The geology of the uranium-vanadium deposit of the Diamond No. 2 mine, near Gallup, New Mexico

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THE GEOLOGY OF THE URANIUM-VANADIUM DEPOSIT OF THE

DIAMOND NO. 2 MINE, NEAR GALLUP, NEW MEXICO

BY

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A

THESIS

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Approved by

J C Armstrong (advisor) ______ R K Christiansen ______

______ A. C. Spreng ______

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DEDICATED TO

EDWARD "ED" L. CLARK

Ph.D. (Univ. of Missouri)

my first guide on Mining Geology on Colorado Plateau, four years ago.

ABSTRACT

This thesis deals with the geology of the Diamond No. 2 Mine east of Gallup, New Mexico. The sedimentary rocks ranging from Triassic to Cretaceous are described in relation to the local stratigraphic setting.

The Dakota formation is the host rock of the ore deposit, and was therefore studied in detail with regard to its petrographic nature and the sedimentary structures such as slumping. Special emphasis is placed on the study of the relationships between the uranium and vanadium deposit and the host rock. Geometrical and geochemical criteria are offered in order to explain the local genesis of the ore deposit at the Diamond No. 2 Mine. The geometric (textural, structural) evidence such as the lack of crosscutting relationships on one hand, and the abundance of congruent features readily explained as depositional sedimentary structures on the other hand, suggest to an originally syngenetic origin. The presence of tuffaceous matter lends probability to a volcanic and thus hypogene source of the uranium and vanadium minerals. Geochemically there is no objection for a syngenetic explanation since the only alteration ("silicification") occurring adjacent to the ore bodies may be diagenetic and thus also syngenetic.

Later epigenetic supergene processes redistributed some of the uranium in form of carnotite (carnotitization) and caused later alterations such as limonitization, jarositization, etc. The field observations are presented on 33 figures and 12 plates (mostly maps and cross sections). A special, probably partly new mapping method was used successfully for the mapping of 60,000 square feet of mine walls at the scale of 1" to 20'.

A. INTRODUCTION

1. HISTORY, PURPOSE, AND SCOPE

In the area studied, uranium minerals were first discovered on the east slope of the Nutria Monocline near Gallup, New Mexico, 4 miles south of U. S. Highway 66 (see Plate No. 1). This discovery touched off the exploration of the radioactive sediments of the area. Diamond No. 2 Mine area is located 3,000 feet southeast of the original discovery on the same back slope of the Nutria Monocline, locally known as the Hogback.

Since 1955, Largo Uranium Corporation, a subsidiary of Four Corners Uranium Corporation, is operating Diamond No. 2 Mine, which is one of the largest underground mining operations in the Dakota (?) sandstone of the Colorado Plateau.

During 1956 and the summers of 1957 and 1958, the writer was engaged in extensive physical exploration and underground geological mapping while working on the staff of Four Corners Uranium Corporation.

This thesis describes the stratigraphy of Diamond No. 2 Mine area, near Gallup, New Mexico, with special reference to its relation to the uranium vanadium mineral content in the Dakota sandstone. It lists and describes observations, methods, and interpretations of the underground and surface geology of the ore-bearing rocks.

Some aspects of the local genesis of uranium and vanadium are considered, and an attempt is made to offer a conclusion.

2. ACKNOWLEDGMENTS

I wish to express my deep appreciation to Dr. Edward L. Clark, Vice President of Four Corners Uranium Corporation, without whose economic support this thesis would not have been possible. Dr. Clark also permitted the use of information and maps prepared by this writer while working for Four Corners Uranium Corporation.

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My thanks are also due to the members of the Staff and my colleagues in the Department of Geology, Missouri School of Mines and Metallurgy.

Last but not least, very special thanks are due to Dr. Ing. G. C. Amstutz, Professor and advisor of the writer's graduate studies, who directed this thesis offering many valuable and inspiring suggestions.

3. LOCATION AND ACCESSIBILITY

The area described in this paper comprises about 2 square miles of western McKinley County in western New Mexico.

Nearly the whole area is located inside sections 33 and 28, T. 15 N., R. 17 W. (Plate No. 1). The nearest town is Gallup, New Mexico, 6 miles northwest of the area, on the junction of U. S. Highway 66 and the county road leading to the mine.

The main supply center for the area is Gallup, the so-called Indian Capital of the Southwest, at an elevation of 6,500 feet and with a population of 9,143. The main adit of Diamond No. 2 Mine is located on an escarpment of the back slope of the Nutria Monocline in the NE1/4 of section 33 at 6,942 feet above sea level.* The west fence of the Fort Wingate Military Reservation is 2,000 feet east of the mine portal.

Accessibility to the area is provided by U. S. Highway 66, Santa Fe Railway system and Frontier Airlines.

* Elevation tied in with USGS and AEC triangulations.

4. PHYSICAL FEATURES

The part of the Nutria Monocline which is described in this thesis forms a slightly sinuous northeast facing escarpment, a massive west backslope, and parallel valleys and ridges of northwest trend. This geomorphic feature forms the western limit of the Gallup basin, inside the complex structure of the Kelley's Gallup sag (Plate No. 1).

Rocks present in the monocline are dipping with gentle dip slopes towards the Gallup coal basin in the southwest. While none of the rocks is highly resistant, the difference between sandstone and weak shales is reflected at places on noticeable differences in altitude and style of surface.

These contacts are more conspicuous where the Hogback rims break off; there the back slope is an escarpment that exposes the Westwater (?) sandstone, and the Dakota (?) formation. The most distinct impression of the Hogback is gained by looking across Fort Wingate from U. S. Highway 66. From there the observer has a colorful view on the east backslope, and from the same place more than one bleached uranium outcrop of the Dakota (?) sandstone can be seen.

B. DESCRIPTION

1. STRATIGRAPHY

A general stratigraphic study of the Nutria Monocline and adjacent area was made without attempting to solve problems of regional correlation that are encountered in the area.

Within the Hogback from the east side center of Largo No. 3 claim in section 33, T. 15 N., R. 17 W. eastward towards Fort Wingate Military Reservation fence, outcrops of most of the geological formations occurring in the area can be recognized. The formations consist mostly of sandstones and shales dipping at moderate angles. The shales are more erodible than the underlying sandstones, hence they are valley makers. Sandstones are more resistant to erosion because of their induration, hence they are rim markers. A geological cross section through the area is illustrated in Plate No. 2; thickness and lithology of the formations are given in Plate No. 3; a general geological map of the thesis area is found on Plate No. 1.

The stratigraphic sequence of the rocks, appearing on Plates No. 1, 2, and 3, has a total thickness of 3,000 feet.

The stratigraphic succession and character of the sedimentary units occurring in the area covered by Plate No. 1 are given in the following paragraphs.

a. Lower (?), or Middle (?), Triassic Series

Moenkopi Formation

The Moenkopi Formation was recognized south of the area in a location called Ojo Caliente (McGaffey Park) which is in section 7, T. 12 N., R. 16 W. There the formation was found to be formed by reddish-brownish sandy shales and basal conglomeratic sandstone which marks an unconformity with the Permian Chupadera limestone.

Chinle Formation

The Chinle formation was studied and named by GREGORY (1917).* It is composed of a group of shales, sandstones, and limestone conglomerates lying between the Moenkopi and the Entrada formations.

Clay and shales are brown, purple, reddish, green, gray or white. In the lower part of the formation the shales are interbedded with innumerable lenses of tan, gray, or pinkish sandstones and conglomerates.

Most of the Chinle formation of the area could not be mapped or studied because it is inside of the Fort Wingate Military Reservation. However, the subdivisions of the Chinle inside the Fort will be summarized from published data (O'SULLIVAN, R. and E. BEAUMONT, 1957). (Preliminary geologic map of the Western San Juan Basin, San Juan and McKinley Counties OM 190 - USGS):

1. "Basal member or 'Shinarump' which consists of moderately orange and yellowish gray sandstone, siltstone, conglomerate, and shale."
2. "The lower member which consists of siltstone, sandstone, and limestone pellet conglomerate."
3. "The Petrified Forest member which consists of claystone, and minor amounts of siltstone and sandstone and which is split to the east into the upper and lower part by the Sonsela sandstone bed."

* All the references are listed in the bibliography.

The uppermost member of the Chinle is called Owl Rock member (O'SULLIVAN, R., E. BEAUMONT, 1957) is exposed on U. S. Highway 66 and formed by lavender, white, thin limestone layers interbedded with shale.

The Chinle formation forms typical gentle slopes, with the exception of the more resistant limestones within the Fort Wingate anticline.

No uranium deposits were found in the Chinle formation of the Gallup area, whereas in other portions of the Colorado Plateau it is an important source rock.

b. Upper Jurassic Series

Entrada Sandstone

The Entrada sandstone is a brick-red earthy, fine-grained quartz sandstone. Much of it is distinctively massive and cross-bedded, and contains little clay and occasionally some fractures filled with gypsum.

The lower part of the unit is exposed as a massive cliff marker at the Kit Carson Cave (section 1, T. 15 N., R. 17 W.). The middle and upper parts contain a large-scale cross-stratification of the same tangential type observed elsewhere in the Colorado Plateau. Crossbeds and festoons of the Entrada sandstone are probably all of wind-blown origin, but the parallel stratified layers could be regarded as a water-laid sand, deposited during intermittent floods (ALLEN, J. and R. BALK, 1954).

The Entrada sandstone was named Wingate sandstone (DUTTON, 1885) because of the excellent exposures north of Fort Wingate (Kit Carson Cave area). Its character and correlation was fully revised by BAKER, DANE AND REESIDE (1947), with the conclusion that the so-called "Wingate sandstone" at Fort Wingate, New Mexico, is actually a part of the higher Entrada sandstone of that area (ALLEN and BLANCK, 1954) and not of the widespread Wingate sandstone farther northwest on the plateau. Despite this correction, O'SULLIVAN and BEAUMONT called these sandstones of this area again Wingate sandstone (USGS Oil and Gas Investigations Map OM 190, 1957).

The writer has applied the name "Entrada Formation" to the red sandstone between the Chinle and Summerville Formation exposed in the Fort Wingate anticline, because the field observations show that these red beds are similar to the Entrada sandstone of Entrada Point in the northern part of San Rafael Swell, Utah, described by GILLULY AND REESIDE in 1926.

Todilto Limestone

East and southeast of the Kit Carson Cave the Todilto member amounts to 4 feet of dense gray limestone containing some well-rounded black cherty pebbles. This narrow band of limestone caps the underlying Entrada sandstone which forms a massive smooth cliff 200 to 300 feet high. The Todilto limestone is thicker to the east and yields uranium ore in Grants-Laguna area (GABELMAN, J., 1955). The Todilto limestone appears to pinch out toward the west, while to the southwest in the vicinity of Diamond No. 2 Mine - exactly on the cross section line, Plate No. 1. The Todilto member is represented by 4 inches of gray limestone on the bottom of the Summerville member.

The Todilto limestone was probably deposited in a brackish water environment (FISHER, R., 1955, p. 148) although SMITH (1955, p. 171) considers it to have formed as marine facies in deeper water. The name Todilto limestone was introduced by GREGORY (1916) and established as a unit of the San Rafael group by BAKER, DANE AND REESIDE (1947) and HARSHBAYER et al (1951).

Summerville

The Summerville Formation is a moderately pink dull arkosic to calcareous sandstone and yellow white siltstone, forming bold cliffs on the top of the Todilto limestone or Entrada sandstone. The sandstones are massive and only slightly crossbedded.

The contacts of the formation are poorly exposed and difficult to trace. The contact with the overlying sandstone of controversial stratigraphic designation (Zuni sandstone ?) or Westwater Canyon sandstone of the Morrison formation (?) can be drawn at a pinkish green shale that could be a tongue of the Recapture shale of the Morrison formation(?). The same shale is thicker and better exposed in the vicinity of Kit Carson Cave.

The Summerville formation is 1,400 feet thick at Diamond No. 2 Mine area. The middle part has well developed crossbedding with remarkably flatter angles than the Entrada sandstone. The top surfaces and the dip slopes of the sandstone's outcrops is criss-crossed by numerous polygonal cracks. Similar features were described in the Summerville of Fort Defiance and Tohachi quadrangles (ALLEN, J. and R. BLANCK, 1955).

Zuni Sandstone

The Zuni sandstone is 500 feet thick at Diamond No. 2 Mine area. The formation is underlain by a reddish purple shale that could be interpreted as a lower tongue of the Recapture shale. The Zuni sandstone is coarse grained and arkosic, and also massive and light pinkish.

Quartz and sandstone pebbles are distributed within the matrix. They have sharp edges or are well rounded; layers of conglomerates are occasionally present.

The Zuni sandstone is partially cross-bedded and contains syngenetic concretions of hematite.

Morrison Formation

Two members of the Morrison formation have been mapped in the area. They are the Recapture shale and the Westwater Canyon members.

Recapture Shale Member

The Recapture shale crops out discontinuously along the west slope of the monocline. Although it is called shale it also contains sandstones, conglomerates, and clays. It is usually not more than 20 feet thick.

Exposures observed are characterized by light gray or green sands, or greenish sand pebbles within pockets of clays or lenses of shales. These pebbles may be beach deposits and probably contain (autigenic?) brookite (if they are the same as pebbles shown to me by DR. ALLEN. He mentions autigenic brookite in similar pebbles (ALLEN, J., 1956).) The pebbles in the unit described in this paragraph contains slight radioactivity. (It is interesting to note that these beach deposits occur below the main concentrations of uranium.)

The clays are maroon, brown, yellow or green due to the weathering effect. The outcrops are restricted to a few places along the east slope of the Nutria Monocline. The continuity of the Recapture shale is questionable because the incoherence of the drill data and the surface observations.

Westwater Canyon (?) Member

O'SULLIVAN and BEAUMONT (1957) draw on their map of the Western San Juan Basin the line marking the Westwater Canyon through the area discussed in this thesis. If the correlation made by various geologists between Westwater Canyon sandstone in other areas and this area is correct, some 20 feet of coarse arkosic and massive sandstone at the Diamond No. 2 Mine occurring below the Dakota sandstone and the spotty Recapture shale might be considered to represent the Westwater Canyon unit. However as DR. KELLEY pointed out (personal communication) it is doubtful whether a limit can be drawn between the Westwater Canyon member and the Zuni sandstone, since no lithologic difference can be observed.

If the Westwater sandstone is only the top position of the Zuni sandstone, the Recapture shale is only an internal stratigraphic marker.

The possible Westwater Canyon sandstone changes from light pinkish to white below every Dakota uranium outcrop observed at the Nutria Monocline. As will be discussed later on in detail, this color change has been assigned to hypogene alteration. The fact, however, that the underlying rock units do not show any effects which could be called alteration, and the fact that even the red alteration in the Westwater Canyon is restricted to surface near portions, as seen along adits and drifts (as shown in Fig. 4) shows clearly that we deal with a surface weathering and leaching effect, and not with any hypogene action. Also the fractures cutting this sandstone unit do not show any alteration or mineral content. But these genetic criteria will be discussed in detail below.

c. Upper Cretaceous

Dakota (?) Sandstone*

The Dakota (?) sandstone, the basal formation of the Upper Cretaceous, lies along the eastern edge of the prominent Nutria Monocline. Also, it is well exposed east of the Kit Carson Cave on the back slope of the Pinedea Monocline. At the latter area on the portal of the Westwater No. 2 uranium mine, section 3, T. 15 N., R. 16 W., the Dakota (?) overlies the sandstone beds known as Brushy Basin member of the Morrison formation.

West and southwest of the Kit Carson Cave, where the Brushy Basin member** pinches out (CRAIG, L., personal communication, 1956), the Dakota (?) sandstone overlies with a remarkable unconformity the controversial Westwater Canyon member of the Morrison formation (KELLEY, V., personal connumication, 1958). The thickness of the Dakota (?) is variable. At some places it is 40 feet thick; at others just only a few feet.

The sandstone is everywhere lenticular with remarkable variations in lithologic features and a peculiar relationship with shales and coal seams.

Details of the Dakota (?) sandstone at Diamond No. 2 Mine will be given in a separate chapter which will emphasize the descriptions and interpretations of the surface, the subsurface geology, and the presence of uranium-vanadium ores.

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* The term Dakota was first applied to a basal member of the Cretaceous system along the Missouri River in northeastern Nebraska by MEEK and HAYDEN (1861). In New Mexico the sandstone that is present in the same stratigraphic position is designated Dakota (?) because its exact relation to the type Dakota is not known (adapted from PIKE, 1947, p. 7).

** Member of Morrison Formation

Mancos Formation

The Mancos formation is partially exposed along the Diamond No. 2 Mine area, in a long narrow valley, parallel to the Monocline between the underlying Dakota (?) and the overlying Gallup sandstone (sections 28, 29, 32, and 33).

Much of the Mancos formation in this area is recognized from numerous drill data, and its lithologic character reveals that it consists of two different rocks, namely, sandstones and shales. As seen from drill holes, these units interfinger as much as could be expected from surface observations. The basal part of the Mancos formation contains a sandstone tongue, the Gallup sandstone, which splits the Mancos formation in two main bodies. The upper one, the so-called "Mulatto Tongue" (SEARS, J., 1925) and the lower one, locally designated as Mancos formation.

The Gallup sandstone, usually considered to be a member of the Mesaverde group, forms the west Hogback of the Gallup monocline. It is a light yellow to buff, fine-grained quartz sandstone. The formation has a well developed system of fractures in rectangular patterns and a fossiliferous bed containing Gryphaea newberryi (PIKE, 1947, p. 27) on the lower part.

The sandstone of the Mancos formation proper is called Tres Hermanos sandstone (RANKIN, 1944). It is a reddish, fine-grained, arkosic sandstone, lithologically similar to some Dakota (?) sandstones.

The shale is gray, soft with some bands or concretions of limestone.

From local observations secured from drill cuttings, the subdivision of the Mancos formation into sandstone and shale as discussed by RANKIN (1944), appears to be justified.

The Mancos shale was elsewhere reported as a body of black shale in nearly equal proportions and contains also some carbonaceous material in the upper part. The sandstone of the Mancos formation, called Tres Hermanos sandstone, might be included in the Granerous shale in accordance with PIKE (1947) and STEARS (1953). There is no agreement in the literature yet on the uppermost contact of the Mancos formation. According to SEARS, HUNT, and HENDRICKS (1941) the Mancos and the Mesaverde formations represent a large scale intertonguing of marine and continental sedimentation, which took place in a broad, shallow geosyncline in the Zuni-Gallup basin, south of the San Juan Basin.

2. REGIONAL STRUCTURAL GEOLOGY

a. General Statement

The structural formation of the Gallup sag began during the Laramide revolution. The sag was derived from tensional forces pulling toward the southwest and northeast because of the respective uplifting of the Zuni and Defiance mountains. Diagonal compressional forces led to doming and tangentional fractures inside the sag which produced contemporaneously parallel anticlinal structures; BUCHER and GILKEY (1953) and KERR (1958), however, assume vertical forces. As KELLEY (1955a) pointed out, it is hard to visualize how a vertical mechanism only can lead to the present structures. These authors recur to vertical forces as major vectors because they need this assumption to support their epigenetic-hypogene ideas on the origin of the ores (KELLEY, 1955b). As will be discussed in the chapters on genesis, the fracture patterns of the area do not show any relationship to the ore deposits. Locally there was a tendency of faulting associated with this folding, however, the faulting was of small magnitude and has not played a primordial part on the structural picture of the Gallup sag.

Easterly and westerly, sinuous, north plunging, uninterrupted monoclines were developed as marginal edges of the sag. Those monoclines are called, respectively, Defiance and Nutria.

b. Nutria Monocline

The Nutria Monocline has a length of 30 miles, a maximum height of 2,500 feet and a maximum dip of 80^{o} (KELLEY, V., 1955a). Locally at Diamond No. 2 Mine the maximum height is 300 feet and the maximum dip 32^{o} (Fig. 1).

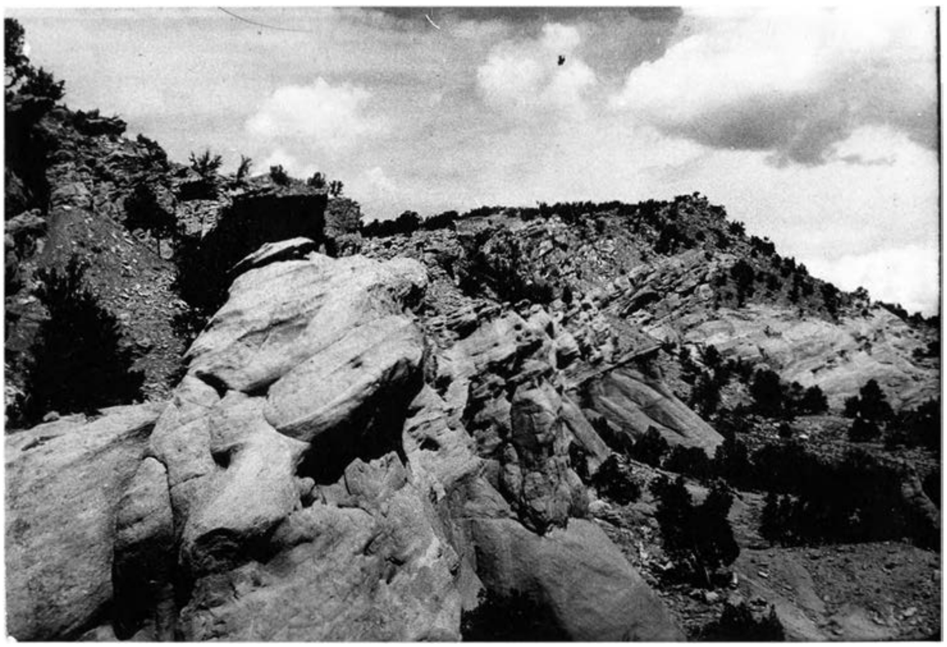


Fig. 1. - View of the Nutria Monocline looking northwest from Diamond No. 2 Mine incline shaft.

The Nutria Monocline (Fig. 2) represents a typical synclinal and anticlinal bend observed elsewhere in the Colorado Plateau (POWELL, J., 1873, H. BUSK, 1929, V. KELLEY, 1955a). Generally the synclinal bend is sharper and appears to be combined with folding and faulting. A drawing of the Nutria Monocline from this area is reproduced in LINDGRENS textbook (1935, p. 127).

One mile southwest from the Diamond No. 2 Mine the synclinal and anticlinal bends are not exposed due to the different surficial section. However, the uppermost layer of the monoclinal structure is slightly bent on the middle part (Fig. 3). The Nutria Monocline is associated with the Fort Wingate anticline forming its east limb. The anticline is not well exposed, however it can be traced following the contacts of the formations and the changes in dip of the top of the Chinle formation.

The nose of the Fort Wingate anticline is shown in section 36, T. 16 N., R. 18 W. There all the formations of the Nutria monocline are wedging out to the east forming gentle mesas with gradational northeast dipping angles.

At Diamond No. 2 Mine area, sections 33 and 29, the toe of the Nutria Monocline is represented by the Gallup sandstone. That sandstone and the underlying formations are forming a slightly transversal fold. That fold is one of several present along the monocline.

The Nutria Monocline involves late Cretaceous strata and overlapping formations. The age of its development might have started during latest Cretaceous time and completed during Paleocene time.

Fig. 2. - Synclinal bend of the Nutria Monocline, north of U. S. Highway 66 east of Gallup, N. Mex., on section 6, T. 16 N., R. 18 W.

Fig. 3. - View of the Nutria Monocline at section 3, T. 14 N., R. 17 W.

3. PETROLOGY AND SEDIMENTARY STRUCTURES

a. Areal distribution

The Dakota (?) formation crops out near Gallup on the rim of the Nutria Monocline. The thickness of the formation is not more than 30 feet in the well developed outcrops as at Diamond No. 2 Mine portal.

Shales and sandstones of the Dakota (?) formation are weathered and frequently covered by detritus. Bedding planes of the shales are much better exposed on the surface than in underground mine workings. Features of the sandstones are not always well preserved on the surface.

The Dakota (?) formation comprises less than the two percent of the sediments mapped at the Nutria Monocline (see Surficial Geological Map, Plate No. 1).

b. Dakota (?) Formation at Diamond No. 2 Mine

I. General description

The Dakota (?) formation at Diamond No. 2 Mine comprises the sandstones and shales between the continental uppermost Jurassic formation (Westwater Canyon sandstone (?), or Zuni sandstone (?)) and the black marine shales and sandstone tongues of the Upper Cretaceous sea.

The contact between the Dakota (?) and the overlying Mancos formation is truncated at places but generally transitional. From exploration drill data as well as from outcrop observations it can be concluded that a gradual lithologic change from sandstone to shaly sandstone to sandy shale is present almost everywhere. The transition zone has a thickness of 20 feet.

The contact between the Dakota (?) formation and the underlying Westwater Canyon (?) or Zuni sandstone (?) is marked by a very flat unconformity which is illustrated in Fig. 4. A thin band of Dakota (?) shale is present in most of the contacts.

The base of the Dakota (?) formation is formed by coarse-grained arkosic sandstone with carbonaceous matter. The upper part of the Dakota (?) presents fine-grained quartz to arkosic sandstone. The sandstones are interfingered with carbonaceous shales, which are somewhat silty at places, and with lenses of siltstone and gray sandstone.

In the underground workings at Diamond No. 2 Mine the Dakota sandstones and shales are seen to form a series of discontinuous sandstone lenses that pinch and swell or grade laterally into shale facies (see underground geological maps). Similar features were noted by GOLDSTEIN (1948) on the Dakota group of the Front Hills, Colorado. GOLDSTEIN remarks that there (p. 34) " ... the lack of continuity along the strike ... " is a characteristic of the Dakota (?) formation. At Diamond No. 2 Mine, however, while the sandstones are discontinuous the shales are continuous, though of varying thickness.

According to the grain size and mineral composition the major members of the Dakota (?) formation at Diamond No. 2 Mine can be divided into:

I. Coarse and medium grained arkosic sandstone, some of them conglomeratic.

II. Fine and very fine grained sandstone to arkosic sandstone.

III. Clays and siltstones.

IV. Dark shales.

These four rock types are described on the following pages.

Fig. 4. - Disconformity between the Dakota (?) formation and the Westwater Canyon (?) sandstone, 425 level.

The dark sandstone seen in the upper half of the photograph is the bottom part of the Dakota (?) formation. The white sandstone is the Westwater (?) Canyon sandstone. Between the two sandstones a thin band of black shale is present which is generally encountered on the top of the Westwater sandstone.

It is important to note that uranium-vanadium mineralization is present in the Dakota (?) sandstone only, in spite of the common presence of faults in both sandstones. This observation speaks against a connection between faults and ore emplacement in this particular place (which agrees with KELLEY'S observation on the whole Colorado Plateau 1955b, p. 51).

Location: 387115N-227500E

Fig. 5. - Two types of arkosic sandstone and their relation with uranium-vanadium content, 500 stope, Becenti ore body.

Uranium-vanadium minerals are contained in the coarse and medium grained arkosic sandstone illustrated on the lower two-thirds of the picture. The upper third of the picture exhibits a "white" fine grained arkosic sandstone lying on thin shale bands.

While the sandstone mentioned first is the host of uranium-vanadium ore, the second does not contain any ore minerals.

Location: 388220N-226700E

II. Coarse and medium grained arkosic sandstone

As a whole the medium sized clastic members of the Dakota (?) formation are dark in color, sometimes with faint buffish tinges. The coarse and medium grained arkosic sandstones form 30 percent of the rocks exposed in underground workings at Diamond No. 2 Mine; this sandstone is the host of the uranium-vanadium ore minerals (Fig. 5).

The sandstone is poorly sorted, loosely cemented and contains carbonaceous matter and clay galls. The average size of the grain ranges from 0.8 to 1.1 mm. as shown with microphotographs on figures Nos. 6, 7, and 8. This arkosic sandstone consists almost only of quartz grains with some fragments of quartzite and microcline; carnotite and carbonates constitute the matrix. As shown in Fig. 32, slightly bipyramidal quartz grains (of possible volcanic origin) as well as undulating quartz are typical. Microcline occurs frequently as relatively large fragments. The mineral grains are held together by a carbonate matrix, occasionally containing traces of clay. Silica matrix was only found in samples from outside the boundaries of the ore bodies (Fig. 9).

Carbonaceous matter is arranged horizontally forming laminae similar to those observed in recent beaches (THOMPSON, 1935) and reported in the Dakota sandstone of the Front Hills by GOLDSTEIN (1948, p. 35)(Fig. 10). Successions of 1 inch (25 mm.) of carbonaceous matter separated by 2 to 3 inches (50 to 75 mm.) of sand layers may represent seasonal banding (SHROCK, 1948, p. 87).

Well preserved dry curly clay galls are abundant in these sandstones (Fig. 11). Clay galls usually contain ore minerals. Vanadium minerals (mostly corvusite) appear to have a stronger affinity for them than uranium minerals (less carnotite). The high concentration of vanadium in clay galls may be due to the high redox potential of the mud (now present as galls, LAHEE, 1952, p. 104) which controlled the syngenetic deposition of the vanadium (RANKAMA and SAHAMA, 1957, p. 599).

The coarse to medium-grained arkosic sandstone is generally thick bedded (about 3 feet) with horizontal stratification slightly deformed because of submarine slumping (see chapter 3, d, I) and because of the pre-existing rolling surfaces of the underlying Westwater Canyon (?) sandstone. (The Westwater Canyon sandstone represents an old erosion surface broadly rolling but locally scarped (see Plate No. 2); some differential degradation of the sandstones, along the whole coast might have resulted from their exposure under arid climatic conditions.) Generally the coarse to medium grained arkosic sandstone shows current crossbedding. Exceptionally, peculiar festoons with graded bedding were observed (Fig. 12). Some of the sandstone lenses in the Dakota may have formed in strike valley lows of the erosion surface in the Westwater sandstone such as described as oil traps, for example by BUSCH (1959).

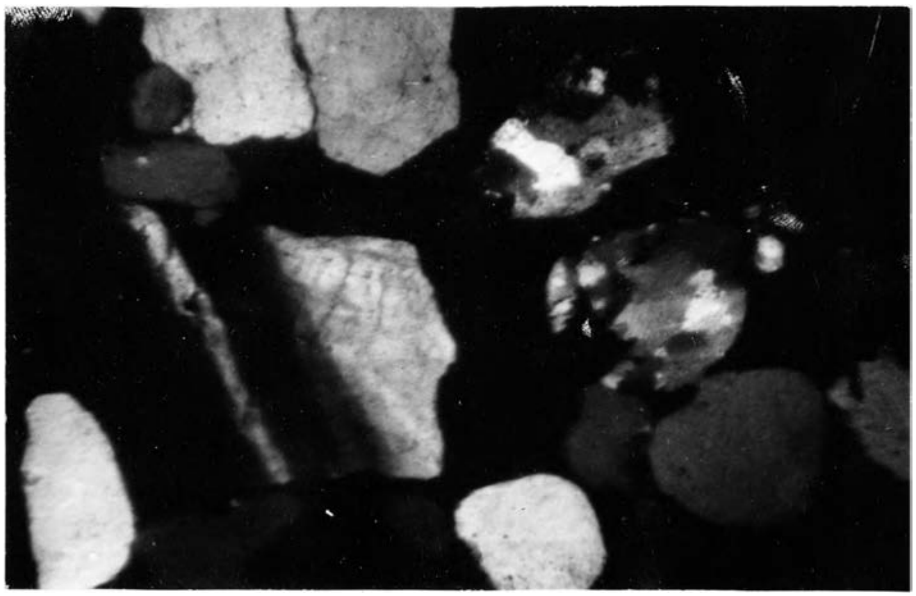


Fig. 6. - Two pieces of mosaic quartz and one large piece of undulating quartz. Crossed Nicols. Enlargement 60x.

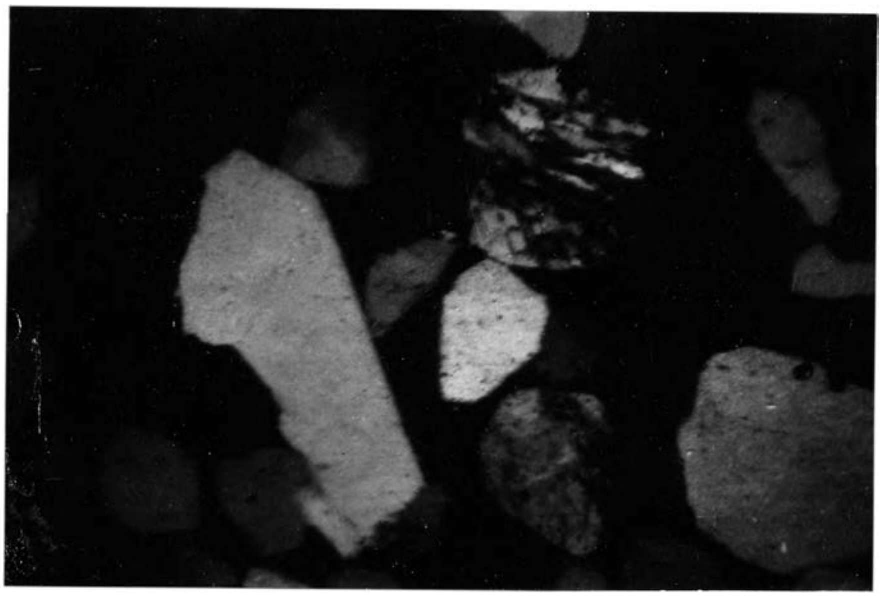


Fig. 7. - Fragment of almost bypyramidal quartz and a piece of possibly devitrified volcanic glass. Crossed Nicols. Enlargement 60x.

Fig. 8. - Mosaic quartz (quartzite or vein quartz fragment?). Crossed Nicols. Enlargement 60x.

Fig. 9. - Coarse-grained sandstone with siliceous matrix.

This type sample illustrates a variety of Dakota sandstone which is present in areas without uranium-vanadium minerals of the Nutria Monocline. The "silicification" is parallel to the bedding planes and may thus be syngenetic. Scale in cm.

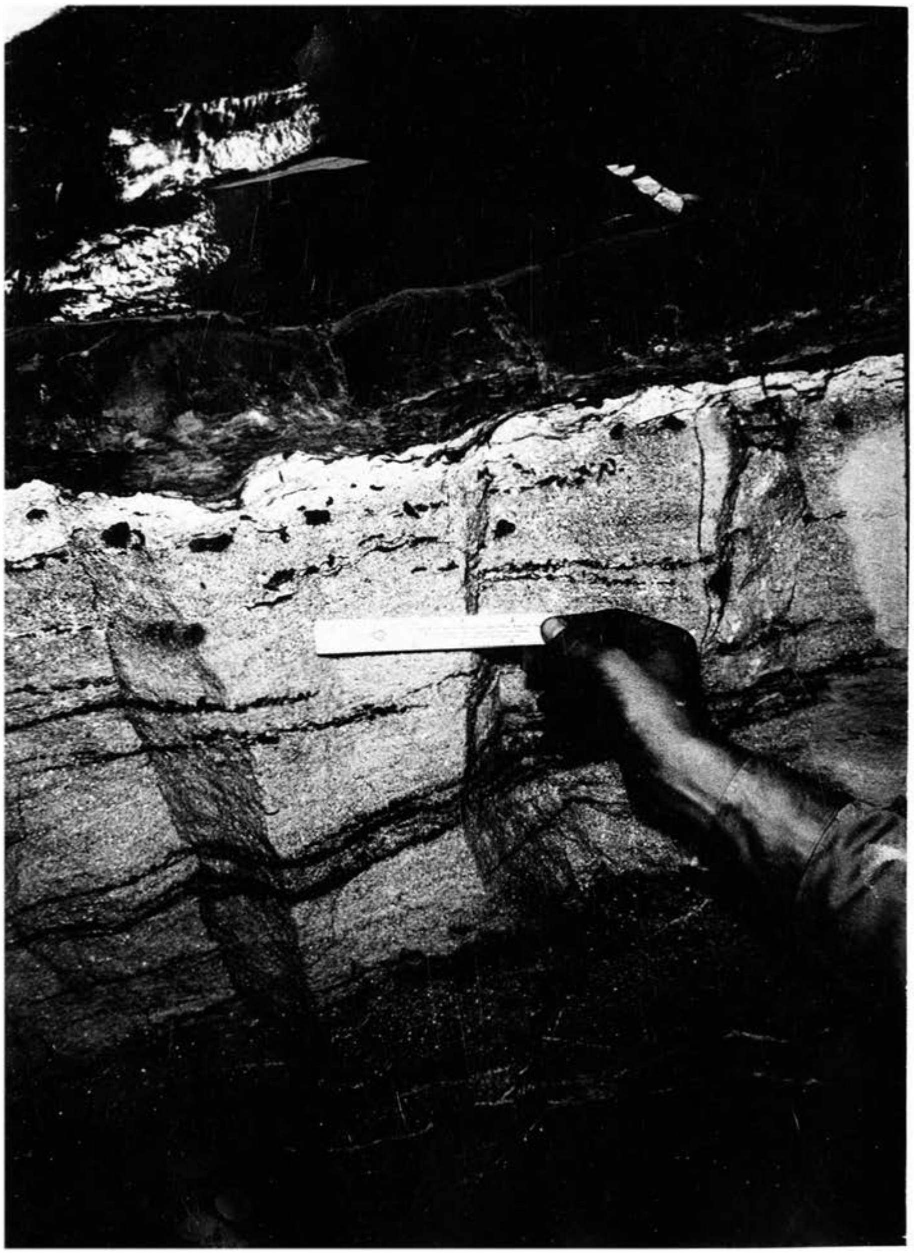


Fig. 10. - Laminae of carbonaceous material in Dakota (?) sandstone.

The upper half of the picture is Dakota shale with slickensides in the upper right corner. The Dakota sandstone is exposed in the rest of the picture. The black inclusions in the coarse sandstone are carbonaceous material, with a laminar arrangement similar to that observed on recent beaches. The uranium-vanadium minerals coffinite and carnotite are present in the sandstone. The greater concentration of ore minerals follows the horizontal arrangement of the carbonaceous matter in the sandstone. The white strip in between the black shale and the sandstone is mostly kaolin.

Location: 388100N - 226715E (Becenti Orebody).

Fig. 11. - Clay galls on Dakota sandstone.

Note the trapezoidal fracture surfaces present within the sandstone. This view is parallel to the direction of the submarine slumping of the Dakota formation (see chapter 3, d, I) and may represent an initial stage of submarine slumping tectonics.
Location: 388220N - 226740E

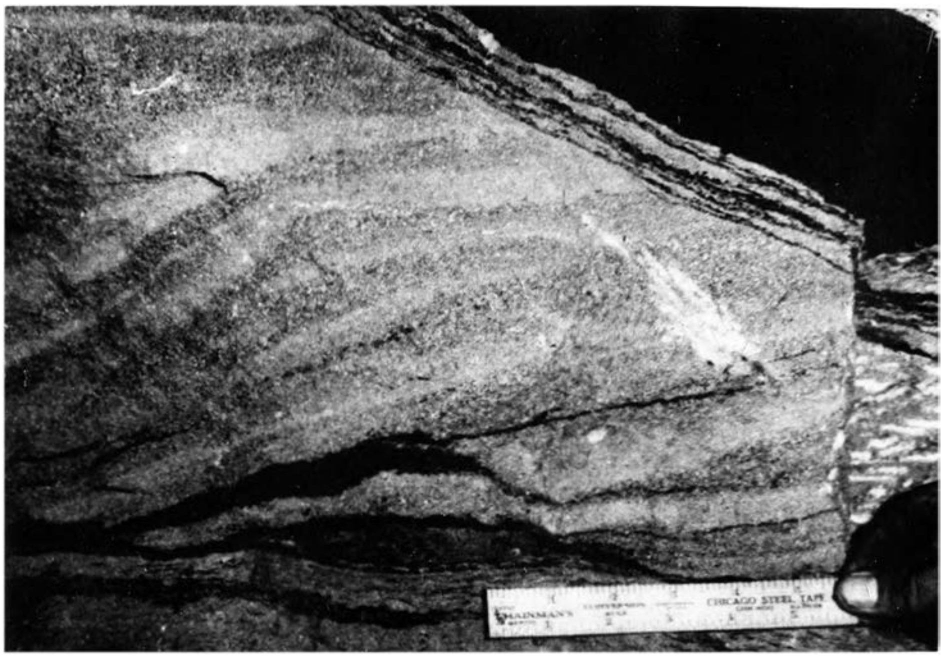


Fig. 12. - Internal structure of crossbedding combined with graded bedding.

Section is vertical to the direction of the sedimentation. According to KUENEN (1950, p. 241) this may be evidence of turbidity currents. Although most of the crossbedding in the Dakota sandstone is homogeneous current crossbedding some graded current crossbedding is also present. Both types show association with carbonaceous matter and often will contain uranium-vanadium minerals.

Location: 388100N - 226690E

III. Fine and very fine grained sandstone to arkosic sandstone

These sandstone beds are generally light gray to white in color. The sandstone lenses are thin-bedded and massive (Fig. 13).

Although the sandstone has the same mineralogic composition as the coarse to medium grained sandstone, it differs from the latter in the following way:

1. Absence of carbonaceous material
2. Absence of clay galls
3. Absence of laminae
4. Absence of uranium-vanadium minerals
5. Partial absence of interfingered relationship with the black shales

The contact between the fine to very fine grained sandstone to arkosic sandstone with the coarse to medium one is generally separated by bands of black shale.

The petrographic composition shows that the size of the grains varies from 0.14 to 0.23 mm. (Fig. 14). The quartz represents about 63 percent of the sandstone while the feldspar (microcline) forms not more than 23 percent in most of the samples and in exceptional cases over 25 percent. Accessory minerals (muscovite, pyroxenes) and cement form the rest. The cement is mostly composed of clay and some calcite pigment of iron oxide is frequently exposed in thin sections as well as in hand specimens.

Fig. 13. - Sandstone lenses of fine grained normal to arkosic sandstone, incline shaft.

Beds are dipping 28° southwest, thus the general dip of Dakota (?) formation at Diamond No. 2 Mine. Location: 387190N - 227350E

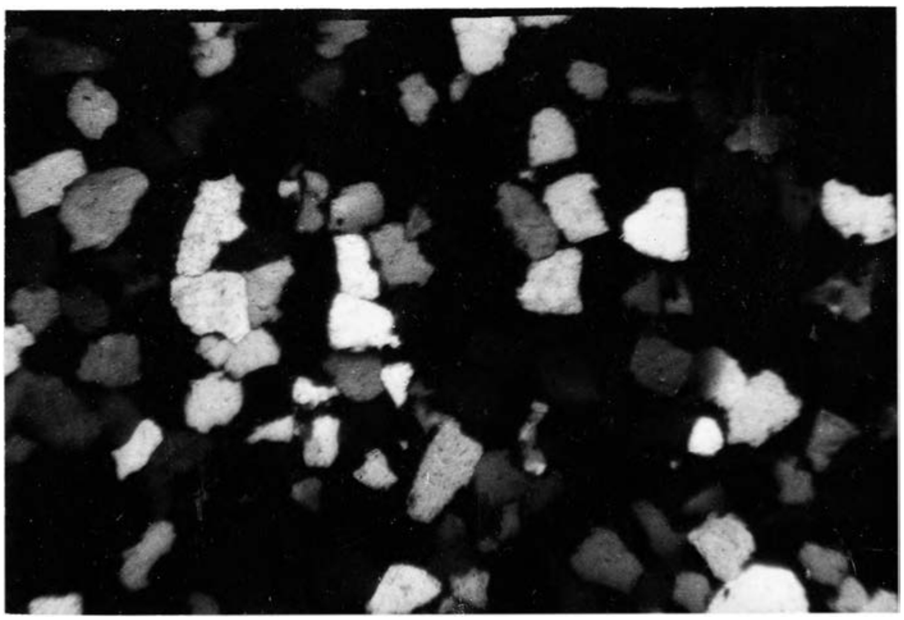


Fig. 14. - Microphotograph of fine grained normal, to arkosic sandstone. Crossed Nicols. Enlargement 60x.

IV. Clays and siltstones

Clays are abundant in the sandstones where they fill small listric fractures and spaces between grains.

Much of the calcite and kaolinite observed in the coarse grained sandstone might be products of devitrification of volcanic glass, according to E-an ZEN (1957)(See also PROCTOR, 1953).

Siltstone lenses are somewhat common in the shales (Fig. 15). The deformation of some siltstone lenses is probably due to submarine slumping. Siltstones are present mostly between the shales. Uranium-vanadium minerals are not present in the siltstone lenses, however post-mineral leaching of uranium is fairly abundant. Very thin bands (2 cm.) of siltstone are showing transitions with gray shales.

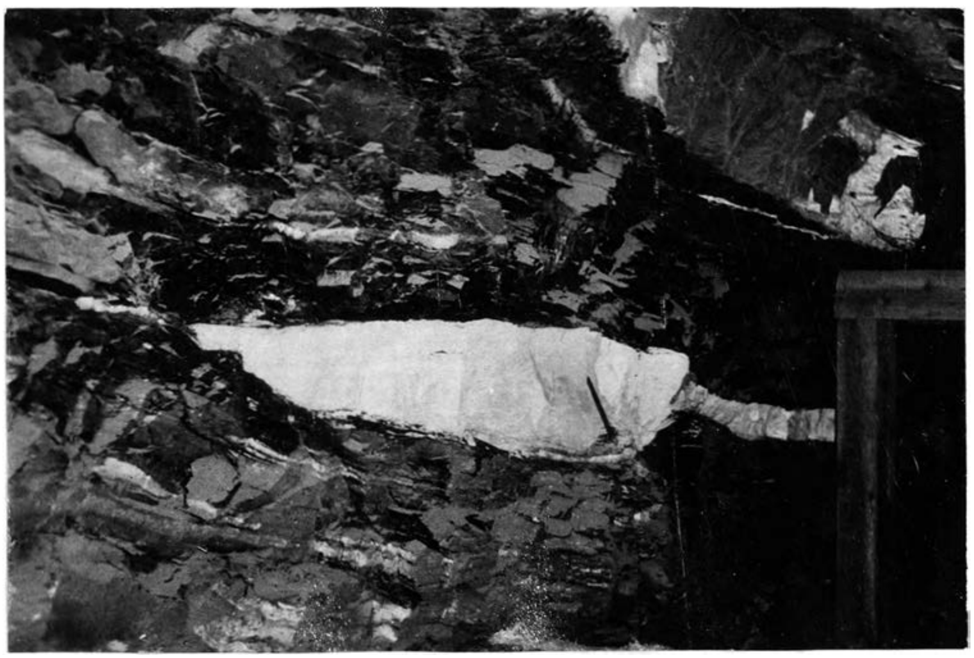


Fig. 15. - Siltstone lens in the black shales.

Note the deformation of the lens which was probably produced by compression during submarine slumping.

Scale: Black rod at right end of lens is pencil.

V. Dark shales

Shales of the Dakota formation do not show the same color and characteristics on the surface as they do underground. On the surface the shales are poorly exposed, however some outcrops are well preserved. Shales apparently disappear south of the Diamond No. 2 Mine portal (see Plate No. 4), however the underground workings are exposing the shales as a series of continuous layers along the extention of the strike.

It was noted underground that shales are black or gray in color. A cross section through the ore bodies shows that the black shales are present where the uranium-vanadium ore occurs. Gray shales are more common in the areas without ore minerals.

Occasionally yellow films of carnotite are present on the planes of contact between sandstones and shales which contain ore minerals.

c. Over-all picture of the sedimentation history

The paleogeography of the Dakota time was studied and analyzed by LEE (1916) and WAAGE (1955). GOLDSTEIN (1948) summarized the paleogeography of the Dakota as follows (p. 57):

"1. The Dakota sandstone was deposited over the entire southern Rocky Mountain province.

"2. The Dakota sandstone was laid down upon an ancient peneplain.

"3. The Dakota sandstone is the near shore sandstone of the advancing Upper Cretaceous sea.

"4. The Dakota sandstone of one locality may not be the same age as the Dakota sandstone of another locality."

MIRSKY (1953, p. 4) says that the Dakota (?) formation at Gallup area was deposited marginal to the sea with interbedded lagoonal, continental, and off-shore deposits suggesting a fluctuating shoreline. GABELMAN (1955, p. 306) states that: "The Dakota formation was deposited along a migrating strandline which probably moved southward across the San Juan Basin and finally buried the Jurassic land mass, the source of the Morrison clastic rocks. The sandstone of the Dakota therefore extends diagonally upward and southward across time lines. The lower Dakota unit represents a combined paludal and lagoonal environment retreating ahead of the encroaching beaches and offshore bars of the upper unit."

The Dakota formation at Diamond No. 2 Mine evidently represents a near shore sandstone and shales of Cretaceous time; it was deposited upon the old erosion surface of the

Westwater (?) sandstone. The continuity of the shales as well as its increase in thickness down dip suggest that there are no paleostream channels (MIRSKY) and/or lagoonal environment (GABELMAN). Also the current crossbedding elsewhere observed denotes that sandstones and shales were deposited in shoreline conditions.

The Dakota formation at Diamond No. 2 Mine was formed under marine environment. Criteria are:

1. Sandstone lenses are convex on the top and on the bottom.
2. The lithology of the sandstones is uniform and lacking heavy minerals as well as flake minerals.
3. Intergradation of shales and siltstones. Interfingering and intertonguing of sandstones and shales.
4. Continuity of shales. Shales showed great lateral extent and increasing thickness down dip.
5. Current crossbedding type.
6. Existence of clay galls.
7. Lack of evidence of continental plants.
8. Evidence of submarine slumping.

d. <u>The general characters of the disturbed and undisturbed sediments</u>

The outstanding feature of the Dakota formation at Diamond No. 2 Mine is the marked contrast in structure between undisturbed beds and those which exhibit, to a greater or lesser degree, evidence of submarine slumping.

Disturbed beds now occur as intercalations in the lower horizons of the Dakota formation. As will be discussed, these portions of the sediments were formed as a result of gravitational submarine sliding or slumping of the sands and muds (now sandstones, siltstones and shales) present near the shore of the Cretaceous sea.

I. <u>Undisturbed sediments</u>

Normal or undisturbed sediments of the Dakota formation are much more abundant in the Nutria Monocline than disturbed ones. However their presence is somewhat overemphasized in the geological literature on the Dakota formation in the Rocky Mountains. GABELMAN (1955) mentions for the first time slumping structures at this particular location and nearby areas.

Undisturbed sediments of the Dakota formation at Diamond No. 2 Mine include several types:

a. Light gray with white fine-grained sandstones usually in thin beds with smooth or even surfaces (Fig. 13).

b. Thick-bedded, gray shales sometimes with very thin carbonaceous bands.

c. Thick-bedded, brown, medium-grained arkosic sandstones with laminae of carbonaceous matter (Fig. 10).

d. Thick-bedded, medium to coarse-grained reddish arkosic sandstones (this sandstone is found outside of the boundaries of ore bodies).

e. Thick-bedded coarse arkosic sandstones with abundant "silicification" (Fig. 9).

II. Disturbed sediments

The outcrop map of Diamond No. 2 Mine shows (see Plate No. 4) that the Dakota sandstone was deposited on a smoothly rolling surface, with gentle rolls along the coast. This pre-existing surface of deposition, together with the inclination of the coastal slope, determined probably the direction of the submarine slumping which has taken place. These movements are illustrated in Figures 16, 17, 18, 19, 20, and 21. The directions of movement were apparently not always parallel. This caused the "Christmas tree" textures (Figs. 22 and 23) which are most probably due to lateral congestions.

It appears from the literature that GABELMAN (1955) was first to recognize slumping structures in the Dakota formation at Gallup, New Mexico. He says that these structures are of diagenetic origin (p. 306).

As far as could be determined the disturbed sediments are composed of the same lithological types as the undisturbed Dakota sandstone in the Nutria Monocline. Gradations of slumping disturbance could be observed. Typical examples can be seen in parts of the outcrops as well as in the underground workings of Diamond No. 2 Mine (see Plate No. 4, bottom, between H and Q).

The nature and effects of the disturbances are, of course, most easily recognized in those sediments which are banded either by silty strips of black shales, they are observed (Fig. 16) in raises or crosscuts of Diamond No. 2 Mine.

In the most disturbed sandstones the bedding planes are folded, or "corrugated" or minutely crumpled in front (Fig. 20A) and piled up in "shingle" type fractures at the end of the lenses (Fig. 20A)(Fig. 22); small vertical faults are seen in all cases particularly in siltstone masses, differing in structure from each other. They may be piled one upon another, reproducing on a small scale Alpines nappe structures (Fig. 20A, see top).

In some exposures the heads of the lenses are folded into overfolds or recumbent folds, the turnover or crest of the fold resembling the anticlinal arch-bend of Alpine folds. The direction of slumping movement illustrated in Figs. 16, 17, 18, 19A, 19B, 21, 24, 25A, 25B, 27A, 27B, 27C, and 27D, is towards SW.

Similar examples of syngenetic recumbent folding by slumping were recently described from many places, and many different types of sediments, for example also in snow (CROWELL, J. 1957, E. ROHRER, 1958, WEISS and McINTYRE, 1957).

Slumping deformations are occasionally also seen from deformations of crossbedded and/or graded sandstones (Figs. 12 and 20). On the walls of the drifts of the mine (thus in vertical direction to the sliding) phacoidal (lenticular) cleavage is frequently seen in sandstone lenses and shales (Fig. 26D'). This is the section vertical to the shingle tectonic. In this section, as in all sections vertical to the slumping movement, it is difficult to recognize that any movement took place. The phacoidal cleavage (which is the product of the schollen or shingle textures, Figs. 18 and 19B) runs down slope through tens of feet of the sandstones at the end of the lenses which slumped. Since in drifts sometimes only the upper or the lower curvature of these lenses can be seen, they were occasionally interpreted as minor anticlinal or synclinal feature.

Drawings of equivalent features as here described are pictured in SHROCK's book on pages 157 and 159 (Figs. 116 and 118). DUNBAR and ROGERS (1957, p. 193, Fig. 99) also show flow roll structures assigned to slumping. All these drawings and pictures are sections essentially parallel to the flow of the movement whereas none of them shows a section vertical to it. On Fig. 26 the four basic types of sedimentary structures are drawn, each of which is shown on two vertical planes vertical to each other. Whereas it is not difficult, generally, to see movement in the planes of the movement, which correspond to the walls of the raises in the mine, it is difficult to recognize it on sections (for example mine walls) vertical to the movement.

DE SITTER (1954, p. 321) says that "gravitational tectonics explain folded and faulted structures by superficial gliding of relatively large and coherent masses down slopes under the influ- of gravity rather than directly by lateral compression, though lateral compression is a possible cause of the slope."

Generally sediments accumulating on subaqueous slopes would slide or slump as hydroplastic masses if the weight of slopes become steeper, or if support was removed lower down the slope, or under the influence of an external impulse such as movements in the water or earthquake shocks (JONES, 1936; AMSTUTZ, 1958).

KUENEN (1950, p. 246) mentions that slumping can occur wherever the inclination of the slope attains 2° to 3°, or occasionally even at 1°. The formation of slumping under these conditions is attributed to the action of turbidity currents (Fig. 12). This could have been the case in the Dakota sandstone.

The thickness of the strata disturbed by slumping in the Diamond No. 2 Mine vary between few centimeters and a few meters. It cannot be ascertained whether the slumping occurred suddenly or by gradual creep; however, evidence that the slumping of disturbed sandstone and shales was a phase of diagenesis is proved by the alternation of disturbed (slumped) with undisturbed strata (Fig. 17). Shales, carbonaceous matter, and possibly sometimes also poorly cemented sandstone may have provided lubricating or listric planes, on which the differential movement of gravitational slumping took place more effectively.

Submarine slumping on angles of a few degrees (also containing ore minerals) is present elsewhere, for example in the sediments of the Mississippi Valley type ore deposits of the Lead Belt of Missouri (SNYDER and ODELL, 1958).

Fig. 16. - Detailed photograph of the head of a sandstone lens which exhibits deformation typical for submarine slumping. The direction of movement is right to left, which corresponds to ENE-WSW direction, which is the dip direction of the coast. Location: 387332N - 227225E

Fig. 17. - Photograph of disturbed and undisturbed sandstone lenses. Top (same as figure 16); bottom: Undisturbed tail of a sandstone lens.
Location: 387332N - 2272225E

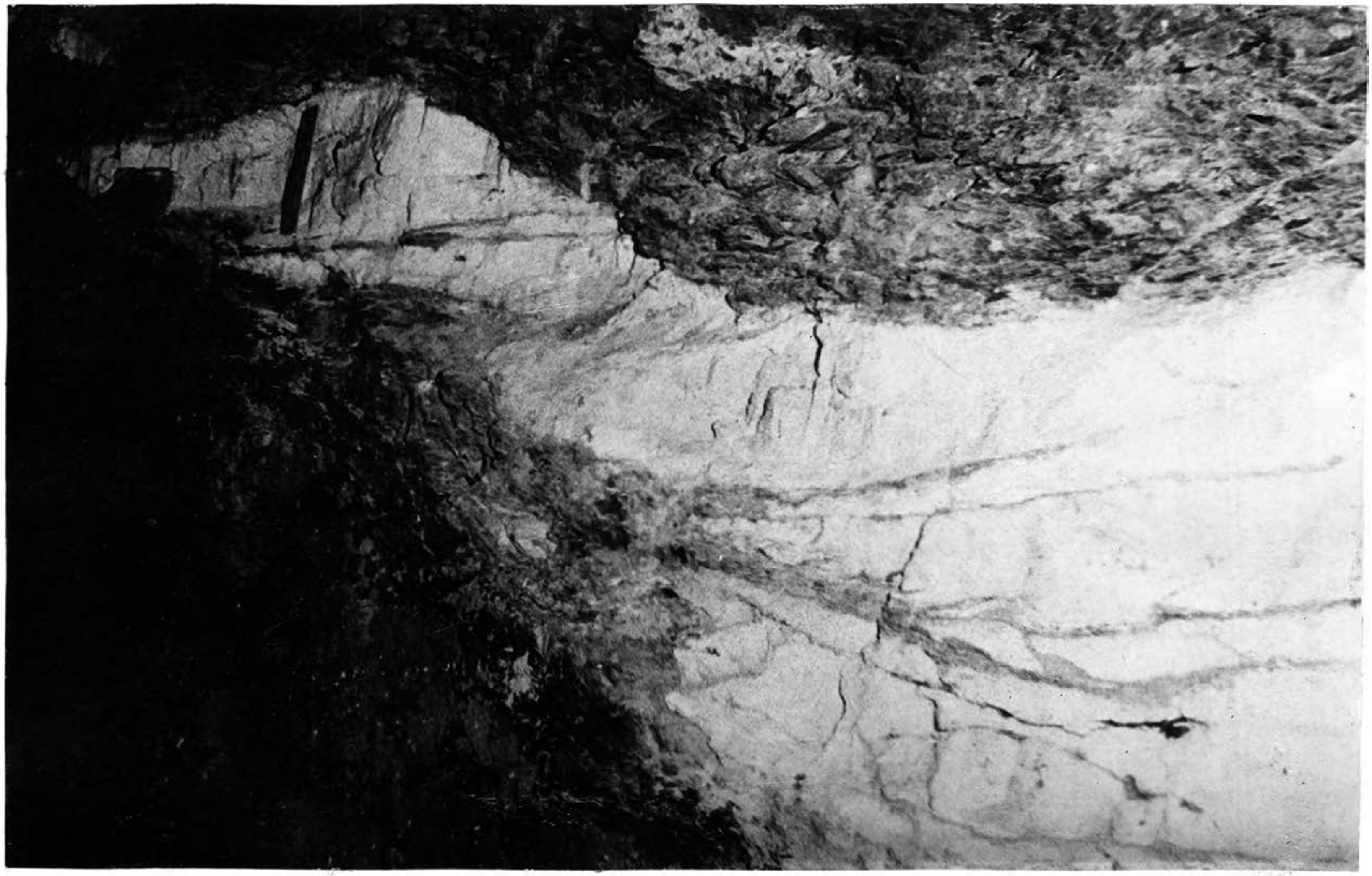


Fig. 18. - Detailed photograph of the tail of a sandstone lens which exhibits a shingle pattern, a tectonic deformation typical for submarine slumping. The direction of the movement is left to right. The scale in the upper left corner of the photograph measures 10 cm. Location: 388145N - 226710E

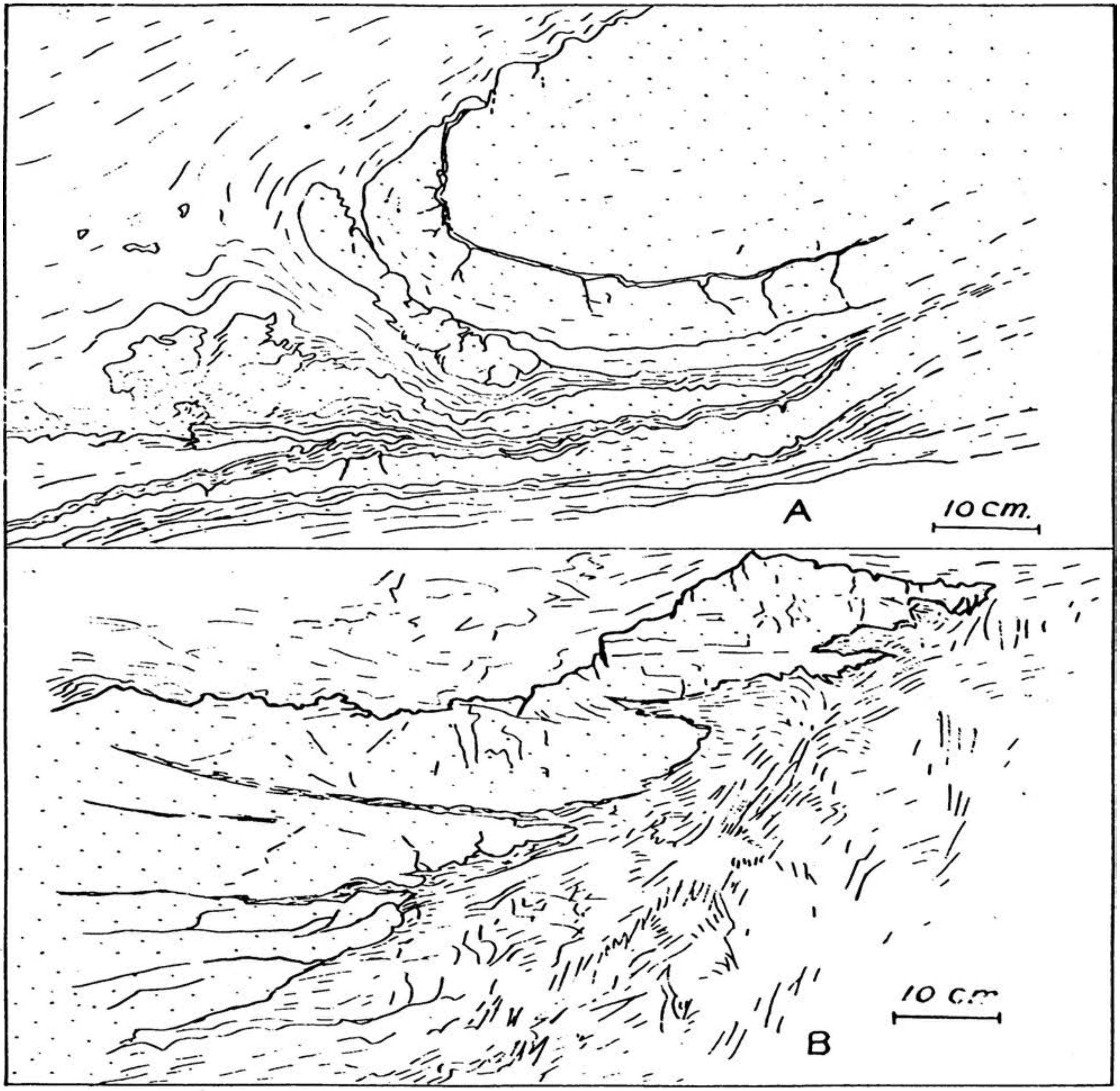
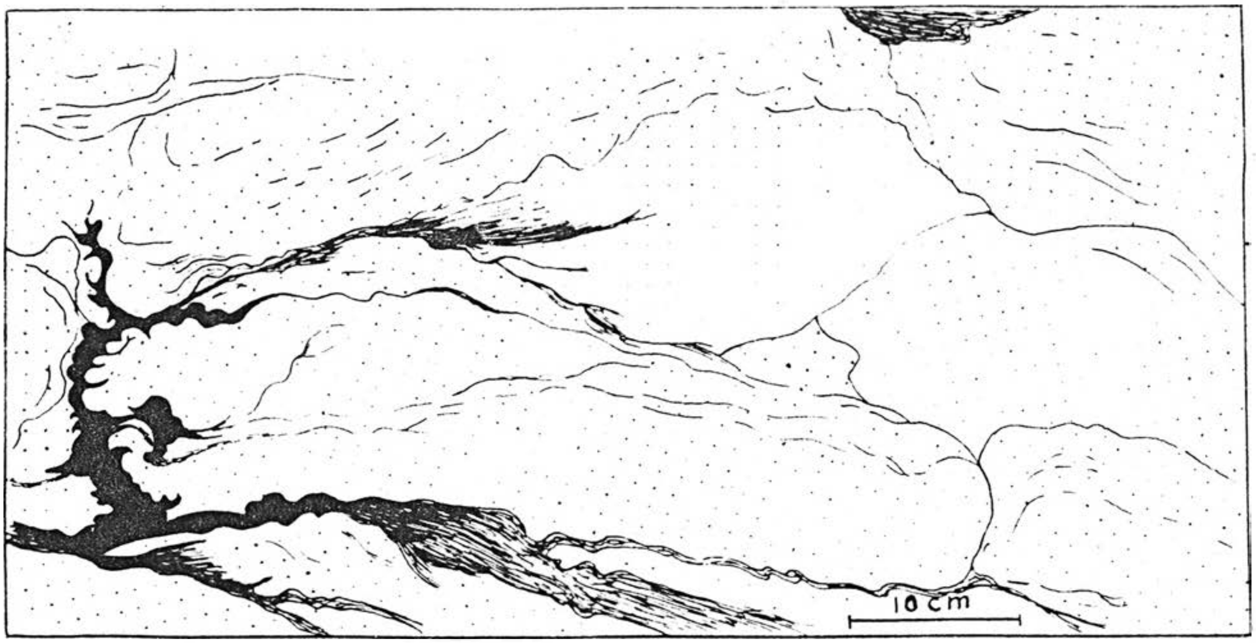


Figure No19A and B. Detailed sketches of a head and a tail of sandstone lenses which show submarine tectonic features.

A) The head shows congested features (see photograph figure No.16) and B) the tail shows shingle (schollen) tectonics. Location: A) 387332 N - 227225 E; B) 388145 N - 226710 E.



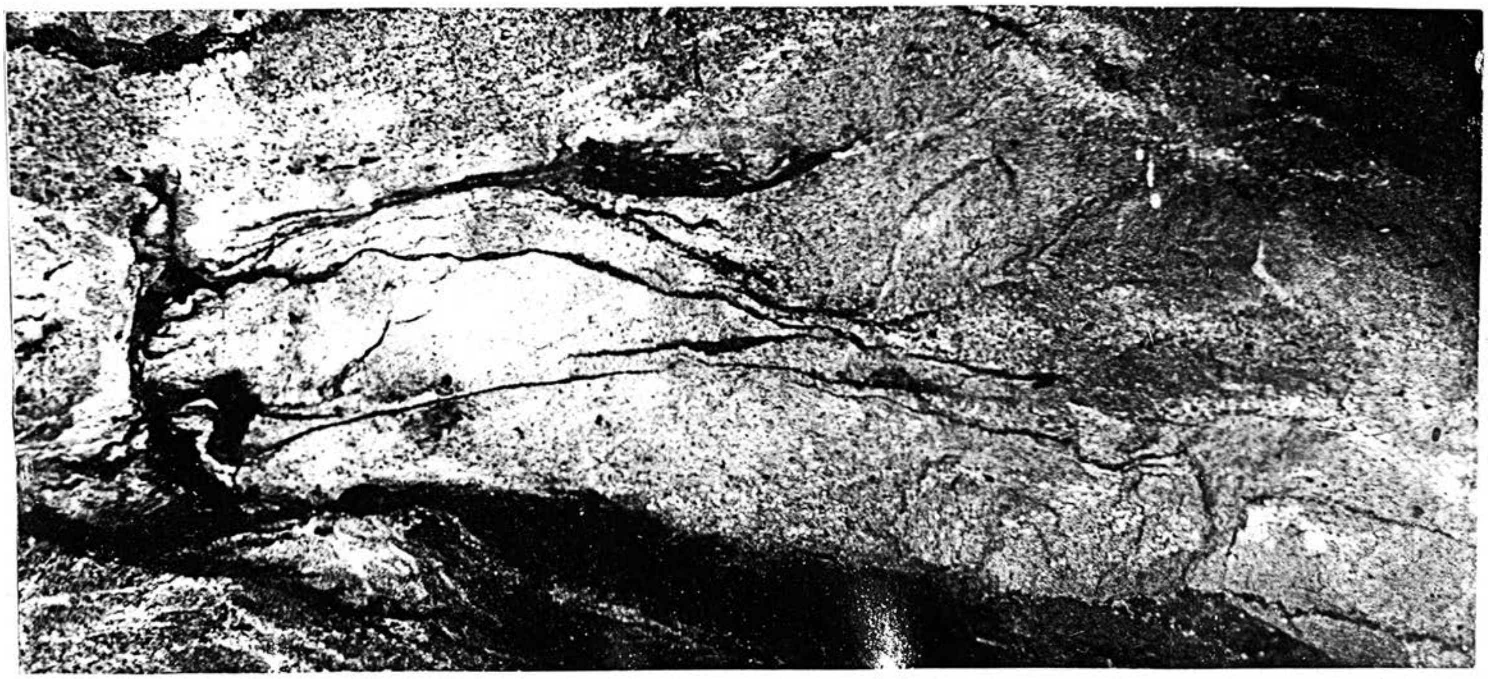


Figure No.20 Sketch and photograph of wedges of crossbedded sand separated by thin seams or sheets of carbonaceous material.

Location: 388115 N - 226740 E.

Fig. 21. - Specimen exhibiting delicate tectonic features indicative for submarine slumping. The differential movements inside the sandstone during the slumping are seen from the small carbonaceous sheets or layers which served as tectonic markers. One such bend or fold is visible in the lower corner of the sample. Figs. 21, 23, 24, and 25 exhibit the same features with well developed carbonaceous markers.

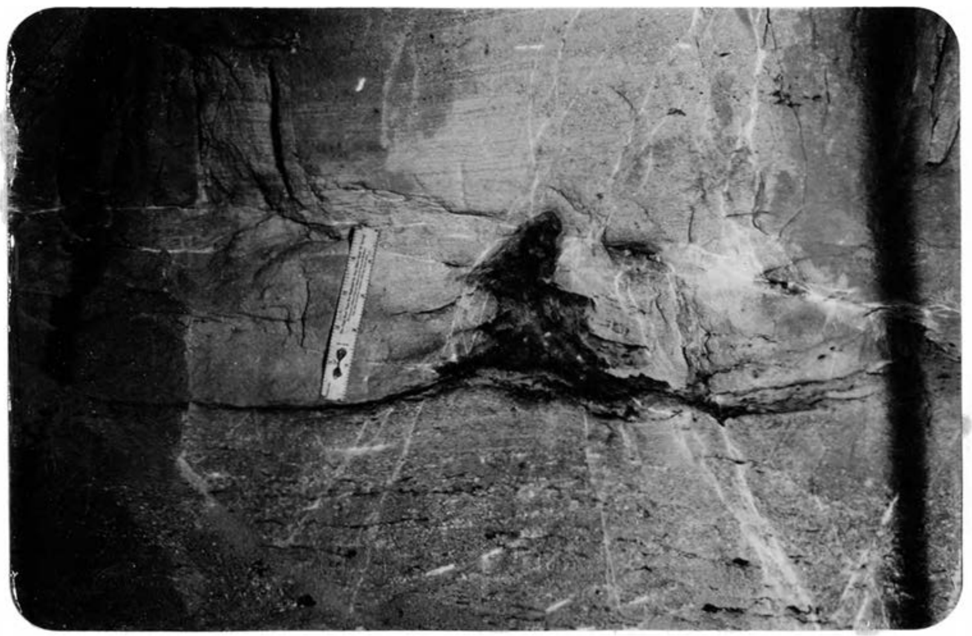


Fig. 22. - "Christmas tree" feature. The blue-black material is corvusite and carbonaceous matter. Yellow is carnotite and jarosite developed in situ from the oxidation of corvusite. The small vertical fractures do not show any relationship with any type of rock of mineral, except that they are not visible in the carbonaceous matter. The age of these fracture systems is not known. The possibility that they may have formed during or right after the last stages of diagenesis may be given high probability.

A sketch offering an interpretation of the movement leading to this "Christmas tree" feature is drawn on the next figure.

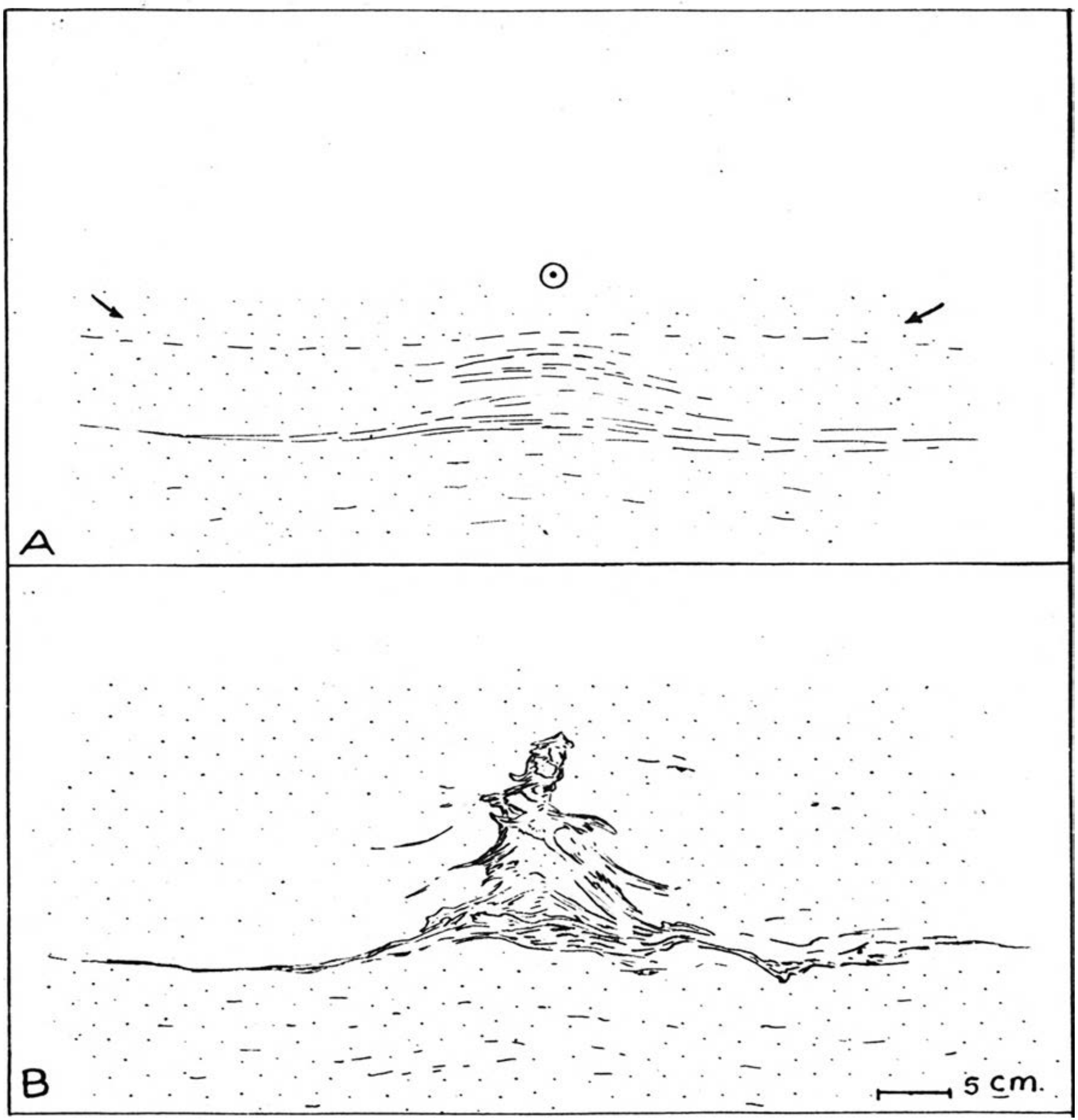


Figure No. 23A and B. Sketch explaining the formation of the "Christmas tree" (see photograph figure No. 22), looking in the direction of the hydroplastic submarine slumping; A) before and B) after the movement. (⊙ means movement vertical to the plane of the drawing). Location: 388190 N - 226665 E.

Fig. 24. - Corvusite in arkosic sandstone. The photograph illustrates a concentration of corvusite (blue black color) with carbonaceous matter and sandstone.

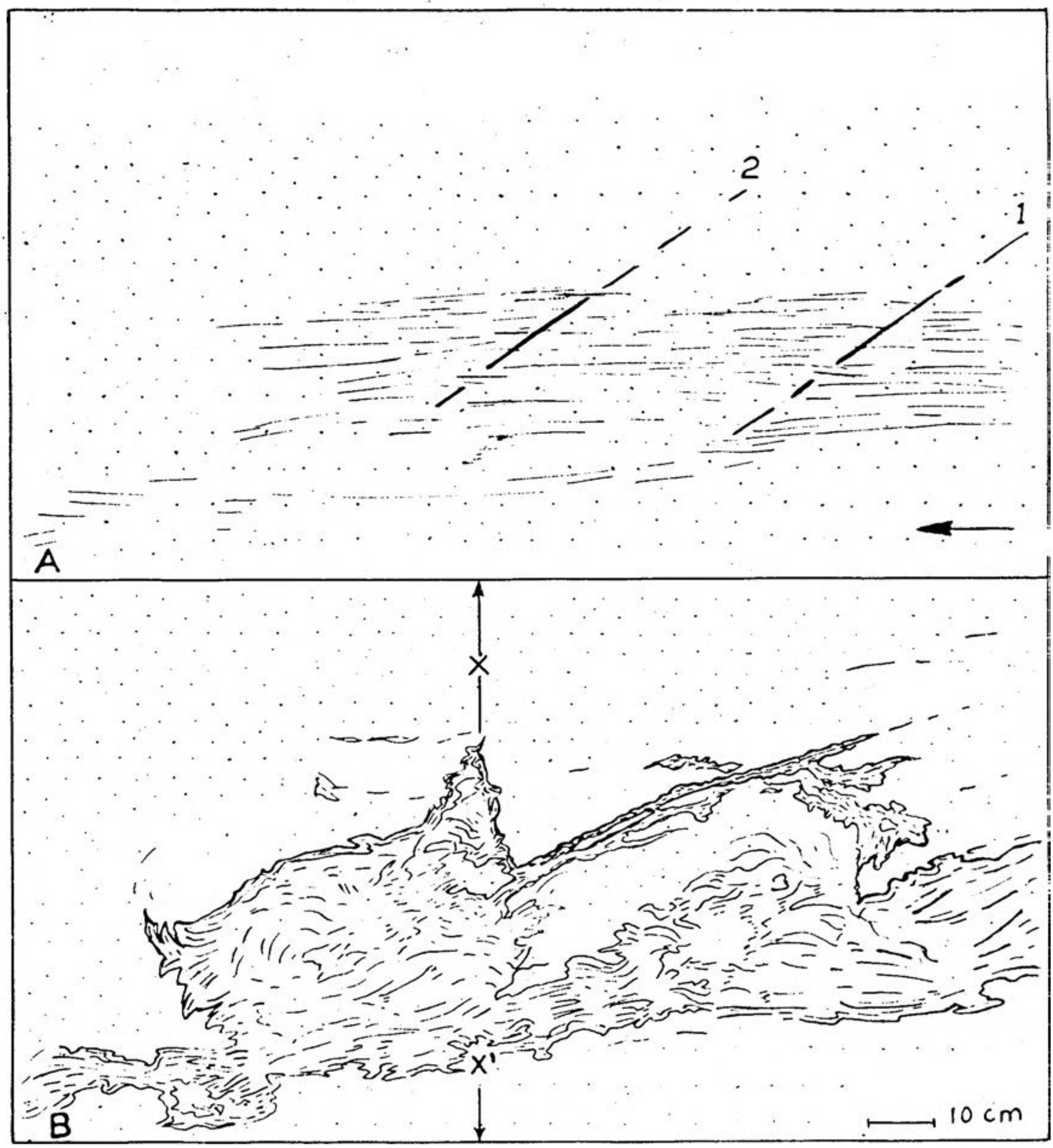


Figure No.25A and B: Side view of the genetic interpretation of the Christmas tree feature, showing the "shingle" tectonics in carbonaceous matter.

1 and 2 are listric surfaces of the shingle texture which lead to the three-fold segmentation and buckling-up of the carbonaceous sandstones. A cross section along X-X' would show features similar to figure No. ("Christmas tree"). Location; B) 387332 N - 226765 E.

Figure No. 26 Location of submarine slumping in the Dakota (?) formation at Diamond No. 2 Mine, Gallup, New Mexico

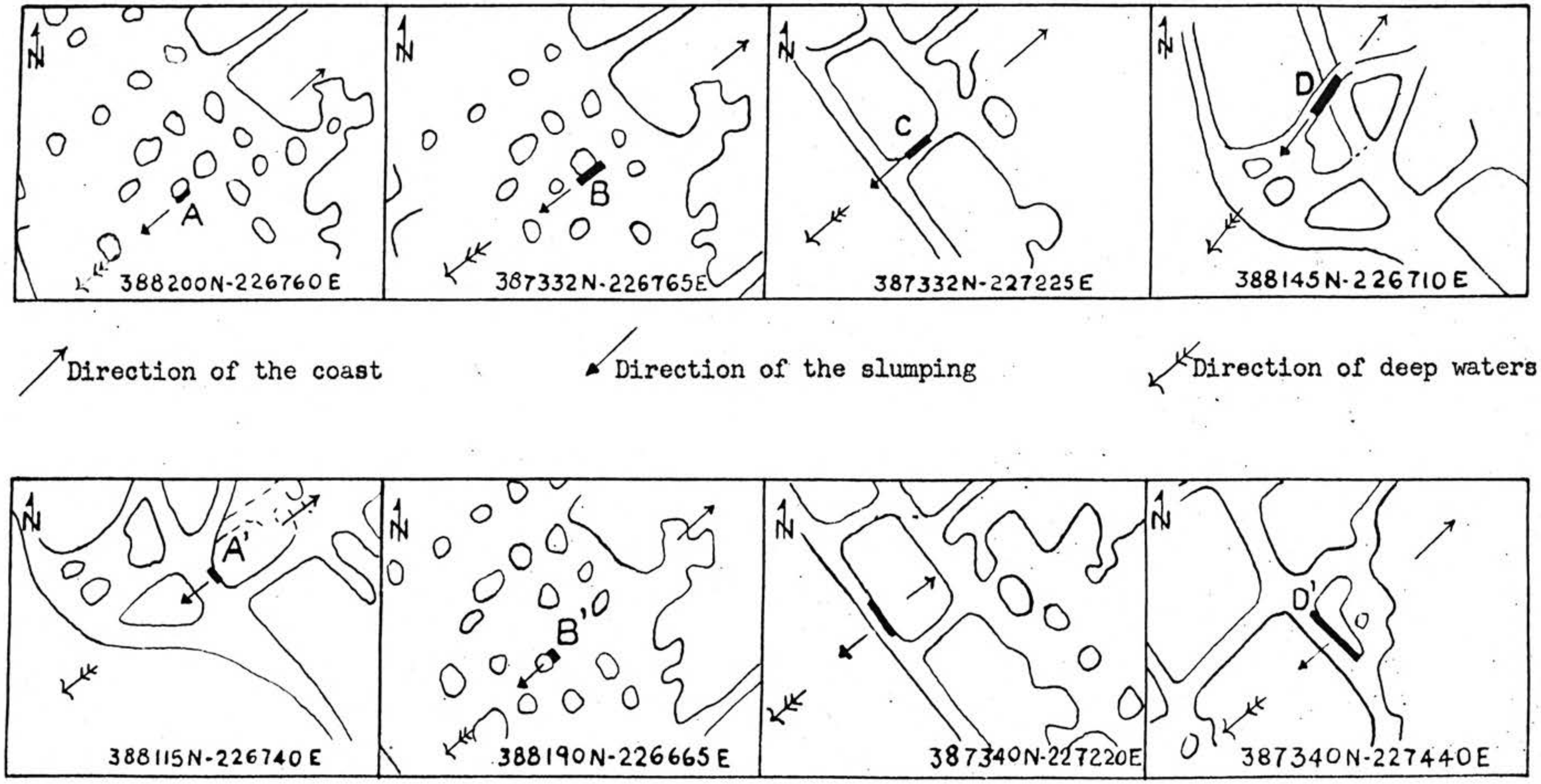
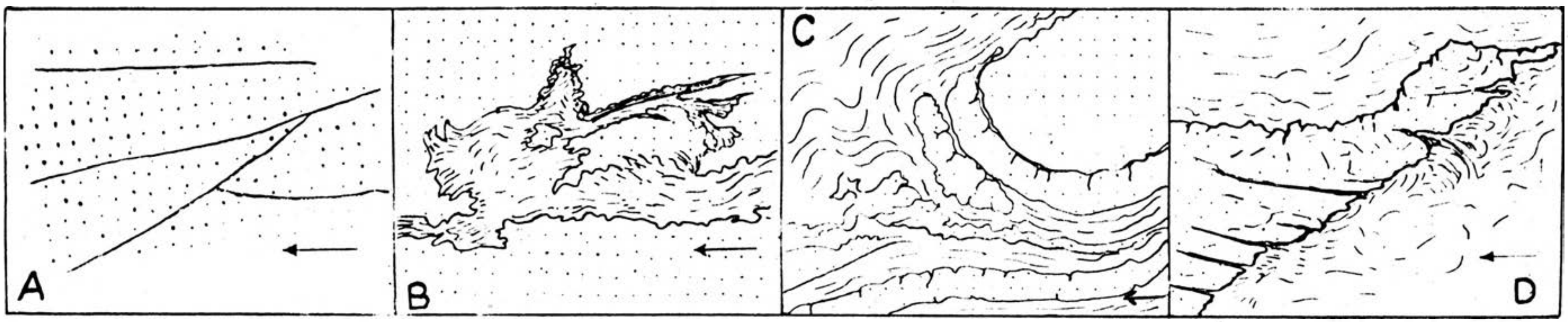


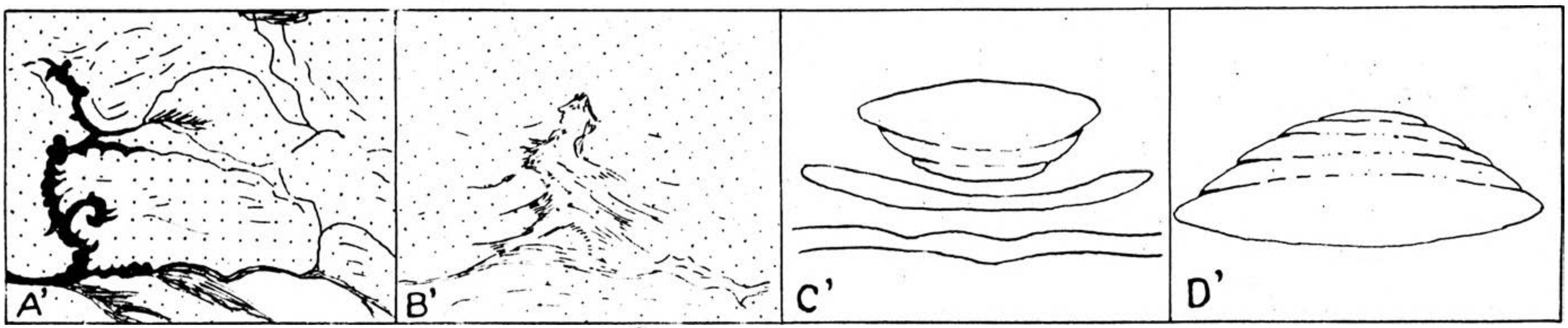
Figure No. 27 Submarine slumping of Dakota (?) formation at Diamond No. 2 Mine,

Gallup, New Mexico



A,B,C,D,: Features parallel to the direction of sliding.

A',B',C',D',: The same features vertical to the direction of sliding.



A and A': Cross-bedding

B and B': Carbonaceous beds (high-grade uranium-vanadium ore)

C and C': Sandstone lenses, lower end

D and D': Sandstone lenses, upper end (echelon or shingle texture)

4. MINERAL DEPOSIT

a. Uranium-vanadium minerals known from Diamond No. 2 Mine

The following uranium-vanadium minerals are present at Diamond No. 2 Mine:

Coffinite: The chemical formula of coffinite is:

$U(SiO_4)_{1-x}(OH)_{4x}$ (HEINRICH, E., 1958)

Coffinite is also mentioned in nearby areas (YOUNG, R. and G. EALY, 1956, p. 11).

Corvusite: The following formula was proposed for corvusite:

$V_2O_4 \cdot 6V_2O_5 \cdot x\ H_2O$ (HENDERSON, E. and F. HESS, 1933, p. 200).

Carnotite: The chemical formula of carnotite is approximately:

$K_2(UO_2)_2\ (UO_4)_2 \cdot 1\text{-}3H_2O$ (HEINRICH, E., 1958)

The chemical formula of corvusite is not certain yet. The "blue-black corvusite" mineral observed at Diamond No. 2 Mine was also reported elsewhere on the Colorado Plateau (WEEKS, 1955, p. 187-193). It is possible that corvusite is a mixture of several uranium-vanadium minerals. Corvusite was mentioned by GARRELS, R. (1955, p. 14, Fig. 2) as a "vanadiferous ore" in equilibrium between the primary assemblage of "black ore" and the final assemblage of "yellow ore" or "carnotite ore."

The mineralogy of uranium-vanadium minerals is, in spite of the great advancement in the last ten years still in progress (FRONDEL, C., 1957).

It is possible that some "unidentified species" of uranium-vanadium minerals are present at Diamond No. 2 Mine. A careful determination of the U and V minerals was never mentioned in previous works (GABELMAN, G., 1955 and P. KERR, 1958) and is still lacking.

b. Large scale geometric features (regional)

Almost the whole Dakota formation exposed on the rim of the Nutria Monocline at Gallup contains radioactive minerals. By radiometric survey uranium minerals were discovered along the narrow strip of Dakota sandstone over an extention of two miles.

The uranium-vanadium deposits in the area (Diamond No. 2 Mine, Hyde and Hogback No. 4 Mines) as well as all those within the McKinley and Valencia Counties, New Mexico (e.g. Ambrosia Lake, Jackpile, etc.) are tabular masses congruent to sandstone layers or exceptionally to shale beds (small outcrop near U Mine, Church Rock area) occurring at major sedimentary boundaries.

At the Nutria Monocline, the uranium deposits occur in pale yellowish-brown arkosic sandstones in the Dakota formation (Plate No. 1). Diamond No. 2 Mine is a typical example for this association.

JENSEN (1958, p. 615) states that the lack of characteristic reddish color of the sediments associated with sandstone-type uranium deposits of the Colorado Plateau is due to the reduction of ferric oxide to ferrous sulfide. Hydrogen which might be provided by hydrogen sulfide and ferric oxide reacts as follows:

$$4\ H_2S + Fe_2O_3 \longrightarrow 2\ Fe\ S_2 + H_2 + 3H_2O$$

Further consideration of the changes of color of the sandstones will be discussed in the chapter about the geochemistry of uranium. The foregoing observations point already to the possibility that the changes of color of the sandstones are an alteration product of supergene-epigenetic nature and not of hydrothermal-epigenetic origin as is postulated by KERR (1958, p. 1080).

Known uranium deposits in the Nutria Monocline occur in pale yellowish-brown arkosic sandstones in the Dakota formation. These typically colored sandstones occur as:

1. Zones in which the entire thickness of the Dakota sandstones changes from reddish-brown to yellowish-brown.
2. Zones where interfingering and intertonguing dark carbonaceous shales and brown arkosic sandstones are present as disturbed (slumped) beds. Type locality: Diamond No. 2 Mine outcrop.
3. Tabular sandstone masses of lenticular shape embayed by dark shales. Sandstone masses are lenticular, with current cross-bedding and abundant carbonaceous matter.

As stated before, in the area of Diamond No. 2 Mine uranium-vanadium minerals occur only in the thin Dakota sandstones with the features described under 1, 2, or 3. The lateral extent is considerably greater than the vertical extent.

c. Medium scale geometry (outcrop to hand specimen)

At Diamond No. 2 Mine the uranium-vanadium minerals outcrop in scattered spots at the surface. Radioactive minerals are proved to be present by the detection of traces of radioactivity at several places of the outcrop (Plate No. 1).

Carnotite is usually accompanied by a brownish-yellow sandstone, of weathered aspect. On the surface carnotite appears as yellow powder coloring the coarse to arkosic sandstone at conspicuous spots. Jarosite and limonite are abundant, and occur as disseminations in the coarse-grained sandstone. The lack of silicification in the sandstone in these "areas of mineralization" is noteworthy.

Small vertical fractures (1 to 2 cm. wide) are present in the sandstones; these fractures are filled with carbonates, limonite, and jarosite. Generally uranium-vanadium minerals are absent in the fractures; however, in a few cases films of carnotite could be found in it. This does not necessarily imply that fractures are pathways for the "ore-bearing solutions" as assumed by KERR, 1958, p. 1080.

Uranium-vanadium minerals are better exposed in underground workings. Carnotite forms most of the "mineralization" of the upper half of the Diamond No. 2 underground workings. Corvusite and coffinite are prevailing minerals in the lower half of the mine workings (see vertical section, Plate No. 5).

Carnotite is always present as disseminations of a nebulitic type (Fig. 27; texture type 10), either inside "rolls" or as "flat ore masses" (see chapter f).

Frequently carnotite is associated with carbonaceous matter or clay galls in the arkosic sandstone. Carnotite appears as yellow films of tissue-like aspect on the boundaries or in the interstices of the carbonaceous matrix matter and the clay galls.

Carnotite along forms pods of amoeboidal shape with spotty distribution in all the orebodies. In these cases the dissemination of the carnotite is congruent with the lens structures (Fig. 19-D).

Aureoles and halos of carnotite can also be observed. These are usually arranged in an ophthalmitic pattern within the nebulitic fabric (Fig. 27; 9-10).

Laminae of carnotite are present on some contacts of the carbonaceous shales and the sandstones with ore minerals.

Aureoles of carnotite occur with amaeboidal shapes peripheral with respect to the corvusite (Fig. 28-23); in these cases carnotite represents an oxidation product, in situ, of the corvusite or coffinite (see geochemistry chapter).

Blue black corvusite occurs in typical lens or tree like shaped accumulations of carbonaceous matter (Fig. 24-29). The blue black uranium-vanadium minerals are arranged as bedded disseminations along the bedding planes of the sandstones. These bedded disseminations pinch out in three dimensions or change laterally to bedded disseminations of carbonaceous matter.

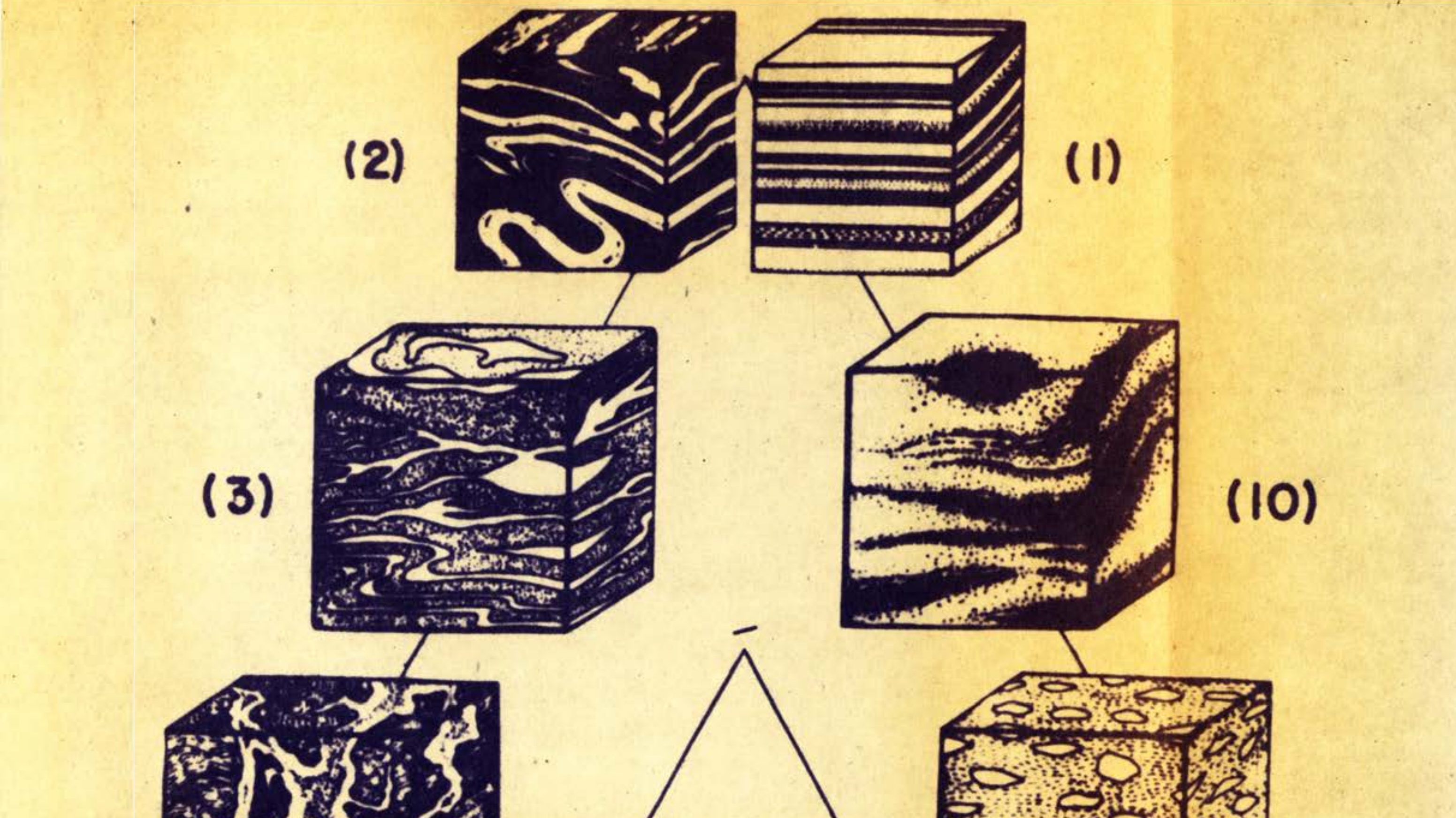
Corvusite "blue black ores" are essentially composed of "blue-black" corvusite, carbonaceous matter and sandstone, and are characterized by a transitional nebulitic-stromatitic fabric (Fig. 27 - types 10-1-2).

The stromatitic fabric - type 2 (Fig. 29) was produced by submarine slumping already mentioned in a previous chapter.

Marcasite occurs inside a single clay gall contained in a layer of arkosic sandstone with uranium-vanadium mineralization. Idiomorphic crystals of marcasite were seen inside the clay gall only. Lack of sulfides outside the clay gall may be typical for the environment in which these rocks formed (Fig. 30).

Fig. 28

THE NIGGLI CLASSIFICATION OF ROCK TEXTURES



Purely geometric nomenclature of rock textures free of genetic interpretations, for chorismites or chorismatic, polyschematic rocks or mineral deposits (= rocks which consist of two or more textural units).

I and 2 = Stromatites

3 and 4 = Phlebites

5 and 6 = Merismites

7, 8, 9 = Ophthalmites

(8 = Miarolithite)

10 = Nebulite

Fig. 29. - Carnotite, corvusite and sandstone. Corvusite (blue black color) is present on the bedding planes of the arkosic sandstone. Carnotite (yellow color) is present with ameoboidal arrangement and was formed as alteration in situ of corvusite.

Fig. 30. - Marcasite in a clay gall.

The rule lies on black shale. Above it the white band is arkosic sandstone with uranium-vanadium mineralization. The dark spot inside the sandstone is a clay gall with marcasite.

d. Small scale geometry (granular to microscopic)

Carnotite is usually disseminated in the matrix, and occurs adjacent to grains of quartz following rectilinear or gently curved boundaries (Type 1a - of the locking type classification, Fig. 31). The mottled, spotty or amoeba type locking to the matrix is also observed (type 1b). Exceptionally, carnotite disseminations correspond to type 2a.

Carnotite is generally disseminated around blue-black corvusite with enveloped, coated, mantled, shell-tissue like texture (type 2a).

Carnotite occurs also as disseminations in the cementing material without a visible connection with corvusite. Disseminated corvusite intergrowth with quartz grains appears to exhibit an emulsion-like, drop-like, buckshot geometry (type 1d) or (type 1c), as seen under the binocular microscope (three dimensions! thus often coatings).

Corvusite forms nodular bodies (concretions?) in the arkosic sandstones. These inclusions are about 2 cm. in diameter. The core of one of the nodules studied contains an amoeba-type attrital coal inclusion (10-mm. diameter) characterized by a bright pseudometallic luster with nearly black asphaltic streak.

The shape of the quartz grains is one of the most significant characteristics in sandstones (DUNBAR and RODGERS, 1957, p. 184). Also the shape of quartz grains is important for the understanding of the geometrical intergrowth.

The shape and size of the quartz grains associated with uranium-vanadium minerals are as follows:

In the sandstones or arkoses containing uranium-vanadium minerals the size of the quartz grains is in the average about 1 mm. in diameter. The sandstones with smaller quartz size are usually barren.

The shape of sand (or any other detrital) grains is basically a function of many factors. A tentative morphogenetic function was set up by AMSTUTZ and CHICO (1958) in a paper on Peruvian Barchan sand.

The morphogenetic function:

$S_{x,t} = f(i_c, i_p, H, s_a, s_r, w_a, w_i, v, s_m, o_a, ch, m_s, m_e, \ldots)$

Sx, t: The shape of a grain or pebble at a certain time t, at a certain place x, whereby x may be the distance from the place of origin.

i_c: internal properties of a monomineralic grain, such as crystal structure or symmetry, inclusions, alterations, flaws, etc.

i_p: internal properties of a pebble, such as the fabric, grain size, etc.

h: hardness.

s_r: original shape and size of a grain or a pebble.

s_a: relative size (and shape) of a grain or pebble compared with the size (and shape) of the rest of the components associated with it. This is important because the relative abrasion loss of a small grain from the impact with a large grain is greater than vice versa.

w_a: path, way, travelled by water transport.

w_i: path, way, travelled by wind transport.

v: velocity of transport; influences the impact of grains on grains and thus also the amount of abrasion.

s_m: symmetry of water or wind motion; harmonic wave motion, creates e.g., trapezoidal pebbles.

o_a: average lithologic, petrographic origin; this parameter may be used instead of i_c or i_p in cases where an approximate, average origin is sufficiently accurate.

q_r: relative quantities of the individual mineral or rock species present; this influences, mainly through the hardnesses, the paths a grain or pebble moves with reference to a certain abrasion loss.

ch: the chemical environment, including humidity; solution or accretion may have a definite influence on the changes of shape.

m_s, m_e: effects which syngenetic (m_s) or epigenetic (m_e) mineralization may have had on the shape of grains or pebbles.

The shapes observed on the quartz grains from Diamond No. 2 Mine have different shapes than for example those of the St. Peters sandstone in Missouri or in the volcanic tuffs of the Piedras in Peru (Fig. 32).

Grains from the St. Peters sandstone are well rounded and without evidence of a possible originally idiomorphic shape; quartz grains from the Peruvian ignimbrites are characterized by an original shape. Quartz grains from the St. Peters sandstone were assumed this shape apparently during transportation or marine scavenging; quartz grains from the Peruvian ignimbrites were not transported.

The shape of the quartz grains from Diamond No. 2 Mine (areas with ore minerals) shows that an approximately idiomorphic shape is present in some grains but not in others (see Fig. 32). Consequently these shapes are suggesting a relatively short way of transportation from the original source. The possibility of autigenic idiomorphic overgrowths is eliminated through the absence of overgrowth zones in all the thin sections seen from Diamond No. 2 Mine. In other areas of the Dakota sandstone autigenic overgrowths were reported. These areas do not have any ore minerals, however (BURTON, 1955).

e. <u>Geochemistry of uranium-vanadium in sandstone type deposits</u>

There are three factors with which we are most concerned with regard to the geochemical approach to the uranium-vanadium sandstone type deposits.

These are: the composition of the sandstones, the oxidation or reduction of ore minerals, and the stability limits of the ore minerals.

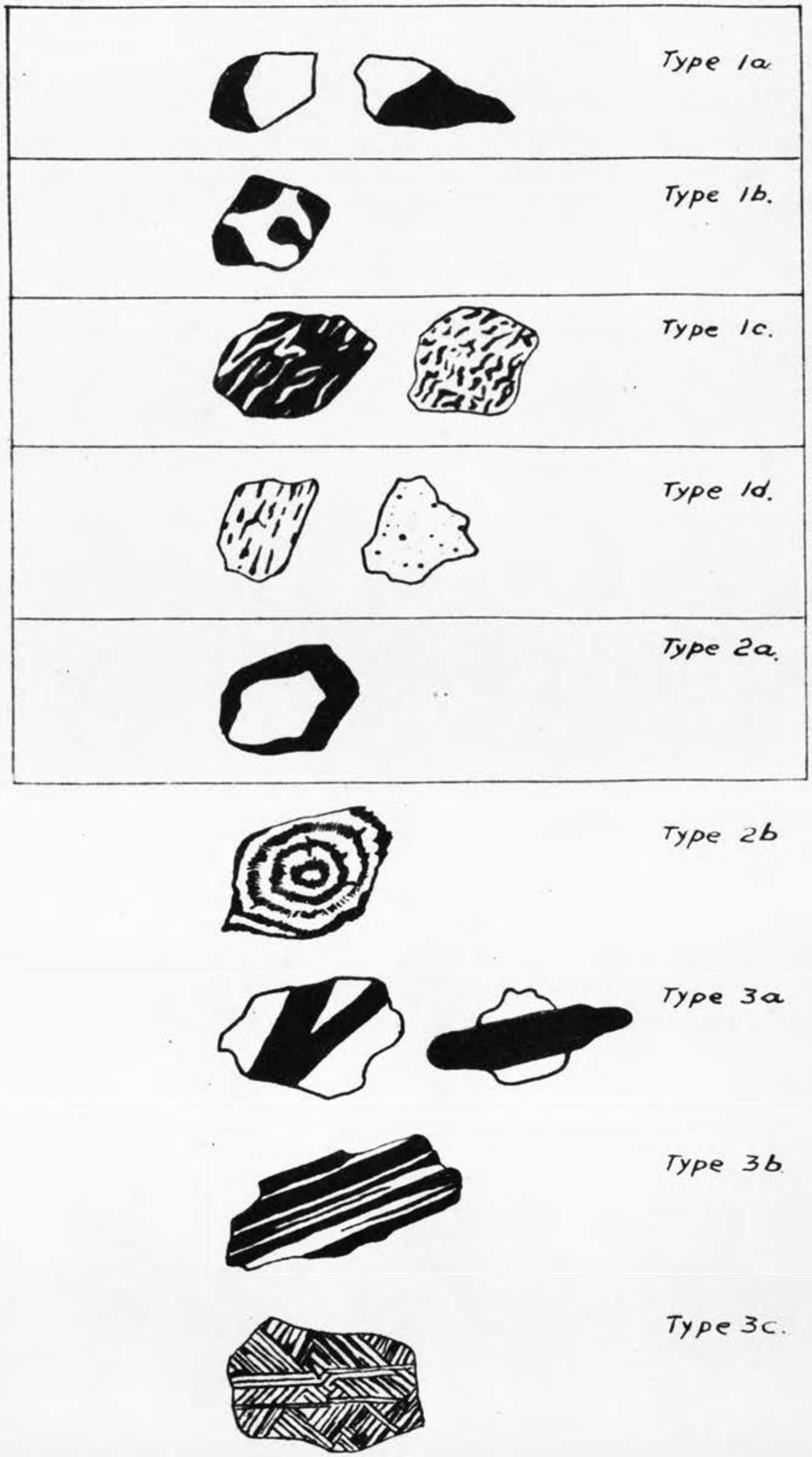
Sandstones with uranium-vanadium mineralization are generally of arkosic composition. At Diamond No. 2 Mine, as well as elsewhere in the Colorado Plateau, uranium-vanadium ore deposits are encountered in arkosic sandstones of tuffaceous origin (GARRELS, R., 1957, p. 1).

A SIMPLE GEOMETRICAL CLASSIFICATION OF INTERGROWTH

TEXTURES OF MINERALS (AMSTUTZ, 1956)

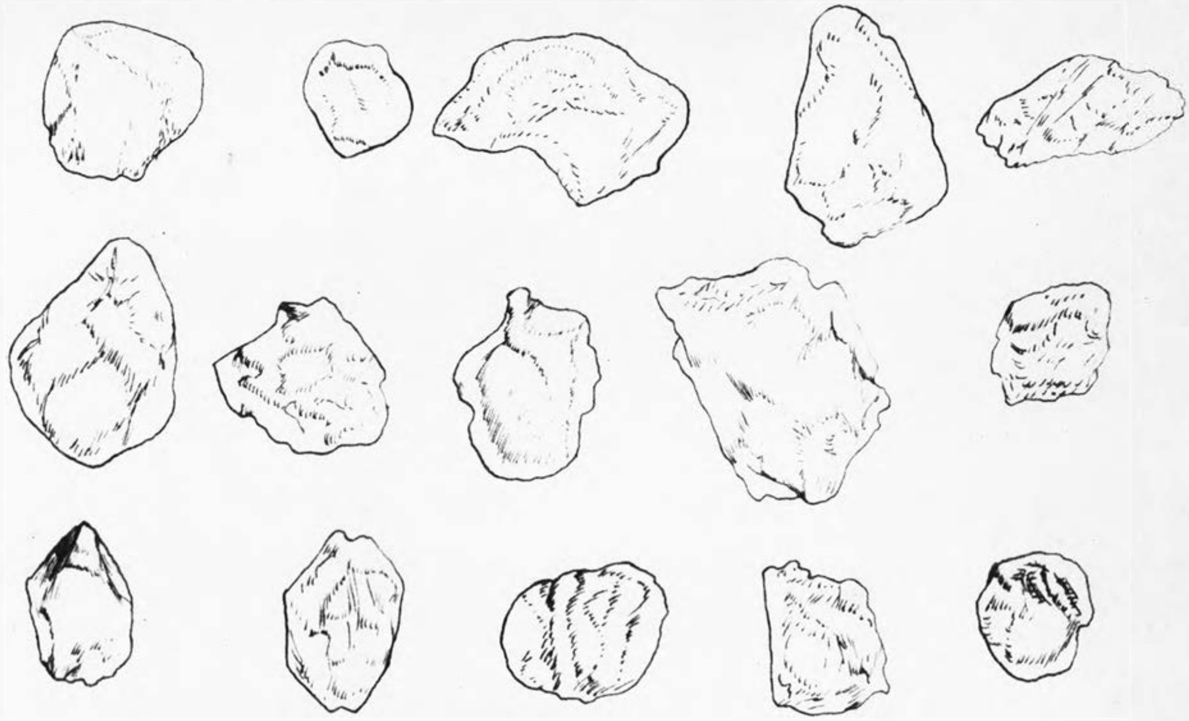
Squares indicate the common types of intergrowth present at the U-V deposits of Diamond No.2 Mine

Figure 31



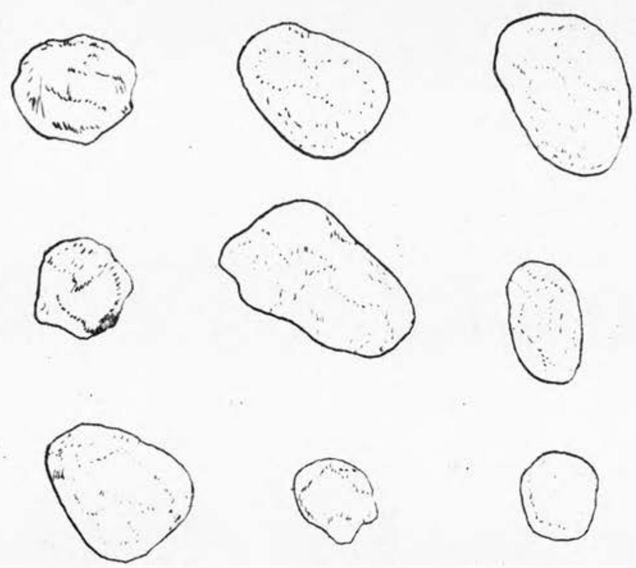
SHAPES OF QUARTZ GRAINS

A



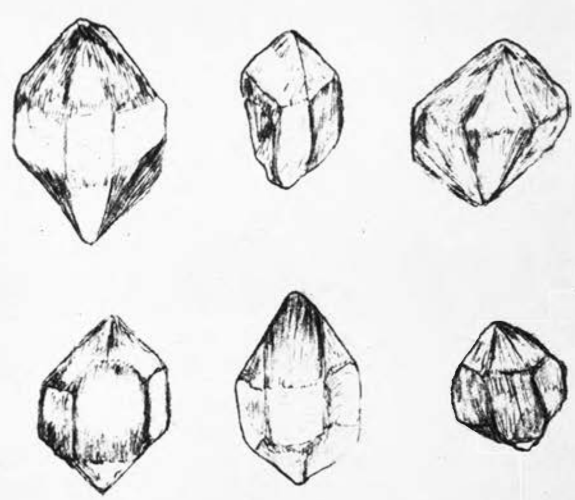
Diamond No. 2 Mine (425 Stope, high grade U-V ore)

B



St. Peters Sandstone
Pacific, Missouri

C



Bosque de piedras, Peru
(Ignimbrite)

Figure 32

Evidence for the volcanic origin of the uranium-vanadium minerals in arkosic sandstones was given by WEEKS, A. and A. TRUESDELL, 1958, p. 154-155; WEEKS, A., B. LEWIN and R. BROWN, 1958, p. 155; WEEKS, A., 1959.

From observations at Diamond No. 2 Mine as well as at Foutz, U Mine, Hogback No. 4, Jackpile in New Mexico; Green River uranium district Utah; Uravan-Bull Canyon in Colorado and Luckachukai in Arizona, it seems evident that the host rock for uranium-vanadium minerals is usually a coarse-grained arkosic sandstone.

WATERS and GRANGER (1953) found volcanic glass in some arkosic sandstone of uranium-vanadium deposits. At Gallup, New Mexico, some volcanic glass is present in some samples from Diamond No. 2 Mine; although no statistical analysis of the whole mineralized sandstone was performed, the presence of some volcanic glass is striking.

The deposition of the arkosic sandstone took place at Diamond No. 2 Mine area under reducing conditions of high redox potential due to the near shore line environment of the Cretaceous sea. This statement is supported by the data from the present-day deposition of sediments in shallow basins as Santa Barbara, California. There, ORR and EMERY (1956, p. 1247) found that: "The sediments in the shallowest basins with the fastest sedimentation rate contains the highest proportion of material soluble in organic solvent and the highest hydrocarbon content even though this sediment is lowest in the total organic matter."

Evidence that fast sedimentation, at least in part, took place within the lower part of the Dakota sandstones at Gallup, is offered by the presence of some crossbedding with graded bedding (Fig. 12).

Organic solvents and hydrogen sulfide were found on the surface of the sediments of the Santa Barbara Basin and not in the overlying water (ORR, W. and K. EMERY, 1956, p. 1249). Both organic solvents and/or carbonaceous matter and hydrogen sulfide are "bread and butter" for high redox potential conditions in a near-shore environment.

On the basis of oxidation-reduction ratios, uranium-vanadium mineralization in arkosic sandstones can be broadly subdivided in oxidized (the so-called "yellow ores") and unoxidized (the so-called "black ores") (WEEKS, A., 1955, p. 187-195). WEEKS showed that both types of minerals are widespread in the deposits of the Colorado Plateau. At Diamond No. 2 Mine this subdivision is readily applied. The difference of colors of the uranium-vanadium bearing rocks is due to the presence or absence of oxidation of the minerals.

Fig. 33 shows a yellow spot of carnotite in a brown sandstone with coffinite. The yellow spot of carnotite was formed after the rock was exposed to the air for a period of one month only; similar examples of supergene oxidation leaching and short distance migration are common in all the places of the mine. In all the cases the oxidation of the uranium-vanadium minerals was produced more or less in situ (e.g.: coffinite oxidized to corvusite or more generally to carnotite).

It was also observed that further oxidation of carnotite produced the brown color of the sandstones, as seen for example in the outcrop of Diamond No. 2 Mine. The same process of coloration was produced experimentally by exposure to the air of samples of carnotite; after half a year the color of the sandstone showed the same color as the sandstone exposed on the outcrop of the mine. Consequently the alteration of the sandstone was more likely produced in situ and not as a consequence of a hydrothermal alteration, as proposed for example by KERR, 1958, p. 1080.

The changes in color and composition of the oxidized and unoxidized minerals are related to the different valence stages of uranium and vanadium. GARRELS, R., 1954, p. 153, proved that the stability of uranium and vanadium is a function of the pH and Eh of the environment, the supply of air, the mineral ratios and the nature of the oxidation processes.

The chemistry of uranium-vanadium in aqueous solutions at low temperatures shows that the stability field of carnotite changes in relation to the pH. BARTON, 1958, p. 802, showed for example that at pH 4.5 uranyl hydroxides are predominant and in the presence of anions such as sulfate, acetate, and especially carbonate, uranium-bearing solutions are stable at higher pH values (up to 11 or 12).

The experimental data of BARTON and GARRELS are unobjectionable; however those experiments cannot explain why the uranium-vanadium mineralization is in the host rock. The question whether the original mineral deposition took place syngenetically or epigenetically is not answered. The reason why the experimental results of BARTON (1958) and GARRELS (1954) appear to offer the most logical explanation is not linked to the fact that they eliminate a time gap between the formation of the rock and the mineral deposit, but rather to the fact that a syngenetic formation of deposition requires a much smaller number of assumptions than any epigenetic theory.

Fig. 33. - Carnotite and other uranium-vanadium minerals in arkosic sandstone with carbonaceous matter.

Carnotite is yellow. The formation of carnotite was due to post-mine oxidation of the unoxidized minerals. The observations showed that the formation of carnotite took place in the short period of one month. Location: 500 level, Becenti orebody, Diamond No. 2 Mine.

Consequently the presence of unoxidized and oxidized mineralization in the orebodies at Diamond No. 2 Mine represent the stages of alteration of an active geologic process in situ - the transition of two broad types of mineral contents, from one mineral assemblage to another.

The unoxidized mineral assemblage consists of coffinite, oxidized by carnotite. Corvusite is the intermediate stage between the unoxidized or primary stage of a highly reducing environment and the oxidized or secondary or near surface oxidizing environment.

The line between the two extremes of the mentioned mineralogical stability systems is drawn, partially, by the water table. When the water table varied through geological time, new changes in oxidation-reduction took place in the sandstones and shales, and in consequence the environment of the "yellow" and "black" minerals also changed.

This "geochemical line" between unoxidized and oxidized ores at Diamond No. 2 orebodies is shown in Plate No. 5.

f. Diamond No. 2 orebodies

The orebodies at Diamond No. 2 Mine are so varied that no single geometric designation can be given to them. The local names given for practical purposes are Becenti, Largo and 425 orebodies.

Geologically speaking the boundaries of the orebodies are not always clearly defined, but generally they are more controlled by lithology or sedimentary structures rather than tectonic structure.

Two types of orebodies are present at Diamond No. 2 Mine. Those with well defined edges and those with poorly defined boundaries. Although both types can be recognized as different types, there are many gradational transitions.

Most of the orebodies are separated by waste areas with or without ore minerals; where ore is present (the better grade 0.30 to 0.50 percent U_3O_8 equivalents), it appears in amoeboidal pockets within the low-grade ore. The ore is generally discontinuous and occasionally forms well defined pockets of blue black corvusite (Fig. 29-23).

In spite of the daily radiometric assays in all the working places and detailed careful geological mapping, the boundaries of the ore pockets were difficult to predict. Ore grade could disappear beyond the face of the richer stope, and could be found a few feet beyond the face of the development drift that never had any ore minerals. The wide experience of Diamond No. 2 Mine operations showed that the exact extention of the orebodies were really only known by mining them out.

However, the uranium-vanadium ore deposit at Diamond No. 2 Mine occurs generally in a type of sandstone of the Dakota formation (Fig. 5 and 29). The ore-bearing sandstone is a medium to coarse grained arkosic sandstone. The petrography of this sandstone was described in a previous chapter. The geometry of the ore-bearing sandstone is illustrated in the underground and outcrop geological maps (Plates Nos. 6, 7, 8, 9a, 9b, and 5).

As can be noticed from the already mentioned geological maps, two types of Dakota (?) sandstones were mapped at a scale 1":20'. Those maps are covering over 60,000 square feet of the underground and outcropping geology. From detailed observations and underground mapping, it is known that the orebodies at Diamond No. 2 Mine are more closely related to the medium to coarse grained sandstone than to the fine grained sandstone. It may be said that half of the Dakota sandstone exposed on underground levels and on the outcrop of Diamond No. 2 Mine can be considered to be ore-bearing sandstone.

Fine-grained "white" sandstone contains ore minerals only in exceptional cases; only once a pocket of carnotite ore was found in this variety of sandstone. This pocket was found in the 400 level and yielded 30 tons of high-grade uranium ore.

There is good continuity between the coarse grained sandstone seen on the surface and underground; but no such continuity with regard to the orebodies and hence the ore mineral content.

The geometry of the orebodies is peculiar. In many cases ore pockets are forming "rolls" of uranium-vanadium ore. The geometry of these "rolls" is partially related to the southeastern pinch-out of the sandstone lenses. These pinch-outs are rather sharp and indicate a clear cut-off of the ore. These "rolls" or parts of them are pictured on Fig. 29, 24, 25, 22, 33; on Fig. 27D' the lens shape of a typical "roll" is pictured. Usually the uranium-vanadium minerals are contained inside these lenses, whereas the outside is barren.

"Rolls" are variable in dimensions but generally they have irregular thin edges of 2 feet with a major thickness of 20 feet in the center. The horizontal dimensions are about 25 feet in width (measured in the direction of slumping) and its length is not more than 50 feet (parallel to the coast line).

Generally the smallest "rolls" (Fig. 29) are more likely to be of high grade than the bigger ones. Both types are more or less lenticular, podlike, cigar shaped, or sinuous, cutting locally across the phacoidal inner parting planes of the lenses or following them.

"Rolls", because of the variations already mentioned, are presenting a difficult problem for ore valuation and the mining methods.

Beside "rolls", another type of geometry is present in the orebodies, the "flat ore masses" that are generally parallel to the stratification and especially parallel to the laminae of carbonaceous material. Such types of laminaes are illustrated in Fig. 10.

Exceptionally "flat ore masses" are connected with "rolls." When this is the case, the "flat ore masses" (lower lens in Fig. 19C') are forming the low-grade substratum of high-grade overlying "rolls."

Another important feature of the orebodies is that the ore is present basically in two main levels. For mining purposes those levels were called "lower" and "upper" ore bed. The "lower" ore bed is mainly present in the lower section of the medium coarse-grained arkosic sandstone. It is the more consistent in extension, grade and thickness, and yields about 90 percent of the ore production of the Diamond No. 2 Mine.

The "upper" ore bed lies mostly in the upper half of the medium to coarse arkosic sandstone. Occasionally it was encountered farther up on the contact between the mentioned sandstone and the fine-grained arkosic sandstone. The "upper" ore bed is very thin (1 foot thick) and consequently it was not always possible to mine it.

The variations of the geometry of the orebodies have been described above. The geometry is very different from that which was expected from data obtained from physical exploration. However, after the development of underground levels and raises, it was possible with the aid of geological maps, cross sections, assay maps and a perfect surveying control, to locate the position of the variable orebodies (compare the attached mine maps).

Finally the experience at Diamond No. 2 Mine showed that the limit of the commercial ore is not only a function of the grade of the ore beds. Other factors are fundamental. One most important one is the mining cost: the lower the mining cost, the more extensive is the tonnage that can be mined, and consequently, the orebodies can be extended. It does not matter how large and valuable any orebody is and how carefully was carried out the exploration and development work. The cost of mining can spell the difference between success and failure of any ore valuation and therefore counteract the business objective of the mine enterprise.

g. Physical exploration and valuation of Diamond No. 2 orebodies

Uranium orebodies at Diamond No. 2 Mine were discovered by physical exploration methods. Drill hole exploration was carried out at different periods and stages.

The valuation of any uranium orebody of the Colorado Plateau type is offering a difficult task. Such a valuation must be as closely as possible related to actual field data and should be based on factors related to the type of the mineral content, and of course on a dependable engineering control. A sound philosophy of exploration consists largely of a reasonable theory on the mode of formation.

The conjunction of these factors is fundamental; they give the clues for mine development and mine production work.

Drill hole exploration at Diamond No. 2 Mine was done on a contract basis. Rotary drill (Mathews 2500 hp. or Portadrill) was used. Shallow holes were drilled "dry", without difficulties. Water injection was required for holes over 200 feet depth.

Cut samples were taken at two and one half foot intervals as the drilling was progressing. Samples from "wet" drilling were not always good, due to the circulation problems.

Drill holes were set from 50 to 100 feet apart on rectangular patterns plotted over the trend of the orebodies and the mine plans. Each hole was logged and probed immediately after it was drilled. A Mineral Engineering Geiger Counter with long probe assemblage was used for the measure of radioactivity inside the holes. Radioactivity values were recorded each one and one-half foot down the holes. The radioactivity and some chemical assays of the cuttings were obtained for the zones with ore minerals.

Occasionally gamma logging of the holes was carried out for the Atomic Energy Commission. One of these logs is illustrated on Plate No. 10. Plate No. 11 presents the radioactivity values obtained with Geiger counter and gamma logging unit in order to show the comparison of both measurements. While both methods are showing some slight differences in grade estimation of percentage equivalent of U_3O_8 on the drill hole D169, none of both methods is completely accurate. Evidence of the grade of the mineralization in D169 hole will be checked when that hole is going to be reached by underground mining. It is quite possible because of previous experience in the same orebody that the ore to be mined from that particular place will not have an ore percentage above .27 percent U_3O_8. The probe with the Geiger counter in consequence might be more conservative in that particular case; however could be slightly high because one or more of the following causes: variation of the intensity of the calibration, due to the discharge of the batteries, variation in the sensibility of the instrument due to some high values of radioactivity present in few inches of rocks ("urano-organic ore")* which produces contamination of radioactivity in several feet of sediments, variation of radioactivity

* Term used by KERR, 1958, p. 1086.

due to the presence of radon gas, variation of the true radioactivity present in the hole due to the presence of cuttings from the ore zone deposited above or below the zone on the periphery of the hole during the drilling process.

Any probe of drill holes gives only the percentage equivalent of U_3O_8 at a determined depth in the holes. A continuation of mineralization several feet away from the hole does not always take place. In spite of the many problems outlined in the above paragraph, physical exploration data proved to be satisfactory for the potential ore evaluation of Diamond No. 2 orebodies. Reliability of such an evaluation is greater with the increase of density of holes in the drill pattern. Also, the interpretations of radiometric records is highly conservative.

The evaluation of the orebodies on the basis the drill exploration data was made is as follows:

Units with ore minerals were correlated between adjacent drill holes and the thickness of the ore (above an "x" grade cut-off of ore) was determined and averaged between holes, to be used as average thickness of the average unit. The edge of the ore deposit was assumed to be halfway between a "strongly mineralized hole" (with ore values below the "x" grade cut-off) and an "ore hole" (with ore values equal or above the "x" grade cut-off) and the rate of change of thickness was assumed to be uniform between holes. The area outlined by the orebody boundary was measured. A factor of 14 cubic feet per ton was used to convert volume to tonnage.

The calculation of "x" grade cut-off of ore in the holes was a function of two factors:

1. Economical estimations, such as mining cost, depth of the orebodies, presence of water and exploration and development budget.

2. The variations of ore grade from adjacent holes. The special relationship of lithology and ore mineral content; presence of representative samples.

The variation of percentage and thickness of uranium ore is great on all the orebodies at Diamond No. 2 Mine. A general picture of such variations are illustrated on Plate No. 12, which shows contour "ore grade thickness." By means of economical estimation and subsurface geological data it was possible to establish under which method and circumstances it was possible to mine, in a profitable manner, the zones in between the contours 1 and 2.

Drill hole exploration at Diamond No. 2 Mine showed a potential uranium ore deposit. Further underground development and exploration proved the validity of the data gathered from drill holes. However the magnitudes of the variations of ore grade were not expected because the physical exploration could not discover the "rolls" and "flat ore masses" already discussed. These showed to have, at Diamond No. 2 Mine, one common denominator: variability. Such variability has become more and more known in the last few years and at present it is the headache of the largest underground projects and mines of the rich and large neighboring district of Ambrosia Lake.

h. Geological maps of Diamond No. 2 Mine

Underground mine workings at Diamond No. 2 Mine are exposing disseminated uranium-vanadium mineral contents in sandstones. These are interbedded with shales. The ore mineral contents follow more or less the gentle dip of the beds. Drifts are parallel to the strike of the ore-bearing rocks. Most of the geological features observed are seen on the sidewall of the drifts. Obviously such features are difficult to be recorded with accuracy on plans, which are horizontal mine maps. We need some means by which we can record observations in plan and section on the same map.

At Diamond No. 2 Mine the underground and surface outcrops were mapped with the methods summarized below:

1. Underground transit surveying and horizontal plotting of the mine workings at scale 1':20".
2. Transit surveying along the outcropping base of the Dakota (?) formation. The surveying data were plotted on a horizontal plane of 6942' (elevation of the mine portal).
3. Geological sections of the walls of the mine workings at scale 1":20' were set up and projected on both sides of the drifts on the geological mine maps.
4. Vertical cross sections using the data of opposite walls. Distances between different cross sections varied from 10 to 20 feet.
5. Intersection of the vertical cross sections (see point 4) with "PR" (plane of reference which is set 4 feet above the sill floor on all the workings).
6. The connection of all these intersections results as a continuous geologic projection which was finally plotted on the 1":20' mine map.

If strong variations between individual cross sections do not permit a connnection of them, the following additional steps are required:

a. Closer spacing of the cross sections.
b. Local changes of scales (scales 1":10' or 1':5").

Geological maps of Diamond No. 2 Mine are presented in Plates Nos. 4, 6, 7, 8, 9a, and 9b.

i. Description of the mine workings

The Diamond No. 2 Mine adit is located on the east slope of the Nutria Monocline (Plate No. 1). The adit is connected with an incline shaft with a 28° slope. This incline is the main haulageway and was partially developed on the hangingwall of the "lower" orebed of the Dakota (?) sandstone. The incline shaft continues down dip for over 500 feet and is connected with lateral levels parallel to the strike of the Dakota (?) sandstone.

These lateral levels are at 200, 300, 400, 450, and 500 feet down the slope of the incline, counting from the mine portal (Plate No. 5).

Levels are generally sinous, and with irregular width because of the lenticular sandstone beds, the interfingering of black shales, and the irregular position of the ore. Levels are connected with raises at irregular distances.

Because of the presence of two main ore beds, and the peculiar characteristic of the mineralization, the mining problems were numerous. The stopes were developed on the basis of the two following principles:

1. The "lower" ore bed was, and still is, being mined by the room-and-pillar method. Slushers are used to remove the ore from the stopes.
2. The "upper" ore bed was mined with (a) Off-track mining of the ore with hangingwall crosscuts, or (b) with sublevel development with vertical raises.

> Both (a) and (b) have advantages and disadvantages. Off-track crosscuts involve more development cost so that it is not always justified, compared with the tonnage to be mined. Sublevel development involves extra ore handling.

The roof of the stopes is very inconsistent. Support was given with timber set. Roof bolts have not been used.

After open pillar stopes were mined out, the pillar recovery begins with additional completion of timbering by retreating from the limit of the orebody toward the haulageway in the levels. Whenever possible the retreat was maintained in a straight line across the width of the stope to undercaving and to keep the cave as close as possible to the pillars. This method, although it was not always effective, permitted the trimming of the pillars to about 10 feet diameter.

The aim of every new underground working is always to drive towards a place where an ore hole found by drilling from surface is located. Drill holes from the surface were drilled vertically; however, a great deviation of most of the holes was encountered. Consequently drill holes were always difficult to find. The experience of drilling at Diamond No. 2 Mine generally corroborated the statements of McKINSTRY (1953, p. 96):

> " ... When drill holes intersect bedding cleavage at a large angle it tends to assume a direction at right angles to the limited structure."

This fact was taken into consideration during the valuation of the orebody. It was important indeed for the correct computation of the true thickness of the ore beds. The deviation of vertical holes drilled on sandstone of 30° dip was found to be from 3° to 5° for drill holes of a depth over 150 feet. In about 20 percent of the drill holes an additional sidewise deviation was also observed. Similar deviation of drill holes were reported by NICOL (1959, p. 59) from other areas of the Colorado Plateau.

Mine ventilation is provided by pushing air through 6-inch or 12-inch drill holes with blowers. Naturally ventilation is provided by the incline shaft and surface raise and a 12-inch drill hole which was projected to be a new surface raise.

The mine is dry in most of the levels. However, considerable water was encountered below the 500 level.

C. INTERPRETATION

1. GENERAL STATEMENT

The genesis of the uranium-vanadium mineralization on the Colorado Plateau has been discussed during the last fifty years and is still being discussed at present. The purpose of the present thesis is the study of the validity of a few criteria in a restricted area of the Colorado Plateau uranium-vanadium deposits.

A clear recognition and a clean separation of time, space, and compositional terms and concept, and their unusual relationships is essential for the correct analysis and interpretation of the origin of rocks and mineral deposits. It may be possible that the present considerable uncertainty with regard to rock and ore genesis is mostly due to the neglect of accurate definitions. Therefore it was thought to be appropriate to enter a chapter on definitions before attempting to discuss some interpretations.

2. GENETIC TERMINOLOGY

a. Definition of the terms syngenetic, epigenetic supergene, and hypogene

In rock and ore genesis processes, minerals or mineral deposits are syngenetic if their formation (deposition, crystallization, precipitation, etc.) took place before or during the formation, crystallization, precipitation, etc. of the enclosed rock.

Diagenesis is an essential phase of the formation of sedimentary rocks; it is somewhat comparable to the crystallization and consolidation of magmatic rocks. Minerals or mineral deposits which form during diagenesis are included in the class of syngenetic ores.

The term syngenetic refers only to a time relationship and does not say anything about the source of the materials, the pressure, or the composition.

The term epigenetic comprises the opposite of the term syngenetic. Minerals, mineral deposits, or the processes forming them are called epigenetic if they are clearly later than the enclosing rock or the process forming these enclosing rocks. This term does not infer either concepts of origin of ore fluids, temperature, pressure, composition, etc.

There are, of course, transitions between syngenetic and epigenetic processes. In such cases one should clearly state where he draws the line, in order not to be misunderstood.

It should be kept in mind that the average rock and mineral deposit has a complex history, i.e. it may have undergone various processes. It is thus possible and probable that a mineral deposit is originally syngenetic, but has undergone at a later date, an epigenetic change, such as metamorphism, weathering, folding, or faulting.

The concept of supergene is applied in this thesis to the uranium-vanadium minerals that have been formed or are formed at the present time, by meteoric water or connate water. The product is carnotite, and therefore this epigenetic supergene process might be termed carnotitization.

The term hypogene will be applied to the formation of mineral deposits from intratelluric or intramagmatic fluids. Those fluids include magmatic or metamorphic waters, or gases and liquids of deep-seated source. They may be deposited epigenetically in the rocks they invade or traverse, or syngenetically on the surface of the earth which they reach and on which they are dumped.

b. Definition of first and second order criteria

First order criteria are the observations and facts. They may be subdivided into geometrical criteria (Gm), geochemical criteria (Gc) and criteria of basic logic (Lg).

Second order criteria are partial or preliminary conclusions or preliminary interpretations reached on the basis of a combination of two or more observations, always in a framework of explicit reasoning or of criteria of logic.

c. Criteria of logic

The rules of Logic (Re. G. H. SMITH, 1901, p. 137):

According to the principles of deductive philosophy, inference is only one of the processes of ratiocination. Judgment (thus the scientific aim of any thesis) is also a ratiocinative process, and like inference, must have its rules by which false or pretended judgments may be distinguished from the real. Moreover, where our reasoning is not apodictic as normally is the case in genesis of ore deposits, we have to use assumptions, and although Logic is not concerned with the truth or falsity of these, the falsity of such assumptions can be detected by logical processes, i.e., by definitions, judgment, and inference.

Rules of Judgment:

"Rule I. TERMS TO BE SIGNIFICANT"

"In every logical proposition - by which is meant every proposition to be used in ratiocination - the terms must be significant, i.e., must have definite signification." SMITH, G. H., 1901, p. 142.

Examples: Supergene
Hypogene
Syngenetic
Epigenetic

"Rule II. TERMS TO BE RIGHTLY DEFINED"

"Terms used in ratiocination must not only have a definite signification, but the signification must be legitimate, i.e., they must not be falsely defined. This implies (1) that the term shall not be used in an improper sense, i.e., in a sense not permitted by the usage of the language; and (2) that the term shall be so defined as to signify a real concept; or, at least, that the contrary shall not affirmatively appear." SMITH, G. H., 1901, p. 143.

Examples: Supergene
Hypogene
Syngenetic
Epigenetic

"Rule III. PREMISES NOT TO BE ILLICITLY ASSUMED"

"A proposition that is obviously untrue, or that can, on logical principles, be affirmatively shown to be untrue, cannot be legitimately used as a premise." SMITH, G. H., 1901, p. 143.

Example: Hydrothermal used in the restrictive sense of including only epigenetic origin, instead of being used in a physico-chemical sense, and thus including also syngenetic processes. BAIN, G. W., 1957, p. 195, "considering from all points of view the evidence bearing upon emplacement of ... the ores owe their present position to solutions that were mildly hydrothermal but not hypogene" (underlying by the present author). (See AMSTUTZ, 1959, b).

"Rule IV. PREMISES TO CORRESPOND TO THE THESIS OR ISSUE"

"In all ratiocination - if designed to be fruitful - the premises, and consequently, also the conclusion, must correspond to the Thesis or Issue, whether that be expressed or understood, or merely determined by the conditions of the problem." SMITH, G. H., 1901, p. 144.

Example: "The limits of any minable uranium deposits are of course, not the limits of mineralization, which more or less gradually fade into the country rock along the bedding. For this reason, and this is true for most mineral deposits, maps of minable deposits tell only a part of the story of the extent of deposition." GRUNER, J. et al, 1953, p. 43.

Rules of Inference:

"Rule V. CONVERSIONS TO BE ILLATIVE"

"A conversion, to be legitimate, must be illative [inferential], i.e., the truth of the converted must be implied in the original proposition." SMITH, G. H., 1901, p. 145.

Example: The procedure from first order to second order criteria, as a means of establishing proof.

"Rule VI. EQUIVALENCE OF TERMS TO BE OBSERVED"

"In all substitutions the substituted term must be equivalent in signification - i.e., equivalent in ratiocinative value - to the term for which it is substituted." SMITH, G. H., 1901, p. 146.

An example somewhat related to this Rule VI is: "The theory which needs less assumptions is more probable, provided that the assumptions of two or more competing hypotheses are of the same weight." (AMSTUTZ, 1959a).

"Rule VII. THE SENSE OF TERMS TO REMAIN UNALTERED"

"Every verbal expression, whether a term or proposition, shall, throughout the ratiocination, be used in the sense originally given it."

An excellent discussion of the importance and application of logic to scientific theories is offered in the works of many great philosophers, for example in Betrand RUSSEL's book "our knowledge of the external world" (1952, p. 126).

3. PREVIOUS LITERATURE

a. Literature on bedded sandstone type deposits in general

I. Syngenetic Theories

HILLEBRAND AND RANSOME (1905) in describing the hypothetical origin of the uranium-vanadium deposits in sandstones of the Colorado Plateau, said (p. 17) that:

> " ... uranium and vanadium mineralization was formed subsequently to the deposition of the host rocks. The shape and position of such deposits indicates clearly that they have been brought to the present position by transportation. Carnotite results from

a local concentration of material already present in the sandstone ... "

This idea is thus based on an originally syngenetic deposition but an epigenetic concentration. It is therefore equivalent to the so-called source-bed concept revived by KNIGHT (1957) and others.

HESS, F. L. (1914) in discussing the formation of carnotite deposits in the Colorado Plateau believes that several deposits were formed from the accumulation of materials in basins of deposition. HESS suggested that vein deposits were eroded and minerals were carried into shallow seas, forming syngenetic disseminations during the sedimentary process. He says (p. 989, 687) that:

> " ... the sulphuric acid formed through the oxidation of pyrite and other sulphides combined with uranium, vanadium, copper, silver, iron, and possibly chromium minerals of the veins to form soluble sulphates which were carried into the shallow sea, and were diffused and brought into contact with decaying organic matter by which the sulphates were reduced, the uranium to an oxide or to a combined sulphide with vanadium or copper or both and the vanadium, copper, silver, and iron to sulphides. Upon the lifting, draining and aerating of the rocks the minerals were oxidized and part of the vanadium formed vanadic acid, which combined with uranium and potassium or calcium to form carnotite or tyuyamunite."

GRUNER (1956, p. 515) states that the uranium-vanadium deposits in the Colorado Plateau "could have been formed any time under the proper, probably arid conditions in a poorly drained continental rock environment. The early stage was the extraction of the metal largely as $Ca_2 UO_2(CO_3)_3$ from weathering granitic or tuffaceous terrain including the detrital material derived from granites. The waters carrying the uranium gave it up on coming in contact with organic matter, H_2S, or perhaps phosphates. This first accumulation was very low in tenor, but extensive. A second stage began when these rather trifling precipitates were exposed, oxidized, redissolved and carried into a new carbonaceous environment for reduction. Each new stage gave rise to higher concentrations."

GRUNER adheres thus also to an originally syngenetic deposition rearranged by later migrations preferably caused by ground water.

WRIGHT (1955, p. 153) postulates:

> " ... that uranium, vanadium, and copper in sediments of the Colorado Plateau were derived from the same provenance as the enclosing sediments; that during the general seaward migration of the dissolved elements they were trapped on the continental surface in certain favored fluvial environments; and that the initial syngenetic concentration of metals was modified by diagenesis by ground water, and perhaps by hydrothermal solutions."

FREEMAN (1935) in his outstanding Bachelor of Arts Thesis (!) concludes that the uranium-vanadium mineralization in the Colorado Plateau is wholly syngenetic. He says (p. 90):

> "The main point in favor of a syngenetic origin of the ore deposits is their apparent persistency of occurrence at approximately the same stratigraphic horizon over wide areas. If we are to believe in the epigenetic theory that percolating waters concentrated disseminated vanadium and uranium in the sandstones, the writer fails to understand how enrichment by ground water could be so well confined to apparently the same horizon over wide areas ... " By "horizon", FREEMAN means stratigraphic horizons.

GETSEVA (1958) as well as other Russians state that the uranium deposits in many sedimentary rocks were formed contemporaneously with the sediments, thus syngenetically. Furthermore GETSEVA also describes the existence of epigenetic supergene processes of enrichment superimposed on syngenetic concentrations. He says (p. 24):

> "The clear development of supergene uranium mineralization (films of recrystallization of sooty uraninite) strictly in form of orebodies of one or another productive horizon, indicating a direct derivation of the metal during supergene activity from earlier formed concentrations."

II. Epigenetic Theories

KERR (1958) in discussing the uranium emplacement in the Colorado Plateau, states that epigenetic hydrothermal activity caused the formation of the uranium deposits. KERR's hydrothermal concept is wholly epigenetic. He summarized the ideas of the epigenetic-hydrothermal school of thought with the following principal considerations:

> "Much of the bleaching of the uranium deposits of the Colorado Plateau resembles the alteration along veins and faults found in igneous rocks as in Marysvale, Utah, where hydrothermal solutions have developed argillic alteration in the wall rock" (p. 1080).
>
> "In places, solutions rising along structural openings have removed calcium and magnesium from carbonate rocks at a lower level and deposit large masses of dolomite above." (p. 1081)
>
> "The weight of evidence supports uranium introduction into Plateau strata by hydrothermal activity. Nevertheless, subsequent distribution by ground-water and superimposed supergene action must be recognized." (p. 1075).
>
> His final conclusion reads:
>
> "It is easily conceivable that the distribution of radioactivity observed could be

> due to the impregnation in the shale, caused by uranium-bearing solutions migrating upward through fractures in the sandstone" (p. 1097).

b. <u>Literature on the thesis area proper and brief discussion</u>

The origin of the vanadium-uranium ore deposit near Gallup is puzzling. The ore deposit was classified and described by GABELMAN (1956) and KERR (1958). Both authors said that the genesis of the uranium-vanadium at Gallup is of epigenetic character.

GABELMAN is not particularly explicit in his conclusions. It seems that GABELMAN was inclined to accept an epigenetic origin. He states (p. 315):

> "The restrictions of the ore to the anticlines where synclines are nearby, implies some sort of hydrostatic or intratelluric pressure to drive the solutions as high as possible."

KERR (1958, p. 1097) says:

> "At Gallup, New Mexico, uranium-bearing shales appear to have received uranium mineralization through fractures in underlying sandstones."

It is correct that some shales in the Gallup area contain some uranium ore minerals. These amounts are however insignificant at Diamond No. 2 Mine, the largest and unique, important deposit in the district. With a few exceptions shales contain only slight amounts of ore minerals and in all the cases these ore minerals can not be recognized megascopically. This observation is confirmed by GABELMAN (1956, p. 515).

Professor KERR's (1958) epigenetic theory for the uranium-vanadium mineralization at Gallup does not do justice to the field evidences. Reasons are:

1. Fractures in the shales do generally not continue in the underlying sandstones.
2. Fractures or faults in the shales do not contain ore minerals. The minerals present in the sandstones occur as lenses in the shales.
3. Fractures and faults in the sandstones (Dakota ? and Westwater Canyon ?) do not contain mineralization (Fig. 4).
4. Fracture patterns are almost vertical and the geometry or the ore mineral distribution is horizontal and congruent.

KERR's (1958, p. 1097) field observations are not complete when he says:

> "The shale lies in the Dakota formation ... about 15 feet and exposed by an open cut for a distance of about 1,000 feet along the strike. The strata are inclined at about 45°, ... "

This statement should read: The shales (plural), a part of the Dakota formation, are about 15 feet thick and are exposed in more than one open cut over a distance of not more than 300 feet along the strike. The strata are inclined 30° at Diamond No. 2 Mine and exceptionally 45° in nearby uranium outcrops. For these reasons, and

and the criteria described on the following pages KERR's epigenetic theory is not supported by the field evidence.

4. GENETIC CRITERIA AND CONCLUSIONS

a. First order criteria

The following list of "first order criteria" is actually a summary of geometric and geochemical observations discussed in the previous chapters.

Geometric observations (Gm):

Gm 1: The Dakota sandstone (host of the uranium-vanadium minerals is everywhere lenticular.

Gm 2: The geometry of the three-dimensional grade contours, and thus largely the geometry of the ore bodies corresponds (is congruent to) beds, layers, wedges, clay galls, etc. and thus to sedimentary, depositional (i.e. syngenetic) features.

Gm 3: The gradients of ore mineral contents are all concentric (circular, lens shaped amoeba shape, or other forms with a symmetry center). By the same token: absence of any crosscutting features such as "alteration," mineralizations," etc.

Gm 4: There are no asymmetric gradients close to, or around organic matter, or from mineral concentrations away from organic matter towards this organic matter. Again the only symmetry is concentric (whereby often vanadium minerals are in the center of organic matter accumulations, whereas uranium minerals prevail towards the outside).

Gm 5: The present ground-water movements cause local redepositions which show practically always crosscutting geometry.

Gm 6: Furthermore, congruence also exists with regard to structures caused by submarine slumping.

Gm 7: Congruence of sulfide grains (idiomorphic crystals of marcasite) inside a clay gall was also observed.

Gm 8: There are no fractures with primary ore minerals. The only ore mineral found occasionally in fractures is carnotite.

Gm 9: The fracture patterns of all sedimentary units of the area do not show any geometric relationship to the ore deposits of Diamond No. 2 Mine.

Gm 10: There is no concentration of uranium-vanadium minerals along possible "tracks," such as for example along the boundaries between the carbonaceous material and the uranium-vanadium minerals. This observation was made by many workers, for example BREGER and DUEL (1955, p. 186).

Gm 11: The geometry (outlines, boundaries) of spaces containing uranium-vanadium minerals corresponds to (is congruent with, or homologous to) the grain size variation inside the arkosic sandstone, but not inside the whole sandstone unit (1). Its grade changes with the grain size and composition.

The high values correspond to coarse to medium size - <u>inside</u> the arkosic lenses.

<u>Gm 12</u>: Carbonaceous matter is areally much more limited than the uranium-vanadium mineral content.

<u>Gm 13</u>: Carbonaceous matter is generally but not always associated with uranium-vanadium minerals.

<u>Gm 14</u>: Quartz grains do not show corrosion. The roundness, sphericity, etc. is perfectly erosional.

<u>Gm 15</u>: The matrix does not show any corrosional features either, except where supergene carnotite formation has started.

Geochemical observations (Gc):

<u>Gc 1</u>: Carnotite represents probably always a product of epigenetic oxidation of the other uranium-vanadium minerals in situ, which takes place even today. (The term CARNOTITIZATION might be used, although it may be misunderstood to mean an introduction of carnotite from unknown sources; yet the distance of transportation, if any, can be measured in cm. or at the most in a few meters.)

<u>Gc 2</u>: The uranium-vanadium minerals never occur in non-arkosic sandstone of the same grain size. (This observation is apparently true in other areas: compare chapter e, geochemistry ...).

<u>Gc 3</u>: Presence of some devitrified volcanic glass in the arkosic sandstone which contains the uranium-vanadium minerals.

Gc 4: Absence of silicification or any other (crosscutting) alteration from within the boundaries of the ore mineral bodies. Even the traces of silicification (Fig. 9) found at a few margins, lateral to the areas containing uranium-vanadium minerals, are horizontal and may be explained as diagenetic without assumptions (SUJKOWSKI, ZB., 1958, p. 2695).

Gc 5: The association of uranium and vanadium minerals with organic material is a rule which holds true in about 60-70 percent within the ore bodies.

Gc 6: There was a core of marcasite found inside a clay gall.

Gc 7: Complete absence of any igneous rock in the immediate vicinity. Also absence of any definite proof of the presence of a deep seated intrusion.

Gc 8: The ground water present today does not appear to get loaded with dissolved uranium and vanadium salts, and to transport it into "favorable beds."

b. Second order criteria (partial conclusions)

1. Gm 1 plus Gm 2 plus Gm 3 plus Gm 4:

The concentric symmetry of the distribution of ore minerals make an epigenetic introduction highly improbable, since any outside source would introduce at least in part a unilateral symmetry of distribution. The zoning is thus most probably syngenetic (AMSTUTZ, 1959, c, d). (These criteria may also apply to the Ambrosia Lake area.)

2. Gm 14 plus Gm 15:

   The lack of corrosion boundaries appears to rule out the possibility of emplacement of the ore minerals by a (syngenetic or epigenetic) replacement process.

3. Gm 11 plus Gc 2 plus Gc 3:

   The coincidence of the contents of sedimentary units of uranium-vanadium minerals and of feldspar fragments (arkoses), of possibly volcanic quartz (pyramidal terminations) and of very probable shards of volcanic glass, points to the possibility of a genetic tie.*

4. Gm 4 plus Gc 5:

   There is no evidence of epigenetic concentration of ore mineral matter by organic material, since there are no directional gradient relationships between the distribution away from organic material to the concentrations inside organic matter.

5. Gm 5 plus Gc 8:

   The geometry and geochemistry of the present ground-water action does not suggest that the shapes of the ore mineral "bodies" were formed by ground-water movement (compare Plate No. 12).

c. <u>Assumptions and logic</u>

Assumptions involved in SYNGENESIS:

1. Uranium-vanadium minerals or uranium-vanadium solutions available during sedimentation. Source on surface, in the erosional basin (weathering or exhalation).

* Proctor, 1953

2. Environment during sedimentation is favorable for the precipitation (or other modes of accumulation) or uranium-vanadium minerals or uranium-vanadium solutions in limited loci or zones.

Assumptions involved in EPIGENESIS:

1. Sources for fluids at depth create availability of uranium-vanadium fluids.
2. Differentiation at depth leads to fluids carrying uranium-vanadium solutions, which lead to the extraction of only uranium-vanadium from complex fluids, at depth, on the way up, or during deposition.
3. Pathways for introduction of the fluids from the source to the site of deposition. (There are those who assume with BROWN (1958) that the ore fluids diffused independently of fractures through the crust underlying the ore deposits and those who assume that the fluids need fractures served as pathways. A reason has to be offered why the 99 percent of the fractures are not mineralized. In both cases, introduction through diffusion or through fractures, we need a reason for the fact that the fluids took a liking to certain stratigraphic units: beds, horizons, lenses, wedges, rolls, etc. only, although it crossed many other stratigraphic units before. As shown above, we also need a reason for the absence of crosscutting features.
4. Favorable conditions for deposition in portions of the sediments in which the ore minerals are encountered today, and only in those portions (no such conditions

may exist anywhere between the source of the fluids and the site of deposition).

5. Space was available for the deposition of the introduced material.
    a. open spaces available
    b. mechanical expansion took place
    c. replacement: original material is removed and the new material is deposited (whereby removal and deposition can take place at the same or with a time gap)
6. If 5c took place, as assumed by most epigenetic theories, another assumption is needed: an epigenetic force and space must have been available to remove the material which was replaced and to move it outward (without leaving any trace of such movements).

Logic:

It is a rule of logic and common sense that, of two theories, the one with the smaller number of assumptions is closer to the truth.

d. Final conclusion

On the basis of the evidence brought out by the first and second order criteria, and on the basis of the number of assumptions required by the various theories, it is concluded that a syngenetic origin is much more probable than an epigenetic one for the Diamond No. 2 uranium-vanadium ore deposit.

As to the origin of the ore fluids or minerals, no definite conclusion can be offered at the present time. There are factors which suggest a possible relationship with volcanic matter in the sediments.

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