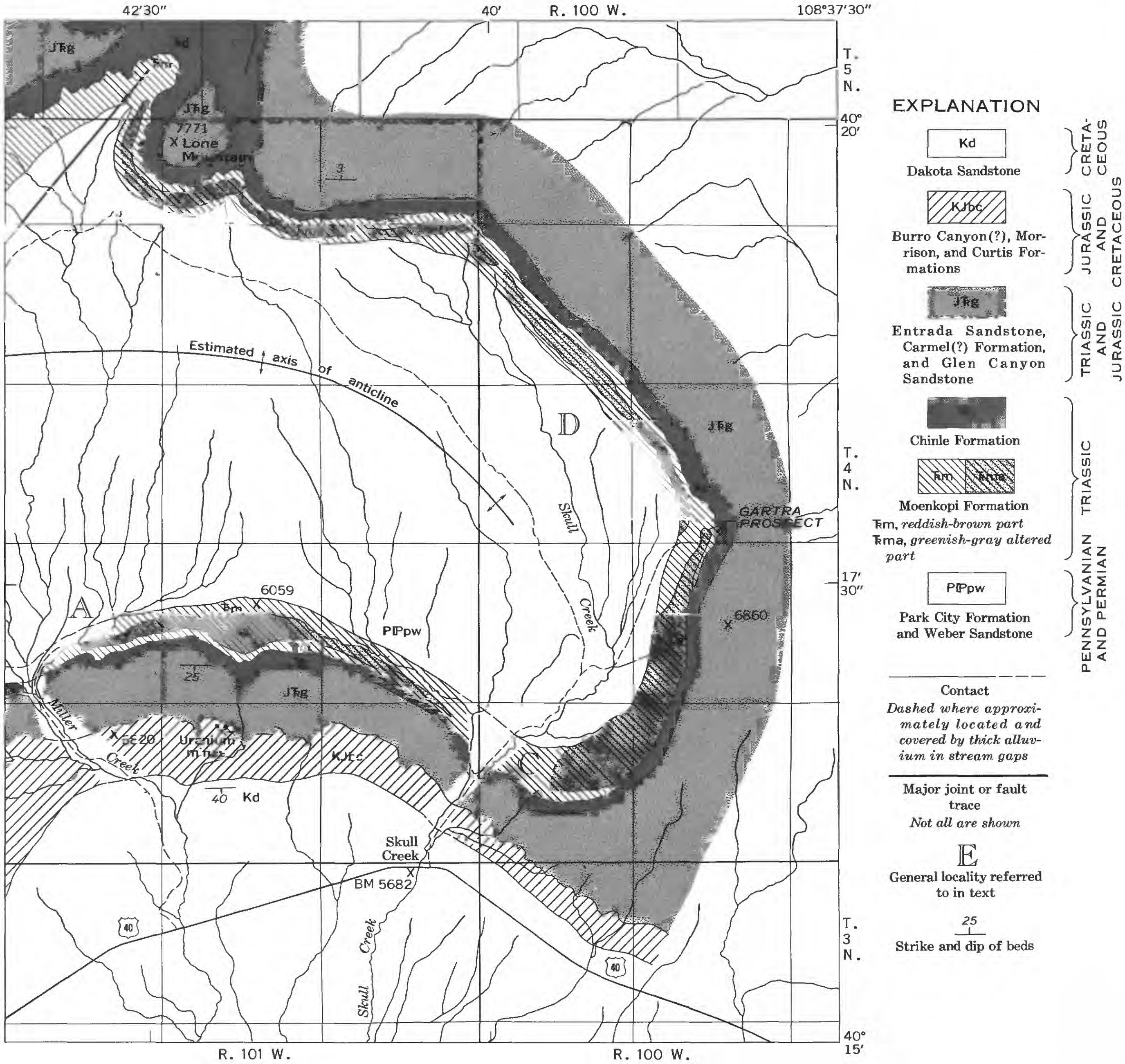


FIGURE 3.—Geologic sketch map of the Skull Creek anticline area showing outcrop of altered strata in the Moenkopi Formation.

contained copper, uranium, and vanadium minerals. Production is believed to have been less than 1,000 tons. According to Stanley (Bud) Biles of Dinosaur, Colo., during the uranium boom of the 1950's, the ownership and the name of the mine changed many times.

The AEC (Atomic Energy Commission) conducted an exploration drilling program for uranium in the hogback area east and west of Miller Creek (N½ NE¼ sec. 35, T. 4 N., R. 101 W., and SE¼ sec. 33, T. 4 N., R. 101 W.) in 1953 (McDougald, 1955). Drill cores were taken through the basal sandstone ledge of the Curtis Formation, and holes were bottomed in the top of the Entrada Sandstone. According to McDougald, the mine in the Curtis was known as The Blue Mountain Group mine during 1953 operations.

A small surface prospect in the base of the Gartra



The map was compiled by the author from field observations and aerial photographs on topographic base maps that are cited in the text.

Member of the Chinle Formation in the northeast corner of the area (S½ sec. 20, T. 4 N., R. 100 W.; fig. 3) was opened in the 1950's, according to Mr. Biles. Small amounts of uranium-bearing clay were found around mineralized logs, and several sacks of this ore were mined and sold. No copper or vanadium minerals are visible in the prospect excavations. The sandstone bed below the mineralized wood layer contains 1-inch pyrite concretions, but no other visible evidence of mineralization is apparent.

A small uranium deposit in the Weber Sandstone just north of Skull Creek anticline is reported (Isachsen, 1955) to have been discovered and mined in 1954. Except for the drilling program conducted by the AEC in 1953, no coordinated modern surface or subsurface exploration has been attempted in the area.

ALTERATION IN THE MOENKOPI FORMATION

The Moenkopi Formation is a red-bed formation typical of several formations in the Colorado Plateau region. Petrologic evidence (Cadigan, 1971b) suggests that the red color is diagenetic and resulted from the oxidation of iron in detrital minerals composing the rock strata. The pigmentation is in the form of megascopic to microlitic crystals of hematite impregnating the clayey and calcareous fractions of the coarse red siltstone and very fine grained sandstone, the dominant lithology of the Moenkopi.

In the Skull Creek anticline area and adjoining areas to the east and west, the Moenkopi Formation contains lens-shaped light-greenish-gray to greenish-yellow bodies of rock with, in most localities, reddish-brown strata both above and below.

An almost continuous zone about 1 cm thick that contains 100–5,000 ppm (parts per million) of copper coincides with the upper boundary of the grayish-green strata. The color boundary and the cupriferous zone are at many localities parallel to the bedding planes, but in others they cross bedding planes (fig. 4). At most localities the color change is not abrupt, but observed in detail the red beds are separated from the green beds by a narrow transition interval of mottled strata, or by an interval of interstratified thin beds or laminae of green and red siltstone (fig. 5). Viewed from a distance the color change is conspicuous and unmistakable, as shown in figure 6*A*, *B*. The thickness of the greenish strata ranges from a few inches to approximately 500 feet in different parts of the area. Along part of the eastern scarp (area C in fig. 3) the entire formation is greenish yellow and there are no red strata to be found (fig. 7) in the Moenkopi Formation except possibly one or two thin beds just below the Moenkopi-Chinle contact.

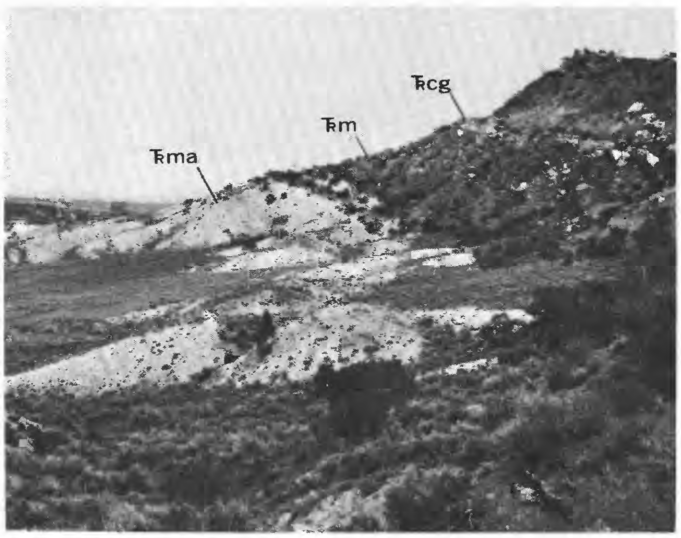


FIGURE 4.—Altered grayish-green Moenkopi strata overlain by unaltered red strata. Note that the color boundary rises in the section away from the camera and crosses sedimentary beds. Exposure at locality A (N½SE¼ sec. 27, T. 4 N., R. 101 W.), southern scarp. ₮ma, green Moenkopi; ₮m, red Moenkopi; ₮cg, Gartra Member forming the base of the Chinle Formation. The view is toward the east.

The cupriferous zone may be detected at the upper color boundary of the greenish strata where these strata are 50–200 feet thick. It could not be found in the eastern scarp where there is no typical green-red color change and the entire formation is light greenish yellow or gray. At some localities (fig. 3*A*, *B*, and *D*) 1-millimeter-thick lenses of malachite ($Cu_2CO_3(OH)_2$) are found along the color boundary. Some unoxidized pyrite nodules occurring below the color boundary in the southern scarp are high in copper (200 ppm) and mercury (9 ppm).

Where red strata interlayed with green strata divide the main green zone into two or more green zones, rock samples from each of the red-over-green contacts may show anomalous copper content, but, in most instances, samples from the highest such contact in the section contain the largest concentration of copper. The light-green strata were originally thought to be related to conditions of deposition or to ordinary diagenesis. Several factors suggest that rock in the green zone was altered from red to green as the result of an extraneous postdepositional event unrelated to normal diagenesis as it is observed in the Moenkopi; these are the restriction of the green strata to the Skull Creek and adjacent areas, the observed extreme variation in thickness of the greenish strata from locality to locality, the crossing of sedimentary structures and textures by the color boundary, and the coincidence of the cupriferous zone with the green-red interface. This alteration evidently occurred before the breaching of the Triassic rocks that formerly covered the Skull Creek anticline and may have been penecontemporaneous with the structural deformation that produced the anticline and adjacent structural features.

The Gartra Member of the Chinle Formation is also highly altered in some outcrops along the southern scarp; the altered rock, a coarse-grained sandstone, is variegated white, red, and purple, and contains clinker-like concretions of purple hematite-cemented grains and areally restricted 10- to 20-cm-thick lenses of discolored chert or jasperoid.

Metal values other than those of copper are anomalously high. Of particular interest are the mercury values found in Moenkopi strata in the eastern and southern scarps, some of which are greater than 10 ppm. The presence of the high content of mercury in the rock suggests the dispersion patterns of mercury that were

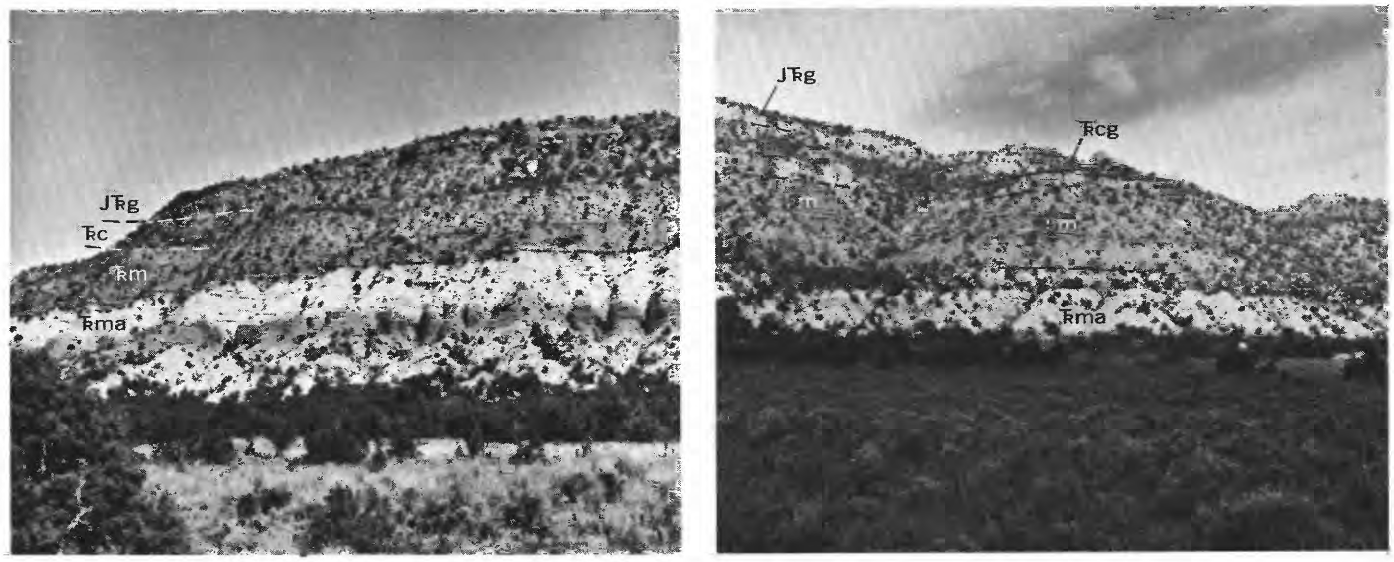
FIGURE 5.—Interbedded altered green and unaltered red strata in the Moenkopi Formation. The cupriferous zone is present in the uppermost part of the green strata. The exposure is on the western scarp at the approximate center of sec. 22, T. 4 N., R. 102 W. Thickness of Moenkopi shown here is 200–250 feet. Ꞧma, green zone; Ꞧm, red Moenkopi; H, upper cupriferous zone.

found related to hydrothermal mineralization by Saukov (1946), Williston (1964), and Erickson, Marranzino, Oda, and Janes (1964).

GEOCHEMICAL STUDIES

ANALYTICAL METHODS

The general metal content of the rocks was determined by six-step spectrographic analysis for 30 elements, supplemented by atomic-absorption analyses for mercury, gold, silver, and copper. Analyses for uranium by a colorimetric method were done on a few selected samples. All samples were checked for radioactivity with a scintillometer. All analyses were made by the Denver laboratories of the U.S. Geological Survey. Analysts were R. N. Babcock, K. J. Curry,



A *B*

FIGURE 6.—Conspicuous altered greenish-gray strata in the Moenkopi Formation seen exposed on *A*, the northern scarp near Lone Mountain (secs. 11, 14, T. 4 N., R. 101 W.), and *B*, the western scarp near locality E (NE¼ sec. 23, T. 4 N., R. 102 W.). In *A*, reddish-brown strata occur in the middle of the altered strata; in *B*, they occur near the top of the altered strata. The major cupriferous zone is at the top of the upper part of the altered strata. JTRg, Glen Canyon Sandstone; TRc, Chinle Formation; TRcg, Gartra Member of the Chinle; TRma, altered strata of Moenkopi; TRm, unaltered reddish-brown strata of Moenkopi.

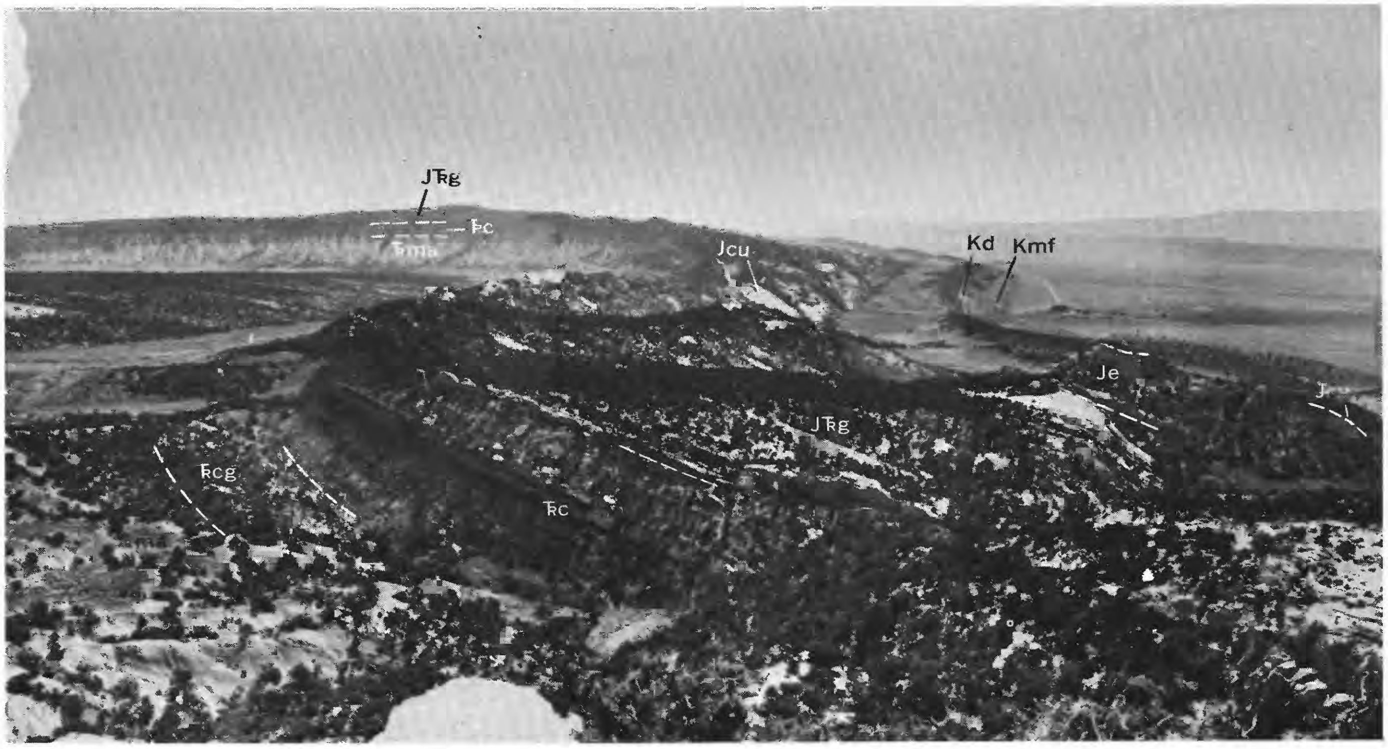


FIGURE 7.—The southeastern arc of the erosion scarp encircling Skull Creek dome as viewed looking eastward from the highest point on the south rim between Skull Creek and Miller Creek water gaps (SW¼ sec. 26, T. 4 N., R. 101 W.). The Moenkopi Formation forming the lower half of the eastern scarp is altered from base to top. The group of houses in the right medium distance is the settlement of Skull Creek. The road was U.S. Highway 40 in 1970. The low grass-covered hogback is formed by the resistant Frontier Sandstone Member of the Mancos Shale (Kmf). Kd, Dakota Sandstone; Jcu, Curtis Formation (basal ledge); Je, Entrada Sandstone; JTRg, Glen Canyon Sandstone; TRc, Chinle Formation; TRcg, Gartra Member of the Chinle Formation; TRma, greenish-gray and greenish-yellow (altered) Moenkopi Formation.

J. V. Desmond, M. S. Erickson, C. L. Forn, J. G. Frisken, D. J. Grimes, J. R. Hassemer, R. T. Hopkins, H. D. King, R. W. Leinz, D. G. Murrey, D. F. Siems, J. G. Viets, L. A. Vinnola, K. C. Watts, Jr., and A. W. Wells. Assistance in the field studies was provided by Laurette N. Bates, Norma L. Noble, and A. J. Toevs. Mrs. Bates also organized the sample collections and analytical data reports.

Element symbols Cu(A), Ag(A), Hg(A), and Au(A) used in tabular presentations indicate results of analyses made by the atomic-absorption methods described by Huffman, Mensik, and Rader (1966), Huffman (1968), and Vaughn (1967). The regular element symbols Cu, Cr, V, and so forth in tables and figures indicate results of analyses made by the semiquantitative six-step spectrographic method, slightly modified from the three-step technique described by Myers, Havens, and Dunton (1961). Both spectrographic and atomic-absorption values for copper and silver are given in the report and treated statistically as separate variables.

The lowest concentration at which an element is detected and reported for quantitative geochemical purposes is called the detection limit. It varies according to element and analytical method used. The highest concentration that can be estimated and reported quantitatively is called the reporting limit, which also varies according to element and analytical method; for example, the reporting limit of most abundant elements is 10 percent or 100,000 ppm for the spectroscopic method. The detection limit in parts per million for the elements reported in this study are as follows:

Magnesium, Mg	200	Uranium, U	20
Iron, Fe	500	Nickel, Ni	5
Calcium, Ca	500	Cobalt, Co	5
Titanium, Ti	20	Beryllium, Be	1
Barium, Ba	20	Scandium, Sc	5
Manganese, Mn	10	Lanthanum, La	20
Strontium, Sr	100	Molybdenum, Mo	5
Zirconium, Zr	10	Niobium, Nb	10
Vanadium, V	10	Boron, B	10
Chromium, Cr	5	Copper(A), Cu(A)	10
Copper, Cu	5	Silver(A), Ag(A)	.2
Yttrium, Y	10	Mercury(A), Hg(A)	.01
Lead, Pb	10	Gold(A), Au(A)	.02
Silver, Ag	.5		

Zinc, Zn, is also occasionally mentioned in the report, but it is not treated statistically; it has a detection limit of 200 ppm.

If the analytical data are to be treated statistically, certain properties of the frequency distributions of the concentrations of each of the elements must be considered (Miesch, 1967). One of the problems involves truncated or censored distributions— those which contain values below the limits of detection or above the reporting limits. It is a common practice to assign arbitrary values where no values can be reported to avoid the use of zero which would also be an arbitrary and probably incorrect value in most instances. In this study, values reported as less than the detection limit have been assigned a value equal to one-half of the detection limit. For example, gold concentrations that were reported as less than 0.02 ppm were assigned values of 0.01 ppm. The problem was discussed in greater detail in an earlier report (Cadigan, 1971a).

Elements discussed in this report for which censored statistical distributions of concentrations constitute a serious problem are uranium, gold(A), beryllium, molybdenum, niobium, and scandium. Absolute values (such as, means) computed for these elements are not reliable, but graphic comparisons of relative abundances and computed correlations are adequate for the purposes for which they are used.

SAMPLING METHODS

Detection and definition of the cupriferous zone were accomplished by the collection and analysis of four separate sets of samples. The first set consisted of stratified samples, as defined by Cochran (1953), of Triassic sedimentary formations of the Colorado Plateau region. Analytical results of Moenkopi samples collected from the south scarp at the Skull Creek locality (Cadigan, 1971a) suggested that the area was one of higher than average metal content.

The first sample collected from the cupriferous zone itself was one of a second set of samples collected during the subsequent and more intensive stratified sampling of the Moenkopi Formation at locality A (figs. 3, 8).

The character of the zone was determined from analyses of a third set of rock and soil samples collected along the strike of the bed represented by the sample collected in the second set which contained the highest copper values. Some of the analyses of the third set of samples were obtained from a Geological Survey mobile laboratory which was brought into the area for a few days to provide "instant" analytical results.

The extent of the cupriferous zone was determined by using a man-carried copper-test kit to confirm the presence of the zone along the 30 miles (48 km) of erosional scarp surrounding the core of the anticline. A fourth set of samples was collected as representative of this cupriferous zone.

For purposes of comparison the sample analytical results are separated into three different groups: (1) Those for stratigraphic samples selected as representative of altered and unaltered but noncupriferous rocks of the Moenkopi Formation and Gartra Member of the Chinle Formation, (2) those for samples selected as representative of the cupriferous zone, and (3) those for miscellaneous unique rock and mineral samples from the Moenkopi, Gartra, and other rock units in the area.

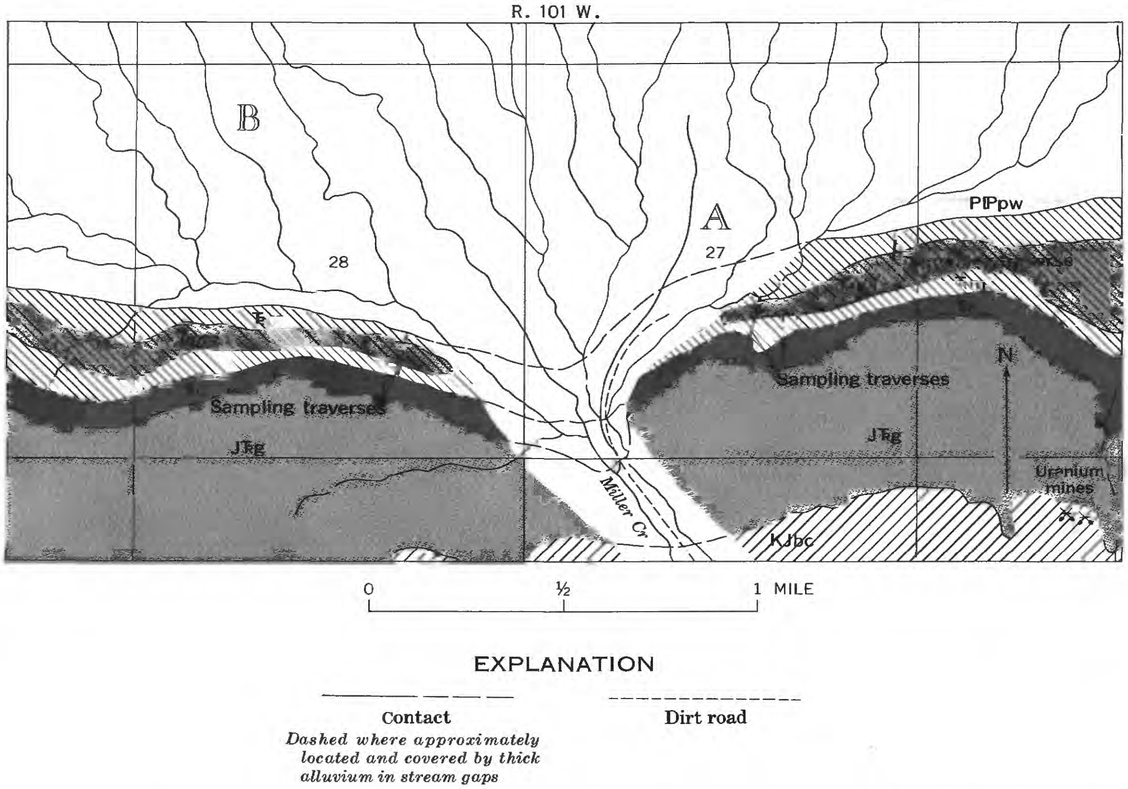


FIGURE 8.—Sampling traverses at localities A and B, secs. 27 and 28, T. 4 N., R. 101 W. The area is divided by Miller Creek water gap. KJbc, Burro Canyon, Morrison, and Curtis Formations; J₸eg, Entrada and Glen Canyon Sandstones; ₸c, Chinle Formation; ₸m, Moenkopi Formation; ₸ma, altered Moenkopi; P₽pw, Park City Formation and Weber Sandstone.

DISTRIBUTION OF ELEMENTS

The distribution-of-elements study of the Moenkopi Formation (Cadigan, 1971a) and the Navajo mercury study (Cadigan, 1969) suggested that the rocks of the Skull Creek anticline area are anomalously high in metal content. This suggestion is confirmed by spectrographic, and other instrumental analyses of samples collected during the present study.

Table 2 shows the analytical results from 20 samples collected at locality A (figs. 3, 8), the second suite of samples collected in the area. The samples consist of 10 pairs of samples, a pair being replicates taken from the same 0.3-meter-square area.

The last four columns of table 2 shown for purposes of comparison are (1) the geometric mean metal values for 10 reddish-brown and reddish-yellow samples, (2) geometric means for eight greenish-gray and grayish-yellow samples, (3) geometric means for 18 of the 20 samples collected in the vertical traverses (fig. 8) at locality A, and (4) geometric means for 323 samples collected from the Moenkopi Formation throughout the Colorado Plateau region. The two samples from the cupriferous zone at locality A were not used in the geometric mean calculations in (3) because of their anomalously high values (for example, copper, vanadium, lead, and zinc).

Comparison of the four columns indicates that red and green and gray samples are not significantly different in metal content and that the geometric-mean metal values of the 18 samples collected at locality A are significantly higher in metal content than the regional geometric-mean values.

Comparison of a similar suite of 20 samples collected from the bottom to the top of the Moenkopi at locality E (figs. 3, 9) showed similar results although the geometric-mean metal values for the samples from E were generally lower than the geometric means for those collected at A.

The suite of samples with the highest metal values was that collected from the cupriferous zone at approximately 75-foot (23-m) intervals on a 600-foot (183-m) east-to-west lateral traverse west of Miller Creek gap at locality B (figs. 1, 8, 10). A partial listing of analytical results in parts per million for nine samples is given below, tabulated in the order collected.

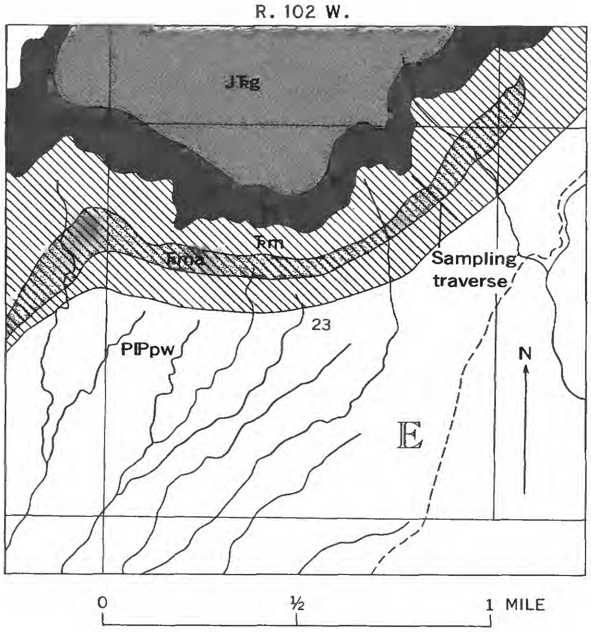


FIGURE 9.—Sampling traverse at locality E, sec. 23, T. 4 N., R. 102 W. The cupriferous zone is present at the intersection of the sample traverse with the top of the altered zone (ma). JTRg, Glen Canyon Sandstone; TRc, Chinle Formation; TRm, Moenkopi Formation; TRma, altered zone in Moenkopi; PIPpw, Park City Formation and Weber Sandstone.

Sample	Hg(A)	Cu(A)	V	U	Ag(A)
CD 5539A	2.1	870	150	<20	1.5
5539B	2.5	270	100	<20	1.7
5540	2.4	5,400	5,000	200	2.3
LB 69–20	3.5	5,200	500	40	1.8
69–22	10.0	2,600	1,000	40	2.0
69–23	1.0	5,100	500	80	12.0
69–24	3.5	2,200	200	40	4.0
69–25	.35	880	50	<20	2.4
69–26	10.0	4,400	500	<20	2.4

Malachite-bearing laminae were observed in the cupriferous zone almost continuously along this lateral traverse at locality B (fig. 8).

A suite of 23 samples taken from bottom to top, normal to the strike of the altered strata in area B but excluding the cupriferous zone, yielded much lower metal values. A summary of values in parts per million follows:

	Hg(A)	Cu(A)	V	U	Ag(A)
Maximum	>10	34	100	<20	1.8
Median	2.4	14	50	<20	.8
Minimum	.4	<10	30	<20	.4

A comparison of the analytical results for the two sets of samples from locality B shows that although the high copper(A), vanadium, uranium, and silver(A) values are confined to the cupriferous zone, high mercury(A) values are dispersed vertically throughout the sampled strata.

Samples collected from the cupriferous zone on the east side of Miller Creek water gap at locality A (figs. 1, 3, 8) at 100- to 150-m intervals along a 1-km lateral traverse are lower in metal content than the samples from the cupriferous zone of locality B. A partial listing of values in parts per million is given below.

Sample	Hg(A)	Cu	V	U	Ag(A)
CD 5527	2.0	86	200	<20	1.1
5529	1.5	250	200	<20	1.1
5530	1.8	17	200	<20	1.7
5531	1.5	300	200	<20	1.6
5533	2.2	800	300	<20	2.7
5535A	2.1	250	100	<20	1.2
5535B	1.8	380	100	<20	1.5

Eleven samples were collected from the cupriferous zone at irregular intervals along the north scarp (figs. 3, 6*A*, 11, 12) from locality D to Lone Mountain during field checking of the continuity of the cupriferous zone. These samples show values of mercury(A) lower by a factor of 100 and values of silver(A) generally

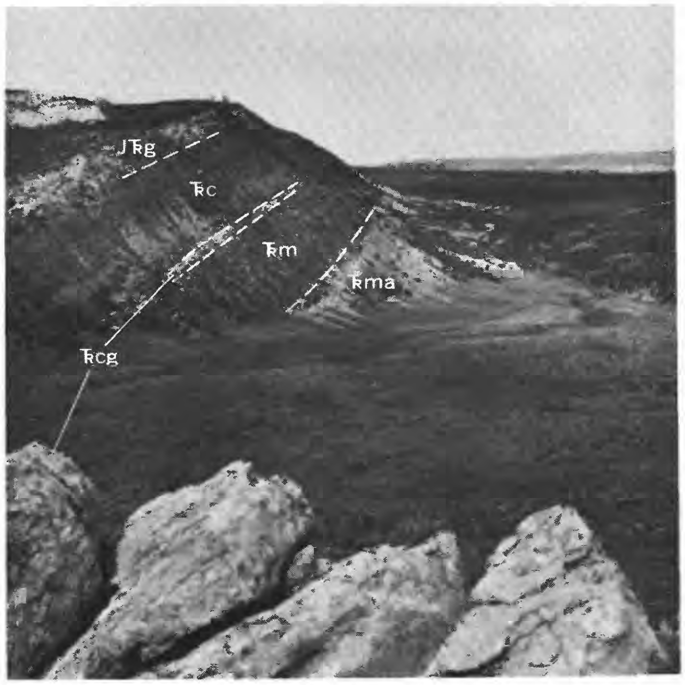


FIGURE 10.—Altered Moenkopi strata (TRma) appear as light-colored beds forming the bottom third of the scarp at Miller Creek water gap (locality B). Surface in the foreground is alluvial fill. Beds forming low white hillocks at the far end of the alluvial plain at the base of the scarp are in the Park City Formation. Rising slope to the right is Weber Sandstone. Rock in the immediate foreground, the Gartra Member (TRcg), also crops out on the scarp slope at locality B. JTRg, Glen Canyon Sandstone; TRc, Chinle Formation; TRm, Moenkopi Formation.

TABLE 2.—*Results of chemical and spectrographic analyses, in parts per million, of 20 samples of the Moenkopi Formation from locality A . the Colorado*

[Numbers in parentheses beneath sample numbers in boxheads indicate distance above base in meters. ----, indicates data not available. Notation (A) as in Ag(A) detected in only two samples, and is not treated statistically. R–Y, reddish yellow;

	Chemical and spectrographic analyses, from locality A, of samples CD—										
	4748A (3.1) R–Y	4748B (3.1) R–Y	4749A (25.9) G–Y	4749B (25.9) G–Y	4738A (51.8) GR–G	4738B (51.8) GR–G	4739A (74.7) GR–G	4739B (74.7) GR–G	4740A (93.0) GR–G	4740B (93.0) GR–G	4742A (93.9) GR
Ca	100,000	100,000	30,000	50,000	70,000	100,000	70,000	50,000	150,000	150,000	2,000
Fe	10,000	10,000	30,000	30,000	10,000	15,000	30,000	30,000	10,000	15,000	50,000
Mg	20,000	20,000	30,000	20,000	20,000	20,000	30,000	30,000	15,000	15,000	20,000
Ti	2,000	2,000	5,000	5,000	2,000	3,000	5,000	5,000	3,000	3,000	5,000
Ba	700	700	700	700	700	700	700	700	700	1,000	700
Mn	300	300	700	700	500	500	500	700	1,000	1,500	500
Sr	1,000	700	200	300	500	500	300	150	1,000	1,000	200
Zr	100	150	500	200	100	100	150	150	200	200	100
V	50	50	100	100	50	50	70	100	100	100	700
Cr	70	70	100	100	50	50	150	100	30	30	100
Cu(A)	18	19	24	25	15	13	22	19	40	58	1,700
Cu	20	20	30	20	15	15	20	20	30	70	1,500
Y	15	10	30	20	15	20	20	20	20	20	20
Pb	20	15	20	15	15	15	15	20	20	30	300
Ni	10	15	50	30	15	15	20	20	10	15	50
Co	<5	<5	15	10	5	5	7	7	5	7	15
Be	<1	<1	<1	<1	<1	<1	1	<1	<1	<1	1
Ag(A)	1.0	1.0	.6	.5	1.2	1.1	.6	.7	1.6	1.2	3.4
Hg(A)	.04	.04	.04	<.01	.80	.60	.18	.04	.03	.07	.05
Au(A)	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02
Nb	<10	<10	10	10	<10	<10	10	10	<10	<10	10
B	20	20	50	50	20	20	30	50	20	20	70
La	20	20	30	30	20	20	30	30	20	20	30
Sc	5	5	15	10	5	5	10	10	5	5	20
Zn	----	----	----	----	----	----	----	----	----	----	200

lower than the values shown by samples from the cupriferous zone in the south scarp at localities A and B. A statistical summary of analytical results is given below (values in parts per million).

	Hg(A)	Cu(A)	V	U	Ag(A)
Maximum	0.04	1,800	700	20	1.8
Median	.02	320	150	<20	.8
Minimum	.01	100	50	<20	.6

Uranium was detected in only one sample (fig. 12) from the north scarp near Lone Mountain. It was detected in five of the six samples collected along the lateral sample traverse in area B (fig. 8), from exposures just west of the gap. Three halo samples from the cupriferous zone in the west rim contain values for mercury(A), copper(A), vanadium, and silver(A) in the same order of magnitude as the samples from the north rim, but none contains detectable uranium.

No cupriferous zone was found in the east scarp at locality C (figs. 3, 7, 11). Values for the five metals in the suite of 16 samples collected at irregular intervals from a 470-foot (143-m) vertical traverse of the grayish-yellow and greenish-gray altered Moenkopi Formation strata of the east scarp are summarized below (in parts per million).

	Hg(A)	Cu(A)	V	U	Ag(A)
Maximum	>10	74	100	<20	1.2
Median	2.3	15	50	<20	.8
Minimum	.5	<10	30	<20	.6

The geometric-mean values for 25 elements in four different sample suites of grayish and greenish rocks are compared graphically in figure 13 with the geometric means for 323 samples from the Moenkopi Formation as a whole in the Colorado Plateau region (Cadigan, 1971a). The geometric means for the 323 samples are referred to for the sake of brevity as Moenkopi M_G. The bottom scales of the bar graphs are multiples of the Moenkopi M_G values shown in parts per million. Thus, the geometric mean for titanium in the 26 stratigraphic samples from the altered strata at locality A (fig. 3) is between four and five times the Moenkopi M_G for titanium, or 2,900–3,700 ppm.

For the Colorado Plateau region, usable analytical data are not available for the computation of Moenkopi M_G values for scandium, lanthanum, molybdenum, niobium, and boron; scandium and lanthanum values were not sought; molybdenum, niobium, and boron values were sought but almost none of the values were high enough to be detected. These five elements, *(figs. 3, 8) and comparisons between geometric means of selected analyses of samples of the Moenkopi Formation from both locality A and Plateau region*

indicates analysis by atomic absorption. Samples from cupriferous zone GR are not used in geometric mean comparisons. Zn has detection limit of 200 ppm, was G–Y, grayish yellow; GR–G, greenish gray; GR, green; R–B, reddish brown]

Chemical and spectrographic analyses, from locality A, of samples CD—Continued									Geometric means			
									Locality A			Colorado Plateau (323 samples; Cadigan, 1971a)
4742B (93.9) GR	4741A (94.5) R–B	4741B (94.5) R–B	4743A (97.5) R–B	4743B (97.5) R–B	4744A (120.4) R–B	4744B (120.4) R–B	4745A (132.6) R–B	4745B (132.6) R–B	R–B, R–Y (10 samples)	GR–G, G–Y (8 samples)	R–B, R–Y, GR–G, G–Y (18 samples)	
2,000	150,000	150,000	100,000	100,000	100,000	100,000	1,000	1,000	43,000	73,000	55,000	22,000
30,000	15,000	15,000	20,000	20,000	30,000	30,000	30,000	20,000	19,000	19,000	19,000	8,900
20,000	15,000	15,000	20,000	15,000	30,000	30,000	10,000	7,000	17,000	22,000	19,000	5,100
5,000	3,000	3,000	5,000	3,000	5,000	5,000	5,000	5,000	3,600	3,700	3,600	740
700	1,000	1,000	700	700	1,500	1,000	700	1,000	870	730	810	410
500	1,000	1,000	700	700	1,000	1,000	500	500	510	710	670	190
200	500	300	300	300	200	150	1,000	1,000	440	400	440	100
150	200	200	200	300	500	300	300	300	230	180	210	76
700	50	50	100	100	100	100	100	100	76	80	77	31
100	30	30	50	70	100	100	70	70	71	66	64	22
1,600	<10	<10	38	<10	13	13	<10	<10	9.5	24	16	13
1,500	15	30	50	20	30	20	30	30	25	24	24	10
20	20	20	20	20	30	30	150	70	28	20	24	11
300	100	20	20	20	30	20	20	20	24	18	21	11
50	15	15	20	15	30	30	30	20	19	19	19	6.2
15	5	5	7	7	10	10	15	10	6.4	7.1	6.9	3.8
1	<1	<1	<1	<1	<1	1	2	2	.71	.55	.65	.53
3.4	1.1	2.4	1.2	1.2	1.2	1.2	.2	.2	1.3	.86	1.1	.26
.05	.06	.05	.02	.13	.24	<.01	.04	.01	.035	.05	.04	.13
<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02	(.01)	(.01)	(.01)	.016
10	<10	<10	10	<10	<10	<10	10	10	7.0	7.1	7.0	----------
70	20	30	50	30	50	50	50	50	34	30	32	----------
30	20	20	20	20	30	30	150	150	33	24	29	----------
20	5	5	10	10	10	10	10	10	7.6	7.5	7.6	----------
200	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------

however, were found in detectable amounts in the Skull Creek samples. To provide some standard of comparison, the numerical limits of detection are shown for scandium and lanthanum and the limits of detection times 0.5 are shown for molybdenum, niobium, and boron.

The geometric means of the metal values for samples of altered strata from four different localities, A, B, C, and E, are significantly higher than the Moenkopi M_G values. In terms of the factor by which the metal values at each locality exceed, on the average, the Moenkopi M_G, the localities are ranked as follows: locality C, 2.5; locality B, 2.1; locality A, 1.9; and locality E, 1.6.

Locality C ranks first in metal content of its samples, as shown above, and it is also the area where the color of all Moenkopi Formation strata is completely altered to greenish-yellow. Localities C and B have the highest mean mercury(A) values (2.0 ppm). Localities A and E, on the other hand, have mean mercury(A) values of only 0.05 ppm.

The geometric means of the analyses of 17 samples representative of the Gartra Member in outcrops between localities A and C are also compared graphically (fig. 13) with those of the Moenkopi M_G. The Gartra as a whole contains neither significantly more nor significantly less of the metals than the Moenkopi M_G with the exception of calcium content, which is significantly lower; iron, titanium, zirconium, vanadium, and chromium are notably (two to four times) higher; these differences suggest less calcite cement and more detrital minerals in the Gartra in the Skull Creek area than the average for the Moenkopi Formation in the Colorado Plateau. Mean mercury(A) content is significantly lower in the Gartra. Compared with samples of altered Moenkopi from localities A, B, C, and E, the Gartra tends to contain significantly lower calcium, magnesium, manganese, nickel, cobalt, and silver(A) but contains approximately the same average amounts of the other metals. Boron and lanthanum averages are well above their detection limit in all groups of Skull Creek samples.

The Gartra Member samples have maximum values of 20,000 ppm for iron, 5,000 ppm for chromium, and 3,000 ppm for barium. Siliceous (jasperoid) concretions in the Gartra contain as much as 5,000 ppm barium and 1,000 ppm strontium.

Geometric mean values for 24 out of the 25 metals in the 36 samples from the cupriferous zone (fig. 14)

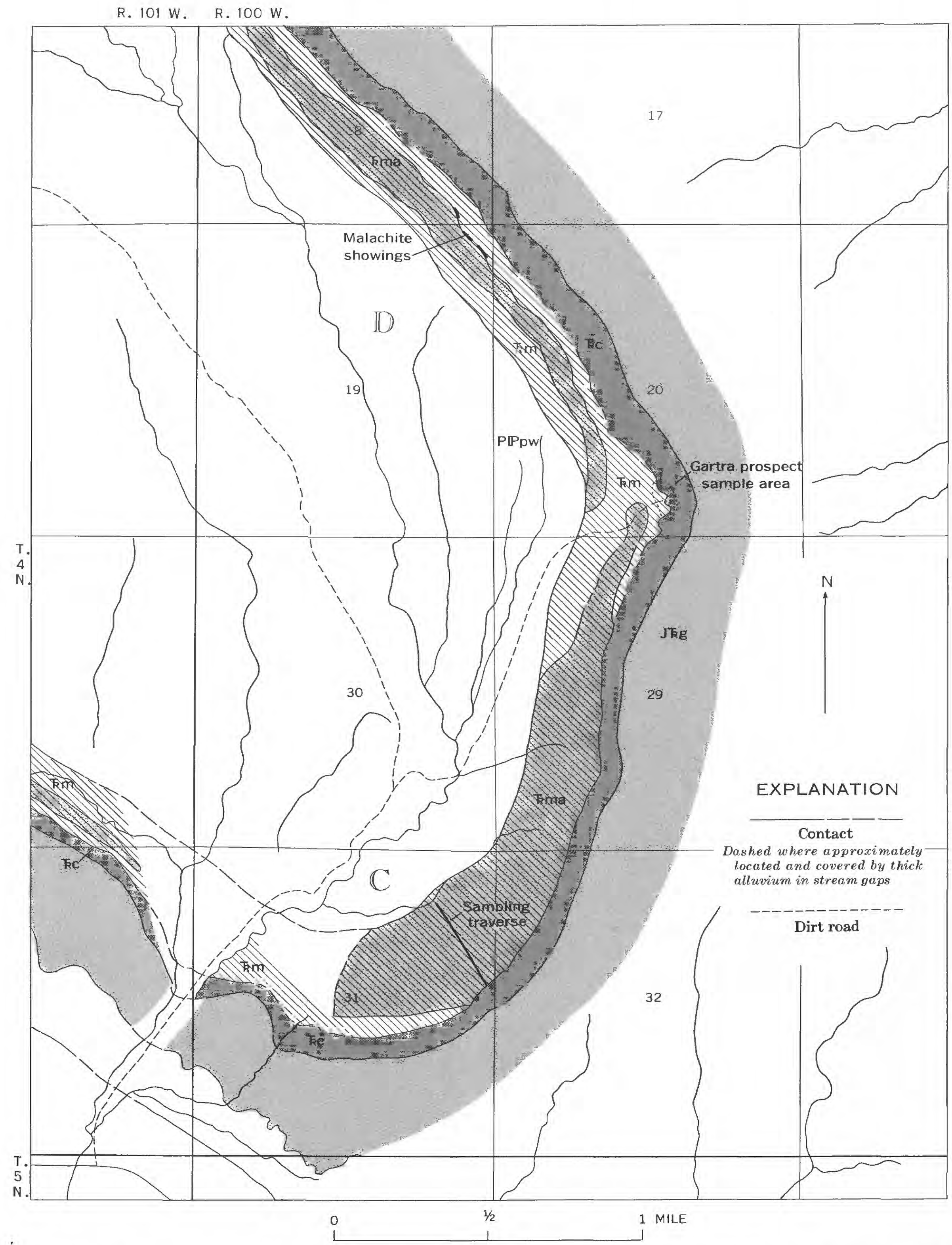


FIGURE 11.—Sampling traverse at locality C (sec. 31, T. 4 N., R. 101 W.), malachite showings at locality D (secs. 18 and 19), and sampled area at the Gartra prospect (sec. 20). JЋg, Glen Canyon Sandstone; Ћc, Chinle Formation; Ћma, altered Moenkopi Formation (greenish gray or yellow); Ћm, Moenkopi Formation (reddish brown); PIPpw, Park City Formation and Weber Sandstone.

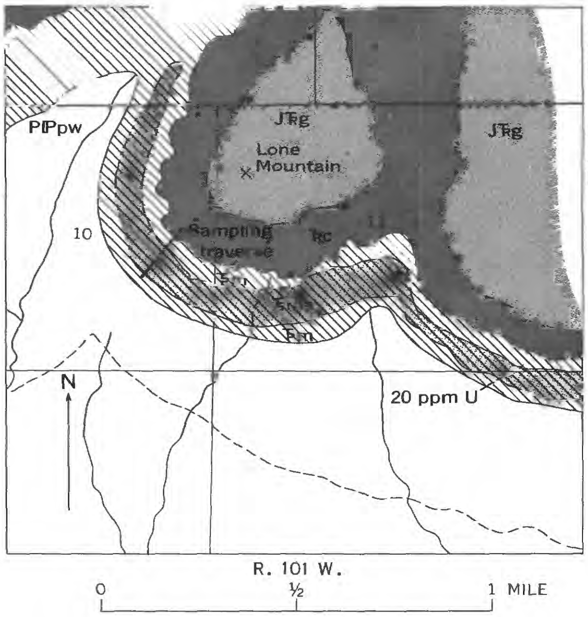


FIGURE 12.—Sampling traverse (sec. 10, T. 4 N., R. 101 W.) at Lone Mountain. JTRg, Glen Canyon Sandstone; TRc, Chinle Formation; TRm, Moenkopi Formation (reddish brown); TRma, altered Moenkopi Formation (greenish gray); PIPpw, Park City Formation and Weber Sandstone.

(all samples collected in previously described horizontal traverses) are higher than those of the Moenkopi M_G. The geometric means for the cupriferous zone samples are significantly (at least four times) higher for copper(A), copper, vanadium, nickel, silver(A), cobalt, and chromium. The 25 Gartra prospect samples (fig. 14) are, on the average, notably higher than the Moenkopi M_G in nickel, beryllium, vanadium, cobalt, silver(A), and gold(A). The most remarkable aspect of the Gartra prospect samples is the high chromium, the geometric mean of which—about 620 ppm—is more than 27 times the Moenkopi M_G. The maximum value for chromium is 10,000 ppm (1 percent); for vanadium, 2,000 ppm; for gold(A), 1.5 ppm; and for silver(A), 22 ppm. High chromium-bearing samples in the prospect area consist of green or fairly bright greenish-yellow soft clays.

An exploratory cross-country traverse (not shown on fig. 3) was made from south to north starting at the mouth of East Rock Wall Draw (NE¼ sec. 5, T. 3 N., R. 101 W.) and ending on the eroded surface of the Weber Sandstone nearest the southern scarp (NW¼ sec. 28, T. 4 N., R. 101 W.). Grab samples collected on the traverse contain evidence of general mineralization; for example, partly altered sulfide joint fillings in the Glen Canyon Sandstone in the creek bottom contain as much as 2,000 ppm arsenic, and black sandy concretions in the canyon walls contain as much as 5,000 ppm manganese. Calcareous veinlets in both red and altered green siltstone in the top of the Chinle Formation exposed in a small window in the bottom of the draw show anomalously high metal values—as much as 700 ppm lead, 200 ppm zinc, and 2,000 ppm manganese. Joint fillings of hematite 25 mm thick are abundant in the Glen Canyon Sandstone near where the East Rock Wall Draw joint (fault?) system intersects the scarp rim north of the draw. Samples of gouge, however, apparently from the same large fault in the Weber, north of the scarp rim, contain only background, or smaller, metal values.

Sulfide concretions in the top of the Weber Sandstone in southeastern outcrops, in the locality C area, contain as much as 700 ppm arsenic, 10 ppm silver(A), 50 ppm molybdenum, and 300 ppm zinc.

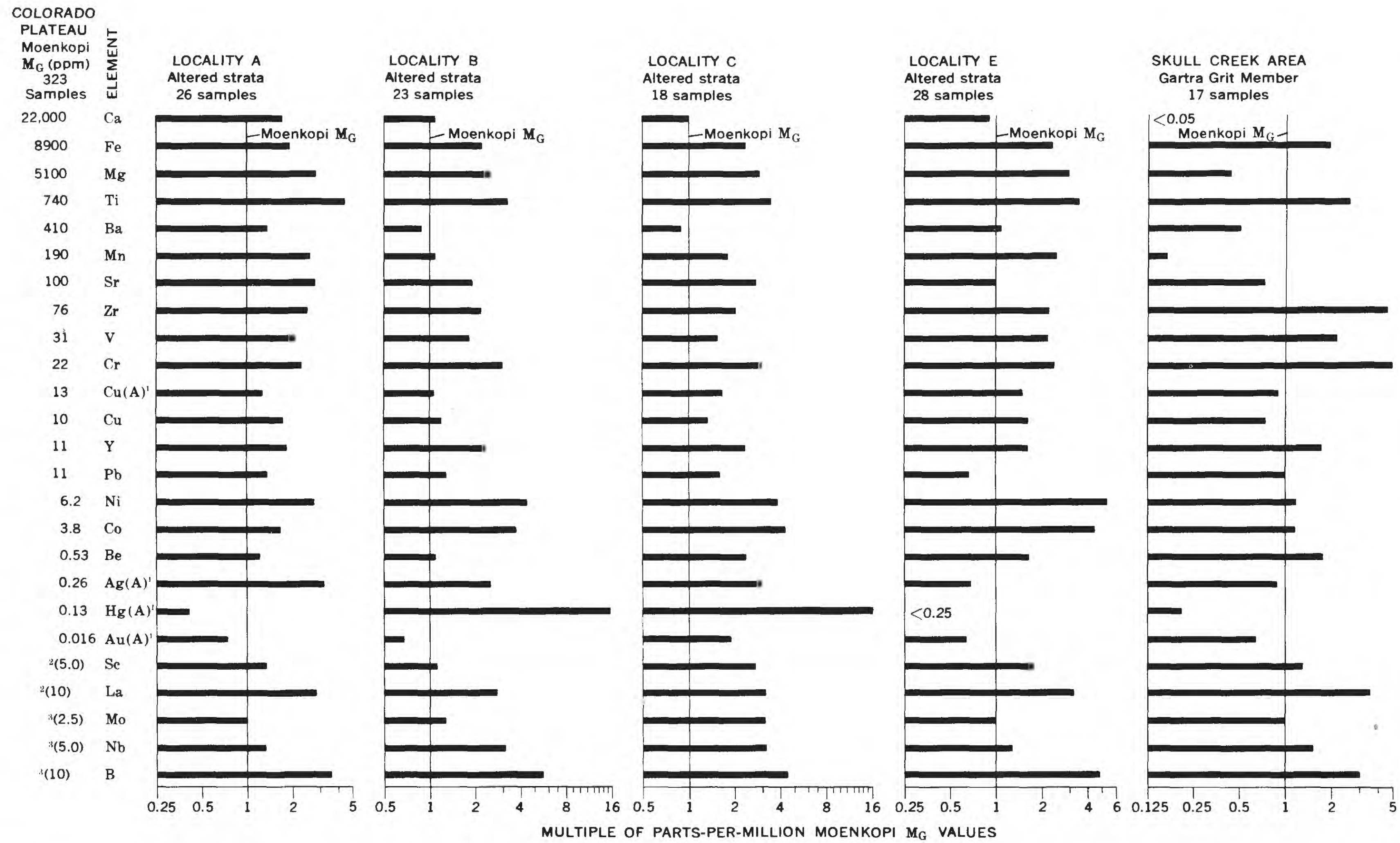
FACTOR ANALYSIS

Many geologic factors or causes control the location and proportion of each metal, but it would be difficult to determine each geologic cause and its proportional effect on the mode of occurrence of each of 26 metals. If we can group the metals that have a relatively high correlation of occurrence, then we can begin to get some idea of the major geologic causes that control the occurrence of identifiable proportions of the metals. Even if grouping the metals does not account for all the variance of occurrence for each metal, general geologic interpretations may still be made on the basis of the determined groupings but with full realization that the groupings account for most of the variance present.

Factor analysis is a form of multivariate analysis that evaluates the covariance among a set of variables and groups the variables according to their mutual dependency and the strength of their relationship to common factors. Factor analysis was used in this study to divide the elements into related groups that, on the basis of geologic experience, could be interpreted as representing a series of geologic events.

The reader who is interested in gaining more than a cursory understanding of factor analysis is referred to the authoritative text by Harman (1967) and especially to an excellent, but brief, detailed introduction to the subject by Imbrie (1963).

Factor analysis (R-mode) was applied to the analytical results for 26 elements in the 36 samples from the cupriferous zone. The first step was the arrangement of the values into a 26×36 data matrix. Logarithms of the element values were used in the data matrix to normalize the statistical distribution of values for each element. Next, correlation coefficients were computed for all possible pairs of elements to produce a 26×26 correlation matrix (table 3). The variance in

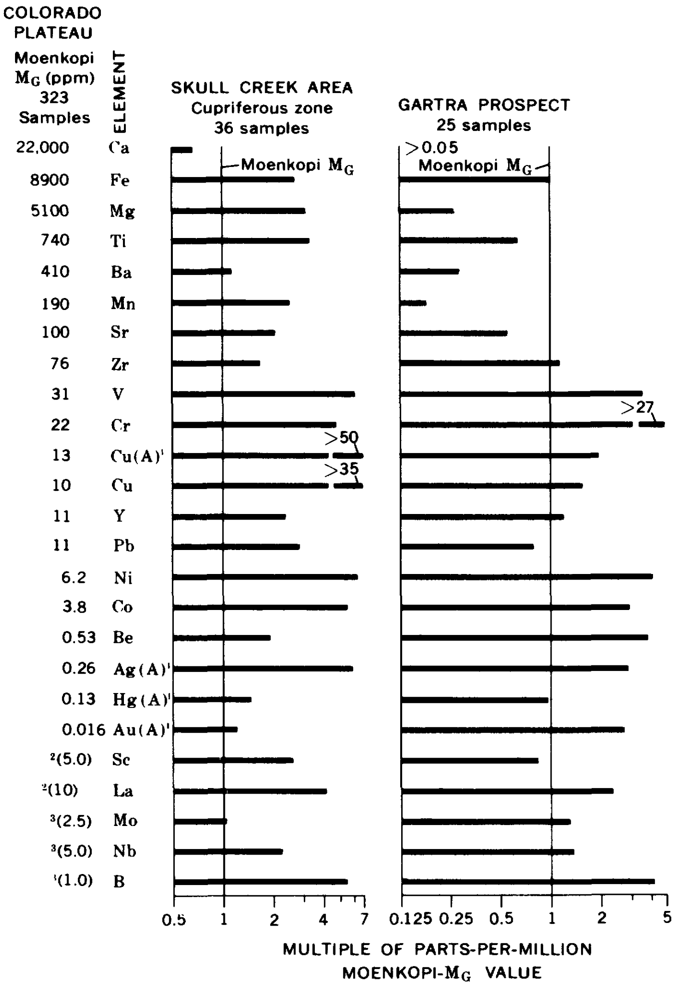


[1] Element symbols followed by (A) indicate analytical data obtained by atomic-absorption method.

[2] Detection limit. Element not sought in the 323 Moenkopi Formation samples.

[3] Half of detection limit. Element sought but not detected in the 323 samples.

FIGURE 13.—Geometric means of metallic elements in suites of samples collected from altered strata in the Moenkopi Formation at localities A, B, C, and E compared with the gometric means (Moenkopi M_G) of the same elements in 323 samples representing the Moenkopi Formation as a whole in the Colorado Plateau region. Also graphically compared are values for a suite of samples from the Gartra Member of the Chinle Formation collected from outcrops in the Skull Creek area between localities A and C. Numbers at left are values in parts per million represented by Moenkopi M_G line at multiple 1.



[1] Element symbols followed by (A) indicate analytical data obtained by atomic-absorption method.
[2] Detection limit. Element not sought in the 323 Moenkopi Formation samples.
[3] Half of detection limit. Element sought but not detected in the 323 samples.

FIGURE 14.—Geometric-mean metal content of cupriferous zone samples and samples from a prospect in the Gartra Member of the Chinle Formation in the Skull Creek area compared with the geometric means (Moenkopi M_G) of the same elements in 323 samples representing the Moenkopi Formation as a whole in the Colorado Plateau region. Numbers at left are values in parts per million represented by Moenkopi M_G line at multiple 1.

the correlation matrix formed the basis for the factor analysis which followed. Factors were taken from the computed reordered oblique factor matrix. Calculations were made by utilizing the U.S. Geological Survey's IBM 360–65 computer and available STATPAC programs.

Only the first six factors in order of importance were selected for this investigation. These six account for 73 percent of the total variance in the correlation matrix. The six factors were selected on the basis of two conventional criteria; only factors with eigenvalues (a measure derived from the factor loadings) of at least 1.0 would be used, and element groupings for the factors should include no single element "groups" in the reordered oblique projection matrix. In this investigation the first eight factors have eigenvalues of at least 1.0, but the seventh and eighth factor groupings contain one or more factors, each consisting of a single element. Beyond factor eight, individual factors increasingly are represented by individual metals until, for 26 factors, each is represented by a single metal.

The results of the factor analysis are the element groups listed in six columns below. The element at the top of each column coincides with the factor axis, and elements are listed in order of their degree of covariance with the axis element. The elements in brackets are minor elements of the group and occur as major elements, without brackets, in other groups; for example, [Ag], a minor element in the factor 1 group, is a major element, Ag, in the factor 2 group.

Factor 1 (Alteration effects)	Factor 2 (Enrichment effects)	Factor 3 (Cements)	Factor 4 (Micas)	Factor 5 (Sulfates)	Factor 6 (Heavy minerals)
Co	Hg(A)	Ca	Be	Sr	Ti
Cr	Cu	Mn	Sc	Ba	Zr
Nb	Ag(A)	Y	[La]	[Sc]	[B]
Fe	U	Mg	[Mg]	[Ag(A)]	[Fe]
Ni	Ag	[Zr]		[Cu]	[Mn]
V	Cu(A)			[V]	
La	Au(A)				
B					
Pb					
[Ag]					
[U]					
[Y]					
[Cu(A)]					

With considerable dependence on the comprehensive work of Rankama and Sahama (1950) and aided by the minor previous experience of the author (Cadigan, 1971a, 1972), each of the factors was interpreted as being related to a geologic cause or event, as indicated. Factor 1 is the most important geologic event, or cause, in terms of its effect on the covariance of the metals. The other factors represent other causes and are listed in order of the importance of their effects on the covariance of the metals. Their relative importance is suggested by the proportion of total variance in the correlation matrix accounted for by each factor and is shown following each interpretation. Interpretations are made on the basis of geochemical relations and mode of occurrence of the major elements in each factor group. Each of the six factors is assigned a title related to a geologic event. The factors are the result of objective mathematical analysis, but the titles are based on interpretations.

Factor 1: Alteration effects—A group of elements similar in constitution and cobalt-nickel ratio to those

TABLE 3.—*Coefficients extracted from the matrix of correlation coefficients of values for 26 metallic elements in 36 samples from the Skull Creek geochemical halo*

	Fe	Mg	Ca	Ti	Mn	Ag	B	Ba	Be	Co	Cr	Cu	La	Nb	Ni	Pb	Sc	Sr	V	Y	Zr	Au(A)	Hg(A)	Cu(A)	Ag(A)	U
Fe	1.000																									
Mg	.386	1.000																								
Ca	−.114	.220	1.000																							
Ti	.576	.404	.005	1.000																						
Mn	.201	.334	.721	.293	1.000																					
Ag	.187	.137	−.116	−.113	−.096	1.000																				
B	.539	.423	−.046	.405	.162	.293	1.000																			
Ba	.187	−.256	.112	.161	.455	.087	.001	1.000																		
Be	.194	.272	−.240	.076	−.171	−.144	.114	−.591	1.000																	
Co	.783	.413	.143	.338	.260	.309	.587	.134	.180	1.000																
Cr	.698	.377	.203	.367	.307	−.019	.353	.053	.110	.700	1.000															
Cu	.302	−.067	−.317	.265	−.137	.430	.346	.114	.144	.265	−.072	1.000														
La	.328	.374	.304	.231	.343	.052	.255	−.114	.332	.489	.416	.001	1.000													
Nb	.402	−.018	.091	.087	.030	.219	.149	.202	−.252	.453	.685	.046	.049	1.000												
Ni	.754	.471	−.143	.489	.121	.254	.681	−.066	.374	.780	.513	.306	.453	.170	1.000											
Pb	.386	.152	−.591	.274	−.274	.288	.415	−.019	.215	.195	.102	.454	−.028	.151	.361	1.000										
Sc	.030	.130	.153	.091	.215	−.219	−.064	−.052	.246	−.090	−.019	−.075	−.027	−.012	.043	.075	1.000									
Sr	−.133	−.480	.210	−.114	.316	−.222	−.033	.358	−.036	−.068	−.016	.195	−.142	.069	−.158	−.121	.160	1.000								
V	.539	.116	−.296	.352	.020	.327	.490	.247	.079	.488	.324	.657	.102	.269	.566	.420	−.027	.144	1.000							
Y	.369	.421	.571	.265	.657	.101	.080	.124	.084	.493	.522	.101	.408	.328	.234	−.021	.349	.156	.161	1.000						
Zr	−.030	.015	.504	.407	.380	−.318	−.006	.137	−.119	−.076	.059	−.105	.101	.012	−.226	−.321	.203	.238	−.302	.247	1.000					
Au(A)	−.174	.070	.285	.072	.130	−.153	.016	.001	−.023	−.095	−.100	.047	−.196	−.040	−.269	−.237	.084	.066	−.039	.130	.269	1.000				
Hg(A)	.219	.261	.171	.258	.168	.340	.270	.146	.108	.380	.015	.556	.221	.010	.193	.302	.040	.049	.343	.465	.150	.377	1.000			
Cu(A)	.259	−.228	−.469	.019	−.317	.533	.092	.279	.159	.168	−.110	.763	−.235	.113	.147	.442	−.134	.083	.567	−.067	−.373	−.134	.302	1.000		
Ag(A)	.110	−.248	−.391	.020	−.219	.429	.175	.286	−.081	.036	−.143	.711	−.226	.060	.058	.516	−.181	.177	.453	−.063	−.207	−.133	.389	.719	1.000	
U	.406	.125	−.204	.149	−.190	.567	.428	.103	.028	.524	.209	.566	.011	.237	.370	.341	−.349	−.101	.668	.050	−.273	.053	.446	.573	.445	1.000

found in metal-rich veins that occur in granite, pegmatite, or other silicic rocks was probably derived from a granitic source and transported by migrating solutions during an event, the final phase of which resulted in the widespread but stratigraphically confined alteration in the Moenkopi Formation in the Skull Creek and adjacent areas. Percentage of total variance accounted for by factor 1 is 25.

Factor 2: Enrichment effects.—A group of metals typical of copper-uranium deposits in the area of study and in the Colorado Plateau region was probably the result of interaction between reducing solutions in the green Moenkopi altered zone and metal-bearing solutions (sulfates, bisulfates, bicarbonates) in equilibrium with the oxidized rocks of the red Moenkopi. The factor 2 group represents the heavy metals most susceptible to leaching and transport as salts; thus, segregation or grouping occurred during the leaching phase, not during the reduction-reaction phase which produced the metal-enriched cupriferous zone. The enriched zone then is composed of metals that were oxidized and separated from the metals introduced by circulating (hydrothermal?) solutions and then in small part recaptured by the reducing environment at the reduction-oxidation interface in the Moenkopi. Percentage of total variance accounted for by factor 2 is 18.

Factor 3: Sedimentary carbonate cements.—A group of elements related to the occurrence of carbonate cements in the samples. The [Zr] covariance is probably the indirect effect of positive correlation between carbonate content and the proportion of fine sediment which is in turn positively related to zircon content. Percentage of total variance accounted for by factor 3 is 11.

Factor 4: Sedimentary micas and clays.—A group of elements related to the presence of micas and their hydrolyzate alteration products in the samples. Percentage of total variance accounted for by factor 4 is 8.

Factor 5: Interstitial precipitated sulfates.—Elements which commonly occur in detrital sediments as sulfate precipitates from interstratal solution. The covariance with [Ag(A)], [Cu], and [V] suggests a similar method of deposition for fractions of these metals. Percentage of total variance accounted for by factor 5 is 6.

Factor 6: Sedimentary heavy mineral deposition.—Sedimentary processes that control the occurrence of elements which are closely associated with heavy minerals. Percentage of total variance accounted for by factor 6 is 5.

Each of the elements listed in the correlation matrix (table 3) has a positive, negative, or zero relationship to each of the factors. The relationship may be stated in terms of the proportion of variance accounted for by the six factors combined. For example, the six factors account for 0.84 (84 percent) of the covariance of iron with other elements. This figure, 0.84, is called the communality. A list of communalities is given in table 4. If the 0.84 is assumed to be the total amount of positive association of iron among the six factors, and if we reduce it to proportions in percent in which 0.84 is 100 percent, then the proportion of positive association (covariance) of iron with each of the six factors is as follows: factor 1, 81 percent; factor 2, negative; factor 3, negative; factor 4, zero; factor 5, 2 percent; and factor 6, 17 percent. Proportions of negative covariance could also be computed but would have limited geologic use beyond indicating only an antipathetic relationship between a particular element and a particular factor. This indication can be made by merely showing that a negative relationship exists.

Continuing with the example for iron, 81 percent of its occurrence in the six factors is related to the alteration event, 17 percent is related to proportion of detrital sedimentary heavy minerals, and 2 percent is related to the proportions of interstitial sulfate minerals. The covariance of the other metals is similarly explained in table 4. Note that only 0.50 of the covariance of gold appears to be related to the six factors. Sixty-one percent of the positive covariance of gold is related to the enrichment effects (factor 2), 25 percent is related to carbonate cements (factor 3), and 14 percent to the detrital heavy minerals factor (factor 6).

TABLE 4.—*Proportion, in percent, of positive covariance of each metallic element with each factor*

[Communalities indicate proportion of total covariance of each element accounted for by all six factors. Axis elements are in boldface type. (—) indicates that the covariance is negative between element and factor]

Element	Factor 1 (Alteration effects)	Factor 2 (Enrichment effects)	Factor 3 (Cements)	Factor 4 (Micas)	Factor 5 (Sulfates)	Factor 6 (Heavy minerals)	Communality
Fe	81	(—)	(—)	0	2	17	0.84
Mg	9	2	39	31	(—)	20	.73
Ca	(—)	(—)	100	0	0	(—)	.89
Ti	(—)	0	0	(—)	(—)	100	.84
Mn	4	(—)	70	0	13	13	.75
Ag	43	57	(—)	(—)	(—)	(—)	.71
B	46	10	(—)	(—)	(—)	44	.59
Ba	12	1	(—)	(—)	75	12	.73
Be	0	(—)	0	100	(—)	0	.82
Co	100	0	0	(—)	(—)	0	.85
Cr	91	(—)	4	0	2	3	.82
Cu	3	84	(—)	(—)	13	(—)	.84
La	41	(—)	29	30	(—)	(—)	.54
Nb	89	(—)	(—)	(—)	11	(—)	.58
Ni	81	(—)	(—)	11	(—)	8	.82
Pb	41	31	(—)	6	13	9	.62
Sc	(—)	(—)	9	50	35	6	.54
Sr	0	0	(—)	0	100	(—)	.71
V	62	20	(—)	(—)	17	1	.71
Y	32	2	40	10	16	(—)	.82
Zr	(—)	(—)	41	(—)	2	57	.66
Au(A)	(—)	61	25	(—)	(—)	14	.50
Hg(A)	(—)	100	0	(—)	(—)	0	.82
Cu(A)	19	64	(—)	(—)	17	(—)	.82
Ag(A)	4	74	(—)	(—)	22	(—)	.75
U	41	59	(—)	(—)	(—)	(—)	.74

Comparison of the communality for gold with those of the other metals indicates that gold has the lowest degree of involvement of any of the metals. To support this statement, when seven factors are selected instead of six, gold becomes a separate factor and increases its communality to 78 percent.

Each of the axis elements (p. 17), cobalt, mercury(A), calcium, beryllium, strontium, and titanium, by mathematical definition has positive covariance (100 percent) with only one factor. Relationships to other factors either are zero or are negative.

The percentages of positive association in table 4 are of some interest. For example, 70 percent of the manganese is related to cements. Lanthanum with a communality of only 0.54 is split three ways—41 percent in alteration effects, 30 percent in micas, and 29 percent in cements. Boron is almost equally split between the extrinsic alteration-effects factor and the intrinsic heavy-minerals factor with a small proportion of association with the enrichment-effects factor.

SUMMARY AND RECOMMENDATIONS

The geochemical evidence derived from the brief investigation of anomalous metal occurrences in the Skull Creek anticline suggests that the anomalies are the effects of a regional alteration event of possible hydrothermal origin. The recognized effects, in summary, are:

1. The area-wide altered strata in the Moenkopi Formation with an accompanying persistent copper-enriched zone. Though the altered strata were studied only in the Skull Creek anticline, they were also observed in exposures immediately east and west of the anticline.
2. The significantly higher average metal content in altered and unaltered rocks of the Moenkopi in the vicinity of Skull Creek as compared with that of the Moenkopi Formation as a whole in the Colorado Plateau region.
3. The copper-uranium-vanadium ore deposit in the base of the Curtis Formation.
4. Anomalously high mercury values found in the Moenkopi Formation and Glen Canyon Sandstone in the southern (loc. B) and eastern (loc. C) parts of the scarp adjoining Skull Creek and Miller Creek water gaps. The highest average mercury values occur at locality C where the Moenkopi is completely altered. Mercury geochemical dispersion patterns are characteristic of hydrothermal mineralizing activity.
5. Anomalous values of gold, chromium, silver, and vanadium in the Gartra Member prospect in the northeast corner of the anticline area.
6. Anomalous values of arsenic, lead, zinc, manganese, and silver in observable sulfide minerals in joints in the Glen Canyon Sandstone and Chinle Formation, in concretions in the East Rock Wall Draw area, and in concretions in the Weber Sandstone in the southeast corner of the anticline area.
7. The two major factor groups in the Moenkopi cupriferous or metal-enriched zone—a cobalt-chromium-niobium-iron-nickel-vanadium-lanthanum-boron-lead covarying suite of metals, and a mercury-copper-silver-uranium-gold covarying suite. These groups suggest (1) an invasion of the Moenkopi by solution-borne metals and (2) interaction between solutions in the reducing (altering) environment characterized by green rocks and solutions in the oxidizing environment of unaltered red rocks above. This red-green contact, the loci of the enriched zone, could have been a mobile interface which moved upward in the section to occupy different levels at different times and to leave traces of previous positions as indicated by isolated weak cupriferous zones.

Major questions left unanswered are: What was the source of the metal-bearing solutions? Did this activity produce only trace mineralization over a wide area, or do the anomalies reflect the presence of economically significant deposits at depth?

The samples collected in this reconnaissance study establish the area as anomalous in terms of metal occurrences, but they do not yield data adequate to define the regional dimensions of the anomalies. Trends are suggested but not defined. Mineralization occurred in both stratigraphically controlled and structurally controlled loci.

The following questions provide a starting point for any additional work that may be done in the area. Are the altered strata of the Moenkopi Formation a sulfide zone at depth, particularly southeast or east of locality C? Does sulfide mineralization in joints or faults in East Rock Wall Draw persist, disappear, or increase at depth? What happens to the unusual mineralization in the Gartra prospect beyond the face? What is the nature of the Curtis-Entrada contact to the east and south at depth, and does it appear to have a potential for additional ore deposits in one or both of these directions? Are there even more anomalous metal occurrences in similar horizons and structures exposed to the east and west of the reported anomalies?

These questions can best be answered by a program of detailed mapping and intensive geochemical exploration, perhaps coupled with drilling, in the Skull Creek anticline area as a whole and particularly in the areas along the scarp between localities B and D.

REFERENCES CITED

Cadigan, R. A., 1969, Distribution of mercury in the Navajo Sandstone, Colorado Plateau region, *in* Geological Survey research 1969: U.S. Geol. Survey Prof. Paper 650–B, p. B94–B100.

——— 1971a, Geochemical distribution of some metals in the Moenkopi Formation and related strata, Colorado Plateau region: U.S. Geol. Survey Bull. 1344, 56 p.

——— 1971b, Petrology of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region *with a section on* Stratigraphy, by J. H. Stewart: U.S. Geol. Survey Prof. Paper 692, 70 p.

Cadigan, R. A., and Stuart-Alexander, D. E., 1972, Geochemical factor analysis of intrusion breccia and reconstituted rocks of Mule Ear diatreme, San Juan County, Utah, *in* Geological Survey research 1972: U.S. Geol. Survey Prof. Paper 800–B, p. B125–B135.

Cochran, W. G., 1953, Sampling techniques: New York, John Wiley and Sons, Inc., 330 p.

Erickson, R. L., Marranzino, A. P., Oda, Uteana, and Janes, W. W., 1964, Geochemical exploration near the Getchell mine, Humboldt County, Nevada: U.S. Geol. Survey Bull. 1198–A, p. A1–A26.

Harman, H. H., 1967, Modern factor analysis (2d ed. revised): Chicago Univ. Press, 474 p.

Huffman, Claude, Jr., 1968, Copper, strontium, and zinc content of U.S. Geological Survey silicate rock standards, *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–B, p. B110–B111.

Huffman, Claude, Jr., Mensik, J. D., and Rader, L. F., 1966, Determination of silver in mineralized rocks by atomic-absorption spectrophotometry, *in* Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550–B, p. B189–B191.

Imbrie, John, 1963, Factor and vector analysis programs for analyzing geologic data: Office of Naval Research Geography Branch Tech. Rept. 6, ONR Task No. 389–135, Contract Nonr 1228(26), 83 p.

Isachsen, Y. W., 1955, Uranium deposits in the Skull Creek and Uranium Peak districts, northwest Colorado, *in* Intermtn. Assoc. Petroleum Geologists Guidebook 6th Ann. Field Conf., northwest Colorado, 1955: p. 124–125.

McDougald, W. D., 1955, Wagon drilling in the Skull Creek area, Moffat County, Colorado: U.S. Atomic Energy Comm. Rept. RME–80 (pt. 1), Tech. Inf. Service, Oak Ridge, Tenn., 15 p.

Miesch, A. T., 1967, Methods of computation for estimating geochemical abundance: U.S. Geol. Survey Prof. Paper 574–B, 15 p.

Myers, A. T., Havens, R. G., and Dunton, P. J., 1961, A spectrochemical method for the semiquantitative analysis of rocks, minerals, and ores: U.S. Geol. Survey Bull. 1084–I, p. 207–229.

Poole, F. G., and Stewart, J. H., 1964, Chinle Formation and Glen Canyon Sandstone in northeastern Utah and northwestern Colorado, *in* Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501–D, p. D30–D39.

Rankama, K. K., and Sahama, T. G., 1950, Geochemistry: Chicago Univ. Press, 912 p.

Ritzma, H. R., 1956, Structural development of the eastern Uinta Mountains and vicinity, Colorado, Utah, and Wyoming, *in* Am. Assoc. Petroleum Geologists, Rocky Mtn. Sec., Geol. Rec., 1956: p. 119–128.

Rocky Mountain Association of Petroleum Geologists, 1941, Possible future oil provinces in Rocky Mountain region: Am. Assoc. Petroleum Geologists Bull., v. 25, no. 8, p. 1469–1507.

Saukov, A. A., 1946, Geokhimiya rtuti [The geochemistry of mercury]: Acad. Sci. USSR Inst. Geol. Sci. Trans. 78, Mineralog.-Geochem. ser. 17, 129 p.

Schell, E. M., and Yochelson, E. L., 1966, Permian-Triassic boundary in eastern Uintah County, Utah, and western Moffat County, Colorado, *in* Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550–D, p. D64–D68.

Thomas, C. R., McCann, F. T., and Raman, N. D., 1945, Mesozoic and Paleozoic stratigraphy in northwestern Colorado and northeastern Utah: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 16, 2 sheets.

Vanderwilt, J. W., 1947, Metals, nonmetals, and fuels, pt. 1, *in* Vanderwilt, J. W., and others, Mineral resources of Colorado: Denver, Colo., Mineral Resources Board, p. 1–290.

Vaughn, W. W., 1967, A simple mercury vapor detector for geochemical prospecting: U.S. Geol. Survey Circ. 540, 8 p.

Williston, S. H., 1964, The mercury halo method of exploration: Eng. and Mining Jour., v. 165, no. 5, p. 98–101.

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