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AN INTERIM REPORT ON THE ORE DEPOSITS
OF THE GRANTS DISTRICT, NEW MEXICO

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AN INTERIM REPORT ON THE ORE DEPOSITS OF THE GRANTS DISTRICT, NEW MEXICO

ABSTRACT

The Grants uranium district is situated in northwest New Mexico, along the southern flank of the San Juan Basin, between the cities of Gallup and Albuquerque. The region is composed of three major structural elements: 1) the Zuni Uplift, which covers an area of 2,000 square miles, 2) the McCarty Syncline of undetermined extent, and 3) the Lucero Uplift which covers an area of 1,500 square miles. Uranium mineralization appears to be confined chiefly to Jurassic rocks are concealed by a thick mantle of Cretaceous sediments and Tertiary extrusives. Known mineralization is restricted to two general horizons: 1) the Todilto limestone and basal Summerville, and 2) the Morrison and basal Dakota formations. These two zones are separated by 500 to 800 feet of barren sedimentary rock. Mineralization in the Todilto limestone is known to extend in an east-west direction over a distance of 60 miles. Deposits in the upper, sandstone horizon have been discovered over a linear extent of 85 miles in the same direction.

Discovery of uranium mineralization in the Grants district, during the spring of 1950, is credited to Paddy Martinez, a Navajo Indian. After a field examination of Santa Fe Railway Company holdings within the district, Mr. Thomas O. Evans, chief mining engineer for the railroad, initiated an exploration program in December of 1950. Test pits 6 feet square were sunk on 100 foot centers through the Todilto and the rim was drilled and blasted to ascertain the magnitude of surface leaching. Test-pitting, which cost approximately $35.00 per foot of depth, was soon replaced by hand-held jackhammer drilling at about $2.00 per foot. Comparative assays from samples recovered by these methods at the same points and over the same depth-range varied by as much as 62 percent. The discrepancy is believed to be the consequence of the difference in the sizes of the samples and the irregular distribution of values. Exploration is now being performed by Santa Fe using half-track mounted wagon drills at an approximate cost of $1.50 per foot.

The Anaconda Copper Mining Company secured leases and began exploration in January 1951. Extensive programs of both air-borne and ground radiometric reconnaissance have been followed by trenching, wagon-drilling, test-pitting, bulldozing, and the driving of prospect adits. Approximately 2,000 tons of limestone ore were mined by open-pit methods to determine costs and grade cut-off.

An initial reconnaissance was performed for the A.E.C. by Mr. Herbert V. Lee in November of 1950. Mr. Millard Reyner and Mr. Jack Sheridan of the A.E.C. spent two weeks in the area during November of 1950 preparing a detailed description of the known deposits. A sub-office of the Denver Exploration Branch of the A.E.C. was established at Prewitt, New Mexico in January of 1950 to study the geology and promote the development of the Grants District. The smaller companies have been handicapped by lack of a market, but the establishment of a buying station by the Anaconda Copper Mining Company in the Spring of 1952, under contract to the A.E.C., should instigate a surge of development.
The uranium minerals of the ore deposits in the Todilto limestone include carnotite, tyuyamunite, uranophane, beta-uranotile, sklodowskite, and pitchblende. Gangue minerals, in traces, consist of barite, pyrite, hematite, and fluorite. Coarsely-crystalline calcite, as replacements along bedding planes and as fillings in fractures developed by Zuni Uplift, also appears to be associated in space with ore. Carnotite and schroeckingerite have been identified in the Morrison formation where they are associated with organic material and limonite.

The sequence of geologic events which has determined the present form and position of the ore deposits is believed to be:

1. Precipitation of the Todilto limestone in a lacustrine basin.
2. Diagenetic recrystallization of the upper limestone possibly contemporaneous with the introduction of uranium.
3. Deformation, which created the Zuni Uplift, and attendant fracturing, faulting, and local flexure.
4. Formation of coarse-grained, black, calcite veinlets along bedding planes and fractures.
5. Vein filling by coarsely-crystalline, white calcite.
6. Replacement of coarsely-crystalline calcite by barite, pyrite, and fluorite.
7. Permeation of uranium-bearing solutions (which may have been introduced at this time from telemagmatic sources) through the Todilto limestone, localization of pitchblende on minor flexures, and the partial replacement of all previous minerals, including clastic quartz, by pitchblende.
8. Oxidation of pyrite to hematite, pitchblende to yellow uranium minerals, and the leaching and downward precipitation of uranium along joints.

Guides to ore in the Todilto formation include:

1. Minor folds, which originally were considered to be primary structures, but are now thought to be secondary structures created by slippage between competent beds during the period of Zuni deformation.
2. A recrystallization of the limestone by Tertiary hydrothermal waters. The recrystallization of the original limestone appears to be more intense, particularly in the crinkly member, in proximity to ore.
3. Traces of barite and moderate amounts of disseminated hematite form halos about some ore bodies in the limestone.

Guides to ore in the Morrison formation include: 1) channels, 2) diastems, 3) areas of interfingering facies, and 4) the presence of organic material.

The uranium deposits in Todilto limestone, insofar as they are now known, form a belt of mineralization which is remarkably parallel to the strandline of the old Todilto basin. The apparent mineral belt transects major regional structure. The ore deposits of the Morrison formation display a similar lineation.
A study of the structure, stratigraphy, and uranium mineralization in the Grants District has produced the following conclusions regarding the genesis of the ore:

1. The present form and mineralogic character of the uranium deposits of the Grants District was achieved by the percolation of telemagmatic waters which transported uranium, iron, sulfur, barium, and fluorine ions in solution. Uranium may have originally been introduced into the sediments during the Jurassic, or uranium may have been derived directly from Tertiary magmatic sources.

2. The apparent ore controls are minor primary and secondary structures.

3. The Todilto's lithologic character, which has been determined chiefly by sedimentary processes, exerted a strong control upon ore deposition. This control is less pronounced in the uranium deposits in sandstone.

4. The temperature of the telemagmatic solutions was low, and percolation through the sediments over a large region was essentially lateral. These conditions imply that the metal-bearing solutions were formed by the commingling of magmatic and ground waters. In the search for ore, these Tertiary hydrothermal solutions may be best regarded as chemically active, slightly heated ground water.

5. Uranium has been dissolved and reprecipitated by recent meteoric waters. However, this process has not been sufficiently active to reconcentrate uranium in topographic traps or Tertiary structures.

6. The pre-Cambrian core of the Zuni Uplift is intensely silicified, locally, by hydrothermal action; patches of hydrothermally altered Permian San Andreas limestone contain traces of vein quartz; the Todilto and Morrison formations exhibit no vein quartz. It may be that hydrothermal solutions became progressively poorer in silica as they ascended.

INTRODUCTION

A thorough geologic investigation of the Grants District was undertaken by the Denver Exploration Branch of the Atomic Energy Commission after the initial reconnaissance work of Mr. Herbert V. Lee, Mr. Charles C. Towle, Mr. Millard Reyner, Mr. Jack Sheridan, and Mr. Abraham Rosensweig. Mr. Reyner and Mr. Sheridan prepared an excellent preliminary report on the basis of approximately three weeks of field work in the area (Preliminary Report on Uranium Deposits in McKinley and Valencia Counties, near Grants, New Mexico, December 1950). This report guided the initial work of the Denver Exploration Branch.

At the beginning of the investigation on which this report is based, little was known of the extent and character of the ore-bearing formations, and no adequate geologic maps of the Zuni Uplift were available. It was therefore decided that the A.E.C. undertake the geologic mapping and complimentary detailed stratigraphic study of the ore-bearing region and its environs. This study, the information from which has been incorporated in the report, "The Jurassic Rocks of the Zuni Uplift", has helped to provide a firm basis for the evaluation of the ore deposits by the A.E.C. The Anaconda Copper Mining Company, The Santa Fe Railway Company, the smaller companies, and private individuals engaged in the exploration and exploitation of the uranium resources of the Grants District.

The present report concerns itself entirely with the economics of the uranium deposits of the Grants District with emphasis on the guides to ore.
This report would not have been possible without the complete, wholehearted cooperation of the Santa Fe Railway Company, The Anaconda Copper Mining Company, and the smaller companies and individuals at work in the Grants District. The contributions and geologic guidance of Dr. Walter H. Bucher, Mr. Arthur K. Gilkey, Dr. John W. Gruner, Mr. Ira B. Joralemon, Dr. George W. Bain, Dr. L. A. School, Dr. L. G. Weeks, Dr. F. P. Kerr, Mr. W. B. Hoover, Dr. R. P. Fischer, Dr. L. B. Riley, Dr. Eugene Callaghan, Dr. Clay Smith, Mrs. Helen Cannon, Mr. Kenneth Cook and Mr. Frank B. Stead are embodied within this report. Appreciation is also due the Navajo, Laguna, Acoma, and Zuni Indian tribes for their aid in field work.

LOCATION AND REGIONAL EXTENT OF THE DEPOSITS

The Grants uranium district is located in northwestern New Mexico between Albuquerque, on the east, and Gallup, on the west. Ore appears to be restricted chiefly to Jurassic sediments. Consequently, the ore-bearing region is best divided into the two structurally distinct uplifts in which Jurassic sediments have been exposed. The Zuni Uplift, an area approximately 2,000 square miles, trends N. 60° W. and extends from Gallup, 60 miles eastward, to Grants. The Lucero Uplift, a broad dome trending north, exhibits about 1,500 miles of gently arched strata and extends from Laguna 20 miles eastward along U. S. Highway No. 66 to Correo. The two uplifted areas, which display sedimentary rocks of the pre-Cambrian through the upper Cretaceous in age, are separated by the McCarty Syncline, a shallow structural trough 15 miles wide in which the ore-bearing Jurassic sediments are concealed beneath a thick upper Cretaceous mantle and a late Tertiary sequence of acidic pyroclastics and basic flows.

Mineralization is confined to two stratigraphic horizons, the Todilto limestone and the immediately overlying calcareous silts and limestone lenses of the Summerville formation, and the Morrison formation. There is a stratigraphic separation of 500 to 800 feet between these ore-bearing zones. Ore deposits in the lower zone, the Todilto limestone, have been discovered in a zone starting from a point 2.5 miles north of Thoreau and continuing 65 miles southeast to a point 7 miles southwest of Correo. The easternmost known deposit in the Zuni Uplift is 30 miles distant from the westernmost deposit discovered in the Lucero Uplift across the prohibitively deep cover of the McCarty Syncline. Known mineralization in the Morrison formation extends from a point two miles northeast of Gallup for a distance of 85 miles southeastward to a point six miles northeast of Laguna. The sandstone deposits of the Zuni Uplift are 30 miles distant from the westernmost known deposits of the Lucero Uplift. The upper Morrison is exposed along the flanks of the intervening McCarty Syncline.

HISTORY OF DEVELOPMENT

Uranium mineralization along the north flank of the Zuni Uplift was discovered by Paddy Martinez, a Navajo Indian, during "lambing season" in the Spring of 1950. The discovery is believed to have been made at a rim exposure in Sec. 19, T. 13 N., R. 10 W., land owned by the Santa Fe Railway Company. Upon learning of the find through Mayor C. Gunderson of Grants, New Mexico, the Santa Fe dispatched its chief mining engineer, Mr. T. O. Evans, to the area. After a field examination of railroad properties, a thorough exploration program was started by the Santa Fe Railway Company in December of 1950. Initial exploration was undertaken on Sec. 19, T. 13 N., R. 10 W. and consisted of test pits six feet square sunk through the ore-bearing strata on 100 foot centers; bulk samples taken at 2 foot intervals were crushed, split, and assayed, and their lithology was recorded. The entire periphery of the Todilto rim was drilled and blasted to secure samples unleached by recent waters. These expensive methods of exploration were replaced by wagon drilling on 100 foot centers when it was determined that the ore-bodies were not continuous, but occurred in erratic pods and blankets very similar in distribution to the ore-bodies of the Colorado Plateau. Test-pitting at
approximately $35.00 per foot gave way to wagon drilling at $1.50 per foot. Perhaps the greatest impetus toward widespread, intensive exploration was the discovery of a large, rich ore-body in Sec. 19, T. 13 N., R. 10 W. during this initial phase of exploration. Santa Fe has expended approximately $400,000 to date for exploration and development work.

The Anaconda Copper Mining Company entered the Grants District in January of 1951 and immediately began to secure leases from private individuals and land-holding companies. Anaconda has since employed a great diversity of methods in its exploration. Extensive programs of both air-borne and ground radiometric reconnaissance have been followed by trenching, bulldozing, test-pitting, wagon drilling, diamond-drilling, and the driving of prospect adits. The Santa Fe Railway Company entered into a contract with the Anaconda Copper Mining Company at the end of November 1951 guaranteeing the delivery of 175,000 tons of ore over a period of five years to a mill to be built by Anaconda. Anaconda has spent approximately $600,000 in exploration to date.

The Atomic Energy Commission established a field office at Prewitt, New Mexico in January of 1951 to evaluate the ore bodies, to ascertain regional and detailed guides to ore, and to promote the development of the district by providing geologic services for the companies and individuals engaged in exploration. Joy Sinyella, a Supai Indian, brought several samples of uranium ore into the A.E.C. office early in August of 1951. A field examination by A.E.C. geologists disclosed the presence of several mineralized areas in Todilto limestone in the Lucero Uplift on the Laguna Indian Reservation. Arrangements were made after a series of protracted talks with the Laguna Tribal Council to enter into a prospecting-with-right-to-lease contract with the Anaconda Copper Mining Company. An air-borne radiometric anomaly obtained by Anaconda in November 1951 over the northern portion of the Laguna Reservation has proven to be an extensive outcrop of rich carnotite mineralization. This discovery and three small but rich mines situated in sand lenses of the Morrison formation in the Zuni Uplift have greatly increased the estimated potential of the Grants District.

The absence of a market for limestone ore and the prohibitive distance to a mill for sandstone ore have impeded exploration by individuals and small companies. The only active private operation has been that of the Blue Peak Mining Company which shipped approximately 300 tons a month of high-grade sandstone ore to the uranium mill at Monticello, Utah during the late summer and the fall of 1951. Several promising prospects owned by individuals have remained untouched throughout this first year, 1951-1952. The installation of a buying-station by Anaconda in the next few months should instigate a surge of mining and exploration.

MINERALOGY

I. Minerals in Limestone

The mineralogy of the uranium deposits of the Todilto limestone is of particular interest in that these deposits are the first carnotite-type ore-bodies in limestone, of major economic significance, that have been discovered in the United States. The peculiarities of this mineral suite may provide information bearing upon the origin of all carnotite deposits. Dr. J. W. Gruner and Dr. A. Rosensweig have performed the mineralogic determinations on Grants ore, as described in this report.
A. Uranium Minerals

1. Pitchblende - UO$_2$.U$_3$O$_8$

Pitchblende from the Grants District was first identified in specimens from Sec. 19, T. 13 N., R. 10 W. in February of 1950 by Dr. J. W. Gruner. Hard, black blabs of this mineral up to three-fourths of an inch in diameter have since been found over a wide area; they have a sub-metallic luster, and a greenish brownish hue. Normally, the pitchblende in this district occurs as microscopic particles and veinlets, and, in the field, its presence can only be suspected by the abnormally high radioactivity of the dark limestone. Most of the megascopic grains can be identified by alteration rims of yellow and orange uranium minerals, by their hardness which is typically greater than that of steel, by their greenish tinge, and by their association with hematite or pyrite. Several specimens consist of a core of pitchblende surrounded by a halo of orange material (gummite ?), surrounded in turn by a halo of yellow material (carnotite ?). Dr. A. Rosensweig determined that the outer rims contain vanadium while the pitchblende seemed devoid of that element. The possibility of the later precipitation of vanadium is suggested.

Recent photomicrographs of ore from Sec. 33, T. 12 N., R. 9 W. show pitchblende as a rim-replacement clastic quartz grains of silt size. Pitchblende is also displayed as veinlets cutting calcite, and as rim-replacements surrounding microscopic, anhedral grains of pyrite.

Gash fractures related to the Zuni Uplift (Miocene ?) in Sec. 28, T. 13 N., R. 10 W. contain pitchblende associated with barite in banded veinlets of white calcite and black "dog-tooth spar". The mineral associations and the structural environment of the pitchblende are evidence that it is of late Tertiary age and of telemagmatic origin.

2. Carnotite - K$_2$O.2UO$_3$.V$_2$O$_5$.1-3H$_2$O and
Tyuyamunite - CaO.2UO$_3$.V$_2$O$_5$.n H$_2$O

Carnotite and tyuyamunite are the chief economic minerals in the known deposits of the Grants District. They vary from dark to greenish-yellow and are indistinguishable in hand specimens. The higher grade ores contain disseminated crystals of these minerals in the recrystallized crinkly limestone. Spectacular films of carnotite along fractures and bedding-planes of the underlying "platy" limestone are misleading in that the rock is seldom of ore grade. "The ratio of vanadium to uranium of 1:1.6 as determined from average ore analyses show that most of the ore minerals probably are vanadates of uranium". (Dr. J. W. Gruner). Despite the fact that carnotite and tyuyamunite form the great bulk of uranium mineralization in the known near-surface deposits, the deepest developments in this district, the Santa Fe shaft in Sec. 25, T. 13 N., R. 10 W., and the Anaconda adits in Sec. 33, T. 12 N., R. 9 W., exhibit essentially pitchblende-type ore. Yellow uranium oxides are limited to open fractures. It appears that carnotite and tyuyamunite are alteration products of pitchblende.

3. Uranophane - CaO.2 UO$_3$.2 SiO$_2$.6H$_2$O: Beta-uranotile - CaO.2UO$_3$.2 SiO$_2$.6H$_2$O and
Sklodowskite - MgO.2UO$_3$.2 SiO$_2$.7H$_2$O

Uranium silicates are second in abundance to the vanadates of uranium in the superficial ore deposits. Uranophane, the most common of the silicates, is most easily identified wherein vugs and open fractures as bundles and rosettes of acicular crystals up to one-half inch long. It is also present as minute yellow particles disseminated through the limestone, and as films on bedding-planes and joints. The dimorph ofuranophane, beta-uranotile, is extremely rare while sklodowskite has been only tentatively identified by Dr. Gruner. The presence of uranium silicates despite the
complete absence of vein quartz is anomalous. The yellow uranium silicates may have obtained their silica from the clastic quartz grains that have been rim-replaced by pitchblende.

4. "Amorphous uranium vanadates resembling uvite and rauvite occur with pitchblende", Dr. J. W. Gruner

B. Gangue Minerals

There does not appear to be a direct ratio between the abundance of the introduced gangue minerals and the intensity of ore deposition; neither is the distribution of these gangue minerals identical with that of the ore. The minerals listed below, with the exception of calcite, are present in percentages as small as, if not smaller than, the uranium minerals. No vein quartz nor any appreciable argillaceous alteration has been found with ore.

1. Calcite

Analyses have shown the limestone to consist of 84 to 99 percent CaCO₃, the average being about 92 percent. The remainder of the limestone is composed essentially of clastic quartz and clay. Of the clay minerals, only nontronite has been identified. The great bulk of ore is situated in the more coarsely crystalline, upper, crinkly bed. Recrystallization is observable throughout the upper bed and the crenulations and minor folds appear to represent plastic flow by recrystallization. Initial recrystallization is believed to have been the result of diagenetic processes. The localization of ore in the upper beds is believed to be an expression of a strong textural preference of the ore-bearing solutions for the coarse limestone of the upper Todilto; this preference may be based on an increase of permeability accompanying recrystallization.

A post-Zuni Uplift (Miocene?) period of calcite deposition is evidenced by veinlets of calcite along fractures and by tongue-like replacements along bedding planes. Bended veins, up to 6 inches wide and 10 feet long, exhibit black crystals of "dog-tooth spar" replacing the walls and projecting outward into the fractures with a center of coarse, white, almost euhedral calcite. These veinlets often cut the ore-bearing horizon.

2. Hematite and Pyrite

These minerals are the second most abundant accessory constituents of the ore. The hematite occurs as cherry-red, dust-like particles which give the limestone a deep red hue out of proportion to the actual abundance of iron oxide. Films of hematite along joint surfaces are common, but do not appear to be indicative of ore. The color of the yellow uranium minerals is sometimes masked by hematite. Hematite is absent in the deeper deposits, but pyrite as microscopic cubes and irregular grains is present. Oxidation from pyrite to hematite appears to have taken place without the formation of geethite.

3. Barite

Clove-brown, resinous barite as blades and clusters is perhaps the most characteristic accessory mineral in the ore. It is found chiefly in veinlets replacing coarse-grained calcite, but it is also disseminated through the crinkly beds.
4. Fluorite

A small patch of dark purple, euhedral fluorite crystals, which selectively replaced calcite along bedding planes, is observable in the southeastern corner of Sec. 25, T. 13 N., R. 10 W., where it is associated with uranium mineralization. Fluorite has been tentatively identified in two sections to the east. Colorless fluorite, associated with the purple fluorite, has been identified by Dr. J. W. Gruner. The fluorite-barite-pyrite veins in the pre-Cambrian and Permian of the Zuni Mountains conform with the structural pattern of the Zuni Uplift and are believed to be of Tertiary age. These same minerals, disseminated through the Todilto limestone locally, are believed to have been introduced during the same period of mineralization.

5. Manganese Oxides

Black films and dendrites of psilomelane and cryptomelane have been identified by Dr. J. W. Gruner, but it has not been demonstrated that these minerals are associated with ore.

The paragenesis and the sequence of geologic events derived by field examination is believed to be:

1. Precipitation of limestone.
2. Diagenetic recrystallization of limestone and possible introduction of uranium.
3. Zuni Uplift and attendant fracturing, faulting, and local flexure.
4. Formation of coarse-grained, black calcite veinlets along bedding planes and fractures.
5. Vein filling by coarsely-crystalline, white calcite.
6. Replacement of coarsely-crystalline calcite by barite, pyrite, and fluorite.
7. Permeation of uranium-bearing solutions (which may have been introduced at this time from telemagmatic sources) through the Todilto limestone, localization on minor flexures, and the partial replacement of all previous minerals, including clastic quartz, by pitchblende.
8. Oxidation of pyrite to hematite, pitchblende to yellow uranium minerals, and the leaching and downward precipitation of uranium along joints.

II. Minerals in Sandstone

Uranium mineralization in sandstone has been found in all members of the Morrison formation and in the Dakota sandstone. No laboratory studies have been completed, but the following generalizations may be made from field investigations and assay results.

A. Uranium Minerals

1. Carnotite - $K_20.2UO_3.V_2O_5.1-3H_2O$

Carnotite appears to be the chief uranium mineral in sandstone deposits. It occurs as canary-yellow material interstitial between sand grains, as coating on
mudstone galls, and as rich laminae which follow bedding planes for short distances and then transect those original planes at mail angles.

2. Schroeckingerite – \( 3\text{CaO} \cdot \text{NaF} \cdot \text{UO}_3 \cdot 3\text{CO}_2 \cdot 3\text{SO}_2 \cdot 10\text{H}_2\text{O} \)

Large amounts of a yellow, powdery to waxy, brilliantly yellow-green fluorescing mineral, believed to be schroeckingerite, have been found in Sec. 24, T. 13 N., R. 10 W. as impregnations of sandstone and as coatings along joints and bedding planes. Greenish-yellow, pseudo-hexagonal, micaceous plates up to one-quarter of an inch in diameter have been observed along fractures in mudstone.

Uranium is believed to have migrated away from the associated vanadium for the following reasons: a) Carnotite, a uranium vanadate, is generally localized along bedding planes with limonite, whereas schroeckingerite, which contains no vanadium, is found as concretions, along fractures, and as impregnations of leached sandstone. b) Schroeckingerite is a carbonate-sulfate; both cations are common in the ground waters of arid regions. c) Graphs depicting the chemical content of uranium and vanadium, and the radiometric assays of the same samples suggest the following conclusions. The vanadium values are erratic, but do not vary with the uranium content. Below .30 percent \( \text{U}_3\text{O}_8 \) the vanadium is present in greater amounts than the associated uranium. Above .30 percent \( \text{U}_3\text{O}_9 \) vanadium is present in lesser amounts than uranium. Below .25 percent \( \text{U}_3\text{O}_9 \) the radiometric assays are high compared with the chemical assays for that sample. Above .25 percent \( \text{U}_3\text{O}_9 \) the radiometric assays are low. The implication is that the richer concentrations of uranium have not had time to achieve equilibrium.

Black, seemingly carbonaceous, sandstones, which assay 3 to 8 percent volatiles, excluding the \( \text{CO}_2 \) driven off from calcite, contain high concentrations of uranium throughout the Grants District. The yellow oxides are not visible in amounts sufficient to justify the high assays. The mineralogy of those black sandstones is being investigated. The fact that these black zones transect bedding planes discounts the possibility that all of the material is organic matter. Analyses for sulfides are now being run.

Carnotite-type mineralization in sandstone appears to be associated with concentrations of limonite. Rims of carnotite are often seen at the interfaces of the black sandstone and limonitic sandstone. The mineralization is often localized along diastems and in complex zones composed of intricate channels of fine to coarse conglomeratic sandstone, and dissected laminae and galls of green mudstone.

GUIDES TO ORE

The regional Tertiary structural control of uranium ore deposits in the Grants area is obscure, if present at all, and it has not yet provided guides to ore. Fairly strong stratigraphic controls and minor structures have afforded regional and local ore guides.

I. Structural Controls

A. Limestone

1. Primary (?) Structures

The primary (?) structures observed consist of folds, faults, basins and channels and are described as follows:
a) Folds

The Todilto limestone presents an irregularly corrugated appearance. Minor anticlinal crenulations from almost microscopic dimensions up to a maximum of 50 feet wide, varying in attitude from the recumbent to the barely perceptible, are distributed throughout the limestone. These folds are believed, for the following reasons, to be the result of creep of un lithified calcareous sediment down a gentle slope under the weight of overlying sediment: 1) Many of these folds are expressed in a single stratum of Todilto limestone; the underlying and overlying strata are horizontal whereas folds related to the Zuni Uplift are reflected in all rocks although the competence of individual strata appears to have controlled and modified the intensity of folding. 2) The axes of these small folds do not align with the structural pattern of the Zuni Uplift. Fractures related to the Zuni Uplift transect these folds at random angles. 3) Thickening along the crests and troughs of these folds, and thinning along their flanks demonstrate plastic deformation. Drag-folding along faults is not of this character. 4) One of the general conclusions drawn from structural mapping of the Zuni Uplift is that all associated structural features are of tensional origin. These folds appear to be the consequence of lateral compression. 5) Folds oriented with the pattern of the Zuni Uplift are monoclinal and are believed to be the expression of faulting at depth. The minor folds of the Todilto are elongate to semi-circular bulges without pronounced intervening synclines. It is possible that widespread tremors during and shortly after the deposition of the Todilto limestone accentuated movement down the initial dip. The Summerville formation in the San Rafael of Utah, which is believed to be approximately contemporaneous with the Todilto, also displays wavy bedding.

The association of ore and primary folds is not universal. Most folds are unmineralized, and flat-bedded limestone often contains ore at many places. However, detailed mapping eight miles east of Haystack Butte showed that five out of seven ore-bodies are localized on primary folds despite the fact that these folds occupy less than 10 percent of the linear extent of the Todilto rim. In other areas, only mineralization over an extent of 1000 feet coincided with the major primary fold over that distance. Structure contour maps drawn on the top of the Todilto also suggest the concentration of ore along bulges.

A detailed analysis of minor folds was undertaken in February 1952 when it was found that they presented a weak conjugate pattern which could be visually related to Zuni diastrophism. All minor folds mapped in the Todilto previously were plotted on individual sheets according to their location. The statistical plot obtained in this manner was transposed to a 2 inch to 1 mile map of the northeast portion of the Zuni Uplift. The information gained through the fracture study undertaken by Mr. Gilkey and Dr. Bucher, and the detailed mapping of the A.E.C. was consolidated. It was then possible to draw a line along the outcrop of the Jurassic sediment that was approximately normal to the direction of bending at any point. This line should be paralleled to the major joints and faults at that point and should align with the axis of any fold in the vicinity. This line usually swings locally with the regional strike where transverse structures assume major importance. A graphic, continuous, generalized picture of the variation in the structures created by Zuni diastrophism is portrayed by this "line of bending".

The following generalizations are based upon detailed mapping of areas of uranium deposits in the Todilto limestone and of the evaluation of that information in the manner described above.

1. Minor folds in the Todilto present a strong, right angle, conjugate pattern in some areas. Areas in which the axes of folds appear to be randomly oriented often display a vague but similar pattern when plotted stratistically.
2. The axes of one series of minor folds appear to be paralleled to the "line of bending", at any chosen point, while the axes of the series are perpendicular to it. The conjugate pattern of minor folds also swings, in a general manner, with the Zuni Uplift.

3. The crests of several minor folds are fractured by longitudinal and transverse joints, and two folds mapped appear to be the result of drag created by minor displacements along high angle normal faults.

4. Slickensides along bedding planes in areas of minor folding appear to result from slippage between beds.

The evidence enumerated above strongly suggests that the so-called "primary" folds are, in reality, unusual structures created by slippage between the competent Entrada and the also competent upper member of the Summerville. The intermediate, incompetent, thinly bedded variable Todilto limestone and basal Summerville responded by flowage to differential stress created during Zuni Uplift.

It is possible that the "line of bending" may indicate the direction of elongation for the clusters of ore bodies in any particular area.

b) Faults

Grabens along irregular fault planes are exhibited in the Summerville and the basal half of the Bluff formations. The upper strata of the Bluff are undisturbed. Within the downthrown block the bedding is highly contorted, but virtually unfractured. This feature is also believed to be a penecontemporaneous structure. Its relation to ore has not been determined because of the depth to the underlying Todilto limestone.

c) Basins

The Santa Fe test-pits in Sec. 19, T. 13 N., R. 10 W. were mapped on a scale of 1 inch to 10 feet and were correlated in detail. The configuration of the ore did not bear any apparent relation to the present form of the limestone. However, when the top of the ore was drawn as a horizontal plane, and the top and base of the limestone was projected in reference to that plane, the suggestion was that the ore had precipitated in a shallow structural basin about 1000 feet long and 300 feet wide with a structural relief of only 12 feet. Mineralization is thickest and richest at the center of this basin and decreases in both grade and thickness quite uniformly toward the edges. This method is not a guide to ore because of the necessity of finding ore in order to determine the plane of reference. The extremely detailed topographic and lithologic data needed also discount the use of this system. However, the method does have some practical application in that data from test-pits implies the existence of another basin and the possibility of another large ore deposit when the information is projected northward under 10 to 100 feet of overburden. Considering ore genesis, the present form of this particular ore-body appears to have been attained before Zuni deformation, but the evidence for this statement is far from conclusive.

d) Channels

Pre-Summerville channels through the Todilto limestone appear to be a strong negative criterion in the search for ore. The Todilto upper crinkly limestone exerted a strong localizing effect upon the ore, and its removal appears to preclude the existence of ore in the remaining limestone at that horizon. Pre-Summerville erosion along a northeast drainage pattern has virtually stripped some areas of limestone.
2) Secondary Structures

The secondary structures observed consist of joints, faults, and folds and are described as follows:

a) Joints

The suggestion has been made (Notes on Uranium Exploration Program, R.M.O. Report 1500, by Mr. Ira Joralemon) that uranium ions may have reached their present position by hydrothermal or pneumatolytic agents which travelled upward along joints. There is a suggestion of a greater density of fracturing below the ore deposit in Sec. 19, T. 13 N., R. 10 W. but this feature cannot be observed beneath any of the other deposits. Factors which militate against this concept are: 1) the position of ore in the top member of the Todilto, 2) the absence of an impermeable horizon above the ore, 3) the lack of hydrothermal alteration along joints, 4) the distribution of known deposits over a linear distance of 85 miles with some of the deposits far from any sign of igneous activity, 5) and the intervening unmineralized sediments, including petrolierous limestone similar to the Todilto, which are more than 2,500 feet thick.

Dr. George W. Bain has suggested in his report, "Impressions of the Uranium Deposits in the Grants, "New Mexico Area", that the ore in the Todilto limestone was derived by the downward migration of supergene uranium-bearing solutions from the Morrison formation. This theory, of course, fails to explain the genesis of ore in the Morrison formation. This theory also appears improbable as 500 to 800 feet of unmineralized sediment, including limestone lenses, separate the two horizons. Uranium in the form of carnotite and schroeckingerite was absorbed on the bentonitic mudstone galls and laminae within the mineralized sandstone, but no absorbed uranium was noted along fractures through the hundreds of feet of bentonitic mudstone which separate the two ore-bearing horizons. The deposits in the Todilto have been followed for as much as 300 feet into the rim to points beneath a basalt capping. Limestone ore deposits on the Laguna Reservation are 15 miles up-dip from the nearest Morrison outcrop; stratigraphic studies demonstrate that the Morrison was eroded during the lower Cretaceous, long before Zuni deformation and fracturing. In addition, the pitchblende-pyrite-barite-fluorite suite of the Todilto deposits does not suggest a supergene origin.

Coatings of carnotite-type mineralization along joints in barren, "platy" limestone extend downward for as much as 10 feet below all ore-bodies. Recent ground water is believed to be responsible for this feature.

b) Faults

Thirty-two faults with as much as 570 feet displacement were mapped in the vicinity of the ore-deposits. Some were walked out for several miles. No mineralization, no abnormal radioactivity, and no sign of hydrothermal activity was noted along these faults. Pre-extrusive faults displace the ore bodies in Sec. 28, T. 14 N., R. 1 W. and on the Laguna Reservation. The evidence for post-ore faulting is not absolute as stratigraphic controls may have been strong enough to create an anomalous appearance.

c) Folds

Mr. Vincent Perry of the Anaconda Copper Mining Company postulated the regional control of mineralization by broad monoclinic structures. The evidence to substantiate this view has not been uncovered. Small-scale structure contour maps of the Entrada-Todilto contact have failed to yield any clue as to Tertiary structural control. Mineralization appears to transect major folds related to Zuni diastrophism.
B. Sandstone

1. Primary Structures

The textural variations and stratigraphic range of ore-bearing sediments within the Morrison formation are much greater than those of the Todilto limestone. Mineralization has been noted in every lithologic facies from mudstone to siltstone through conglomerate over a stratigraphic range of 500 feet. Certain primary structures appear to have controlled ore deposition in all facies.

a) Channels

Cross-bed, log, channel, and "roll" orientation have been taken at virtually all active uranium prospects within the Morrison formation. The direction of stream flow thus determined appears to have varied from slightly north to slightly south of east over this region. This data is confirmed by stratigraphic studies which established the fact that Morrison sediments were shed from highland to the south and west. The elongation of the sandstone ore bodies should trend with the local channels at that horizon. Substantiation of this data is attendant upon further mining.

b) Diastems

Minor local unconformities (diastems) appear to have created zones of increased permeability through which uranium-bearing solutions flowed and were precipitated. Dissected mudstone fingers often project along the bases of diastems to a line at which truncation by overlying coarse clastics is complete. These "mudstone splits" also appear to have exerted influence upon permeability and the precipitation of ore. A maximum of four distinct horizons of mineralization, a total separation of thirty-five feet, has been noted in the Grants Area. Carnotite-type rolls seem to have resulted from the percolation of uranium-bearing solutions across bedding from an upper to a lower zone of permeability.

c) Facies Change

The two sandstone deposits mapped in detail in Sec. 19, T. 13 N., R. 9 W., and Sec. 24, T. 13 N., R. 10 W., revealed the fact that ore had been localized in areas of intricate facies change. The relatively uniform continuous sandstone lenses were barren. This feature may be more apparent than real as there is a greater probability for the occurrence of those delicate, obscure, physical and chemical conditions, which act to precipitate uranium, in areas of diverse sedimentation.

2. Secondary Structures

Tertiary structural guides to ore in the Morrison are virtually indeterminate in the Grants District. The lenticularity of beds precludes the preparation of structure contour maps or structure cross-sections. Fractures throughout the Morrison appear to be weak and widely spaced.

II. Stratigraphic Controls

A. Todilto Formation

The stratigraphic control of ore deposition in the Todilto limestone appears to be strong. It is the best regional and local guide to ore that has been yet developed.
Uranium deposits in the Todilto limestone appear to be in a 60 mile belt that bisects the distance between, and is roughly paralleled to, the strand-lines of the limestone and gypsum members. The gypsiferous facies of the Todilto is believed to have been deposited in the central, deeper portion of the basin whereas the limestone pinch-out line represents the farthest trangression of Todilto waters throughout this period of deposition. The Todilto basin appears to have been highly asymmetrical. Forty-five miles separate the pinch-cut lines along the northern flank of the Zuni Uplift. In the Lucero Uplift, the progression from the line of deposition, through the thickest known section of limestone (40 feet), to a point at which the overlying gypsum member of the Todilto is 100 feet thick, can be observed in a distance of but 5 miles. The conclusion gained from this study is that uranium mineralization is directly or indirectly related to Todilto sedimentation. There is no connotation as to the age of mineralization. The limestone is silty toward the old shore-line and thin, shaly, and gypsiferous toward the sink of the basin. The thicker, purer, uranium-bearing limestone is situated between these lines. Uranium may have originally precipitated from syngenetic or diagenetic solutions and suffered subsequent hydrothermal effects, or the uranium may have been introduced directly by late Tertiary telemagmatic waters. Employing either assumption, it is apparent that the ore deposits of the Todilto limestone are restricted to limestone of a definite lithologic character and that lithology has been controlled by sedimentation.

B. Morrison Formation

The ore deposits of the Morrison and Dakota formations which are distributed throughout a stratigraphic range of 300 feet, transect bedding in detail, and therefore, in their present form cannot be considered of syngenetic origin. It is possible to postulate a belt of sandstone deposits 85 miles long, offset 2 to 10 miles north of the deposits in the Todilto. Lower Cretaceous truncation of the Morrison formation has made it impossible to precisely determine the position of the line of non-deposition during the close of the Jurassic. The Morrison, however, is coarser than any other Jurassic sediment, and, therefore, it is believed to have been derived by erosion of pre-Jurassic sediments and pre-Cambrian crystalline rocks. The axis of the source area, the Zuni Highland, is believed to have shifted southward at the close of the Jurassic. The apparent localization of uranium in coarse clastics, at this horizon, limits the favorability of the Morrison formation to the northeast because of the increased distance from the source and the consequent predominance of fine clastics.

ORE GENESIS

A study of the structure, stratigraphy and uranium mineralization in the Grants District has produced the following conclusions regarding the genesis of the ore.

1. The present form and mineralologic character of the uranium deposits of the Grants District was achieved by the percolation of telemagmatic waters which transported uranium, iron, sulfur, barium, and fluorine ions in solution. Uranium may have originally been introduced into the sediments during the Jurassic, or uranium may have been derived directly from Tertiary magmatic sources.

2. The apparent ore controls are minor primary and secondary structures.

3. The Todilto's lithologic character, which has been determined chiefly by sedimentary processes, exerted a strong control upon ore deposition. This control is less pronounced in the uranium deposits in sandstone.
4. The temperature of the telemagmatic solutions was low, and percolation through the sediments over a large region was essentially lateral. These conditions imply that the metal-bearing solutions were formed by the commingling of magmatic and ground waters. In the search for ore, these Tertiary hydrothermal solutions may be best regarded as chemically active, slightly heated ground water.

5. Uranium has been dissolved and reprecipitated by recent meteoric waters. However, this process has not been sufficiently active to reconcentrate uranium in topographic traps or Tertiary structures.

6. The pre-Cambrian core of the Zuni Uplift is intensely silicified, locally, by hydrothermal action; patches of hydrothermally altered Permian San Andreas limestone contain traces of vein quartz, the Todilto and Morrison formations exhibit no vein quartz. It may be that hydrothermal solutions became progressively poorer in silica as they ascended.