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Dr. Phillip L. Merritt, Assistant Director
Division of Raw Materials
U. S. Atomic Energy Commission
P. O. Box 30, Ansonia Station
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Dear Phil:

Transmitted herewith are six copies of TEI-338, "Uranium-bearing copper deposits in the Coyote district, Mora County, New Mexico," by Howard D. Zeller and Elmer H. Baltz, Jr., May 1953.

We are asking Mr. Hosted to approve our plan to publish this report as a Circular.

Sincerely yours,

Dwight M. Lemmon
for W. H. Bradley
Chief Geologist

UNCLASSIFIED

Geology and Mineralogy

This document consists of 40 pages,
plus 1 figure.
Series A

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

URANIUM-BEARING COPPER DEPOSITS IN THE COYOTE DISTRICT, MORA COUNTY, NEW MEXICO*

By

Howard D. Zeller and Elmer H. Baltz, Jr.

May 1953

Trace Elements Investigations Report 338

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It is not for public inspection or quotation.

*This report concerns work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

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GEOLOGY AND MINERALOGY

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URANIUM-BEARING COPPER DEPOSITS IN THE COYOTE DISTRICT, MORA COUNTY, NEW MEXICO

By Howard D. Zeller and Elmer H. Baltz, Jr.

ABSTRACT

Uranium-bearing copper deposits occur in steeply dipping beds of the Sangre de Cristo formation of Pennsylvanian and Permian age south of Coyote, Mora County, N. Mex. Mapping and sampling of these deposits indicate that they occur in lenticular carbonaceous zones in shales and arkosic sandstones. Samples from these zones contain as much as 0.067 percent uranium and average 3 percent copper. Metatyuyamunite is disseminated in some of the arkosic sandstone beds, and uraninite was identified in some of the copper sulfide nodules occurring in the shale. In polished section these sulfide nodules were found to be composed principally of chalcocite with some bornite and covellite, as well as pyrite and malachite. Most of the samples were collected near the surface from the weathered zone.

The copper and uranium were probably deposited with the sediments and concentrated into zones during compaction and lithification. Carbonaceous material in the Sangre de Cristo formation provided the environment that precipitated uranium and copper from mineral-charged connate waters forced from the clayey sediments.

INTRODUCTION

Location and Accessibility

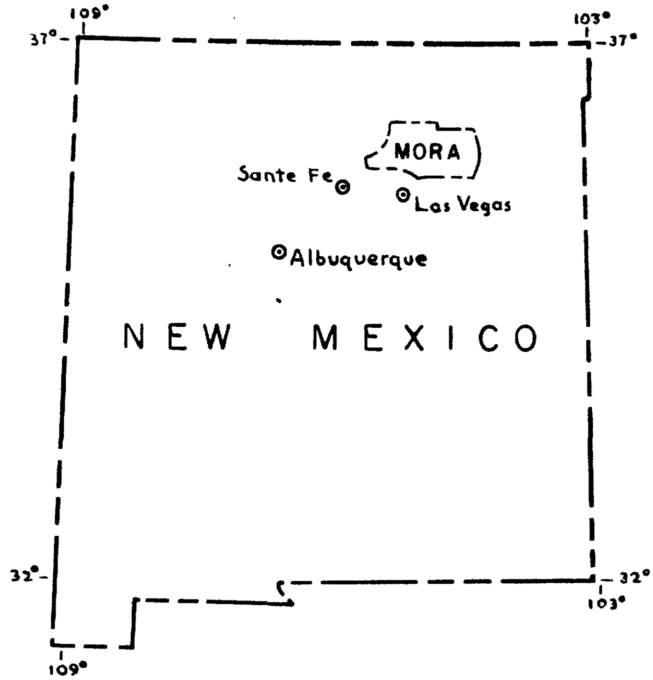
The Coyote district in the west-central part of Mora County, N. Mex., (fig. 1) is located about 10 miles northeast of Mora, the county seat of Mora County, and about 34 miles north of Las Vegas, N. Mex., the nearest railroad shipping point. Uranium-bearing copper deposits of the district are in the narrow belt that extends from the village of Coyote approximately 6 miles south along the west side of Coyote Creek.

The Coyote district may be reached from Las Vegas by following New Mexico State Highway 3 north for 24 miles to La Cueva, then 5 miles north on State Highway 21 across Coyote Creek, and 3 miles west on a dirt road to Lucero. The south end of the area of this report is 2 miles north of Lucero by dirt road. The district may also be reached from Mora, N. Mex., by turning north at the center of the town and following New Mexico State Highway 38 for about 9 miles, then east about 2 miles on a dirt road.

Geography

The Coyote district lies in an area of considerable relief. Altitudes in the mapped area range from approximately 7,240 feet to 8,000 feet. In the mapped area the south-trending valley of Coyote Creek approximates the eastern boundary of the Southern Rocky Mountains and the western boundary of the Raton section of the Great Plains province.

Immediately west of Coyote Creek is a belt of vertical to steeply dipping hogback ridges of sandstone, shale, and limestone. West of the



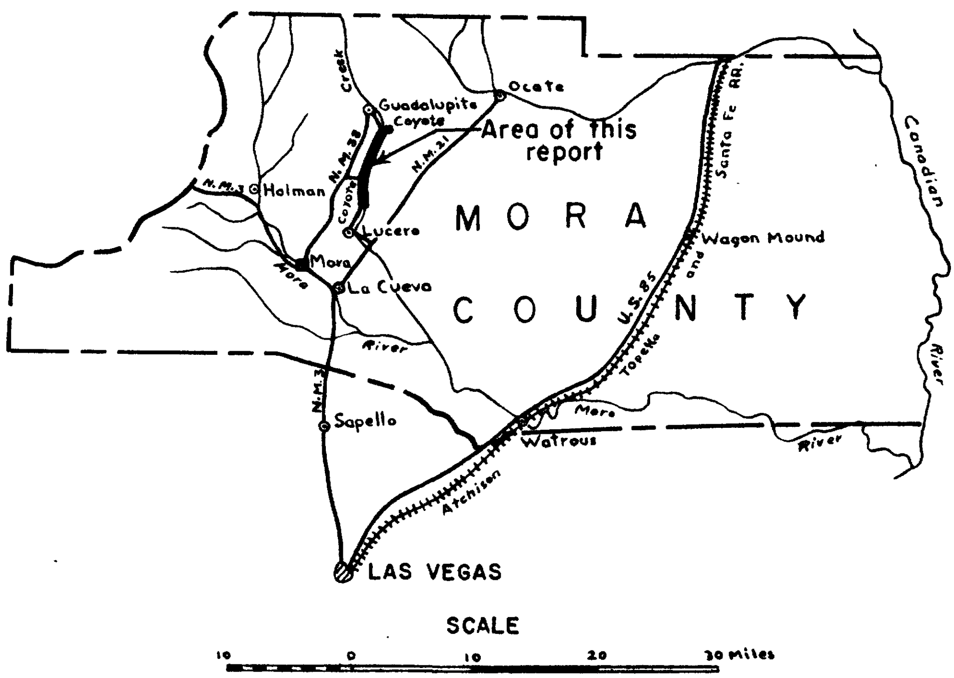


FIGURE 1.--INDEX MAP SHOWING AREA DESCRIBED IN THIS REPORT

hogback belt is a broad generally south-trending alluvial valley that separates the belt of hogbacks from the Rincon Range, also called the Mora Range, the easternmost ridge of the Sangre de Cristo Mountains. The main mass of the Rincon Range in this vicinity is composed of quartzites that form mountains rising to altitudes above 10,000 feet.

East of Coyote Creek, a broad, gently sloping, relatively little-dissected plateau is underlain by massive sandstone to the south and by extensive remnants of basaltic lava flows to the north. Altitudes on this plateau range from 7,700 feet south of Coyote to almost 9,000 feet north of Coyote.

The only permanent stream in the area is Coyote Creek that flows south to Lucero where it cuts eastward through the hogbacks and drains into the Mora River to the southeast.

The hogback ridges and the Rincon Range west of Coyote Creek support heavy growths of scrub oak, pinon pine, and juniper on the lower slopes and fir and western yellow pine on the higher slopes. The northern part of the plateau east of Coyote Creek also has a heavy growth of timber that gradually gives way to grassy plains to the south. The lower valleys are grassy and have clumps of cottonwood and willow along the streams.

No temperature or precipitation figures are available for this area but the summers are pleasingly cool and sub-freezing temperatures are common during the winter months. At Chacon, approximately 10 miles northeast of Coyote and about 900 feet higher than Coyote, the precipitation is 20.88 inches per year (Harley, 1940, table 1, p. 13).

Nearly all of the inhabitants are of Spanish or Mexican descent and many of the older people speak little or no English. Farming in the irrigated Coyote valley is the principal occupation, and lumbering and grazing of cattle and sheep are also important means of livelihood. The graded roads in the area are passable in dry weather but become slick and rutted in rainy weather and may be impassable after heavy snowfalls.

Previous Work

Copper deposits of the Coyote district have been known since the late 19th century. Lindgren, Graton, and Gordon (1910, p. 109) mention them briefly. The district has also been mentioned by Lasky and Wooton (1933, p. 84) and examined and described by Harley (1940, pp. 42-43).

In 1944 Read, Sample, and Shelton of the U. S. Geological Survey examined the deposits and briefly described them in a short unpublished report. Bachman and Read (1952) re-examined the deposits and found traces of radioactivity. The present writers have made a preliminary report (Zeller and Baltz, 1952) on the results of detailed examination of the deposits.

Purpose and Methods of Examination

The present report is the result of geologic study of the Coyote district recommended by Bachman and Read (1952).

Approximately two months were spent in mapping topography and geology with plane table and alidade, tracing mineralized zones, and examining and describing individual prospects and zones. Numerous field counter readings were made and 29 samples were collected for copper and uranium analysis and polished section study. A table containing results of the copper and uranium analyses is appended at the end of this report.

Acknowledgments

The writers were assisted for the first week of field work by C. B. Read, G. O. Bachman, and R. B. O'Sullivan. Radioactivity measurements, chemical analyses, and mineralogical determinations were made by the Trace Elements Denver Laboratory. This work is part of a program of exploration for radioactive raw materials undertaken by the U. S. Geological Survey on behalf of the U. S. Atomic Energy Commission.

GEOLOGY

Stratigraphy

General Description

Rocks of Pennsylvanian and Permian age are exposed in the valley of Coyote Creek within the area of this report. West of Coyote Creek the highest hogback ridges are formed of dark-gray shale and limestone and gray to buff sandstone of the undifferentiated Magdalena group of Pennsylvanian age. The westernmost Magdalena beds are in fault contact with pre-Cambrian quartzites which make up the bulk of the Rincon Range and a considerable amount of the lower Magdalena probably is cut out by the faulting.

Conformably above and geographically east of the Magdalena beds is the thick series of variegated shale, and interbedded conglomeratic arkosic sandstone and limestone of the Sangre de Cristo formation of Pennsylvanian and Permian age. In the mapped area, the Coyote valley is underlain by the Sangre de Cristo formation. West of Coyote Creek the lower beds of the Sangre de Cristo form steeply dipping hogbacks. East of Coyote Creek, the beds flatten progressively and pass under the high plateau with low eastward dips.

The high plateau east of Coyote Creek is capped by the massive buff-colored Glorieta sandstone member of the San Andres formation of Permian age that conformably overlies the Sangre de Cristo formation and probably intertongues with it. Above the eroded top of the Glorieta sandstone are remnants of basaltic lava flows, either late Tertiary or Quaternary in age.

Sediments of the Magdalena group and Sangre de Cristo formation were deposited in a deep subsiding trough which has been called the Rowe-Mora basin by Read and Wood (1947, p. 227). This basin was flanked on the east and west in Pennsylvanian and Permian time by highlands that served as source areas for much of the detrital material in the basin. The presence of these highlands composed of pre-Cambrian crystalline rocks has been well demonstrated in mapped areas to the southeast, south, and southwest of the Coyote area (Read and Wood, 1947; Northrop, and others, 1946; Read and Andrews, 1944).

Sangre de Cristo formation

All of the mineral deposits described in this paper occur in the Sangre de Cristo formation. Lasky and Wooton (1933, p. 84) state that the copper deposits of the Coyote district are in carbonaceous shale of Cretaceous age. According to Harley (1940, p. 42) the deposits occur in beds of the Dockum group of Triassic age. Apparently the Glorieta sandstone on the plateau east of Coyote Creek was miscorrelated in both papers with the Dakota sandstone to which it bears some resemblance. Bachman and Read (1952), on the basis of regional investigations in previous years, recognized the red beds on Coyote Creek to be in the Sangre de Cristo formation. The present writers found carbonized plant remains of the Permian conifer Lebachia in the Sangre de Cristo formation at map locality 1. Exposures east of Lucero show normal succession of Triassic, Jurassic, and Cretaceous beds above and to the east of the Glorieta sandstone.

The Sangre de Cristo formation is composed of a series of interbedded thick conglomeratic arkosic sandstone; variegated clay shale, sandy shale and siltstone; and dense, gray, bedded and nodular limestone. Sandstone beds are thin to massive and the thicker beds generally form strong persistent ledges. The sandstone is fine- to very coarse-grained; sorting is characteristically poor. Many beds contain conspicuous quantities of pebbles and cobbles of granite gneiss, schist, and quartzite. The most common mineral in the sandstone is quartz, but all of the sandstone beds contain notable amounts of fresh to slightly weathered angular potash feldspar fragments that give the beds their typical salmon-pink color. Some of the sandstone contains as much as 50 percent feldspar with unweathered cleavage fragments as large as 3/4 inch in diameter. Sericite, muscovite, and biotite are present in some beds. The principal cementing agent is calcite but kaolin, silica, and iron oxide are also present. Cross bedding and cross lamination are prominent and in many places both are marked by thin layers of magnetite sand. Sandstone beds form about 35 percent of the bulk of the Sangre de Cristo formation.

The thicker shaly intervals form small valleys and flats between ridges of arkose and are persistent for considerable distances, although individual shale beds appear to be lenticular (fig. 2A). The shales are laminated clays, commonly sandy or silty, containing interbedded siltstone and shaly fine-grained sandstone. Lateral and vertical gradation between beds of all types is common. Many of the less permeable clay beds are light-green to gray, whereas the beds of more permeable silty and sandy shale tend to be reddish or brown on the weathered outcrop. In some of the prospect pits the reddish colors of the oxidized beds appear to die out with depth. This may indicate that the distinctive "red beds" color of parts of the Sangre de Cristo formation is due to recent oxidation near the surface rather than being an original depositional color of the sediments. Approximately 60 percent of the Sangre de Cristo formation is composed of shale.

Thin-bedded and nodular limestone is interbedded with shale throughout the formation. Many of the limestone beds, particularly the nodular beds, appear to have been partly recrystallized. Limestone forms about 5 percent of the formation. Most of the limestones are probably of fresh water origin but some of the lower beds are undoubtedly marine.

Figure 2A.--View north from south end of the Coyote district, showing prominent arkosic sandstone ledges and less resistant shale beds of the Sangre de Cristo formation.

Figure 2B.--Typical prospect (Locality 5) showing mineralized zone in gray carbonaceous shale and siltstone between arkosic sandstone ledges.

A sandy copper-bearing limestone exposed in the prospect at locality 22 about 1,000 feet stratigraphically above the base of the Sangre de Cristo formation contains numerous small complete gastropod shells, crinoid columnals, and a few pelecypod valves. According to S. A. Northrop (personal communication, 1953) there are several genera of gastropods that are bellerophontids, but surface textures are too poor to permit specific identification. One well-preserved pelecypod valve was identified as Myalina sp. All of the forms are definitely marine. The variety of gastropod genera and lack of broken or fragmental specimens indicates that these marine invertebrates are part of an indigenous fauna and do not represent re-worked material. Field observations of the lithology further substantiate this conclusion.

The lower contact of the Sangre de Cristo formation is generally placed at the top of the highest marine limestone of the Magdalena group. However, in the Coyote area the contact as shown by Bachman and Read (1952) is marked by a lithologic change from dark shale and light-colored quartz sandstone of the Magdalena group to pink arkosic sandstone and variegated shale of the Sangre de Cristo formation. The fossiliferous marine limestone noted above is in the arkosic sandstone and variegated shale sequence. There is no lithologic basis for moving the contact upward stratigraphically as the thin fossiliferous limestone and enclosing shale and sandstone are entirely similar to other unfossiliferous limestone-bearing intervals throughout the Sangre de Cristo formation. For this reason the writers have not changed the contact to the position of the limestone and they consider the lower part of the Sangre de Cristo to be composed of both marine and nonmarine sediments.

Most of the shale beds contain at least small amounts of carbonaceous material and some of the beds are highly carbonaceous to coaly containing numerous recognizable carbonized stems, twigs, and leaf impressions. Carbonaceous material ranging from microscopic fragments to large logs occurs in the coarser sediments but is not as common as in the shale beds. Nearly all of the copper and uranium deposits are in, or are associated with, these carbonaceous zones.

It was impossible to measure the thickness of the Sangre de Cristo formation accurately in the Coyote area because of thrust faulting in the western part of the area. According to G. O. Bachman (personal communication, 1953) the Sangre de Cristo formation is approximately 3,500 feet thick on Mora River, about 12 miles south of the Coyote area, and is known to thicken considerably to the north. The authors estimate that the formation is at least 4,000 feet thick in the Coyote area. The uranium and copper deposits occur in the stratigraphic interval between 1,000 and 2,000 feet above the base of the formation.

Structure

Along the west side of Coyote Creek, beds of the Magdalena group and Sangre de Cristo formation are generally vertical or dip steeply to the east. In the northern part of the mapped area, beds are overturned and dip steeply to the west. The beds dip to the east progressively more gently east of Coyote Creek and pass under the mesa east of Coyote Creek dipping 7° to 10°.

Beds of the hogbacks were folded during uplift and eastward movement of large crustal blocks in the Sangre de Cristo Mountains. The folding occurred in front of large high-angle thrust faults that are the eastern boundaries of these crustal blocks.

The major belt of thrust-faulting is located in the valley west of the hogbacks and is not shown on figure 4 of this report. Most of the thrust faults in the mapped area are essentially parallel to bedding planes but are discernible in areas where they cut across beds. These faults probably occur as "splinters" from the major faults in a marginal zone of deformation between the eastward-thrust Sangre de Cristo blocks and the relatively undeformed high plains to the east.

MINERAL DEPOSITS

General Description

All of the observed mineralized zones occur in the stratigraphic interval between 1,000 and 2,000 feet above the base of the Sangre de Cristo formation. It is possible that other mineralized zones are stratigraphically higher in the Sangre de Cristo formation but none were observed. Two to seven uranium-bearing copper zones were mapped at various places in the area. The largest number of zones was mapped at the north and the south ends of the area where exposures are best. Outcrops in arroyos indicate the presence of other zones that extend under soil cover and have not been prospected and which could not be traced beyond the arroyos in which they are exposed.

The individual deposits were traced mainly by the presence of prospect pits in the zones (fig. 2B); however, there are a few outcrops at the surface. The zones shown on the map were drawn conservatively and extended only where surface exposures indicated the presence of copper. Many of the deposits are undoubtedly more extensive than shown.

Copper and small amounts of associated uranium are widely disseminated throughout the stratigraphic interval of the Sangre de Cristo formation in which the mineralized zones occur. The mapped zones contain localized concentrations of uranium-bearing copper sulfides and carbonates in the shale and sandstone beds. The mineralized bodies are generally lens-shaped and paralled to the sedimentary beds which enclose them. The size and shape of these lenses are mainly controlled by the amount and distribution of carbonaceous material in the sediments. A zone, as mapped, may be a series of lenses within 2 or 3 feet of the same stratigraphic horizon. Only a little copper is present in the recrystallized parts of some of the nodular limestone beds. No carbonaceous material was seen in the limestone.

At all localities where radioactive material has been found it is intimately associated with copper minerals. The greatest radioactivity generally is in the most highly carbonaceous zones. No radioactive material was observed in non-carbonaceous zones although non-radioactive copper minerals are found in them.

Individual prospects and sample localities are described in the Appendix at the end of the report.

Occurrence

Uranium-bearing copper deposits of the Coyote district may be grouped in four general categories that are defined by the lithology of the enclosing sediments. The categories are:

(1) Nodules of copper sulfides and small amounts of copper carbonates in shale and sandy shale beds.

(2) Small amounts of copper sulfides and larger amounts of copper carbonates in sandstone beds.

(3) Traces of copper sulfides and carbonates in recrystallized parts of nodular limestone beds.

(4) Copper carbonate (and sulfide ?) finely disseminated throughout the interval of the Sangre de Cristo formation that contains the mineral deposits.

Deposits in shale and sandy shale

The most important copper and uranium deposits are in shaly beds of the Sangre de Cristo formation. Nodules composed mainly of chalcocite, but also containing bornite, covellite, pyrite, and carbonaceous material, occur as replacements of plant stems, twigs, and leaves, and as irregularly shaped masses in highly carbonaceous shale and siltstone. Nodules dug from unweathered parts of prospect pits show practically no alteration except for a few nodules that are surrounded by a thin film of azurite or malachite. Average size of the nodules found is about 2 inches in largest dimension; however, much larger nodules have been found during small-scale mining and prospecting. According to local inhabitants nodules "the size of a man's head" were removed from the prospects at localities 31 and 32 near the south end of the area.

Many of the nodules contain uranium intimately associated with the copper minerals. Uraninite was identified in polished sections of nodules collected at locality 26 by W. I. Finch and H. Stager of the U. S. Geological Survey _/. Unusually high radioactivity of small

_/ Personal communication from W. I. Finch; minerals determined by A. Rosenzweig of the U. S. Atomic Energy Commission and L. B. Riley of the U. S. Geological Survey.

nodules found at other localities, particularly map localities 12 and 13, may indicate the presence of uraninite.

Coaly clay shale at map locality 3, and at several other localities, contains considerable amounts of copper and some uranium, apparently in a disseminated state. The only minerals observed in these shales were slight stains of azurite and malachite.

Deposits in sandstone beds

Copper carbonates and sulfides occur in the thick arkosic sandstone beds that are intercalated with shale beds in the mineralized part of the Sangre de Cristo formation. Malachite is the cementing agent around some sand grains and often grades imperceptibly into interstitial calcite, which is the principal cementing agent of the sandstone. In places malachite appears to have replaced calcite, but generally it grades into greenish-colored calcite and both probably were deposited at the same time. Twigs, logs, and wood fragments which occur in the sandstone are commonly replaced by copper sulfides. On the weathered surface of the sandstone sulfide-replaced wood fragments are usually altered to azurite and malachite with only a small core of copper sulfide remaining. Much of the calcite cement of the sandstones is replaced by malachite around these weathered sulfide bodies.

Uranium is present in small irregular masses of copper sulfide, particularly those which still contain particles of carbonized original vegetable matter. "Blooms" of a yellow mineral identified as metatyuyamunite (King, 1952) were found at localities 8, 15, and 18 associated with malachite in weathered outcrops and at the surface of dumps of the prospects. This metatyuyamunite is a recent alteration product of some other uranium mineral which is associated with the copper sulfides. Compressed carbonized logs found in the sandstone beds at various localities and thin, highly carbonaceous sandstone beds contain uranium but no uranium minerals were observed.

The highest grade of copper mineralization in the thick sandstone beds is near both upper and lower contacts of the sandstone with the enclosing copper-bearing shale. The grade of mineralization generally decreases rapidly toward the center of individual beds of sandstone so that there are only traces of copper 3 to 8 inches from the contact.

Deposits in limestone beds

Traces of copper carbonates and sulfides are present in the recrystallized parts of some of the limestone beds of the Sangre de Cristo formation. Small grains and irregular nodules of copper sulfide with a maximum diameter of a quarter of an inch were found at a few places in bands of acicular calcite crystals that surround irregular masses of dense gray limestone. Malachite occurs as green disseminations in the acicular calcite and fills small fractures in the dense limestone. No abnormal radioactivity was noted in the limestones.

Finely disseminated copper minerals

Finely disseminated copper carbonate, and probably copper sulfide, are present in almost all beds in the stratigraphic interval of the Sangre de Cristo formation that contains the more concentrated deposits. Slight green stains were observed at various places on weathered outcrops of most of the sandstone beds. Samples of greenish-gray and gray shale collected at random from several stratigraphic horizons across the mapped area contain as much as 0.03 percent copper and 0.003 percent uranium.

Mineralogy

Fifteen polished sections of copper sulfide nodules from the Coyote mining district were prepared and studied. Chalcocite is the most common copper mineral present; however, bornite and covellite are also present in smaller quantities in most of the nodules. Some pyrite is present in all but two of the nodules. Malachite stringers occur as fracture fillings. Other associated minerals include quartz grains, calcite, and possibly siderite. Irregularly shaped fragments of vitrain surrounded by chalcocite are common in many nodules (fig. 3B).

Woody cell structure is well preserved in many of the nodules. In others the cells have been crushed to form compact vitrain, or have been partly replaced by copper and iron sulfides. Most of the nodules exhibit textures inherited from replaced cell structure and one specimen contains all gradations from the inherited texture through partly replaced cell walls to complete cells filled by copper sulfide. The cell walls are generally composed of vitrain with chalcocite filling the cell interiors. Cell walls replaced by pyrite were observed in only one specimen. Covellite and chalcocite are found in spaces between the rows of cells (fig. 3A). All gradations were observed from slight permineralization to complete replacement of woody material by copper sulfides.

No order of replacement among these copper minerals could be determined, except that malachite formed last in small fractures in the nodules. Although some pyrite is present in most of the nodules, only a few specimens suggest that chalcocite replaced the pyrite. In most cases, pyrite and chalcocite seem to have been deposited contemporaneously. Bornite and chalcocite (fig. 3C) are found in a more or less graphic intergrowth which indicates that they are contemporaneous. Covellite is found associated with plant cell structure and appears to be contemporaneous with the chalcocite inasmuch as one grades into the other (fig. 3A).

Figure 3A. --Photomicrograph of a part of a copper sulfide nodule showing plant cell structure. Chalcocite (cc), covellite (cv). Cell walls are composed of vitrain. X 132.

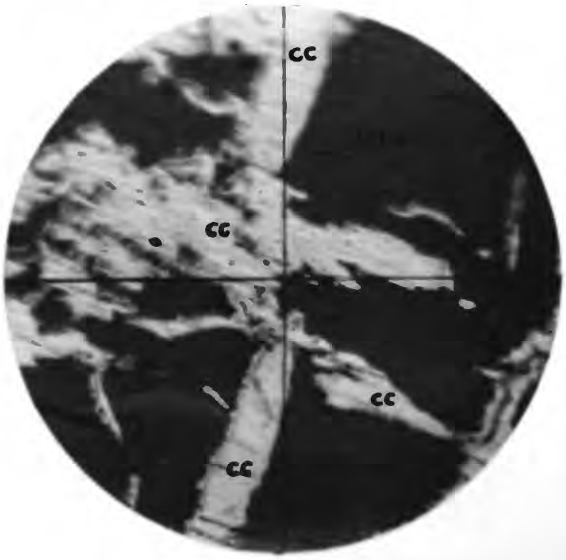


Figure 3B. --Chalcocite (cc) and vitrain along margin of a copper sulfide nodule. X 340.

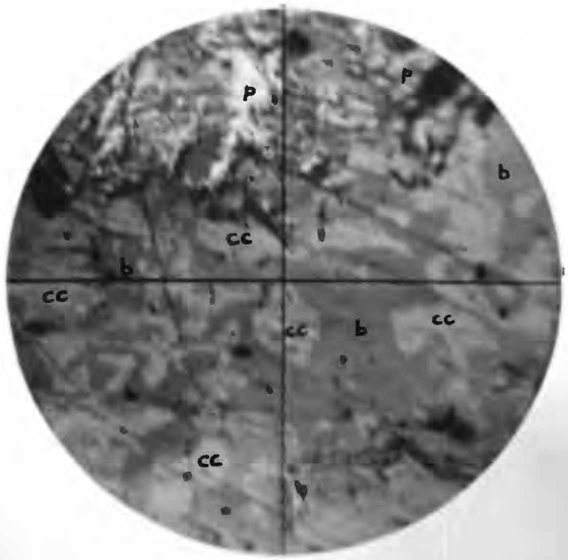


Figure 3C. --Graphic association of bornite (b) and chalcocite (cc) in a copper sulfide nodule. Pyrite (p) is present in upper part of photomicrograph. X 380.

Origin of deposits

General statement

The copper and uranium deposits of the Coyote district appear to be of sedimentary origin. It is believed that small amounts of copper and uranium were originally deposited with the sediments of the Sangre de Cristo formation and later concentrated into zones during compaction of the sediments. No evidence of post-depositional introduction of mineral-bearing solutions could be recognized, and only slight alteration of the deposits by ground water and surface water has occured since lithification of the sediments.

Evidence of syngenetic origin

Sediments of the lower part of the Sangre de Cristo formation are relatively impermeable to ground water. Examination of numerous samples of sandstone and conglomerate indicates that they are tightly cemented by calcite and other fine material. Large quantities of unaltered magnetite sand and copper sulfide nodules are present in sandstone and shale beds near the weathered surface. Oxidation of the minerals and weathering of the enclosing sediments below the surface has progressed downward for only a short distance at most localities.

The impermeability of the lower part of the Sangre de Cristo formation suggests that the copper and uranium mineralization, which is widespread throughout this interval, occurred prior to lithification of the sediments.

Delicate plant cell structure preserved in many of the copper sulfide nodules collected from shaly beds suggests mineralization at or shortly after burial of the plant remains and before compaction of the surrounding shale caused collapse of the cell structure. Almost all of the unmineralized plant material which was observed has been compressed and flattened. Large pieces of compact slightly permineralized vitrain were observed at several localities and many of the sulfide nodules contain slightly mineralized particles of vitrain indicating that the process of mineralization continued during compaction of the sediments.

It is believed that small amounts of copper and uranium were carried in solution by the water in which sediments of the lower part of the Sangre de Cristo formation were transported and deposited. The favorable environment presented by fairly large accumulations of plant material in areas where mud and silt were being deposited caused precipitation of part of the copper and uranium carried by the water. Hydrogen sulfide gas generated by decaying vegetable matter may have been an agent in precipitation of copper and iron sulfides. A small amount of copper sulfide may have been formed by the replacement of iron sulfide which was accumulating in decaying vegetable matter; however, polished sections examined by the writers contain only a small amount of pyrite, and that appears to have been deposited contemporaneously with the copper sulfides.

Evidence of diagenetic concentration

Many of the nodular limestone beds show evidence of partial solution and recrystallization. Copper carbonates and sulfides occur both as fracture fillings and in the recrystallized parts of the limestone, but they are not present in the original dense limestone cores of the nodules. Solution and recrystallization must have occurred during the early stages of compaction at a time when the enclosing shaly sediments contained much water and were still in a highly plastic condition. Solution cavities around the limestone nodules and on the surface of limestone beds are completely filled by shale. There is no slaty cleavage or other evidence of shearing which would have developed in the shale around voids left by the dissolved parts of the limestone if solution had occurred after induration of the shale.

Sulfide bodies are concentrated at the contacts of sandstone with mineralized shale and the amount of mineralization of the sandstone generally decreases rapidly inward from the contact. Any individual sandstone bed may be mineralized at either the upper or lower contact, or both. The writers believe that the sandstone beds served, prior to lithification, as aquifers for circulation of mineral-charged connate water driven from the surrounding shale beds during compaction. The carbon of partly decomposed stems, twigs, and leaves and other woody fragments present in the sandstone provided an environment which caused precipitation of copper and uranium minerals from dilute solutions which were forced through the sandstones. Much of the calcite cement of the sandstone was probably deposited from the mineral-charged water at this time as was the interstitial malachite.

Migration of mineral-charged connate water through the shale during compaction also caused greater localization of uranium and copper deposits in the more highly carbonaceous parts of the shale beds.

The process of diagenetic concentration was halted when all, or nearly all of the connate water was forced out of the shale, or when the sandstone beds became cemented by calcite.

The writers observed no features which would indicate that mineral-bearing solutions were introduced after lithification of the sediments. Mineralized zones appear to be controlled entirely by sedimentary structures and no relationship of amount or distribution of mineralization to joints and faults was observed. At several localities faults cut and offset the zones. No mineralization was observed in the principal joints and faults except for slight stains of malachite which occur near weathered sulfide bodies. At many places across the area, thin stringers of calcite and gypsum occur as fillings in small fractures in the shale beds. These stringers transect mineralized zones and have no apparent relation to them.

Original source of copper and uranium

The Sangre de Cristo formation is composed in part of eroded Pennsylvanian rocks, but it is composed mainly of first-cycle sediments derived from pre-Cambrian crystalline rocks which are predominantly granitic. These basement rocks were exposed in the rising highlands on the east and west flanks of the Rowe-Mora basin in Late Pennsylvanian and Permian time.

Small copper deposits in pre-Cambrian rocks occur at many localities in the mountains of northern New Mexico. Minor amounts of uranium are also present at some of these localities, notably in the Petaca district of Rio Arriba County. Some of the deposits are located on the ancient highlands, and erosion of these mineral bodies in Pennsylvanian and Permian time undoubtedly furnished small quantities of copper and uranium to the sedimentary basins. However, most of the copper and uranium in the Coyote deposits is believed to have been derived from the decomposition of large quantities of predominantly granitic rocks. Katz and Rabinowitch (1951) report the abundance of copper in igneous rocks of all types to be 100 grams per metric ton (0.01 percent) and Rankama and Sahama (1950) give the average copper content of acidic igneous rocks as 16 grams per metric ton (0.0016 percent). The abundance of uranium in all types of igneous rocks, according to Katz and Rabinowitch (1951), is 4 grams per metric ton (0.0004 percent) and Rankama and Sahama (1950) give the abundance of uranium in granitic rocks as 3.963 grams per metric ton (about 0.0004 percent). If the granitic rocks that were eroded to supply the sediments of the lower part of the Sangre de Cristo formation in the Coyote district were average in their copper and uranium content they could have supplied sufficient quantities of copper and uranium to mineralize the rocks. Environmental conditions of deposition of the Sangre de Cristo formation then would have played an important part in localizing the deposits.

No mineral deposits were observed in the upper part of the Sangre de Cristo formation in the Coyote district. Physical evidence indicates that this part of the formation was deposited under subaerial conditions which did not permit the accumulation of carbonaceous material that could have provided the environment necessary for precipitation of copper and uranium minerals.

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APPENDIX

RADIOACTIVITY AND CHEMICAL ANALYSES OF SAMPLES FROM COYOTE DISTRICT, MORA COUNTY, NEW MEXICO

Radioactivity and chemical analyses of samples from
Coyote district, Mora County, New Mexico [1]

Sample and locality number	Laboratory serial number	Radioactivity: Equivalent uranium (percent)	Chemical analysis: Uranium (percent)	Chemical analysis: Copper (percent)	Description
1	D-76591	0.009	0.006	2.21	The prospect is on the slope of a steep hill overlooking Coyote Creek. The sample is from dark-gray lenticular carbonaceous shale which is overlain and underlain by greenish-gray, silty, very coarse-grained arkosic sandstone. The shale contains many carbonized stems, leaves, and twigs. Much malachite occurs as small flat flakes in the sandstone.
2	D-76592	0.007	0.007	1.73	At the same locality (1) a grab sample of arkosic sandstone that overlies the shale contains much malachite and some chalcocite as both irregular masses and interstitial material between highly angular to sub-angular quartz and feldspar grains. The arkose contains carbonaceous material, some sericite, and much clay and silt. Copper mineralization is concentrated near the contacts of the sandstone.
3	D-76593	0.020	0.004	2.51	A small trench is located between two arkose ledges. Copper and uranium occur in a dark carbonaceous clay shale that shows traces of malachite and azurite. A two-foot channel sample was taken.
4	D-76594	0.007	0.003	2.72	A grab sample was taken from the dump of a badly filled prospect having no exposures. Dark-gray to black shale contains much disseminated carbon and plant remains. Fossil twigs replaced by chalcocite were found on the dump.

[1] Analyses furnished by Trace Elements Denver Laboratory, Lewis F. Rader, Jr., in charge. Radiation by Furman. Chemistry by McCarthy, Mountjoy, Niles, Schuch, and Skinner. Mineral analyses(referred to in text) by A. G. King.

Radioactivity and chemical analyses of samples from
Coyote district, Mora County, New Mexico

Sample and locality number	Laboratory serial number	Radioactivity Equivalent uranium (percent)	Chemical analysis Uranium (percent)	Chemical analysis Copper (percent)	Description
5	D-76595	0.018	0.014	6.13	Black carbonaceous shale was sampled from the dump of a small filled prospect pit. The shale contains much coaly material (probably vitrain) and much disseminated malachite.
6	D-77032	0.002	0.001	0.005	A greenish-gray clay shale, typical of those occurring throughout the lower part of the Sangre de Cristo formation was channel sampled. This locality was not prospected and no copper mineralization was observed.
7	D-76596	0.014	0.010	4.16	A small caved prospect has much medium-grained arkosic sandstone on the dump. This grab sample of sandstone contains much disseminated malachite and carbonaceous material.
8	D-76597	0.065	0.048	6.39	A small filled pit is located on same zone as sample 7. A grab sample of arkosic sandstone contains much carbonaceous material in the form of twigs and leaves. A considerable amount of malachite and chalcocite are found on the dump of the pit. Almost all rocks on the dump are at least moderately radioactive.
9	D-76589	0.039	0.018	14.38	A grab sample of arkosic sandstone contains malachite, chalcocite and a "bloom" of a yellow mineral that is highly radioactive. In a similar occurrence at sample locality 18, the yellow mineral was identified as metatyuyamunite.

Radioactivity and chemical analyses of samples from
Coyote district, Mora County, New Mexico

Sample and locality number	Laboratory serial number	Radioactivity Equivalent uranium (percent)	Chemical analysis: Uranium (percent)	Chemical analysis: Copper (percent)	Description
10	D-77033	0.003	0.001	0.010	A light olive-green clay shale crops out along the side of an arroyo. No copper mineralization was observed.
11	D-77034	0.001	< 0.001	0.030	A channel sample of a greenish-gray clay shale that is exposed along the margin of a shallow prospect pit. No copper mineral was observed in the shale; however, malachite stains were present in an adjacent nodular limestone.
12	D-76598	0.011	0.008	3.72	The prospect is a large, partly filled trench. A grab sample composed of shale and arkosic sandstone from the dump contains much carbonaceous material and malachite.
13	D-76599	0.018	0.015	4.65	A vertical shaft 15 feet deep with a filled crosscut at the bottom has a large quantity of black carbonaceous shale on the dump. The black shale contains malachite and small reniform pieces of chalcocite. The quantity of black carbonaceous clay material on the dump suggests thicker shale beds at depth. The radioactivity of some of the chalcocite nodules and coaly material is unusually high.
14					Coaly fragment (1" x 1" x 1/4") was found in the dump of the shaft described for sample 13. Radioactivity was 10 times background on the field counter, which may indicate that the sample contains uraninite.

Radioactivity and chemical analyses of samples from
Coyote district, Mora County, New Mexico

Sample and locality number	Laboratory serial number	Radioactivity Equivalent uranium (percent)	Chemical analysis Uranium (percent)	Chemical analysis Copper (percent)	Description
15	D-76600	0.068	0.067	13.65	A small filled longitudinal trench is cut in the center of an arkosic sandstone ledge. The sandstone is fine- to medium-grained and contains much malachite. Copper and uranium are concentrated in fossil twigs and leaves. A grab sample was taken.
16					A small circular pit contains much nodular limestone. The limestone nodules appear to have been dissolved and recrystallized in part. Flakes and stains of malachite are found only in fractures of the dense portion, but disseminations of malachite are found throughout the recrystallized portions.
17	D-76587	0.004	0.0002	57.33	A partly filled shaft 25 feet deep, with north and south drifts at the bottom, follows beds for an undetermined distance. Sample is composed of chalcocite nodules, hand-picked from the dump.
18	D-76601	0.054	0.032	0.66	A grab sample of fine- to medium grained arkosic sandstone contains much disseminated malachite and carbonaceous material. A yellow uranium mineral, metatyuyamunite, occurs as fine disseminations and "blooms" in the sandstone. Metatyuyamunite is associated with carbonaceous and micaceous layers in the sandstone and also occurs in cracks within the sandstone. The prospect where the sample was taken is 20 feet by 10 feet and badly filled; however, most of the arkosic sandstone on the dump counts over 5 times background with a field counter.

Radioactivity and chemical analyses of samples from Coyote district, Mora County, New Mexico

Sample and locality number	Laboratory serial number	Radioactivity Equivalent uranium (percent)	Chemical analysis Uranium (percent)	Chemical analysis Copper (percent)	Description
19	D-76590	0.039	0.026	0.41	A grab sample of an arkosic sandstone from prospect 18 shows a "bloom" of metatyuyamunite.
20	D-76602	0.009	0.004	1.81	A grab sample of a carbonaceous shaly sandstone contains disseminated malachite and chalcocite. Malachite also replaces twigs and plant leaves.
21	D-77035	0.005	0.003	0.005	Small prospect pit contains greenish-gray clay shale cropping out along the sides. A channel sample was taken.
22 and 23					Marine fossils in sandy limestone were found along margins of a small prospect pit. See page 16 in text.
24	D-77036	0.003	< 0.001	0.005	A channel sample of a greenish-gray clay shale exposed along a road cut. No copper mineralization was observed.
25	D-76603	0.008	0.004	7.49	A recent prospect pit 18 feet deep and approximately 15 feet square is in a gray shaly siltstone, some of which is red. The sample is a 1.5 foot channel sample of a highly carbonaceous shaly siltstone. The carbonaceous siltstone is overlain by red shaly siltstone and underlain by a conglomeratic arkosic sandstone. Many plant fossils are replaced with copper sulfides. Some copper sulfide nodules are ellipsoical in shape and are oriented parallel to the bedding.

Radioactivity and chemical analyses of samples from Coyote district, Mora County, New Mexico

Sample and locality number	Laboratory serial number	Radioactivity Equivalent uranium (percent)	Chemical analysis Uranium (percent)	Chemical analysis Copper (percent)	Description
26	D-76588	0.048	0.041	32.85	The sample represents nodules of copper sulfides from locality 25 that were hand-picked for highest radioactivity. Uraninite was found disseminated in the nodules collected from this locality by W. I. Finch and H. Stager. (See note page 21 in text.)
27	D-77037	0.003	0.002	0.020	A greenish-gray clay shale was channel sampled on the outcrop. No copper minerals were observed.
28	D-76604	0.054	0.061	3.84	A 3-1/2 inch carbonaceous gray shaly sandstone is exposed in a small prospect. The sandstone is overlain by red oxidized sandstone, siltstone, and shale. Malachite and chalcocite were observed in the sandstone and the highest radioactivity is in the more carbonaceous portions of the sandstone. A grab sample was taken.
29	D-76585	0.011	0.003	2.23	A weathered outcrop about 300 feet south of locality 28 consists of very carbonaceous sandstone, siltstone and shale with much malachite and some chalcocite. The thickness is about 3 feet; however, only 6 in. of the more carbonaceous material was sampled. The carbonaceous beds are overlain by a very angular fine- to coarse-grained sandstone.
30	D-76586	0.015	0.008	0.80	A carbonaceous black shale was grab sampled on the dump of a filled in prospect pit. Malachite was observed in the shale. Some limestone nodules in the carbonaceous material have malachite in the recrystallized portions.

Radioactivity and chemical analyses of samples from Coyote district, Mora County, New Mexico [1]

Sample and locality number	Laboratory serial number	Radioactivity Equivalent uranium (percent)	Chemical analysis Uranium (percent)	Chemical analysis Copper (percent)	Description
31	D-77038	0.003	0.002	5.245	A 100-foot long badly caved trench is located between two arkosic sandstone beds. The dump contains sandstone with many carbonaceous layers in which are malachite and copper sulfides. Malachite-coated sericite grains are common in the sandstone. A grab sample was taken.
32	D-77039	0.004	0.003	6.759	A dark-gray carbonaceous clay shale containing malachite, azurite and some copper sulfides was grab sampled from locality 31.
33	D-77040		Parts per million 0.015	None	A water sample from a covered well near a school house and 80 feet west of the road.

[1] Analyses furnished by Trace Elements Denver Laboratory, Lewis F. Rader, Jr., in charge. Radiation by Furman. Chemistry by McCarthy, Mountjoy, Niles, Schuch, and Skinner. Mineral analyses (referred to in text) by A. G. King.