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National Uranium Resource Evaluation

GEOLOGY AND RECOGNITION CRITERIA FOR SANDSTONE URANIUM DEPOSITS OF THE SALT WASH TYPE, COLORADO PLATEAU PROVINCE

FINAL REPORT

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
Grand Junction Office, Colorado

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DISCLAIMER

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SUMMARY

The uranium-vanadium deposits of the Salt Wash Member of the Morrison Formation in the Colorado Plateau are similar in many respects to sandstone uranium deposits elsewhere in the United States. Important similarities include (a) the occurrence of the deposits in rocks younger than Paleozoic; (b) relatively high permeability of the dominantly fluvial host sandstones; (c) associated or interbedded tuffaceous sediments; and (d) the occurrence of the ores in reduced sandstone characterized by some combination of detrital plant debris, redistributed humates, and iron sulfides. The shapes of the mineral zones are also superficially similar with those of the Salt Wash, displaying both tabular and roll shapes similar to, respectively, the tabular deposits in the Grants Uranium Region and the roll-type deposits of Wyoming, South Dakota, and Texas.

The differences between Salt Wash deposits and other sandstone uranium deposits are significant but have been underemphasized by many investigators. The Salt Wash deposits are unique among sandstone deposits in that they are dominantly vanadium deposits with accessory uranium. The uraniferous humate deposits of the Grants region and the roll-type deposits of Wyoming and Texas contain insignificant vanadium concentrations. The Salt Wash vanadium-uranium deposits are commonly associated with detrital plant trash, but redistributed humic material, such as occurs in the Grants ores, is not a significant ore component. Finally, the Salt Wash ores do not occur at the margins of oxidized sandstone tongues as do the roll-type deposits of the Wyoming basins and those in Texas that have not undergone re-reduction.

The Salt Wash ores are generally described as occurring entirely within reduced sandstone, without adjacent tongues of oxidized sandstone, suggesting that they did not form by the mechanism that forms roll-type deposits. They are, in this respect, more like the deposits of Grants, which similarly occur in "reduced" sandstones. Recent studies of the Grants deposits (Adams and Saucier, 1981) have identified alteration assemblages which are asymmetrically distributed about the deposits and provide a basis for a genetic model for those deposits. The alteration types recognized by Shawe in the Slick Rock district may provide similar constraints on ore formation when expanded to broader areas and more complete chemical analyses. At present, neither the mineralogic and chemical data bases, nor the chemistry of the vanadium systems, appear sufficiently developed to support such a model, but studies underway at the U.S. Geological Survey are likely to make substantial improvements in the near future.

The principal objective of this study has been to identify the geologic characteristics, or recognition criteria, that are most diagnostic for the occurrence of Salt Wash-type vanadium-uranium deposits, for use in exploration and resource studies. The extent to which this objective has been realized can be briefly reviewed by referring to the important geologic characteristics of these deposits.

Source of Uranium

(1) The source of uranium in the Salt Wash deposits is presumed, by most investigators, to have been within the tuffaceous material of the Salt Wash and/or the overlying Brushy Basin siltstones and mudstones. Such a source for the uranium has been proposed for all the principal sandstone uranium deposits in the United States, and in all cases, including the Salt Wash, it is still based more on the presence of such volcaniclastic sediments in each of these districts than on any convincing documentation. Although these relations provide a strong circumstantial argument that these sediments were the source of the uranium, chemical studies are required to test this hypothesis.

(2) Most uranium districts have been shown to occur within regions that contain possible source rocks with anomalous concentrations of uranium. These concentrations may occur as high background values in granites, volcanic sequences, or metasediments. Both uraniferous granites and volcanic rocks are present in the vicinity of the Wyoming basins and the Grants Uranium Region, and the ore-bearing sands of the Texas deposits are almost always in juxtaposition to the locally uraniferous Catahoula Formation. Similarly, the Colorado Plateau, including the areas of Salt Wash mineralization, is interpreted to be within a province of uraniferous Precambrian basement (Silver et al, 1980). The importance of a uraniferous province to the formation of uranium deposits seems reasonable. It is uncertain, however, whether normal concentrations of uranium in source rocks are adequate to form the deposits, or whether the source rocks need contain truly anomalous uranium concentrations.

Source of Vanadium

The Salt Wash deposits are essentially vanadium deposits, but as yet no convincing case has been made for the source of that vanadium. Favorite hypotheses suggest that it was (a) derived from altered ilmenite and magnetite, (b) introduced diagenetically from the overlying Cretaceous sediments, or (c) was derived from the leaching and erosion of Paleozoic sediments well to the west of the Colorado Plateau. All of these hypotheses are, to some extent, plausible, but are as yet unsubstantiated.

Host Rocks

(1) The Salt Wash Member is a continental fluvial sediment, essentially identical to the host rocks of the other major sandstone uranium districts in the United States. The sediments are orthoquartzites to feldspathic orthoquartzites. They display sedimentary structures and contain plant debris, clay galls, and interbedded siltstones and mudstones that are typical of fluvial sediments.

(2) The sediments are generally interpreted to have been deposited by braided streams similar to those that deposited the Westwater Canyon and Jackpile sandstones of the Grants district, New Mexico. The deposits in the Henry

Mountains mineral belt, for example, appear to be hosted by sediments of this type. Recent studies in the Uravan mineral belt, however, suggest that deposition by meandering streams may have been more important than previously appreciated.

(3) Small, low-grade occurrences of uranium mineralization are widespread within the reduced rocks of the Salt Wash. Larger economic deposits, however, are restricted to major sandstone channels or thicker alluvial sand accumulations. The numerous clusters of deposits within the Uravan mineral belt are typical of the former; the deposits in the Henry Mountains may be an example of the latter. As in other sandstone uranium districts, therefore, major deposits are associated with major transmissive sandstones.

Oxidized and Reduced Sandstones

(1) Shawe (1976a) described red-bed, carbon-, and altered-facies sandstones and mudstones in his study of the Slick Rock district in the Uravan mineral belt. The studies on which these sandstone types were defined covered only a small part of the region in which Salt Wash deposits occur. There are no data that justify extending these sandstone types to other districts, although we expect that they are characteristic of much of the Salt Wash sands in the vicinity of known mineralization. With these reservations, we use Shawe's terminology recognizing that the distributions of these sandstone types, particularly in a regional depositional and hydrologic sense, need to be determined.

(2) The red-bed facies sandstones and mudstones accumulated as oxidized sediments under floodplain and overbank depositional conditions. They do not contain uranium deposits and rarely contain uranium occurrences. Carbon-facies sandstones are megascopically buff to gray sands which contain plant debris and are similar to the downdip unaltered sandstones of the roll-type districts and much of the host sands in the Grants Uranium Region. The altered-facies sandstones are megascopically similar to the carbon-facies sands, but their detrital ilmenite and magnetite grains have been largely or completely altered by the removal of iron. All significant uranium deposits occur in altered-facies sandstones. This alteration pattern may be sufficiently related to ore formation to be a reliable exploration guide.

(3) The Brushy Basin Member of the Morrison Formation is largely, if not dominantly, oxidized in the general region of the Salt Wash deposits. This is consistent with the oxidized nature of mudstone sequences marginal to major Salt Wash channels. It is in contrast, however, to the dominantly reduced (green) habit of the Brushy Basin in some other parts of the Colorado Plateau. Whatever waters of compaction the Brushy Basin contributed to the Salt Wash, therefore, were likely oxidizing rather than reducing.

(4) The colors of the Salt Wash sediments also seem to be regionally zoned with oxidized sediments more common toward the sediment source areas and reduced sediments more common toward the distal depositional areas. The Uravan mineral belt occurs within the zones of transition and interfingering between the dominantly oxidized and dominantly reduced sediments.

Ore Habits

(1) In general, the distribution of vanadium-uranium mineralization in Salt Wash deposits is more erratic and unpredictable than in the more systematic roll fronts of the Wyoming basins and tabular uraniferous humate masses of the Grants Uranium Region. This habit leads to the development of widespread, but generally thin, mineralization which only locally becomes sufficiently thick and high grade to be economic. This probably reflects the combined effects of an unusual ore-forming process and the variable transmissivity of the host sediments. The small deposits for which the Salt Wash is known, therefore, are economically defined uranium accumulations within broader zones or trends of thin, discontinuous but reasonably high-grade mineralization.

(2) Even within deposits, the shapes and orientations of stopes are highly unpredictable, and mining must literally "follow the ore". This is particularly true of the deposits in the Uravan mineral belt, whereas the deposits in the Henry Mountains appear to be more tabular and continuous, probably reflecting the more uniform hydrology of the host sands.

(3) Essentially all significant deposits occur in altered-facies sandstones, as defined by Shawe (1976a). Ilmenite and magnetite are largely or totally destroyed within the sands suggesting both reducing conditions and ground water flow.

(4) All major deposits occur within altered-facies sands, in proximity to the boundary with oxidized sediments. In some cases, the oxidation-reduction boundary separates reduced sands from red-bed overbank deposits. In other cases it separates reduced sands from oxidized, but otherwise similar, sandstones. These relations are considered important for exploration and resource studies.

Recognition Criteria

(1) Available data permit the identification of geologic characteristics, or recognition criteria, that are diagnostic for the presence or absence of Salt Wash-type deposits. Reasonably adequate data are available to support the recognition criteria selected, but the lack of thorough studies in most ore districts, and the absence of a coherent and generally accepted ore-forming process, make any conclusions speculative and tenuous.

(2) The use of geologic recognition criteria for exploration has been used by exploration geologists for decades. Such informal methods will continue to be valuable, and appropriately so. It now seems useful, however, to identify those geologic criteria that are the most important guides to Salt Wash-type deposits and establish at the least their relative importances.

(3) A method is also presented for accumulating the favorability of numerous recognition criteria in a simple but systematic fashion, so that the relative favorability for a deposit in an area under study can be evaluated. Even geologists experienced with Salt Wash deposits may find this process helpful as a checklist in selecting exploration targets or estimating resource potential.

(4) The selection of recognition criteria and the assignment of relative levels of importance are subjective judgements and will continue to be so. It seems better, however, to have experienced geologists evaluate the geologic data and document where and how subjectivity is used than to simply apply brute-force numerical techniques or leave the interpretation to others, who may be less familiar with the deposits.

Continuing Studies

The recognition criteria presented in this report are based on the descriptions of a limited number of Salt Wash deposits and districts, and even fewer studies of the unmineralized sands that host those deposits. Furthermore, no generally accepted ore-forming mechanism has yet been proposed and tested. The need for continuing studies as a means for improving confidence in recognition criteria, hence their usefulness in exploration and resource studies, is quite apparent, and some suggestions are presented.

Potential of the United States for New Deposits

The potential of the United States for the occurrence of new Salt Wash-type deposits was not evaluated as part of this study. The review of the geology and controls of the Salt Wash deposits conducted in the course of developing the recognition criteria provided, however, an opportunity to re-evaluate the potential of the Salt Wash and identify other sandstones which might have comparable potential. Some suggestions on untested Salt Wash areas are included.

INTRODUCTION

Background

Important amounts of uranium-vanadium ores have been produced from the Salt Wash Member of the Morrison Formation. Known ore reserves are modest compared to the large producing districts in New Mexico and Wyoming but should be sufficient to sustain current production levels for many years. Drilled-out Salt Wash ore reserves seldom have exceeded the amount of ore required for near-term production and milling requirements. Most of the ore deposits and mines are small by industry standards, and most operators do not define more ore reserves by drilling than are necessary to support the costs of new development. Historically, a large part of the ore has been found by mining. Successful exploration and development drilling of larger orebodies in both old and new districts probably have increased known reserves to an all-time high. In addition to the known reserves, the Salt Wash may contain a significant exploration potential within producing areas, as well as in areas which have not been explored as thoroughly.

Uranium ores were first mined in the United States from Salt Wash sandstones. The initial discovery was made at Roc Creek, near Uravan, Colorado, before the turn of the century; some of the earliest ore shipments were made from areas within the Uravan mineral belt. Other outcrops of Salt Wash ores were discovered in the Henry Mountains area of Utah in 1913, and in northeast Arizona on the Navajo Reservation in 1918. Early mining efforts were small and sporadic. From 1900 to 1923 the ores were mined for their radium content; between 1923 and 1937 there was essentially no production; and from 1937 to 1944 the ores were mined for vanadium (Motica, 1968). Interest in Salt Wash ores as a domestic source of uranium was revived in the early 1940s with the advent of the nuclear age. Since the early 1950s, the producing areas have been intensively explored and mined, mainly for uranium, but vanadium has been an important co-product of most ores. Federal drilling programs, conducted from 1948 to 1956 by the United States Geological Survey and the United States Atomic Energy Commission, explored many of the then-known districts, providing both geologic information and incentive to private industry.

Ore deliveries to mills since 1950 have fluctuated with economics and markets, but production has been reasonably steady, averaging about 400,000 tons of ore per year. Current production is above that level. Three mills are fed either wholly or in large part by Salt Wash ores; two new mills are under construction, and a third is in the planning stage.

Production from Salt Wash sandstones from 1947 to January 1, 1979, totals 17,645,000 tons of ore averaging 0.24 percent U_3O_8 and about 1.25 percent V_2O_5 (Table 1). Major production has come from the Uravan mineral belt in western Colorado and eastern Utah; lesser amounts of ore have been produced from Arizona and New Mexico.

Early reports and publications on Salt Wash ore deposits were mainly descriptive, but many authors speculated on the source of the ore metals and on the origin of the ore deposits. Two basic genetic theories evolved, one involving hypogene processes, and the other involving supergene processes. The major

Table 1. Salt Wash ore production by state to January 1, 1979, based on U.S. Department of Energy records (Chenoweth, written communication 1980).

State	Tons of Ore	Pounds U_3O_8	Percent U_3O_8
Colorado	13,808,000	67,495,000	0.24
Utah	2,990,000	14,405,000	0.24
Arizona	812,000	3,857,000	0.24
New Mexico	35,000	155,000	0.22
TOTAL	17,645,000	85,911,000	0.24

differences between the two theories center around the source of the ore metals and the transporting media. The hypogene theory, now largely discarded, assumes that ore solutions rose from underlying deep-seated plutonic sources, mixed with ground waters, and migrated through permeable sandstones to deposit the ore minerals in favorable reducing environments containing carbonaceous material. The supergene theory, to which there are many variations, assumes that moving ground waters leached the ore metals from the host rock, overlying strata, or rocks exposed at the surface to the aquifer recharge waters, and that the metals were precipitated from solution by reduction within or close to a reducing environment containing carbonaceous material.

More recently, various investigators have called attention to the similarities, or differences, between the tabular Salt Wash deposits and the roll-type deposits of Wyoming (Brooks et al, 1978; DeVoto, 1978; Rackley, 1976; Fischer, 1970). Since the Salt Wash deposits, and probably the processes which formed them, do not appear to be identical to the roll-type deposits, they are considered as a separate and distinct model in this report. Future work may resolve a few or many of the apparent differences, but at this point the Salt Wash deposits appear to warrant consideration as a separate model.

Sources of Information

Published and open-filed literature on the geology of the Salt Wash and its associated ore deposits is voluminous. Hundreds of reports by government agencies or their contractors record the results of federal investigations and drilling programs conducted during the 1940s and 1950s. Most of the mineralized districts and sub-districts, as well as many individual mines and some prospects, were described. Some of the more comprehensive area reports are listed below:

Uravan Mineral Belt, Colorado and Utah: Fischer and Hilpert, 1952; Motica, 1968. Green River (San Rafael) District, Utah: Trimble and Doelling, 1978;

Young et al, 1957. Henry Mountains District, Utah: Peterson, 1980; Chenoweth, 1980. Carrizo and Lukachukai Districts, Arizona: Chenoweth and Malan, 1973; Nestler and Chenoweth, 1958. Thompson District, Utah: Stokes, 1952. Blanding (Cottonwood Wash) District, Utah: Pitman, 1958. La Sal Creek District, Utah: Carter and Gualtieri, 1965. Meeker District, Colorado: Boyer, 1956; Isachsen, 1955. Slick Rock District, Colorado: Shawe, 1968, 1970, 1976a, 1976b; Shawe et al, 1968; Shawe et al, 1959. Montezuma Canyon District, Utah: Huff and Lesure, 1962, 1965. East Canyon-Dry Valley District, Utah: Doelling, 1969.

Acknowledgements

Many geologists and engineers have contributed to the knowledge of the Salt Wash and its uranium-vanadium deposits. Published literature from many sources has been freely used in the preparation of this paper, especially publications of the United States Geological Survey by L. C. Craig, R. A. Cadigan, R. P. Fischer, Fred Peterson, and D. R. Shawe.

We are indebted to Plateau Resources Limited and Union Carbide Corporation for permission to tour some of their mines and for granting permission to include in this paper some of their proprietary information. We held many interesting and open discussions with geologists from both companies. While there was not always unanimous agreement on all subjects, the differences of opinion served to remind us that many aspects of Salt Wash geology and ore genesis remain open to interpretation and debate.

The manuscript has benefited from reviews by S. R. Austin, W. L. Chenoweth, R. A. Crawley, M. A. Goldhaber, H. C. Granger, and C. A. Jones. Although their comments substantially improved the report, they do not necessarily endorse its contents. Jo Ann Fankhauser skillfully prepared numerous drafts of the manuscript and performed innumerable other tasks essential to the completion of this contract.

REGIONAL GEOLOGIC HISTORY

The dominant feature of the geologic history of the Colorado Plateau has been its comparative structural stability since the close of Precambrian time. During most of Paleozoic and Mesozoic time, the Plateau was a stable shelf without major geosynclinal areas of deposition, except during the Pennsylvanian when several thousand feet of black shales and evaporites accumulated in the Paradox Basin of southwestern Colorado and southeastern Utah. Folding and faulting during the Laramide orogeny produced the major structural features of the Plateau. Early Tertiary fluvial and lacustrine sedimentation within the deeper parts of local basins was followed by laccolithic intrusion and extensive volcanism beginning in mid-Tertiary time. Faulting along the south and west sides of the Plateau was followed by epirogenic uplift and northeastward tilting of the Plateau and by continuing erosion which has shaped the present landforms.

At the beginning of Paleozoic time, the Precambrian basement had been eroded to a nearly flat plain. Cambrian clastic sediments overlain by Devonian and Mississippian limestones are separated by a hiatus marking Ordovician and Silurian time (Hunt, 1956). In Late Paleozoic time, the northwest-trending Paradox Basin developed in southwestern Colorado and southeastern Utah and was filled by approximately 7,000 feet of marine black shales and evaporites. Folding within the basin along pre-existing zones of weakness was accompanied by flowage of salt toward the anticlinal axes. The Uncompahgre Uplift continued to rise along the northeast edge of the basin, supplying the arkosic debris which formed the continental sediments of Permian age.

The Plateau continued to be a stable area throughout Mesozoic time. A few thousand feet of sediments of Triassic, Jurassic, and early Cretaceous age, largely of continental fluvial origin, were deposited from source areas to the east, and from the south and west. Submergence of the region as a block preceded widespread deposition of thick black marine shales of the Mancos Formation. The region was then uplifted, and deposition of marginal marine and continental sandstones of the Mesaverde Formation marked the end of the Mesozoic Era.

The Laramide orogeny of Late Cretaceous and Early Tertiary time affected the Plateau only slightly, compared to the bordering areas. The nearly horizontal strata were gently flexed, producing the uplifts and basins identified on Figure 1. The spectacular monoclines of the region, actually the steeper limbs of asymmetric anticlines, displace the strata vertically as much as 8,000 feet, and some exceed 100 miles in length. The monoclinal folds are interpreted to overlie basement faults; the flexible sediments responded by bending, rather than breaking, across the faults. In Early Eocene time, sediments of fluvial and lacustrine origin were deposited in the deeper basins flanked by highlands, notably in the Uinta and the San Juan Basins.

Igneous intrusions of diorite and monzonite porphyry penetrated the sediments at several points during Middle Tertiary time to form the laccolithic mountains of the central Plateau. Dikes and sills of similar composition were intruded along the eastern edge of the Plateau, probably in Miocene time (Shawe, 1976b). Near the southern and western margins of the Plateau, probably beginning in mid-Tertiary time, the volcanos of the Mt. Taylor, Datil, and San Francisco fields and the volcanic fields of the High Plateaus were formed.

Epirogenic uplift in mid-Tertiary time raised the Plateau to its present structural position; erosion since that time has produced the present landforms.

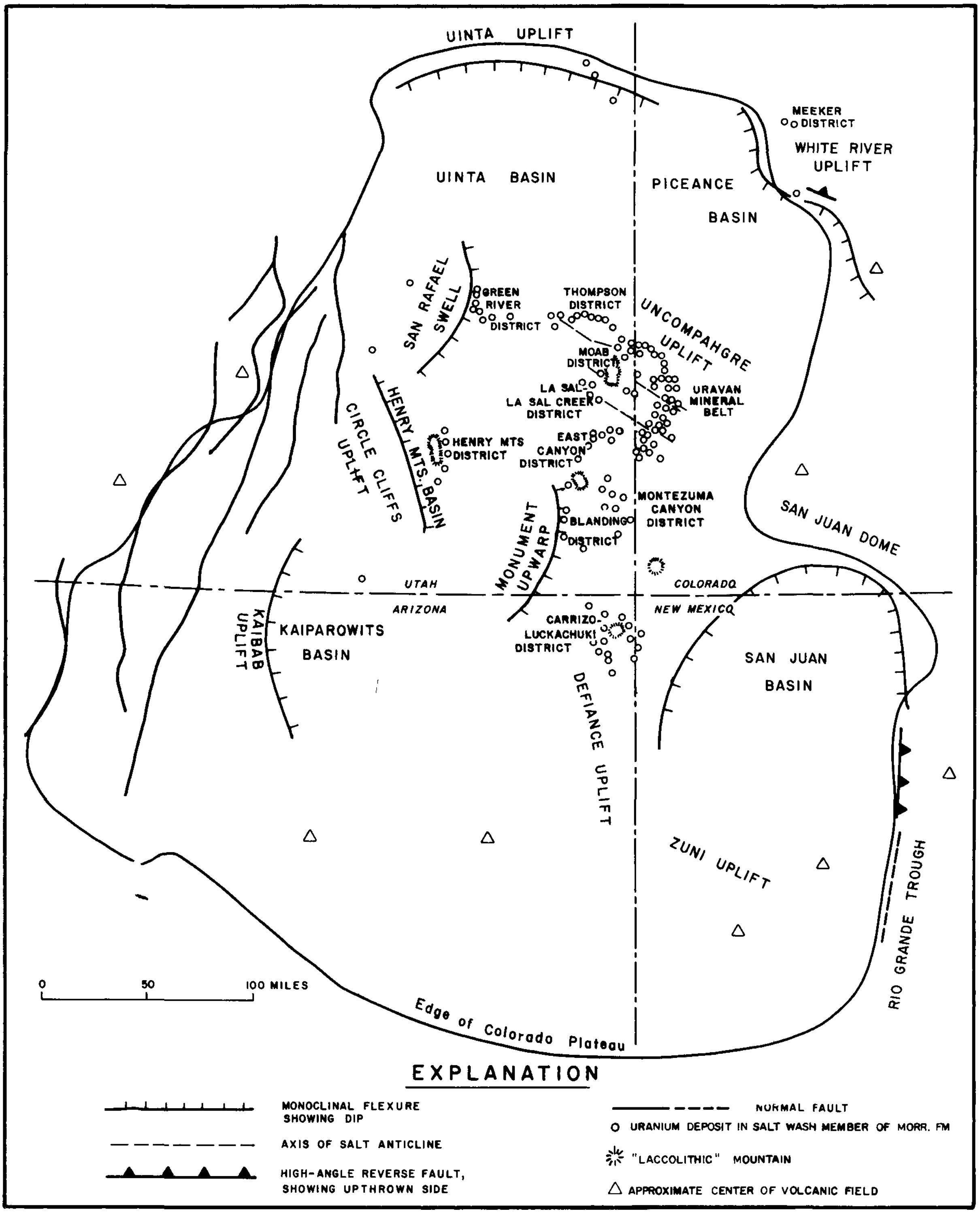

Figure 1. Location map of uranium deposits in the Salt Wash Member of the Morrison Formation and the principal structural and igneous features of the Colorado Plateau (modified from Fischer, 1968).

MORRISON FORMATION

The Morrison Formation is a complex fluvial deposit of Late Jurassic age that occupies an area of approximately 600,000 square miles, including parts of 13 western states and small portions of three Canadian provinces (Fig. 2). The Morrison extends into the Rocky Mountains and Great Plains provinces, far to the north and east of the boundary of the Colorado Plateau.

In the Four Corners area of Colorado, Utah, Arizona, and New Mexico, the Morrison Formation is made up of four members, each of continental fluvial origin (Fig. 3). From bottom to top, the four members are named the Salt Wash Member, the Recapture Member, the Westwater Canyon Member, and the Brushy Basin Member. Each is recognized as a mappable unit in the Four Corners area, and the distribution of each is approximately shown in Figure 2.

The Morrison exhibits either conformable or disconformable relationships to the underlying formations of Late Jurassic age within the area of the Colorado Plateau. Formations of Early Cretaceous age conformably overlie the Morrison except in the southwestern portion of the Plateau, where the Brushy Basin Member has been removed by pre-Dakota erosion; in this area the Morrison is unconformably overlain by the Dakota Sandstone of Late Cretaceous age (Cadigan, 1967).

In the areas of major Salt Wash uranium production in Colorado and Utah, the Morrison Formation consists of only the Salt Wash and the conformably overlying Brushy Basin Member. In northeastern Arizona and northwestern New Mexico, an area of relatively minor Salt Wash production, the Salt Wash intertongues with and is partially overlain by the Recapture Member. The Brushy Basin Member is interbedded with and generally overlies the Westwater Canyon sandstone. Both the Recapture and Westwater Canyon extend only into the southernmost portions of Colorado and Utah, and along with the Brushy Basin and Salt Wash Members they intertongue and merge southward into the Cow Springs Sandstone. Figure 3 shows these relations.

Salt Wash Member

Distribution and Stratigraphic Relationships

The Salt Wash and Recapture Members make up the lower part of the Morrison Formation. Both members were deposited synchronously as separate alluvial systems which merge together in the Four Corners area. In general, the Recapture overlies the Salt Wash where both members are present, but the members intertongue in some areas. The Recapture pinches out northward from the Four Corners area and is not recognized south of a line drawn between Rough Rock, Arizona, and Sanostee, New Mexico. The southwestern edge of the Salt Wash, along the Utah-Arizona border, is an erosional limit.

The Salt Wash is conformably overlain by the Brushy Basin Member of the Morrison over much of the Colorado Plateau. Its relationships with underlying units are more complex (Fig. 3). Recent work by Peterson (1974, 1977, 1978) in the Henry Mountains region of south-central Utah has recognized and mapped

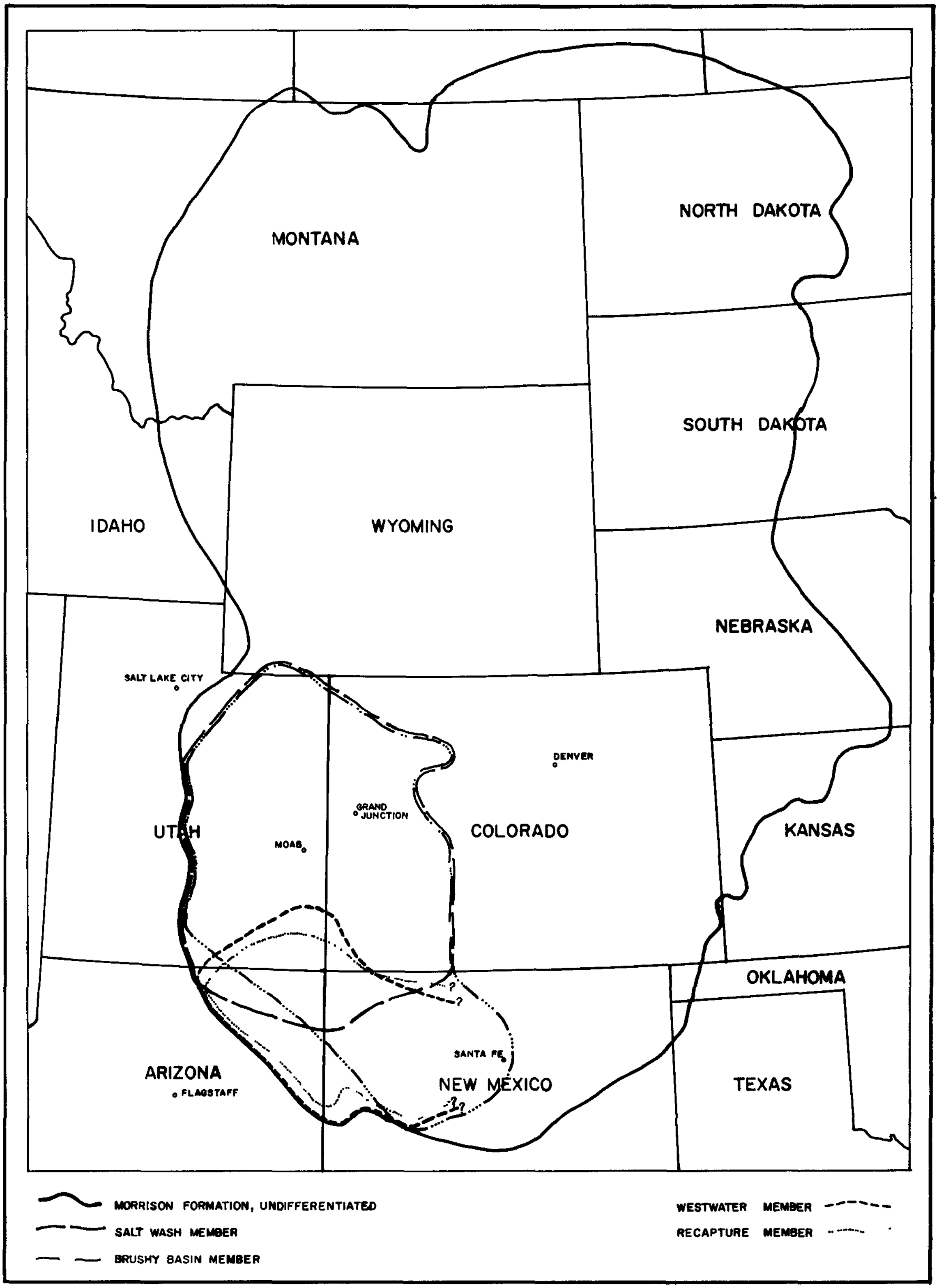

Figure 2. Map showing the distribution of the Morrison Formation and its members (modified from Craig et al, 1955).

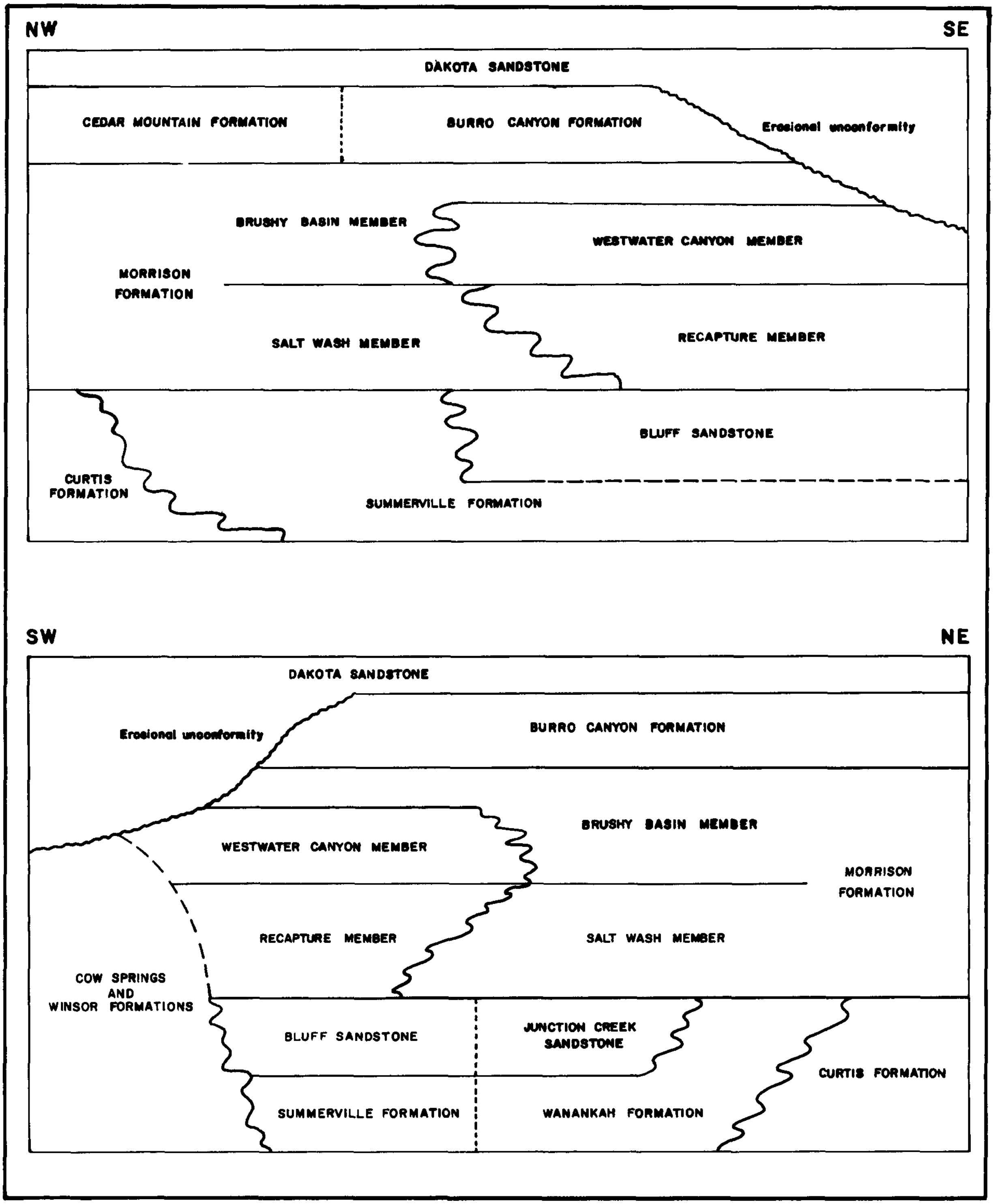

Figure 3. Generalized stratigraphy of the Morrison Formation, Colorado Plateau (from Cadigan, 1967).

a lower member of the Morrison Formation below the Salt Wash. This lower member, called the Tidwell unit, of non-marine origin, unconformably overlies the marine Summerville Formation. Pipiringos and O'Sullivan (in Turner-Peterson, 1980) have conducted regional studies which indicate that the Morrison Formation throughout the Plateau may be separated from the Summerville or equivalent rocks by a regional unconformity.

Major Facies

Craig et al (1955) and Mullens and Freeman (1957) subdivided the Salt Wash Member into three major facies, as shown in Figure 4. Extending northeast from the Arizona-Utah border is a conglomerate facies of scour-fill sandstones which contain pebbles of chert and silicified carbonates up to 4 inches in diameter. Marginal to the conglomeratic sandstone facies on the northwest, north, and east is a sandstone and mudstone facies composed of scour-fill lenticular sandstones interbedded with lesser amounts of gray-green or red siltstones and mudstones. Peripheral to the sandstone-mudstone facies, and gradational outward from it, is a third facies, composed dominantly of gray-green or red siltstones interbedded with lesser amounts of horizontally bedded sandstones. Uranium-vanadium orebodies have been found in each of the three facies, but the great majority of ore has been mined from the intermediate sandstone and mudstone facies.

Although it is convenient to review the Salt Wash under the three generalized facies outlined above, the reader should be aware that each of the three facies probably is much more complex than the simplistic terms imply. The work of Peterson (1980), for example, has demonstrated that several types of depositional environments exist within the area mapped as "conglomeratic facies" on Figure 4. Detailed work within the other two facies presumably would result in similar conclusions.

Figure 4, an isopach and facies map of the Salt Wash, shows the generalized thickness of the three facies of the Salt Wash. The thickest portion of the member is in the conglomeratic sandstone facies in south-central Utah, where thicknesses in excess of 700 feet have been measured (Peterson, 1980). The Salt Wash thins to the north and east within the sandstone and siltstone facies, where it averages approximately 200 to 400 feet thick over much of the area. Still farther north and east, within the dominant siltstone and minor sandstone facies, the Salt Wash Member is generally less than 200 feet thick, but near the common boundary of Utah, Colorado, and Wyoming, a pronounced, local thickening of the Salt Wash is apparent. Measured sections of the Salt Wash in the Dinosaur Quarry Quadrangle, Utah, within this area of local thickening, show more than 200 feet of sandstone and conglomeratic sandstones with only minor amounts of interbedded gray-green siltstone (Bilbey et al, 1974). The thick conglomeratic sandstone in this area appears to indicate contributions of coarse sediments from a separate source area to the west.

Lithology

The Salt Wash is composed of two characteristic lithologies over most of its extent: reddish-brown, tan, or gray sandstone or conglomeratic sandstone; and brownish-red or gray-green siltstone or mudstone. Both the sandstone and siltstone units are lenticular, and individual beds generally cannot be traced

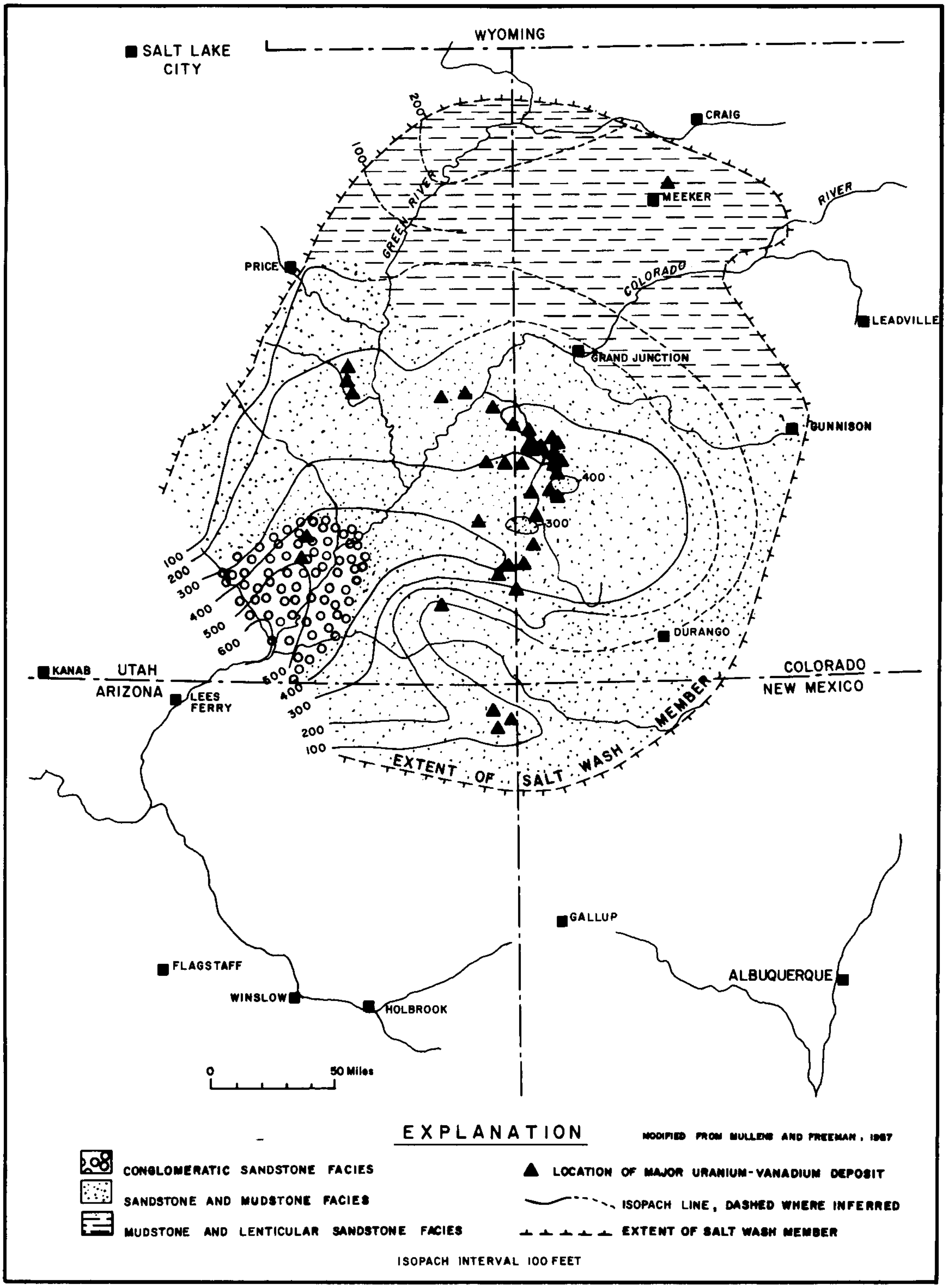

Figure 4. Isopachous and facies map of the Salt Wash Member of the Morrison Formation showing the locations of the major Salt Wash uranium-vanadium producing areas (modified from Craig et al, 1955, and Mullens and Freeman, 1957).

over long distances. The sandstones, usually thick bedded to massive, weather to form prominent ledges resistant to erosion. Interbedded with the sandstones are siltstones or mudstones which are less resistant to erosion, in some places forming broad benches above resistant sandstone strata.

In outcrop, the Salt Wash is exposed as one or more massive, ledge-forming sandstones, the number varying from one district to another. Closer to source areas, as in the Henry Mountains, the western Carrizo Mountains in northeast Arizona, and near Vernal, Utah, the Salt Wash is mainly a massive sandstone or conglomeratic sandstone, broken only by a few, thin interbeds of siltstone or clay. Farther from the source areas, as in the area of the Uravan mineral belt, three or more discontinuous sandstone ledges are common, generally interbedded with approximately equal amounts of thick, laterally persistent siltstones or mudstones.

Each of the major ledges is built of many smaller individual bodies, few of which are traceable laterally over long distances. In contrast, the composite ledge may be traceable for many miles. In the Uravan mineral belt, as well as in other areas where discrete channel systems are recognized, a single composite channel, composed of many separate units, can be followed in drill holes for several miles along the depositional axis; most, however, are not traceable for more than one or two miles in a direction perpendicular to channel axes.

Sandstones

Salt Wash sandstones are dominantly shades of red, tan, or gray. Each of the three types can be found in all of the mining districts. Reddish or pink coloration in the sandstone is caused by the presence of thin films of hematite on detrital grains and as finely dispersed dustlike particles of hematite in the matrix. Presumably the hematite formed early in the depositional history of the sandstones through the oxidation of iron-bearing detrital minerals which were exposed to alternately wet and dry cycles in a floodplain environment (Shawe, 1976a). The red color is stable both at surface and beneath the water table; weathering processes effect no significant color change. Neither carbonaceous material nor pyrite is found in red sandstones. Any vegetal remains which may have been deposited within these sands were destroyed by oxidation soon after burial. Bedding structures within the red or pink sandstones are principally horizontal or gently inclined, but highly cross-bedded structures are uncommon. The reddish-colored sandstones host only scattered small ore deposits, usually close to the margins of the more favorable reduced sandstone bodies.

In contrast to the oxidizing conditions implied by the reddish colors, the tan and gray sandstones are reflective of a reducing environment. Below the water table, reduced sands are light to medium gray, variably pyritic, and contain carbonaceous material in amounts ranging from sparse to abundant. In some places these reduced sandstones host uranium-vanadium deposits containing primary ore minerals.

The reduced sandstones exposed in outcrop and in near-surface workings above the water table are shades of tan or light brown and contain relict carbonaceous material and specks of limonite derived from the oxidation of pyrite. Hematite is not reported in the reduced facies of the sandstone either in subsurface below the water table or in outcrops exposed to surface oxidation and weathering. The tan or brown sandstones host secondary oxidized uranium-vanadium deposits in some places. Both the parent gray reduced facies and their oxidized tan or brown derivatives are characterized by bedding structures dominated by cross-bedding types related to channel filling. Interbedded clays and clay galls incorporated within the sandstones are shades of gray or green, although small amounts of red clays may be present.

Regional transmissivity of the Salt Wash sandstones has been studied by Jobin (1962), who compared several formations. The Salt Wash, like most fluvial sandstones, has low to moderate mean permeability and regional transmissive capacity with large non-uniform local gradients. As might be expected, the fluvial sandstones of the Salt Wash are much less transmissive than, say, the Navajo Sandstone.

Sandstone Mineralogy

The sandstones of the Salt Wash have been classified as modified or impure quartzites, ranging from orthoquartzites to feldspathic or tuffaceous orthoquartzites (Cadigan, 1967). Detrital minerals, the most abundant of which are quartz (85 percent), feldspar (8 percent), and silicified tuff and chert (7 percent), account for more than 80 percent of the average sandstone. The remaining 20 percent is made up of carbonate cement (15 percent) and volcanic fragments (4 percent); dark minerals, including magnetite and ilmenite, and mica components make up the remaining 1 percent of the average sandstone. Detailed comparisons of mineralized and unmineralized Salt Wash sandstones are included in following sections of this report.

Sedimentary Structures in Sandstones

Sedimentary structures in the sandstones include current lineations, infrequent mud cracks and ripple marks, horizontal laminations, and several types of cross-bedding, the most common of which are festoon, wedge, and low-angle compound cross-lamination. Cross-bedding studies have been made in many of the producing districts of the Salt Wash as a means of mapping current directions and channel axes (Green River District, Trimble and Doelling, 1978; Thompson District, Stokes and Mobley, 1954; Blanding District, Stokes, 1954d; Uravan Mineral Belt, Butler and Fischer, 1978; Carrizo Mountains, Stokes, 1953a; Colorado Plateau, Craig et al, 1955). Peterson (1977, 1980) and Peterson and Turner-Peterson (1980) have produced an excellent series of papers on the Henry Mountains area which describe the interpretation of sedimentary structures and lithologies as an aid to reconstructing ancient depositional environments.

Mudstones and Siltstones

Fine-grained units of siltstones and mudstones make up variable portions of the Salt Wash, occurring as massive beds tens of feet thick between major sandstone units, as minor thin discrete lenses within thick sandstone bodies, as angular rip-up clasts incorporated within cross-bedded sandstones, and as interstitial material between detrital grains in sandstone. Braided stream deposits closer to source areas generally contain fewer and thinner siltstone or mudstone intervals than meandering stream deposits distant from source areas. The stream deposits of the Salt Wash in the Henry Mountains area, dominantly of braided stream origin, contain probably less than 10 percent interbedded mudstones. The fluvial deposits of the Uravan area, interpreted as meandering stream complexes by Tyler and Ethridge (in press), contain approximately 50 percent mudstone interbeds.

Massive interbeds of siltstone or mudstone separating major sandstone units generally are red. The thinner mudstone intervals within sandstone bodies usually are the same color as the enclosing sandstone; red clays are found associated with reddish sandstone, and gray clays are dominantly enclosed by gray reduced sandstone. Chemically and mineralogically, the mudstone and siltstones are very similar to their related sandstone counterparts, the major difference being one of grain size.

Interbeds of red mudstone are not directly associated with Salt Wash ore deposits. Red clays underlying many ore-bearing sandstones, however, have been diagenetically reduced to a gray or gray-green color. These "altered" mudstones, usually pyritic but containing no apparent carbonaceous material, have been used as an exploration guide to ore, in many cases with some degree of success. Rather than being directly related to ore-forming processes, these "altered" clays probably reflect only the presence of a favorable carbonaceous environment in the overlying sandstone. Alteration results from the migration of reducing fluids along the base of the sandstone. The major change resulting from such red-to-gray alteration is a reduction of the iron from ferric to the ferrous state (Weeks, 1951).

Three other types of gray or gray-green mudstones have been identified by Peterson (1980) in his study of the Salt Wash in the Henry Mountains area of Utah: noncarbonaceous, calcareous mudstone containing thin limestone beds; carbonaceous mudstone containing spores and pollen, including the fresh-water algae Botryococcus; and ore-associated "favorable" gray carbonaceous mudstones containing spores and pollen but lacking Botryococcus. Each of the three types occurs as interbeds not more than a few feet thick within thick units of reduced sandstones.

The "favorable" gray mudstones, so named by Peterson because of their close association with the ore deposits in the Henry Mountains, resemble the other types of gray mudstone which are not related to ore deposits, but careful field or microscopic examination can differentiate between them. The "favorable" gray mudstones are dark gray or greenish-gray, finely laminated to very thin bedded, slightly to non-calcareous, and contain appreciable amounts of swelling clays. They can be differentiated from the similar-appearing Botryococcus clays by the fact that the latter contain sooty carbonaceous matter which stains the fingers. The reader should consult Peterson (1980) for a complete description of the several types of gray clays.

The "favorable" gray mudstones appear to be closely related to all presently known uranium orebodies in the Henry Mountains area. In most cases, the gray mudstone lies directly above or below the ore-bearing portions of the reduced sandstones, but in some instances the gray mudstone may be a short distance lateral to the ore deposits, usually within a few hundreds of feet. Peterson (1980) has identified the "favorable" gray mudstones in ore-producing Salt Wash districts in western Colorado and eastern Utah, but insufficient work has been done in these areas to appraise their relationships to the orebodies. The apparent constant and universal association between ore deposits and "favorable" gray mudstone in the Salt Wash of the Henry Mountains area is so close that similar studies in other Salt Wash producing areas are warranted.

Sources of Sediments

Figure 5 shows the direction of movement of sediment into the Colorado Plateau region during deposition of the Lower Morrison (Salt Wash and Recapture). In general, Recapture sediments were derived from sources lying to the south, while Salt Wash sediments were derived from sources to the southwest and west. Sediments from different source areas moving generally in the same direction apparently retained recognizable differences in spite of the mixing action of fluvial sedimentation. Apparently there was little convergence of the major fluvial systems (Cadigan, 1967).

Source areas of the Salt Wash have not been definitely identified, but are thought to be included within a rising arc of highlands lying south and west of the Plateau which became active sources of sediment at the beginning of the Sierra Nevada orogeny. The source terrain probably contained an abundance of sedimentary rocks and possibly minor amounts of silicic intrusive and extrusive igneous rocks. Active volcanism within the source areas supplied large quantities of ash to the depositional basins.

Brushy Basin Member

The Brushy Basin Member of the Morrison Formation conformably overlies the Salt Wash, and in the central portion of the Plateau the two members are coextensive. Distribution of the Brushy Basin is shown in Figure 2. It is present in western Colorado, eastern Utah, northwestern New Mexico, and northeastern Arizona. The southwestern edge of the Brushy Basin is an erosional limit caused by beveling of the Morrison Formation by pre-Dakota erosion. The northern and eastern limits are arbitrarily drawn along a line beyond which the Salt Wash and Brushy Basin Members cannot be differentiated (Craig et al, 1955).

The Brushy Basin ranges in thickness from a zero erosional edge along its southwestern boundary to a maximum of 700 feet near Slick Rock, Colorado. Over much of the central Plateau, it averages 200 to 500 feet in thickness.

The Brushy Basin is composed predominantly of massive, horizontally laminated grayish-green, reddish-brown, and purplish siltstones and mudstones. Interbedded with the silts and muds are lesser amounts of sandstones and conglomerates, and a minor amount of thin limestones. The sandstones and conglomerates, which may account for approximately 10 percent of the total thickness of the member, occur more frequently near the base. Distinct facies of the Brushy Basin have not been recognized in most areas of the Plateau, but in the Slick Rock region of western Colorado, Shawe (1968) identifies a lower brown unit, a middle green unit, and an upper brown unit. Phoenix (1958) mapped lenticular conglomerates at and near the base of the Brushy Basin in western Colorado and eastern Utah and correlated them with uranium-vanadium deposits in the upper sandstone strata of the underlying Salt Wash.

Detrital minerals of the conglomerates, sandstones, and siltstones of the Brushy Basin Member are qualitatively similar (Cadigan, 1967). The most abundant detrital minerals are quartz, quartzite, chert, feldspars, silicified rock fragments, and fragments of altered tuff. The most prominent clay mineral is montmorillonite, derived from volcanic ash. Common authigenic minerals are secondary silica, calcite, dolomite, and minor amounts of barite, chlorite, leucoxene, anatase, and hematite.

Organic remains found in the Brushy Basin are limited mainly to partially silicified dinosaur bones and silicified and carbonized wood; fresh-water gastropods and algae have been reported from a few localities (Craig et al, 1955).

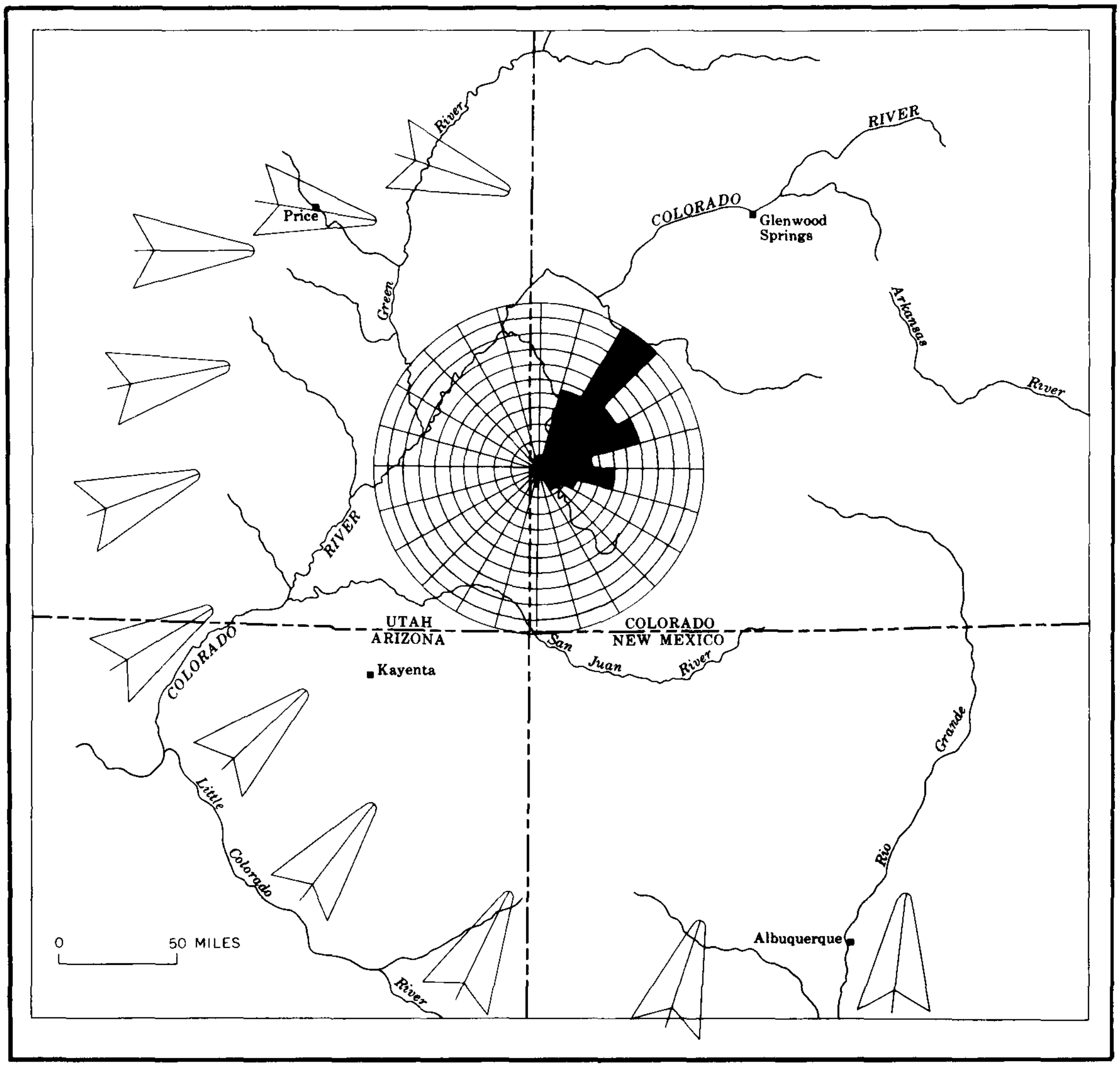

Figure 5. Directions of sediment transport into the Colorado Plateau region during deposition of the lower part of the Morrison Formation (Salt Wash and Recapture Members). Rose diagram shows orientation of sedimentary structures (from Cadigan, 1967).

ORGANIC MATERIAL

Organic remains are abundantly preserved in the Morrison Formation. Silicified bones of several species of dinosaurs have been found, and museums throughout the world contain dinosaur skeletons excavated from the Salt Wash or Brushy Basin Members of the Morrison. In mineralized areas, pieces of bone are brightly colored by impregnations of uranium and vanadium minerals.

Silicified or carbonized wood are the most common organic remains. Wood replaced by calcium carbonate or barite is less common but by no means rare. The carbonized wood is preserved only in the reduced gray facies or its weathered equivalent. The oxidized red-bed facies sediments, which are primarily floodplain deposits, contain little if any carbonized material. If it was deposited in the floodplain environment, carbonaceous material was not preserved in the oxidizing environment.

The carbonized wood ranges in size from finely macerated flakes concentrated along bedding planes and dispersed through portions of the sandstones to large logs up to 3 feet in diameter and as much as 100 feet in length. Some is coalified, lacking any resinous or vitreous luster, and some is silicified. Humic material is found locally impregnating the sands adjacent to plant trash. All of the recognizable wood examined has been identified by Scott (1961) as belonging to the genus Araucarioxlyon Krause, similar to some present-day conifers.

Many writers have pointed out the close association between uranium-vanadium mineralization and carbonized wood. Whether there is a direct cause and effect relationship is less clear, but the nearly universal association between mineralization and carbonized wood in Salt Wash sandstones is beyond debate. There is also little argument that uranium and vanadium can be extracted from solution by carbonaceous matter, and many examples of richly mineralized logs have been reported from several areas. The tabular orebodies found in horizontally bedded sandstones of the Salt Wash generally contain carbonaceous material as finely disseminated flakes on bedding planes and dispersed in the sandstone. The orebodies within highly cross-bedded sandstones are generally more erratic in shape and are associated with larger carbonized fragments, including tree trunks and branches. In some of the ore deposits, large wood fragments are thickly clustered into so-called "log jams" or "trash piles", but even in these more spectacular concentrations the volume of carbonized material usually makes up no more than a few percent of the volume of ore-grade rock. Uraniferous humate masses similar to those in the Grants Uranium Region, New Mexico, have not been identified in Salt Wash ores.

Most of the carbonaceous material in the Salt Wash sandstones is unmineralized, although drill cores or cuttings containing carbon are regarded as indications of a favorable environment. Within the boundaries of an ore deposit much of the carbon is mineralized, but some is not. Many examples of ore-grade logs within a few feet of similar-appearing but barren logs have been documented. Presumably subtle changes in permeability of the host sandstone did not permit equal access to mineralizing solutions, or some of the wood may not have reached the proper stage of degradation to react with the mineralizing solutions.

Some of the carbonized or coalified wood within ore deposits has been partially or wholly replaced by ore minerals. In partially mineralized fragments, ore minerals appear to fill fractures and shrinkage cracks in the wood, an indication that mineralization was preceded by some amount of degradation of the wood. Studies by Breger (1974) indicate that under the conditions assumed to be present in Late Jurassic time, degrading wood could approach the properties and composition of lignite in as little as 30,000 years. The same author concluded that coalification to the sub-bituminous stage was probably complete prior to mineralization of the sediments.

ORE DEPOSITS

Production and Reserves

Figure 1 shows the locations of the most significant Salt Wash ore-producing districts. By far the largest producer has been the Uravan mineral belt of southwestern Colorado and adjoining parts of southeastern Utah. Approximate production by district to January 1, 1979, is shown below in Table 2.

Table 2. Uranium ore production from the Salt Wash Member for the principal ore districts based on U.S. Department of Energy records (Chenoweth, personal communication, 1980).

District	Tons of Ore	Pounds U_3O_8	% U_3O_8	% V_2O_5
Uravan Mineral Belt	13,987,000	68,590,000	0.25	1.29
La Sal-La Sal Creek District	989,000	6,426,000	0.32	1.46
Lukachukai-Carrizo District	846,000	4,009,000	0.24	1.15
Green River District	670,000	2,632,000	0.20	0.19
East Canyon-Dry Valley	487,000	1,525,000	0.16	1.30
Cottonwood Wash District	295,000	896,000	0.15	0.96
Thompson District	135,000	571,000	0.21	1.16
Henry Mtns. Mineral Belt	79,000	475,000	0.30	1.35
Moab District	83,000	457,000	0.28	1.50
Montezuma Canyon District	31,000	88,000	0.14	1.25
Meeker District	38,000	228,000	0.30	1.13
Other areas	5,000	14,000	0.15	1.27
TOTAL	17,645,000	85,911,000		
Average (weighted)			0.24	1.25

Significant reserves are known to remain in the Uravan mineral belt, the La Sal-La Sal Creek district, the Green River district, and in the Henry Mountains mineral belt. Other listed areas or districts probably contain smaller reserves.

Groups of closely spaced Salt Wash ore deposits are concentrated within several small areas. Salt Wash orebodies are generally characterized in the literature as numerous but small. While it is true that many small deposits are known, this characterization more correctly reflects the size of individual mines than the size of the orebodies. Almost all of the early mining was in areas where ore outcropped or was found at shallow depth. Several mines worked parts of a single deposit or parts of a closely spaced group of deposits. Individual mine production was small, but the aggregate tonnage of ore produced from many small mines working a single deposit or group of deposits was considerably larger. As exploration progressed into deeper ground, ore discoveries were developed by fewer mines producing larger tonnages of ore. It seems likely that had all the orebodies been covered by a few hundred feet of overlying rock, fewer than 50 mines, rather than several hundred, might well have accounted for the bulk of the Salt Wash ore produced to date.

The brief discussion above is a roundabout way of stating that the majority of significant Salt Wash ore deposits are concentrated within a small number of areas. In fact, some 15 small areas within the Uravan mineral belt have produced the bulk of the ore from that district. Many of the more productive areas within the Uravan mineral belt are shown as "cross trends" in Figure 6. The belt was first described by Fischer and Hilpert (1952) as "a narrow, elongated area in which the carnotite deposits generally have a closer spacing, larger size, and higher grade than those in the adjoining areas and the region as a whole". The belt has accounted for approximately 79 percent of Salt Wash production and probably focused exploration attention for more than two decades, deferring the discovery of new major deposits such as those in the Henry Mountains mineral belt.

Most of the Salt Wash production outside the Uravan mineral belt has been mined from approximately ten small, widely separated areas within the Plateau, as indicated in Figure 1. The point to be made here is that only a small number of areas, each of restricted size, contained a large percentage of the ore mined. The large number of small mines outside of these areas has produced only a small fraction of the mined ore.

The average grade of ore mined to date is approximately 0.25 percent U_3O_8. More recently, the higher prices paid for uranium have permitted lower grades of ore to be mined, and the current average grade of mined ore is closer to 0.15 percent U_3O_8. Unlike other uranium-producing districts, however, most mineable Salt Wash orebodies have not been found to be bordered by large haloes of low-grade mineralization which can be mined if more favorable economics permit.

In most of the producing areas, the ores contain from 3 to 15 times more vanadium than uranium; the mined ore has averaged approximately 1.25 to 1.50 percent V_2O_5. Important exceptions are the Green River, Utah, district, where the V_2O_5 to U_3O_8 ratio is less than 3 to 1, and the larger orebodies in the Henry Mountains area, where the ratio is approximately 1 to 1. Discounting the usual few local exceptions, the ores, both reduced and oxidized, are in radioactive equilibrium. No important exceptions are known.

Orebodies tend to be clustered within elongated favorable areas a few miles long by a few thousand feet wide. Average production from these elongated favorable areas has ranged from a few hundred thousand tons of ore to a few million tons of ore. Individual orebodies range in size from a few tons to large masses containing more than one million tons of ore.

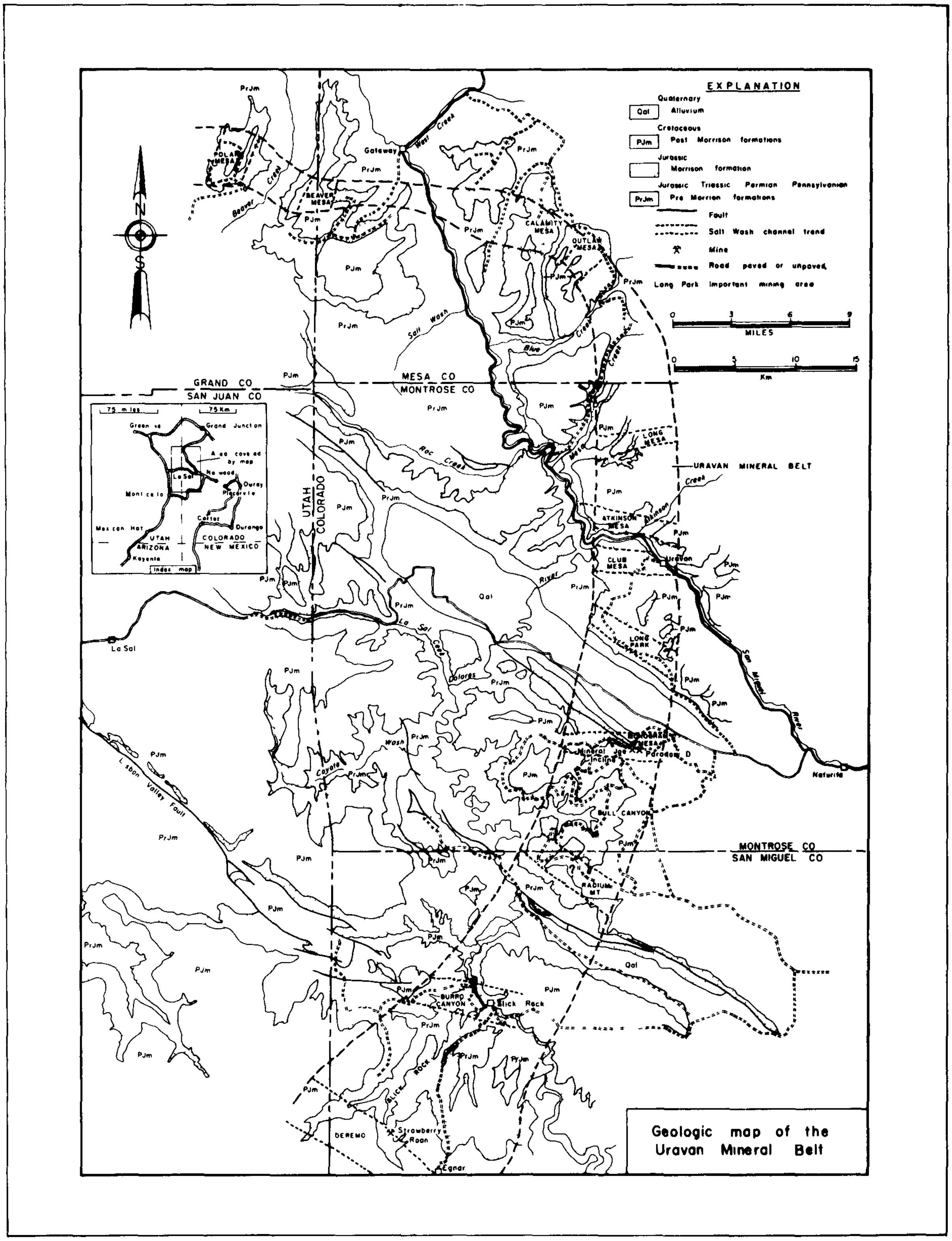

Figure 6. Generalized geologic map of the Uravan mineral belt. Major producing areas are shown as "cross trends" (from Chenoweth, 1978).

Shapes of Deposits

Salt Wash orebodies typically are elongated parallel to sedimentary trends, tabular, and concordant to bedding. The ore averages about 4 feet thick, but in a few places ore thicknesses approaching 30 feet have been mined. Individual orebodies may be connected by weakly mineralized ground, but generally the ore terminates abruptly against barren rock. Figure 7, a plan view of the Deremo Mine at the south end of the Uravan mineral belt, illustrates the typically erratic distribution of orebodies and the relatively small size of individual stopes. The mineralized area at the Deremo was defined by surface holes drilled on 200-foot centers, but most of the ore has been found by mining and close-spaced underground drilling. Figure 8 is a similar map for the King Solomon Mine.

Although much of the mineralization in the Salt Wash sandstones is tabular and concordant with bedding, in some places, and commonly in some deposits, the ore abruptly crosses bedding in smooth curves to form "rolls". The rolls in plan view are generally narrow, not more than a few feet wide, sinuous, and decidedly elongated parallel to local sedimentary structures, major channels, or axes of greater permeability. Most rolls are C- or S-shaped in cross section, but various other shapes have been reported.

The term "roll" was originally used by miners to describe Salt Wash mineralization that cuts sharply across bedding features, and the term was adopted by Fisher (1942). Its use pre-dated, therefore, the discovery of the roll-type deposits in Wyoming, and its use as a descriptive term was unambiguous. As Shawe and Granger (1965) subsequently pointed out, "roll" or "roll front" later assumed genetic implications for the roll-type deposits, implications that may not be entirely applicable to the Salt Wash deposits. In this paper, the term "roll" is used as a descriptive term and not in the genetic sense generally applied to roll-type deposits which occur adjacent to tongues of oxidized sandstone.

Shawe et al (1959) conducted detailed mapping of the Cougar Mine, Slick Rock district, which provides an excellent basis for portraying relations between roll and tabular mineralization. Figure 9 is a series of cross sections through the deposit showing the distribution of uranium-vanadium mineralization as a sequence of complicated roll and tabular forms. Figure 10 is a cutaway block diagram that shows the relations between the mineralization zones shown in the sections of Figure 9. It is readily apparent that the mineralization is essentially one continuous surface which is much contorted in response to sedimentological features in the sandstone. Obviously, rolls and tabular ore are essentially continuous and have been formed by the same ore-forming processes. They differ only in form due to local hydrology in response to sedimentological features.

As Shawe points out, the upper and lower surfaces of the rolls are commonly terminated against clay-rich zones. In many instances, however, tabular orebodies are physically continuous into roll-shaped bodies. Detailed sampling across the ore zones of both tabular and roll orebodies by Shawe (1966) indicates that the zonal distribution of uranium, vanadium, and selenium is similar, suggesting that both types were formed by the same mineralizing processes and that the ore horizon separated waters of different

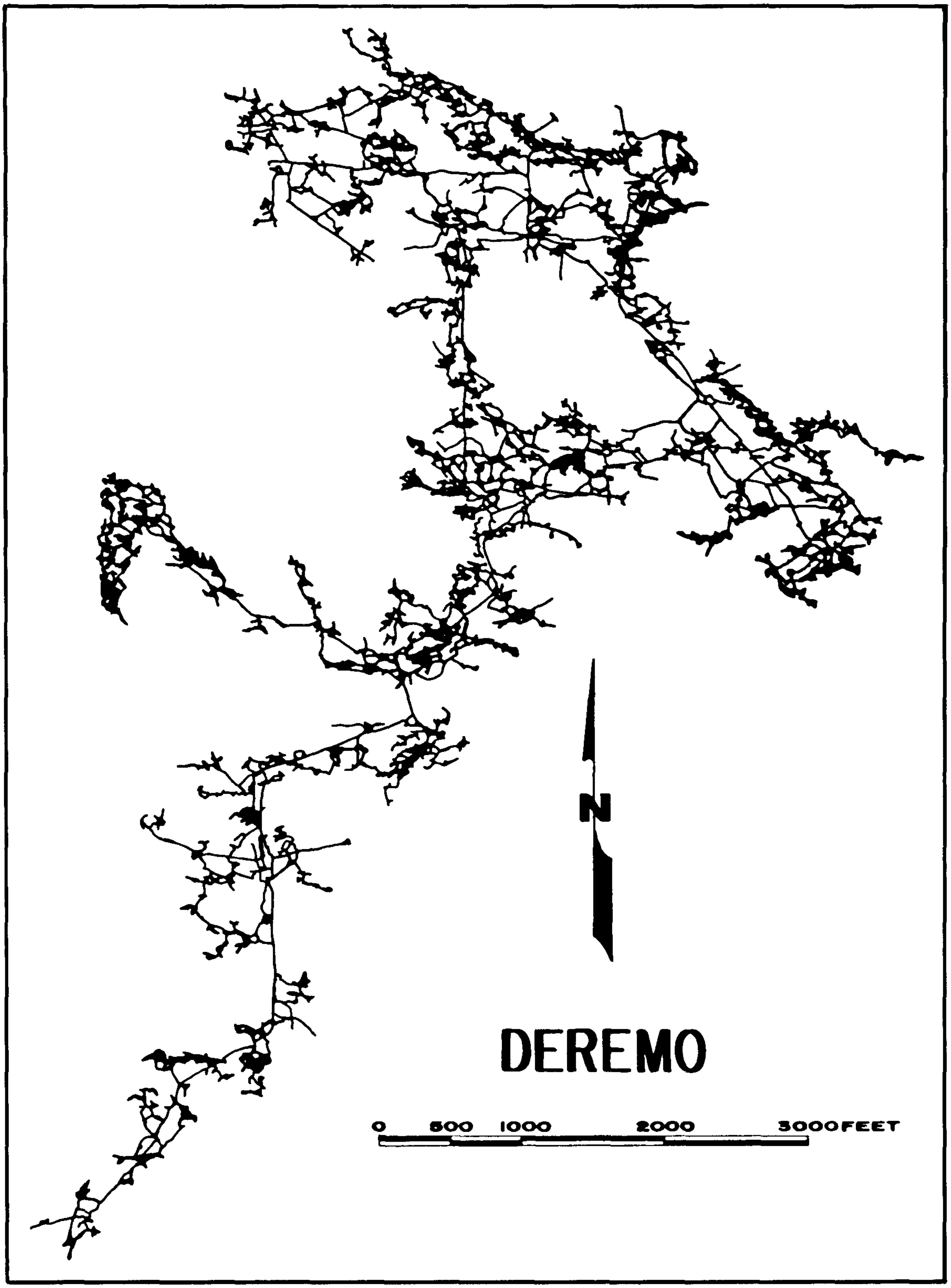

Figure 7. Plan view of the Deremo Mine, south end of the Uravan mineral belt, showing the small size of individual stopes and the complexity of the workings (courtesy of Union Carbide Corporation).

oxidation potential and, probably composition. Oxidation of this shallow orebody has not significantly affected the distribution of elements.

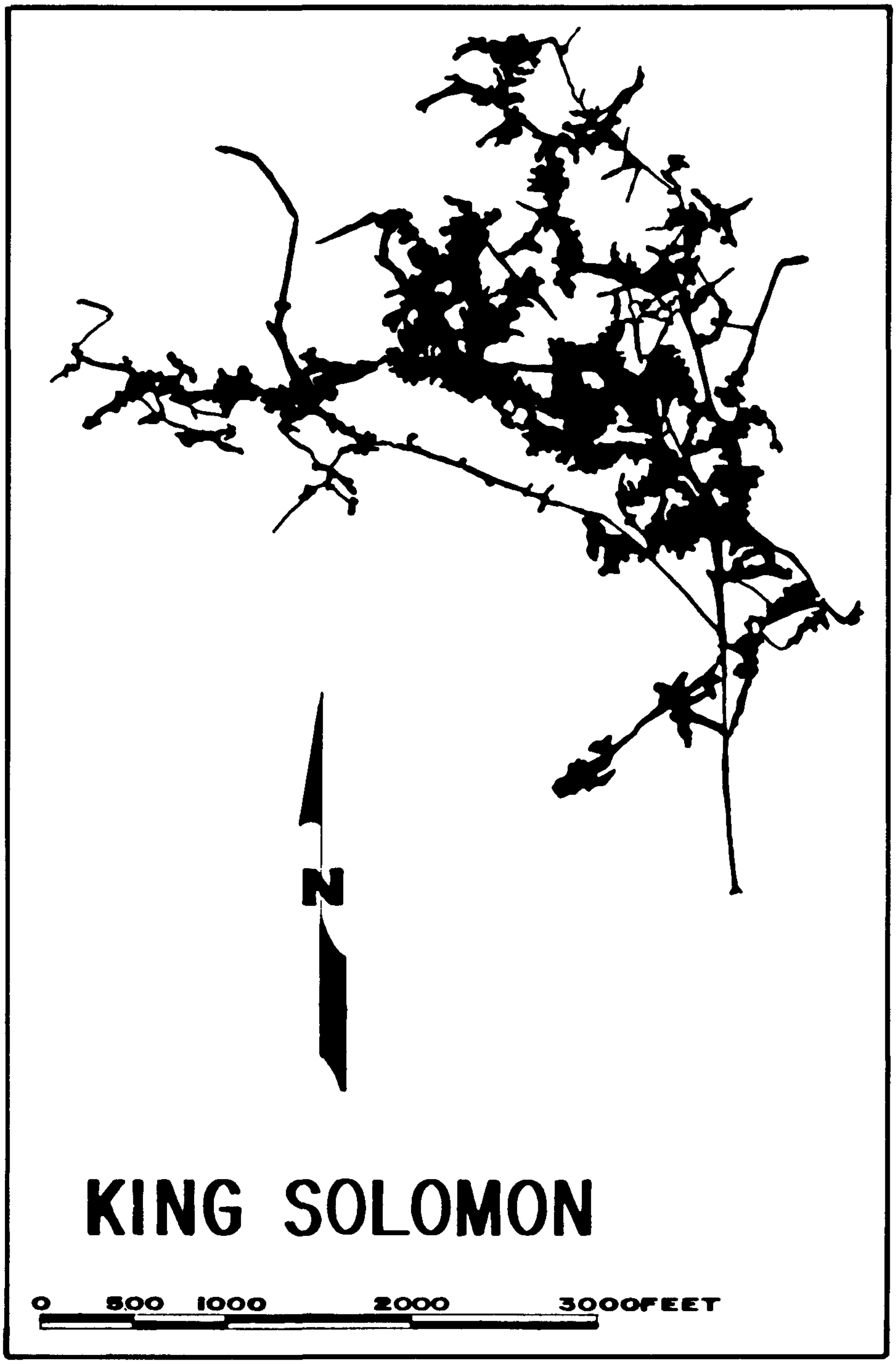

Figure 8. Plan view of the King Solomon Mine, central Uravan mineral belt, showing the complexity of the mine workings (courtesy of Union Carbide Corporation).

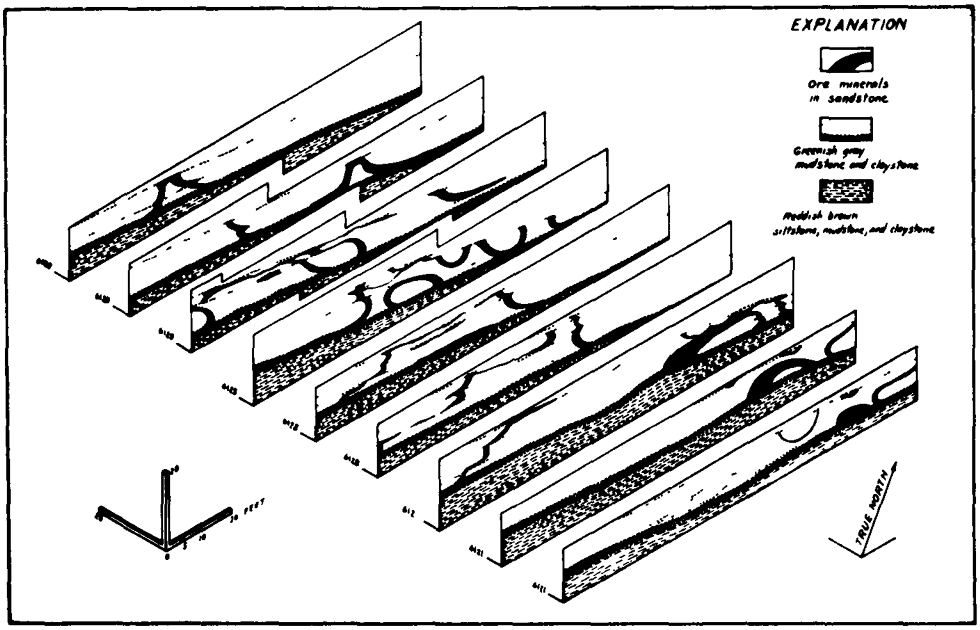

Figure 9. Geologic cross sections for the west-central edge of the Cougar Mine, Slick Rock district, San Miguel County, Colorado (modified from Shawe et al, 1959).

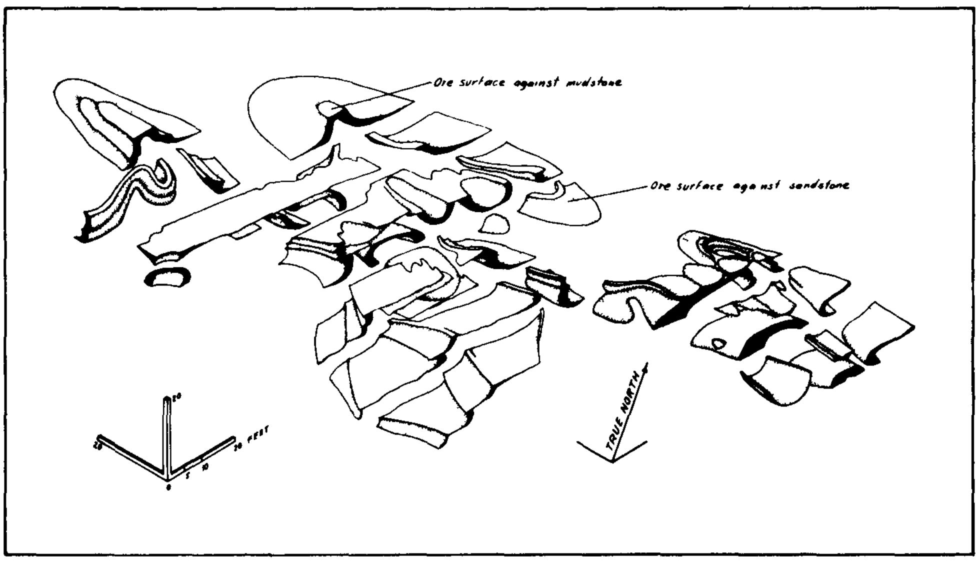

Figure 10. Cutaway block diagram of the west-central edge of the Cougar Mine, Slick Rock district, San Miguel County, Colorado (modified from Shawe et al, 1959).

Rolls tend to be crescent-shaped but can assume a variety of complex forms, as can be seen in Figure 9. Figure 11 illustrates some of the shapes noted by Shawe (1956a). The influence of sedimentological features and fluid flow toward the convex side of the rolls is apparent. The inside boundary, or concave surface of rolls, is generally sharper and more darkly colored. A "knife edge" contact between barren and mineralized rock is very common (Shawe, 1966). Calcite is commonly concentrated at the inside, concave boundary of a smooth, sculptured surface that commonly remains after blasting and mining. The outside, convex, side of the roll, by contrast, tends to be diffuse, reflecting a gradual transition to unmineralized rock. Coloration of the sandstone by uranium-vanadium mineralization strongly accents the difference between the concave and convex sides of the rolls.

Concentric banding or layering within rolls and parallel to the concave surfaces is common. The bands are represented by color changes ranging from light gray to black, presumably reflecting differences in the concentration of ore constituents. Close to the concave surface, the bands mimic the ore waste boundary, whereas farther toward the convex boundary swirls and irregular geometric shapes become more common. Where rolls cut obliquely across well-developed cross-stratification, additional dark-colored mineral concentrations occur as bands parallel to the cross-stratification. A similar mineral distribution pattern has been produced experimentally by Ethridge et al (1980).

Opinions differ as to the relative abundance of roll- and tabular-shaped mineralization. This most likely reflects differences in the proportions of the two ore shapes between individual deposits, the difficulty of systematically differentiating between and measuring the proportions of each shape, and the different perceptions and training of the observers. For example, tabular mineralization is reportedly common in the Uravan mineral belt, whereas roll mineralization is reportedly dominant in the La Sal trend. Shawe et al (1959) made the important observation that roll-shaped mineralization appears to be more abundant where the host sandstone contains numerous shale horizons, which appear to break the mineral horizon into a series of rolls within the intervening sands. Massive sandstones, by contrast, are characterized by more tabular mineralization. This seems simply to reflect the tortuous hydrology of interbedded sand-shale sequences, which tend to produce rolls in contrast to simple hydrologic interfaces which can form in a more homogenous aquifer.

Sedimentary features exert a strong control on the shape and distribution of Salt Wash uranium deposits. On a broad scale, clusters or trends of deposits are associated with major sedimentary channels and tend to occur along their margins. On a more local scale, individual deposits or lenses of mineralization commonly terminate against shale horizons, channel margins, and any other sedimentological feature that produces permeability changes. The effect of such sedimentological features on local ore distribution is unquestioned, but they are probably not significant in controlling the regional position of mineralization or the ore-forming process. The general position of deposits and/or trends reflects broader hydrologic conditions which are more important to exploration and resource studies. Even the distribution of uranium and vanadium within the ore lenses is strongly affected by sedimentological features which lead to concentrations along cross bedding, adjacent to scour surfaces, and in association with clay gall zones. Such features, although dramatic in underground exposures, are exceedingly complicated and generally not a fruitful subject for regional studies.

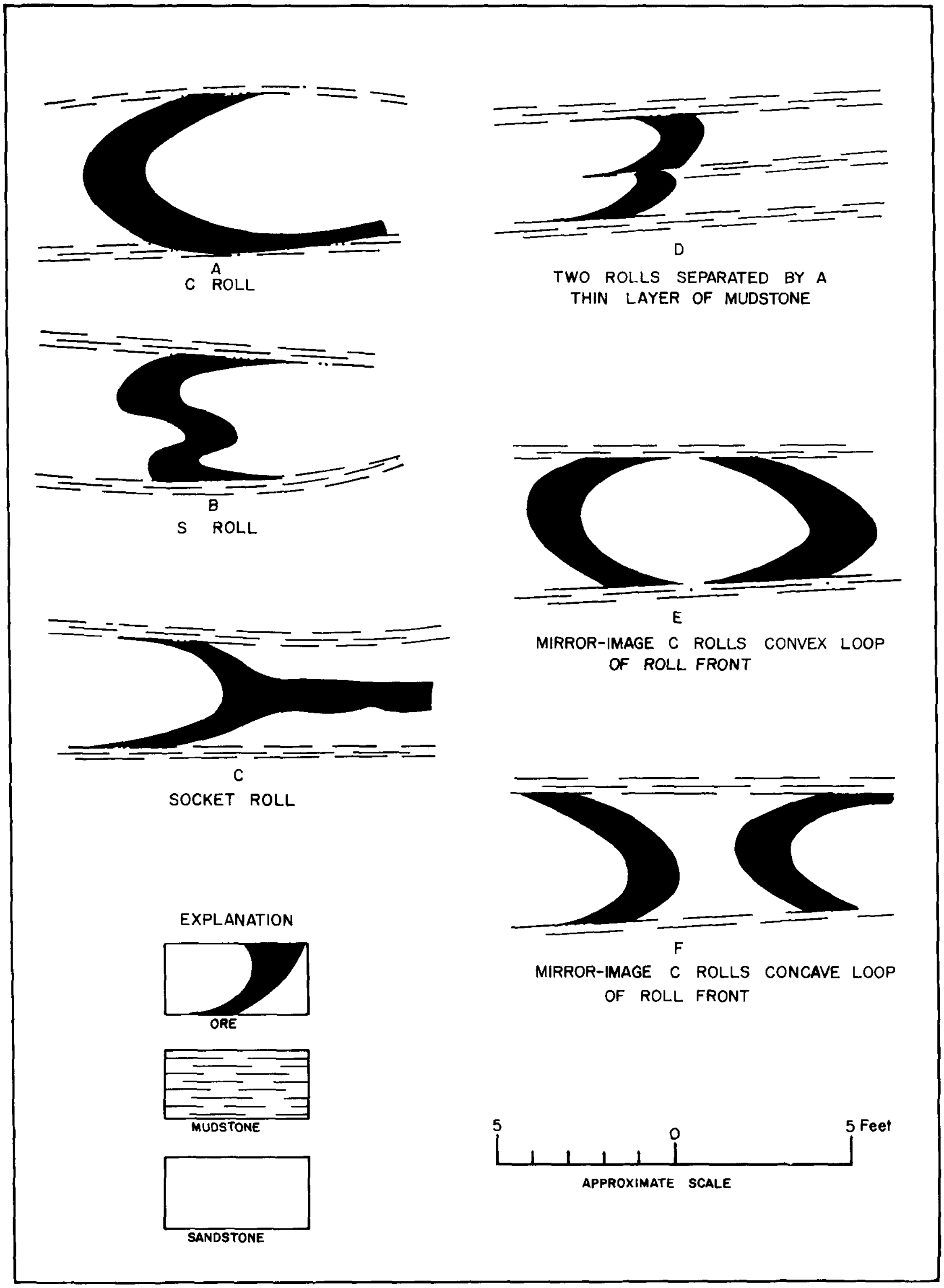

Figure 11. Schematic cross sections for various shapes of uranium-vanadium roll deposits (from Shawe, 1956a).

Structural Control

Neither large- nor small-scale structures of Laramide or younger ages have influenced the patterns of Salt Wash sedimentation or the localization of ore districts or orebodies. However, faults of Laramide or younger ages consistently displace the orebodies. On the other hand, there is considerable evidence which suggests that existing or growing structures active at the time of Salt Wash sedimentation were influential in determining patterns of Salt Wash sedimentation which in turn influence the localization of ore districts.

Many of the ore trends in the Uravan area are adjacent and parallel to the northwest-trending salt anticlines of the region, and it seems probable that these structures, active at the time of Salt Wash sedimentation, diverted major stream flows into channels paralleling those axes. The detailed work by Peterson (1980) in the Henry Mountains strongly suggests that growing structures influenced depositional trends and patterns of the lower Salt Wash Member in that area. Huffman and Lupe (1977) concluded that active structures in northeastern Arizona and northwestern New Mexico exerted a pronounced influence on depositional patterns of Morrison sedimentation in the Lukachukai-Carrizo area.

Sedimentary Control

The most obvious controls influencing the location of Salt Wash orebodies and ore trends are sedimentary. On a large scale, the ore-producing districts appear to be localized along thick depositional axes of sedimentation. Figure 4 illustrates an apparent coincidence of the Henry Mountains mineral belt and the Green River district with a thick, north-trending depositional axis; the Lukachukai-Carrizo deposits fall within a southeast-trending depositional thick. The deposits of the Uravan area, while within a generally thicker area of sedimentation, also appear to be localized within an area of large-scale facies changes. Immediately west of the mineral belt the Salt Wash is composed dominantly of floodplain deposits interspersed with relatively few but large distributary channels. Within the mineral belt, smaller but more numerous distributary channels are interspersed with areas of floodplain deposits. Shawe (1962) suggested that the slightly thicker Salt Wash sediments in the area of the Uravan mineral belt were deposited in a small shallow basin developed during Salt Wash time. East of the Uravan mineral belt, the Salt Wash is composed of nearly continuous layers of horizontally bedded sandstone which appear to have been deposited in standing water (Shawe, 1962). A cross section drawn from west of the Uravan belt to east of the Uravan belt would probably show Salt Wash transitions from a coarse-grained meander belt to fine-grained meander belt and finally to prograding delta sands.

Individual ore deposits or groups of deposits are localized within reduced, permeable, carbonaceous Salt Wash sandstones. Many of the deposits in the Uravan area are within well-defined sandstone "channels" a few thousand feet wide and up to a few miles long. Recent work by Noel Tyler (personal communication, 1980) in the Slick Rock district of Colorado has demonstrated that the construction of percent sandstone maps based on detailed sections of the total Salt Wash can be useful in defining the major depositional axes of

Salt Wash sedimentation in that area. Figure 12 identifies the major axes of sand deposition in the Slick Rock area, and Figure 13 (modified from Tyler, written communication, 1980) shows the detail of the north channel shown in Figure 12.

In reduced Salt Wash sandstones outside of the Uravan mineral belt, clearly defined channels are generally of less obvious importance as ore controls. The La Sal district appears to be an exception in that several orebodies have been defined along the southern margin of an east-trending channel system over a distance of several miles (Fig. 16). Individual deposits tend to be several hundred feet long parallel to the channel axis and are separated by a few hundred feet of sandstone. These areas are probably not barren but contain thin, low-grade and erratic mineralization that may in some instances lead to connections between deposits when mining has been completed (see, for example, Fig. 7). In all mineralized Salt Wash areas, however, zones of reduced gray sandstone containing carbonaceous material and interbedded gray clays appear to be directly associated with ore deposits.

The upper third of the Salt Wash Member is the most productive unit within the Uravan mineral belt. The so-called third rim or upper sandstone in that area refers to a single, semi-continuous sandstone unit at the top of the Salt Wash. Outside of the Uravan mineral belt, the upper sandstone is not necessarily the most important ore horizon, even though it may be present in the stratigraphic section. In both the Meeker and Thompson districts, most of the production has been mined from the lower sandstones. The large deposits in the Little Rockies district of the Henry Mountains are within the lower sandstone of the Salt Wash.

It is locally common for major Salt Wash orebodies to be overlain by sporadically mineralized Brushy Basin sandstones. In the La Sal district, for example, several ore-grade mineralized holes in the Salt Wash have mineralized horizons in the overlying Brushy Basin sandstones. In one area in the La Sal district, several holes intersected mineralization greater than 5 feet at 0.2 percent U_3O_8 in the Brushy Basin and also intersected ore-grade mineralization in the Salt Wash. Phoenix (1958) noted the proximity of basal conglomeratic horizons in the Brushy Basin Member to deposits in the underlying Salt Wash Member of the Uravan mineral belt. These observations suggest that permeable horizons in the Brushy Basin are significantly related to Salt Wash deposits, possibly as channels for de-watering the shales and focusing the uraniferous solutions into the Salt Wash where hydrologic continuity existed.

Relationship of Orebodies to Oxidation-Reduction Boundaries

Most of the major orebodies and clusters of closely spaced orebodies within the Salt Wash sands appear to be spatially related to the boundaries of reduced host sandstones with adjacent oxidized sediments (Nestler and Chenoweth, 1958). This relationship has not been well documented in the literature. In areas such as the Uravan mineral belt, where channel systems strongly influence the localization of ore, the major orebodies are generally found to be clustered along one edge of the channel, in close proximity and parallel to red oxidized sediments. The bordering red sediments in some areas probably represent overbank and floodplain equivalents to the channel sandstone, but in other areas the gray channel sands pass abruptly into pink or red sandstone which appears to be depositionally continuous with the gray reduced sands. In the Shootaring Canyon district of the Henry Mountains, which is not obviously channel controlled, large Salt Wash orebodies are reported to occur in reduced gray sand along a trend parallel to, and not more than a few hundred yards from, reddish-brown oxidized sandstone (see Fig. 14).

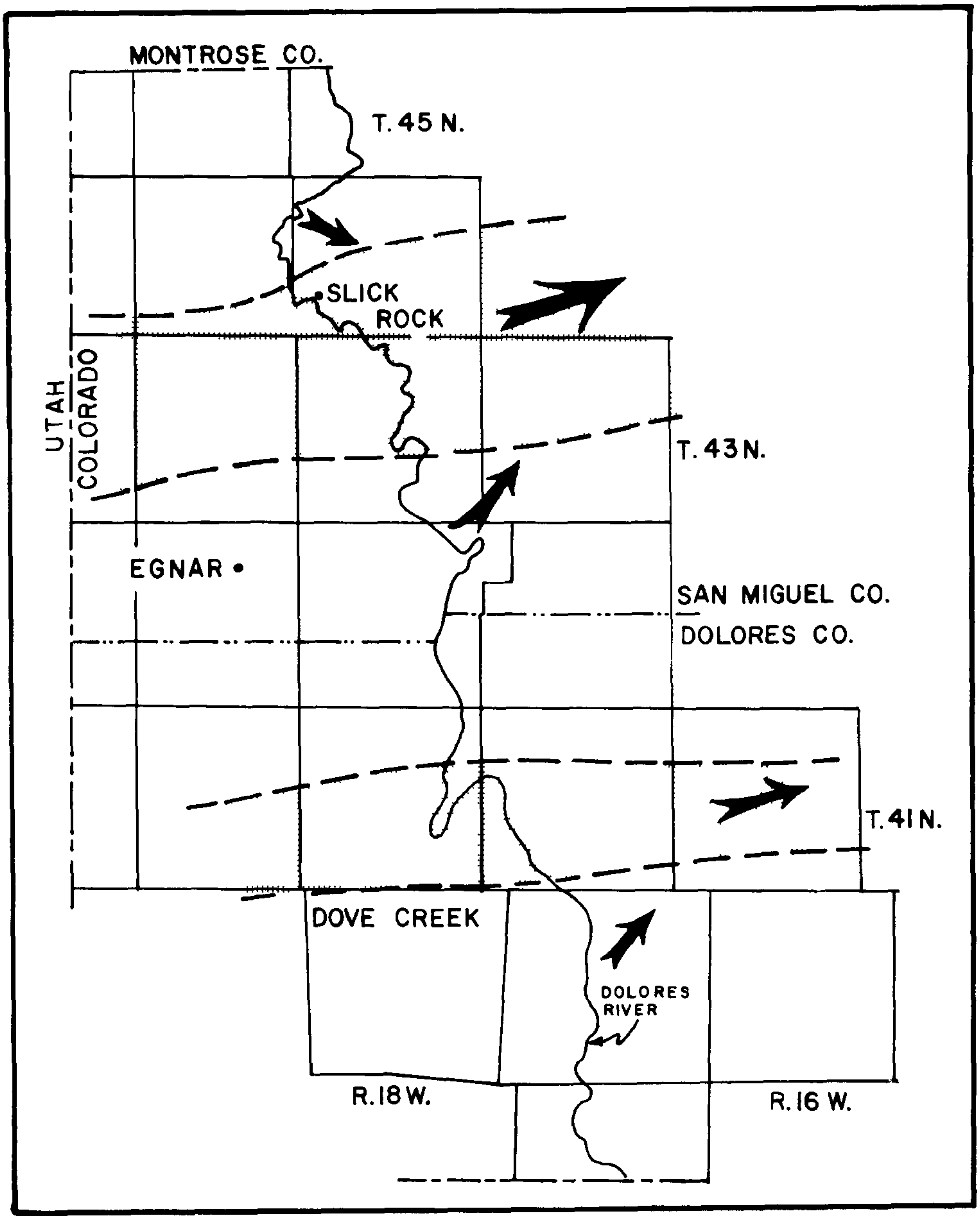

Figure 12. Generalized and inferred patterns of major sandstone depositional axes and tributary fluvial systems of the Salt Wash sandstone in the Slick Rock area of the Uravan mineral belt (from Ethridge et al, 1980).

There apparently are, therefore, two different types of oxidation-reduction boundaries, those entirely within sandstone and those between dominantly sandstone and dominantly mudstone sections, that have different distributions and probably different significances with respect to uranium formation and distribution. The type of oxidation-reduction boundary that occurs entirely within sandstone is not well described in the literature. Such boundaries seem to occur within major channel systems, generally with the oxidized sands occurring in the direction from which the sediments were derived. This relation is similar to the regional distribution of oxidized and reduced sediments which is interpreted to change from red toward the source area to grays and gray-greens toward the distal part of the depositional system.

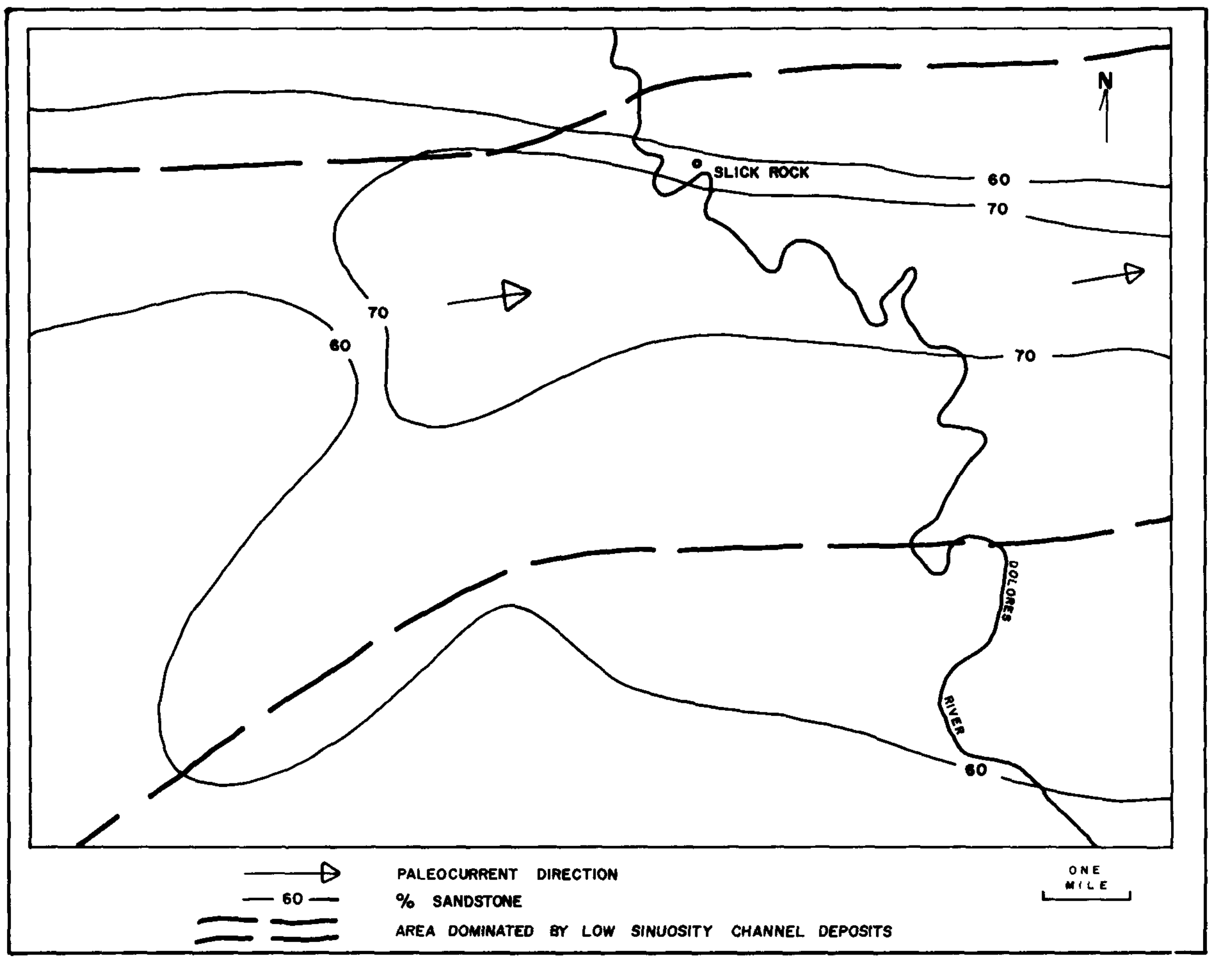

Figure 13. Generalized map of the Slick Rock area, San Miguel County, Colorado, showing major sedimentological features for the Salt Wash Member (modified from Tyler, written communication, 1980).

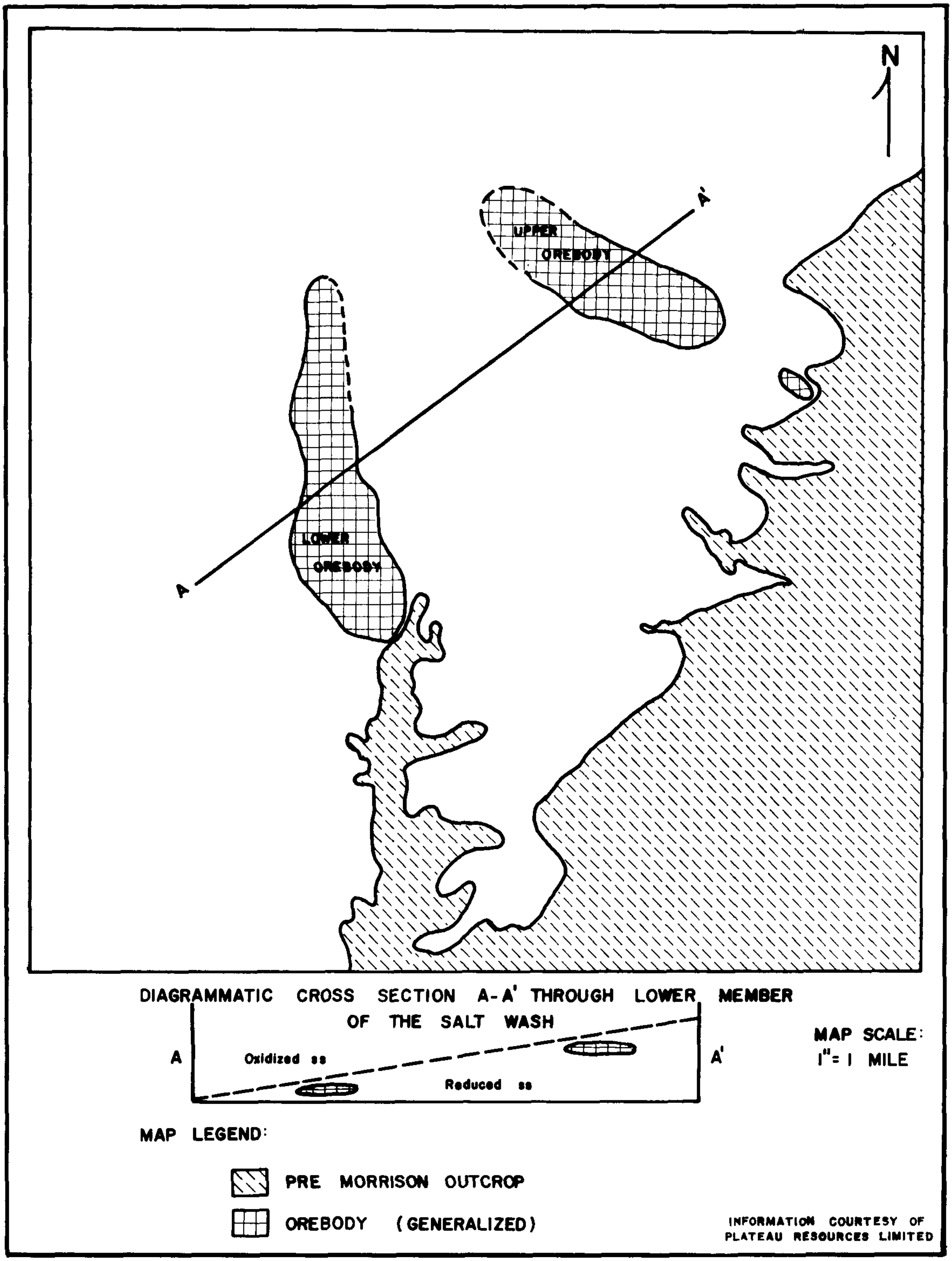

Figure 14. Generalized geologic map and cross section of the major uranium orebodies at Shootaring Canyon, Garfield County, Utah, showing relations of orebodies to oxidized and reduced sandstone boundaries (courtesy of Plateau Resources Limited).

On a much more detailed scale, an oxidation-reduction boundary was exposed in the Deremo Mine and is schematically represented in Figure 15. The cuspate, roll-like forms along the boundary suggest that the vanadium-uranium-bearing sandstone was at least locally invaded by oxidizing waters from the hematitic sandstone. Minor redistribution and enrichment of the ore minerals appear to have occurred at the boundary. The intermediate "bleached" zone between the ore-bearing sands and the hematitic sands contains copper carbonate which may have formed during the oxidizing event or may be a product of oxidation of sulfides in the mine workings. Table 3 presents chemical analyses for a suite of samples collected across the boundary. The element distributions are similar to those across oxidation-reduction boundaries in other types of uranium deposits, except that strong zoning does not seem to be present. The absence of carnotite and the evidence for destruction of the ore assemblage suggest that the oxidation occurred during or soon after ore deposition when the mineralization was still easily redistributed. Although this feature is expressed only locally in mine workings, it may be part of a broader oxidation zone, possibly an oxidized channel sand as described above, but this has not been confirmed.

Orebodies within reduced channel sands, adjacent to oxidized overbank deposits, tend to be larger and more numerous near the oxidation-reduction contacts than in reduced sands more distant from such contacts. In the La Sal channel, the orebodies occur only along the south side of the reduced sandstone (Fig. 16). The central and northern portions of the channel are barren of economic deposits, although they contain dispersed mineralization associated, apparently, with plant debris (Fig. 16). Figure 17 illustrates the close association of the major orebodies in the Slick Rock district of Colorado to oxidation-reduction boundaries in that area. The major orebodies shown in Figure 16 appear to be closely associated with the northern edge of the Slick Rock channel shown in Figures 12 and 13. Other examples of ore concentrations near oxidation-reduction contacts could be cited, but these examples serve to emphasize this important association.

Reduced channel sandstones bounded by red-bed sequences not uncommonly contain islands of red shale and, less commonly, red sandstone with no apparent connection to the bounding red sediments. This suggests that portions of the channel sequence were originally red beds but have been engulfed in the diagenetic reducing event which characterizes the channel axes. It is likely, in fact, that the oxidation-reduction boundary oscillated for some period of time depending upon ground water flow rates within the reduced channels and from the compacting oxidized sediments. Local islands of red sediments within gray, and vice versa, even in close proximity, may be expected.

In general, the highest grade ore in any deposit occurs next to the oxidation-reduction boundary. Where narrow zones of gray reduced sandstone extend into red oxidized sands, the grade and continuity of the ore increase substantially. These zones, bounded above and below by red sediments, do not make major mines in themselves, but produce high-grade, low-cost "sweet spots" within larger mines.

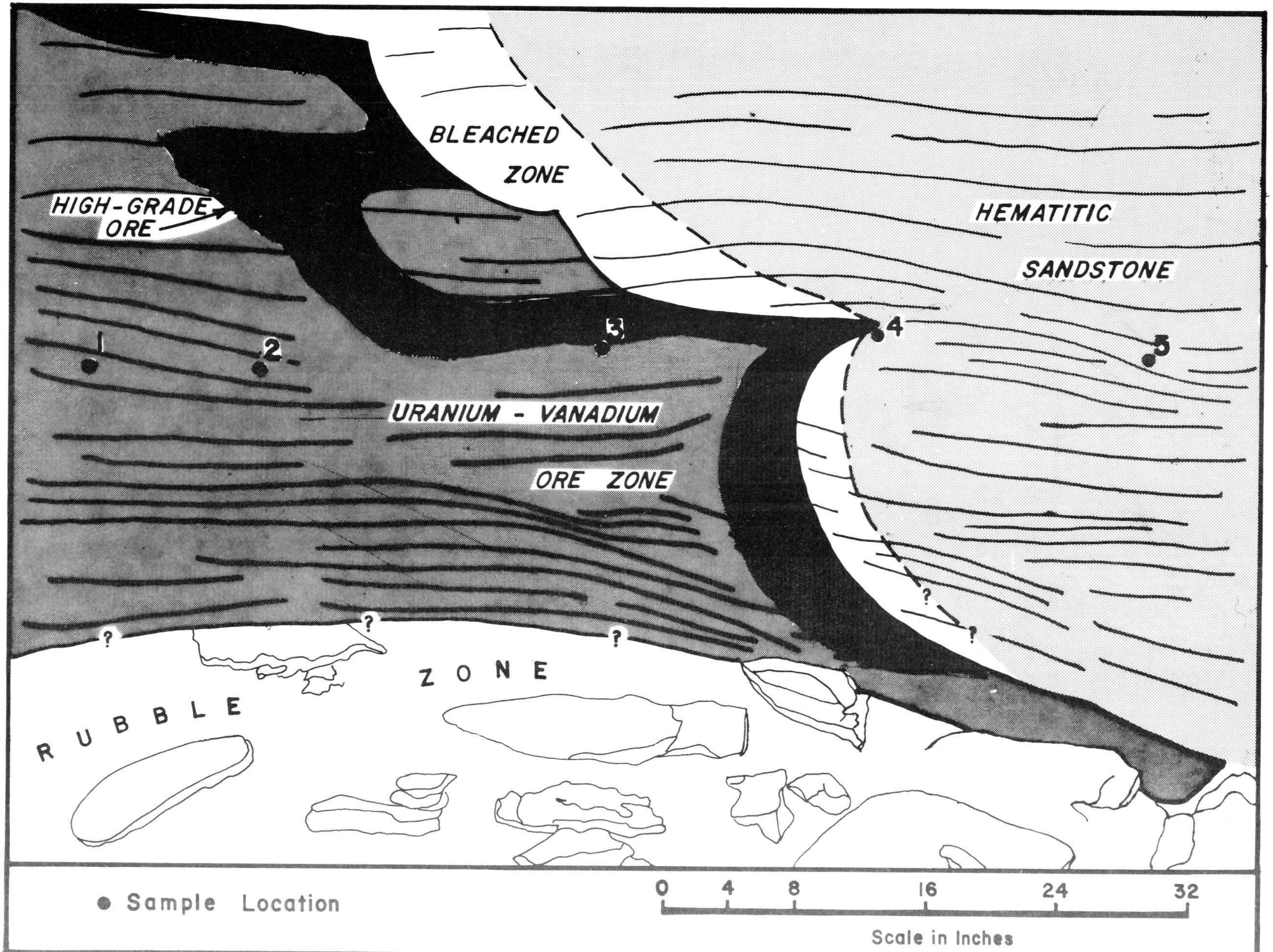

Figure 15. Schematic cross section of an oxidation-reduction boundary entirely within sandstone, Deremo Mine, south end of the Uravan mineral belt (courtesy of Union Carbide Corporation).

Table 3. Concentrations of some elements in samples collected across an oxidation-reduction boundary in the Deremo Mine (see Fig. 15 for sample locations).

Element (concentration in ppm)	Sample Number				
	1	2	3	4	5
U	803	878	1013	113	371
V	17807	38037	52939	280	250
Se	365	520	470	255	115
Mo	20	25	5	< 5	< 5
Cu	78	170	502	302	40
Pb	< 5	< 5	15	190	10
Zn	19	38	62	13	9
As	63	38	68	20	25
S	635	1012	736	220	230
Cr	8	14	13	5	5
Fe^{+3}/Fe^{+2}	2.5	1.9	2.8	4.1	9.8

Courtesy of Union Carbide Corporation

Small-Scale Ore Guides

Small-scale guides to ore deposits in Salt Wash sandstones have been discussed in many publications. Probably the most important are the presence of a relatively thick section of reduced sandstone, carbonaceous material, and interbedded gray mudstones or mudstone conglomerates. Many orebodies occur within highly cross-bedded channel sandstones. Most ore trends parallel paleocurrent directions, but the long axes of individual orebodies may be oriented at sharp angles to the major trend axes.

Ore Mineralogy

The ores occur, however, in various degrees of oxidation, depending largely upon their proximity to the surface and their position with respect to the water table.

Emphasis in this report is placed on the economically important unoxidized, black vanadium-uranium ores which have accounted for the majority of uranium production. A brief discussion of the mineralogy of unoxidized and oxidized ores is pertinent to exploration and resource studies. The primary unoxidized ores are generally referred to as primary or black ores, whereas the secondary oxidized ores are dominated by tyuyamunite and carnotite and are referred to as supergene, carnotite or oxidized ores.

Primary Ores

The primary ores represent the majority of the deposits currently being mined, including the Deremo, Shootaring Canyon, La Sal, and numerous smaller deposits. The preservation of these unoxidized deposits is due to their position below the water table. Mineralogy of these ores was studied in the middle 1950s, soon after the discovery of the primary ores, and has received little attention since then. Papers compiled by Garrels and Larsen (1959) discuss both unoxidized and oxidized ores but emphasize the latter, since they comprised the majority of ores mined to 1959.

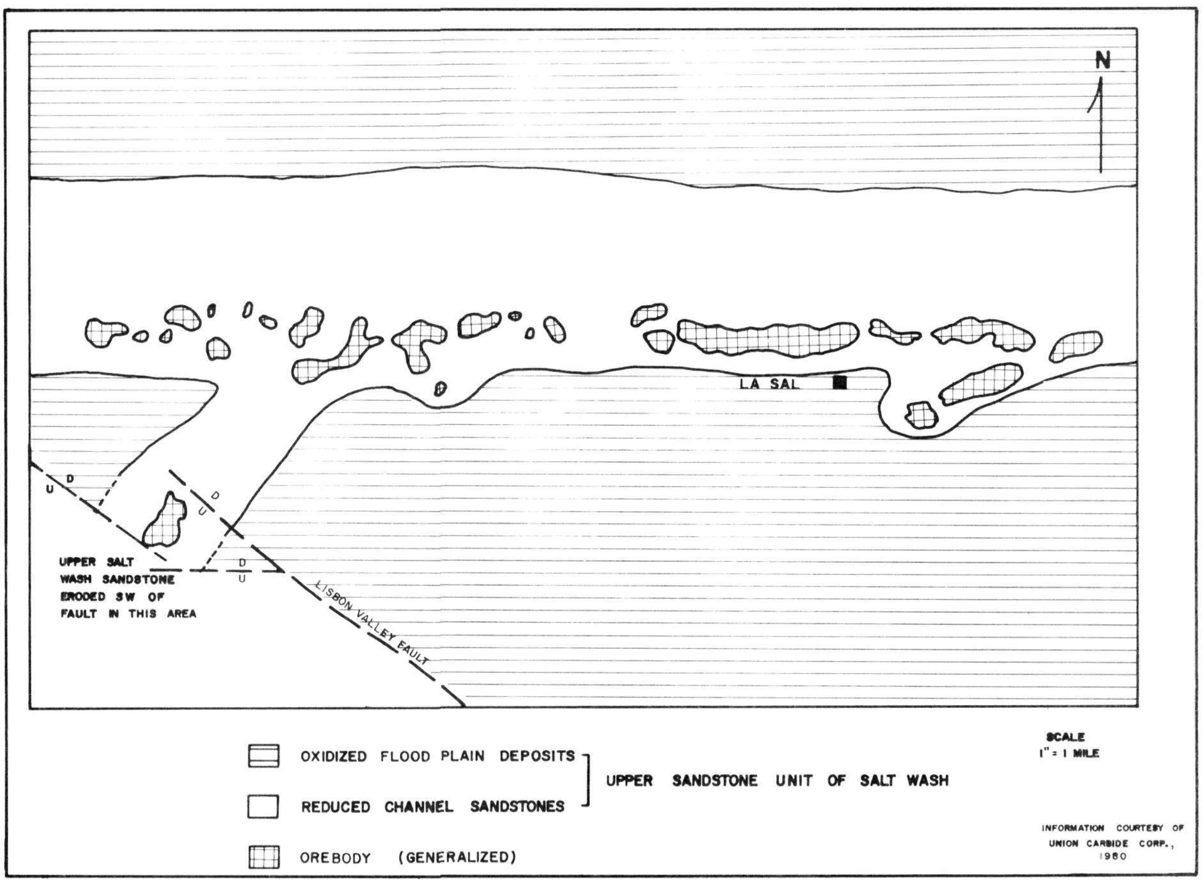

Figure 16. Generalized map showing the distribution of orebodies in the upper sandstone unit of the Salt Wash Member, La Sal channel, San Juan County, Utah (courtesy of Union Carbide Corporation, 1980).

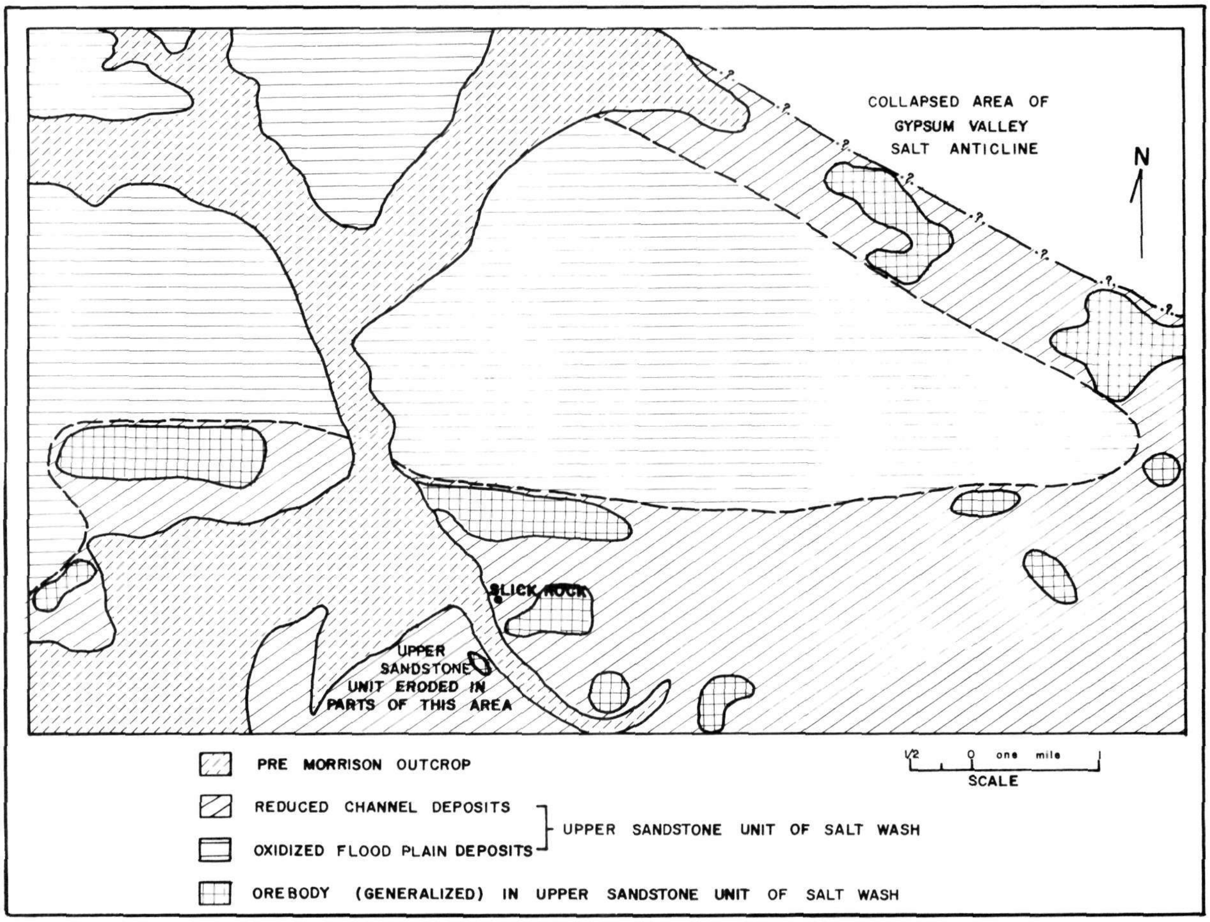

Figure 17. Generalized geologic map showing relations of major orebodies in the Slick Rock area, San Miguel County, Colorado, to oxidized and reduced boundaries in the upper Salt Wash sandstone (courtesy of Union Carbide Corporation).

The primary ore impregnates the matrix of the sandstone and replaces some detrital quartz and feldspar grains. It is dark gray to black and tends to be homogenously distributed, except for the heterogeneities of the sandstone itself. The ore minerals of uranium and vanadium and associated gangue minerals are fine grained and intimately mixed, making megascopic mineral identification virtually impossible. The primary ore is composed of the low-valent (IV) uranium minerals uraninite and coffinite, the low-valent vanadium mineral montroseite (III), and vanadium alumino-silicates. Minor amounts of copper, iron, lead, zinc, and molybdenum are known. Arsenides and selenides are less common, and thorium and associated rare earths are uncommon in Plateau ores.

The uranium minerals uraninite and coffinite are very fine grained and are commonly intimately associated with carbonaceous trash or coalified wood. Uraninite has been reported occurring as hard lustrous grains and as soft waxy material. "Sooty" uraninite does occur, but it is not common in oxidized ores. Uraninite has been found as a replacement of plant material, in particular the cell walls of fossil wood. It also replaces iron sulfides and detrital quartz grains in sandstones near carbonaceous trash. Coffinite is largely restricted to carbonaceous material and is commonly found filling cell cavities.

In the primary ores, vanadium occurs in the low-valent vanadium mineral montroseite and in a suite of vanadium alumino-silicates including vanadium-bearing chlorites and vanadium hydromicas. Vanadium oxides predominate over vanadium alumino-silicates in deposits with vanadium-uranium ratios of less than 15:1 (Weeks, 1959). Montroseite, VO(OH), (III) is the most important of the vanadium oxide minerals in the ore. It is black in color and occurs as steel-black, prismatic lath-shaped crystals, or as brittle crystalline jet-black masses. Montroseite oxidizes easily to paramontroseite (Evans and Mrose, 1955), and samples of montroseite exposed to air will alter to paramontroseite in a matter of a few months (Weeks, 1959). Montroseite fills the cell structure of fossil wood, but because of its elongate bladed crystal habit it obscures the wood structure. Montroseite tends to form rosettes in sinuous bands in sandstones or fossil wood. Vanadium oxides and silicates occur in the pore spaces of the sandstone and replace detrital quartz grains and fossil wood.

Pyrite and marcasite are important accessory minerals in primary ores. Pyrite formed during diagenesis of the sandstones (pre-ore) impregnates or forms pseudomorphs after wood and occurs as discrete nodules (Weeks, 1959). Framboidal pyrite of diagenetic origin has not been reported in the Salt Wash. In Shawe's carbon facies, pyrite constitutes about 1 percent (by volume) of heavy minerals (Shawe, 1976a). This is a low percentage, and the lack of framboidal pyrite would indicate an environment of formation with a very low iron and/or sulfur content.

A younger generation of pyrite, characterized by euhedral and massive pyrite and enriched in cobalt and nickel, is associated with ore formation. Studies in the Slick Rock district indicate that pyrite constitutes 7 percent of the heavy mineral fraction in the altered ore-bearing facies of the third rim sandstone (Shawe, 1976a). The increase from 1 percent in barren reduced sandstone to 7 percent near orebodies suggests an addition of sulfur and possibly iron. This is compatible with roll-type deposits and Shoemaker et al (1959) indicate that iron is strongly enriched in the ore zones. The Salt Wash ores contain noticeably less pyrite than most roll-front ores.

Jordisite is reportedly the most common and abundant of a group of accessory minerals that includes galena, sphalerite, jordisite, and copper and silver minerals. In our experience, jordisite is almost always found underneath the vanadium-uranium mineralization and never intermixed with or crosscutting it. Jordisite occurs in layers 1 to 2 feet thick, and it is a steel-gray color. The Deremo Mine contains some of the best examples of massive jordisite found in the Salt Wash deposits. Calcite, dolomite, and barite are present within and close to ore as cement in the sandstone. Total carbonate contained in most Salt Wash ore is less than 6 percent.

Secondary Ores

The earliest mined uranium-vanadium ores of the Salt Wash were the oxidized carnotite ores which cropped out on the surface and in canyon walls. These ores can be divided into the partially oxidized "blue-black" ores and the completely oxidized yellow carnotite ores. The mineralogy of the Salt Wash ores is controlled more by the extent of oxidation than by changes in the vanadium-uranium ratios (Botinelly and Weeks, 1957).

Intermediate between the unoxidized black ores and the fully oxidized yellow carnotite ores is the "blue-black" mineralization. This ore is common to all areas of the Uravan mineral belt, as are the other two ore types. It shows a strong preference for carbonaceous accumulations as does the carnotite ore, presumably reflecting areas of greatest protection from intense oxidation and destruction. The predominant ore minerals are partially oxidized vanadium (IV) and (V) minerals, principally doloresite and hewettite. Rauvite is the principal uranium mineral in these ores and is a uranyl vanadate containing uranium (VI) and vanadium (V).

Carnotite has been known in the Uravan mineral belt since the 1880s, and the early mines of the area exploited shallow carnotite ores. Hillebrand and Ransome (1905) and Hess (1914) recognized the possibility that the yellow carnotite ores were a secondary product derived from older materials. In the late 1940s, the popular theory suggested that the ores were contemporaneous with the sandstone and that the carnotite was a primary mineral. As late as the early 1950s, it had not been recognized (Fischer, 1950; Stokes, 1952) that the carnotite ore was a secondary product formed from primary mineralization. Progressively, however, there was an increase in the amount of unoxidized black ore discovered and mined, and its relations to the carnotite became appreciated. Several studies have now shown how carnotite ore forms through the progressive oxidation of primary "black ore" (Weeks, 1956; Weeks et al, 1959).

With sufficient oxidation of the vanadium-uranium ores, montroseite and the uranium minerals alter to rauvite and finally to carnotite. The vanadium alumino-silicates of the primary ore are, however, relatively stable. Once vanadium has been completely oxidized from a mixture of (IV) and (V) to only (V), the mineral assemblages tend to be brown, red, and orange rather than black and blue-black. Vanadium fixes all of the available uranium (VI) and forms uranyl vanadates. Excess vanadium may form a variety of vanadates including hewettite, pascoite, hummerite, and, rarely, navajoite.

Virtually all the uranium oxidized from the primary vanadium-uranium ores is protected against leaching and mobilization by incorporation into vanadate minerals. The deposits, therefore, undergo essentially no loss of uranium or other metals. Uranium movement is more significant in ores with low vanadium contents (Fischer, 1955). The Bitter Creek deposit (Heyl, 1957) provides an excellent example of the progressive oxidation of primary ore (Fig. 18). The near-surface ore zones (first zone) are completely oxidized and are typical of the carnotite mineral assemblages common through the Uravan mineral belt. The deeper portions of the deposit (second zone) were partially oxidized by downward-percolating oxygenated surface waters and contain the "blue-black" ores of mixed and intermediate oxidation states. The deeper ore zones (third zone) are relatively unaffected by oxygenated surface waters and contain the primary ore.

Composition of Sandstones

Non-Uraniferous Sandstones

Several studies of the chemical composition of mineralized and unmineralized Salt Wash sandstones have yielded analyses which are remarkably similar (Newman and Elston, 1959; Shoemaker et al, 1959; Foster, 1959). Most of these analyses, however, were performed prior to 1960. Since that time, new drill holes and new mine sampling opportunities, and improved analytical techniques, have provided better opportunities to compare non-uraniferous and uraniferous sandstones. Essentially no new studies have, however, been conducted.

The average chemical composition of Salt Wash sandstones varies only moderately from the average composition of Paleozoic and Mesozoic sandstones of the Colorado Plateau (Shoemaker et al, 1959). Table 4 illustrates the similarities between these various unmineralized sandstones. The Salt Wash sandstones contain significantly more calcium, magnesium, and copper than the average

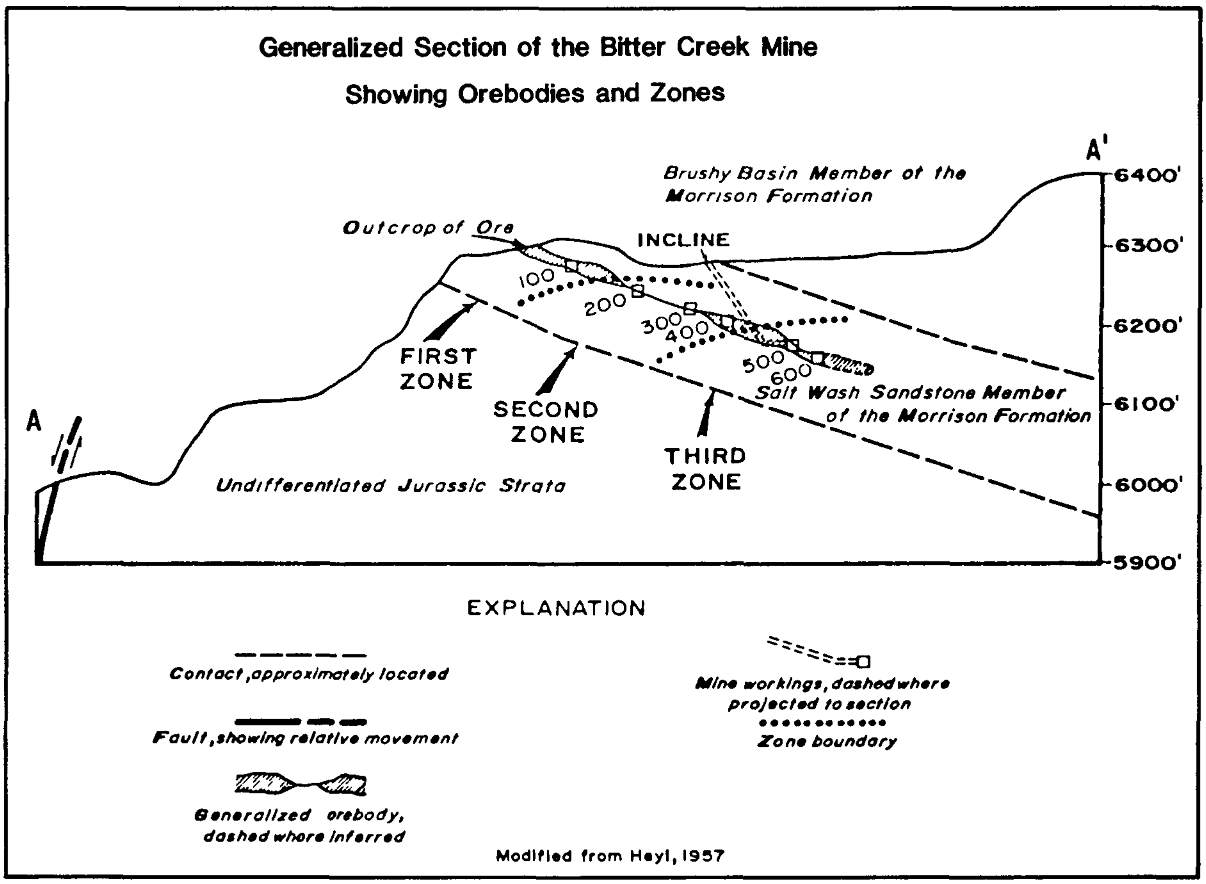

Figure 18. Generalized cross section of the Bitter Creek Mine showing orebodies and oxidation zones (modified from Heyl, 1957).

sandstones from other formations of the Colorado Plateau, but are significantly lower than average in iron and probably lower in potassium, boron, cobalt, nickel, and yttrium. The sandstones of the Moss Back and Shinarump Members of the Chinle Formation are similarly high in copper and lower in potassium, when compared with averages for Paleozoic and Mesozoic sandstones.

Table 4. Average chemical composition of Paleozoic and Mesozoic sandstones from the Colorado Plateau and non-uraniferous sandstones of the principal uranium ore-bearing strata (modified from Shoemaker et al, 1959).

Concentration in Parts Per Million

Element	Salt Wash Member, Morrison Formation[1]	Shinarump and Moss Back Members, Chinle Formation[2]	Paleozoic and Mesozoic sandstones, Colorado Plateau[3]
Si	> 100,000	> 100,000	> 100,000
Al	11,900	33,000	10,000
Fe	2,400	12,000	3,700
Mg	2,300	1,300	2,700
Ca	33,000	2,500	12,000
Na	890	900	690
K	≃ 3,000	≃ 2,000	4,300
Ti	510	1,800	580
Zr	103	250	88
Mn	220	120	140
Ba	340	520	280
Sr	49	60	45
B	≃ 8	≃ 16	16
V	10	30	11
Cr	6.6	14	7
Co	≃ .5	≃ 5	1
Ni	≃ .5	≃ 9	2
Cu	13	100	9
Y	≃ 2	16	4
U	[4] ≃ 1		

[1]Geometric-mean composition (96 samples).

[2]Geometric-mean composition (32 samples).

[3]Geometric mean of the geometric-mean composition of sandstones in each of 24 formations on the Colorado Plateau ranging in age from Cambrian through Cretaceous (289 samples, averaged by formations).

[4]Geometric mean of 23 samples analyzed by fluorimetric method.

Uraniferous Sandstones

Shoemaker et al (1959) also compared the chemical composition of non-uraniferous and uraniferous Salt Wash and Moss Back sandstones and identified what they referred to as intrinsic and extrinsic elements. The intrinsic elements are those that occur in non-uraniferous sandstone, whereas extrinsic elements are believed to have been introduced in association with uranium in uraniferous sandstones. In Table 5, the elements are identified as intrinsic or extrinsic (Shoemaker et al, 1959). The intrinsic elements are subdivided into

Table 5. Elements characteristic of non-uraniferous (intrinsic) and uraniferous (extrinsic) sandstones of the Morrison Formation and estimated abundance ratios (modified from Shoemaker et al, 1959).

		Element	Abundance Ratio
Dominantly Intrinsic			
	Dominantly Syngenetic	Si	≃ 1
		Al	2.1
		Fe	3.7
		K	≃ 1
		Zr	2.3
		Zr	2.3
		B	≃ 2
		Zn	2.2
		Zn	2.2
		Ag	≃ 2 (?)
		Sb	≃ 0.5
	Dominantly Epigenetic	Mg	3.0
		Ca	0.6
		Na	≃ 1
		Mn	1.4
		Ba	2.4
		Sr	2.5
Dominantly Extrinsic			
	Ore Elements	U	> 1000
		V	500
	Accessory Elements	Co	≃ 20
		Ni	≃ 20
		Cu	7
		As	> 17
		Se	> 6
		Y	≃ 8
		Mo	> 3
		Pb	> 9

[1]Ratio of estimated geometric-mean concentration in uranium ores to estimated geometric-mean concentration in unmineralized sandstones.

syngenetic, denoting elements contained principally in clastic material, and epigenetic, denoting elements derived from the sediments but now found primarily in authigenic minerals. The dominantly extrinsic elements are identified as either ore elements (economically recoverable) or accessory elements.

Element concentrations for non-uraniferous sandstone and uraniferous ore pulps are also presented by Finch (1967) and are given in Table 6. Comparisons of these data to those of Shoemaker et al (1959) (see Tables 4 and 5) indicate general agreement for many elements but numerous differences, both in element concentrations and enrichment or abundance factors. These discrepancies are probably due both to the different sources for the samples analyzed and the different analytical methods used.

Element Zoning

Element zoning within the uranium deposits of the Salt Wash Member has been reported by several authors. In particular, selenium, vanadium, uranium, and molybdenum have been found zoned across roll and tabular deposits in much the same habit described by Harshman (1974) for roll-type deposits in Wyoming, South Dakota, and Texas. In the roll-type deposits the elements selenium, vanadium, uranium, and molybdenum, and the distribution of pyrite, were found to have particular distribution patterns (Fig. 19). Selenium and vanadium tend to be concentrated toward the concave, oxidized (altered) side of the uranium-bearing roll, whereas molybdenum and pyrite are more abundant toward the convex, reduced (unaltered) side of the roll front. Shawe (1956a) had noted in the 1950s that uranium, vanadium, and selenium occur in zoned distributions in some deposits he studied in the Salt Wash Member. Figure 20 shows three rolls in the Salt Wash Member and the associated element zoning (Shawe, 1966).

Brooks and Campbell (1976) studied the distribution of elements in a single sample suite across a tabular ore lense in the Salt Wash sandstone of the La Sal Mine, San Juan County, Utah. Their conclusions are similar to Shawe's (1966), in that selenium, vanadium, uranium, and molybdenum are systematically zoned, in this case from the bottom to the top of the ore zone (Figs. 21 and 22). The similarity of the zoning patterns to those of Harshman (1974), even in the absence of an oxidized sandstone tongue, suggests an oxidation-reduction gradient was involved in ore formation and that the oxidation potential generally decreased up through the ore zone.

Iron is considered an important element in the Salt Wash deposits because of its presence in pyrite in association with many types of sandstone uranium deposits. Shoemaker et al (1959) list iron as an important intrinsic element (Table 5), but they also point out that it is significantly enriched in ore, i.e., it is also extrinsic. Finch (1967) did not report iron among the elements analyzed for in non-uraniferous sandstones and uranium ore pulps (Table 6).

The orientation of the selenium-vanadium-uranium-molybdenum zoning sequence reportedly differs between ore shapes and between deposits. Rolls or C-shaped

Table 6. Geometric-mean content of dominantly extrinsic elements in uranium ore and barren sandstone for parts of the Morrison Formation, Colorado Plateau region, and their enrichment factors (modified from Finch, 1967).

Element	Morrison Formation, Salt Wash Member		
	Geometric mean (percent)		Enrichment[1] factor (rounded)
	Barren sandstone (97 grab samples)	Uranium ore (215 mill-pulp samples)	
U	0.00018	0.15	830
V	.0012	.69	575
Cu	.0017	.0090	5
Ag	≈.000003[2]	≈.00005	17
Se	≈.00003	.0014	45
Mo	≈.00003	≈.002	65
Pb	≈.00007	.0096	135
Zn	≈.0005	.010	20
Ni	≈.00008	.00098	12
Co	≈.00005	.0012	25
As	≈.0006	.0085	14
Sb	≈.00006	≈.00009	
Y	≈.0002	.0014	7
Ba	.032	.075	2
Cr	.00086	.0016	2

[1]Enrichment factor is the estimated geometric-mean concentration in the uranium ore divided by the estimated geometric mean in unmineralized sandstone.

[2]Figures shown as approximate are based on fewer samples than are indicated at the top of the column.

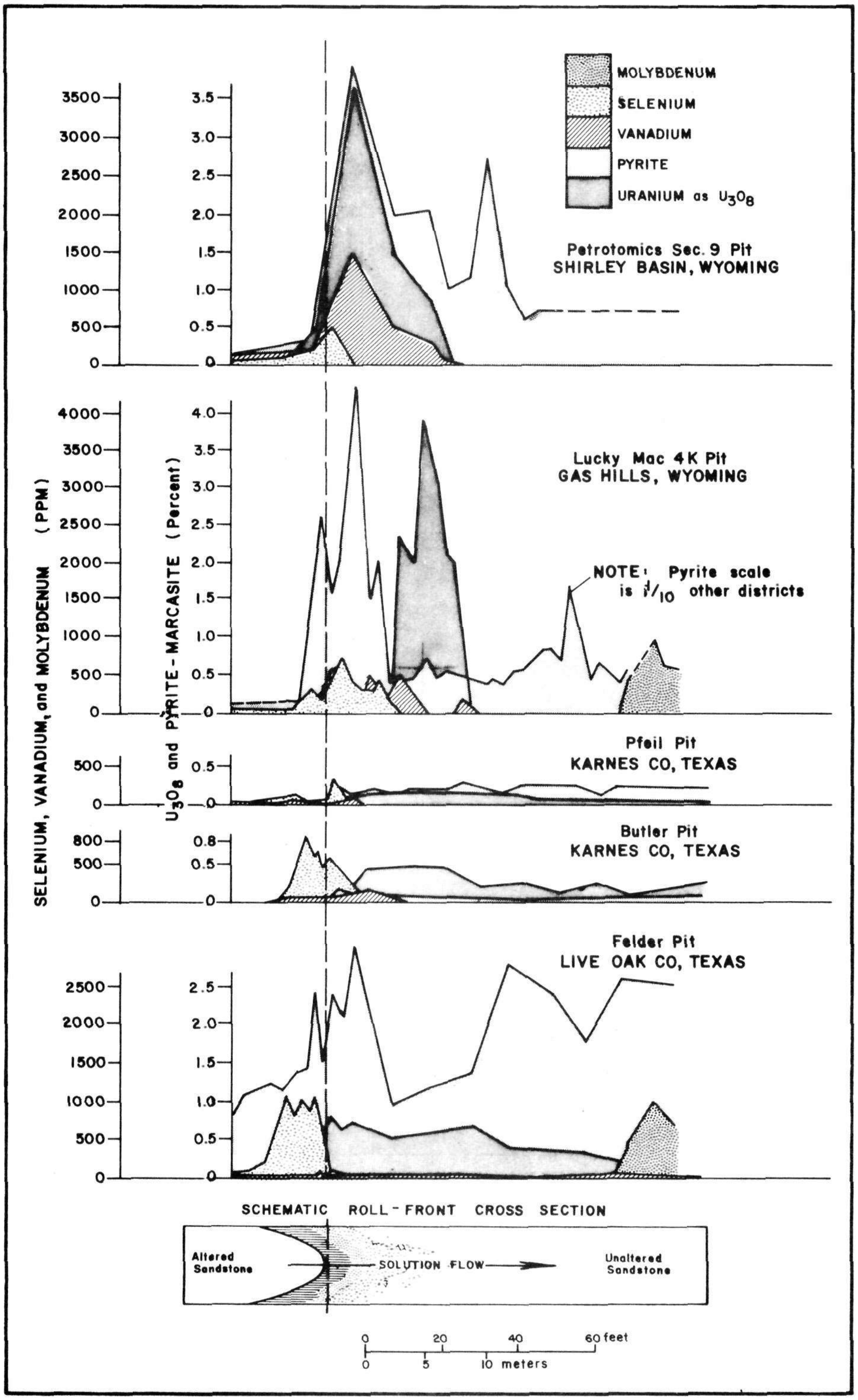

Figure 19. Distribution of some elements across roll-type deposits from four uranium districts (modified from Harshman, 1974).

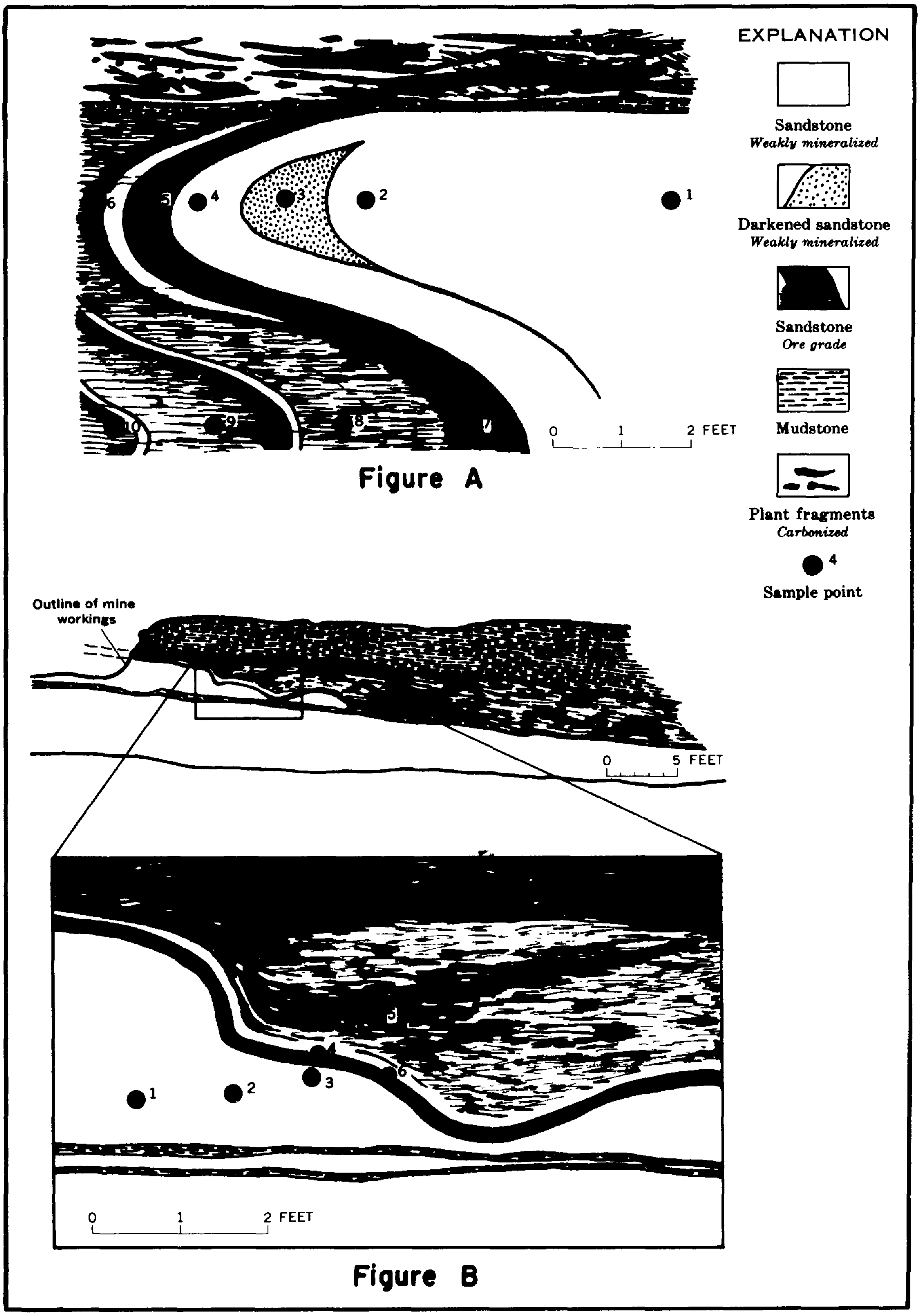

Figure 20. Cross sections and analyses of vanidium-uranium rolls in the Virgin No. 3 Mine, Uravan mineral belt, Montrose County, Colorado (modified from Shawe, 1966).

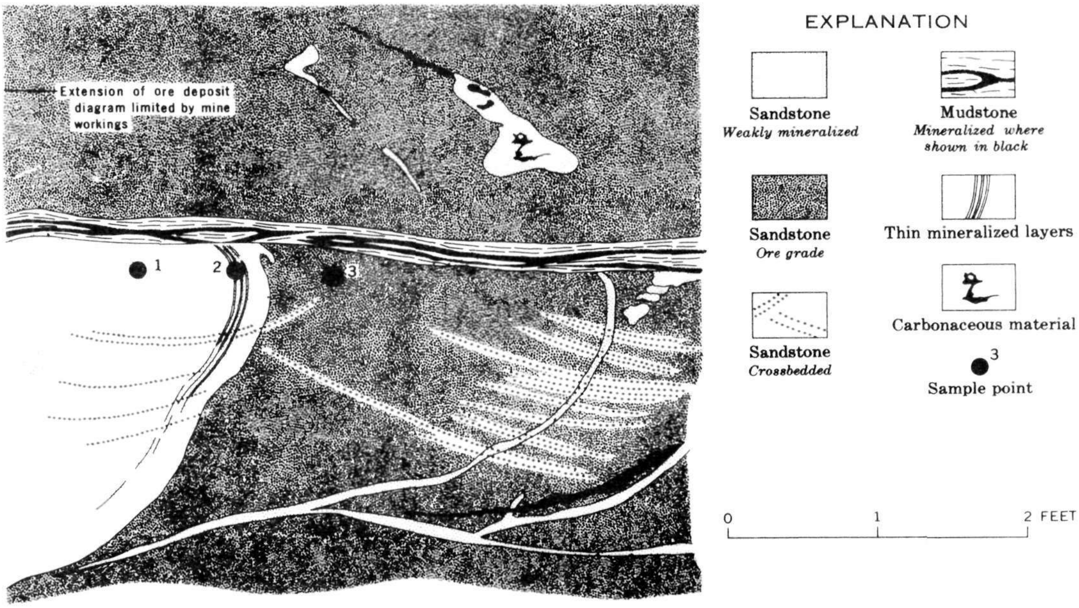

Figure C

Sample No.		Percent			Parts per million	
		eU	U	V	As	Se
Figure A	1	0.004	-	0.3	20	10
	2	0.005	0.006	0.2	50	20
	3	0.003	-	0.3	40	20
	4	0.003	-	0.2	10	200
	5	0.065	0.068	1.5	40	70
	6	0.11	0.12	2.5	40	15
	7	0.073	0.12	2.5	60	7
	8	0.016	0.021	2.5	20	10
	9	0.041	0.051	2.5	40	10
	10	0.13	0.15	2.5	90	15
Figure B	1	0.009	0.011	0.09	40	20
	2	0.008	0.009	0.09	10	10
	3	0.030	0.027	0.2	20	50
	4	0.22	0.34	1.2	100	150
	5	0.26	0.40	1.5	150	20
	6	0.39	0.61	1.2	150	1,500
Figure C	1	0.008	0.012	0.09	10	40
	2	0.10	0.15	0.2	20	1,500
	3	0.17	0.17	6.0+	40	30

Figure 20. Cross sections and analyses of vanadium-uranium rolls in the Virgin No. 3 Mine, Uravan mineral belt, Montrose County, Colorado (modified from Shawe, 1966).

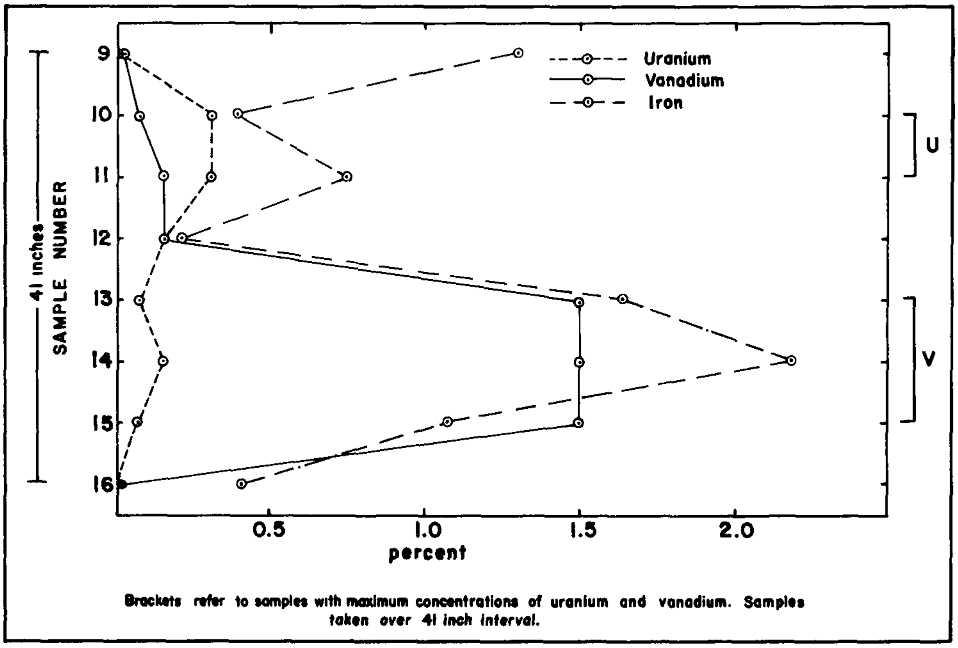

Figure 21. Distribution of uranium, vanadium, and iron across a tabular vanadium-uranium zone in the La Sal Mine (modified from Brooks and Campbell, 1976).

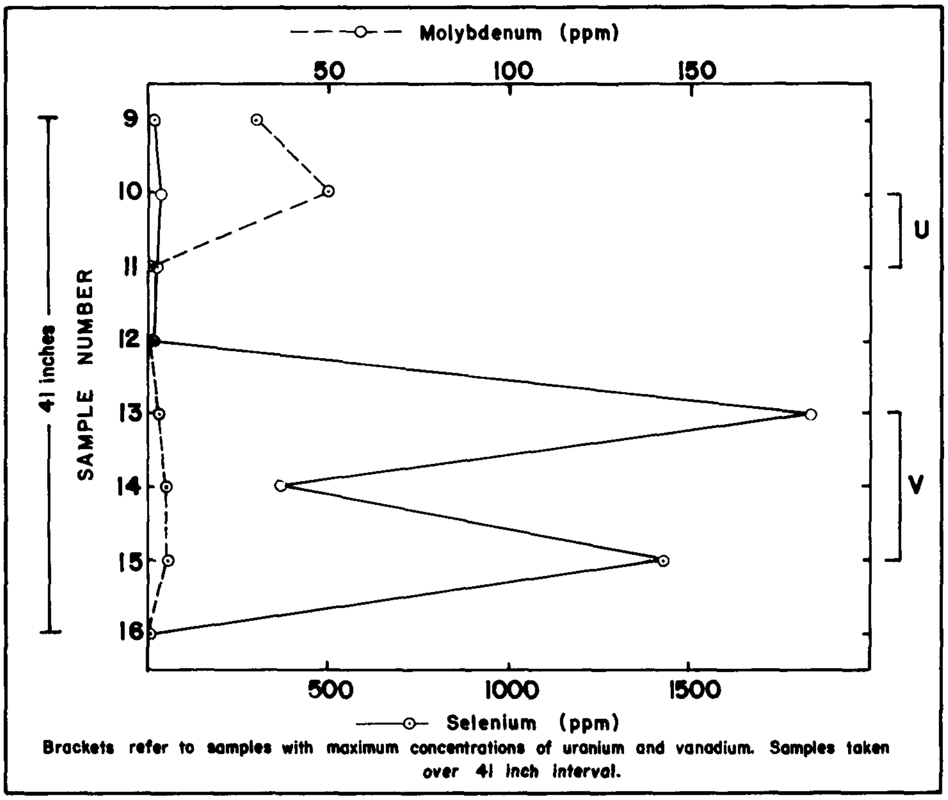

Figure 22. Distribution of selenium and molybdenum across a tabular vanadium-uranium zone in the La Sal Mine (modified from Brooks and Campbell, 1976).

configurations are almost always zoned with selenium on the concave side of the uranium-vanadium zone. Tabular deposits seem to show more variation with selenium concentrations at the top, bottom, or top and bottom of the ore lense. The tabular limbs of roll-type deposits consistently show selenium enriched against the oxidized sandstone tongue. Data for the Salt Wash deposits suggest that the selenium enrichment is most common at the top of the tabular ore zones studied by Shawe (1966), whereas the single sample suite for the La Sal Mine (Brooks and Campbell, 1976) indicates the opposite.

Carpenter (1980) recently studied chemical variations in several core holes from the Tony M Mine at Shootaring Canyon in the Henry Mountains district. The deposit occurs generally as two tabular ore zones (Fig. 23) within the mixed fluvial-lacustrine sediments of the Salt Wash. The deposit is approximately 4 km in a northwest-southeast direction and 1 km wide, hence is a tabular mineralized zone of considerable dimensions. Coffinite and montroseite are the dominant ore minerals. Zoning of selenium and molybdenum is generally present in both ore zones, with selenium concentrated at the tops of the zones. Carpenter (1980) recognized a barren zone between the two ore zones which contains (a) uranium concentrations generally only slightly above the background, (b) considerable vanadium in chlorite rather than montroseite, (c) abundant quartz overgrowths, and (d) lower concentrations of virtually all elements including aluminum, sodium, potassium, and calcium. He interprets the latter as evidence of clay and feldspar dissolution. Alternatively, it may reflect the dilution of these elements by the introduction of considerable silica into the matrix of the sandstone. Carbonaceous plant debris is disseminated throughout the ore zones, barren zone, and the adjacent unmineralized sandstone. Minor amounts of structureless organic matter have been noted, but humate lenses have not been described.

Element zoning is strongly developed in the Salt Wash deposits that have been studied. Selenium is generally concentrated at the concave side of ore rolls and at the top of tabular ore zones. In those cases where selenium is concentrated at the base of tabular zones, it is possible that the orientation of the entire ore-forming system was inverted. It is also possible, indeed likely in some cases, that irregularities in the ore horizons have produced the observed inverted element zoning. For example, where tabular ore curves through a roll front, the ore lense becomes inverted and, presumably, so does the element zoning. Such inversions have been well documented, for example, in the Rifle deposit in the Glen Canyon and Entrada sandstones, demonstrating that geologic mapping and ore-lense correlation are required for studies of element zoning.

Systematic element zoning has not been described in the primary deposits in the Grants district, New Mexico. The data of Shawe (1966) indicate that vanadium and selenium enrichments occur locally at the tops and/or bottoms of the tabular uraniferous humate zones. The conditions of formation were different, therefore, than those for the Salt Wash deposits. Element zoning in different districts, although superficially similar, may have formed under significantly different conditions and may, therefore, have significantly different implications for ore genesis and exploration and resource studies.

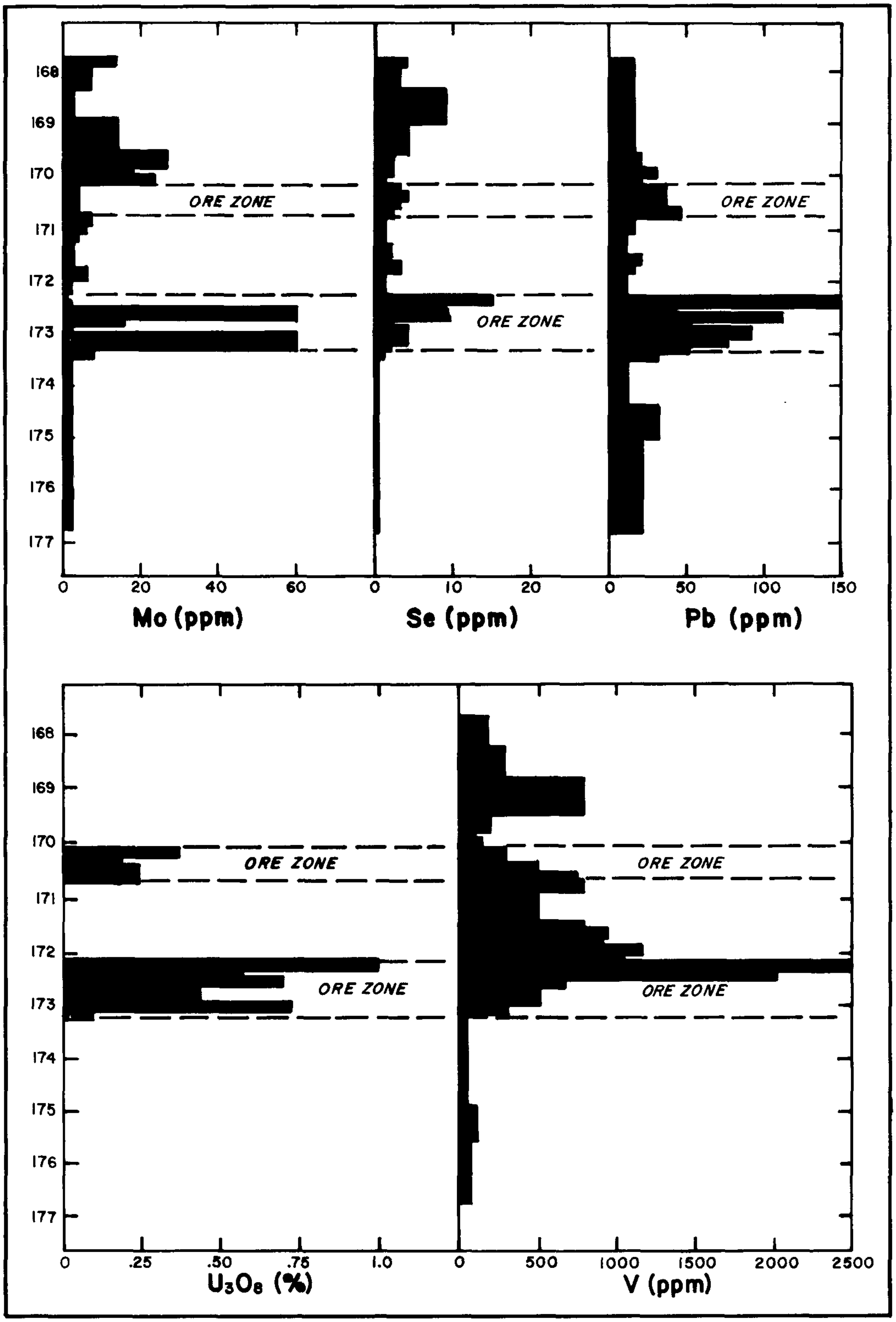

Figure 23. Distribution of U, V, Mo, Se, and Pb in samples from core hole 324 through the ore zones of the Tony M Mine, Shootaring Canyon, Henry Mountains district, Utah (modified from Carpenter, 1980).

Brief descriptions of oxidized and reduced Salt Wash sandstones were included in a preceding section of this report. Shawe (1976a) has published the results of his investigations of oxidized and reduced rocks in the Slick Rock district of Colorado. The following discussion is drawn from his work in that district. Shawe's paper includes data on several formations as well as speculations on the genesis of the uranium-vanadium ores and the source of the ore metals, but this review is limited to a summary of his information on oxidized and reduced facies of the Salt Wash.

The oxidized and reduced sediments described by Shawe (1956b, 1976a) have not been rigorously established in other Salt Wash ore districts. Although they may accurately reflect geologic relations in the Slick Rock district, they should be extended to other districts with reservations. The Slick Rock district is associated with extensive faulting which is not characteristic of all districts and which may have affected the distribution and significance of oxidized and reduced sediments. Even where districts are geologically similar, the distribution of sediment types and rock alterations, as described by Shawe, may not be identical. We suspect that the relations described by Shawe will be found in other districts but we introduce his work with the foregoing reservations.

Shawe recognizes three facies of the Salt Wash in the Slick Rock area: an oxidized red-bed facies; a reduced carbon facies; and a reduced altered facies. The red-bed facies rocks and the carbon-facies rocks are interpreted by Shawe to be products of diagenetic processes; the altered-facies rocks are interpreted to be epigenetically altered. Although the three facies contain similar detrital minerals, there are differences in the amounts of black opaque minerals present in rocks of the three facies, as well as in the form, abundance, and distribution of some of the authigenic and epigenetic minerals. The chemical and mineralogical composition of sandstones, siltstones, and mudstones of each separate facies is similar, differing principally in clay content and grain size. Table 7 shows the average mineral composition of 38 Salt Wash sandstones from the Slick Rock district. Table 8 shows the average

Table 7. Average mineral composition of 38 samples of Salt Wash sandstones in the Slick Rock district (modified from Shawe, 1968).

MINERAL COMPONENT	AVERAGE COMPOSITION (percent)
Quartz	72.0
Quartz Overgrowths	4.3
Chert	5.6
K Feldspar	4.0
Plagioclase	0.8
Calcite	8.3
Clay	2.5
Other	2.5

Table 8. Average chemical composition of major components of rocks from the Morrison Formation in the Slick Rock district (modified from Shawe, 1976a).

Semiquantitative spectrographic analyses, in weight percent.

	MORRISON FORMATION			
	SANDSTONES		SILTSTONES, MUDSTONES & CLAYSTONES	
	Salt Wash Member (26 Samples)	Brushy Basin Member (12 Samples)	Salt Wash Member (5 Samples)	Brushy Basin Member (8 Samples)
SiO_2	85	85	58	68
Al_2O_3	2.8	3.2	8.7	17.2
Fe_2O_3	0.9	1.7	2	4.3
MgO	1.3	0.8	1.2	1.7
CaO	3.4	3.4	12.6	1
Na_2O	0.4	0.8	1.3	1.9
K_2O	1	0.8	3.6	2.9
TiO_2	0.2	0.2	0.4	0.5
MnO	0.03	0.06	0.04	0.03
CO_2	4.1	3.5	11.3	1.6

chemical composition of the major components of rocks from the Morrison Formation in the Slick Rock district; Table 9 tabulates the average composition of minor components from the same suite of samples, a mixture of red-bed facies, carbon-facies, and altered-facies rocks.

Red-Bed Facies Rocks

The red-bed facies of the Salt Wash is composed of reddish-brown, oxidized rocks which contain hematite derived from the in situ breakdown of iron-bearing detrital minerals. The average composition of red-bed facies sandstone is shown in Table 10.

Clay minerals in the red-bed facies of the Salt Wash are mainly illite and mixed-layer illitic clays. Silica cement and barite are widespread but irregularly distributed minor components. The average calcite content of the

Table 9. Average chemical compositions of minor components of rocks from the Morrison Formation in the Slick Rock district (modified from Shawe, 1976a).

Semiquantitative spectrographic analyses, in weight percent.

	MORRISON FORMATION			
	SANDSTONES		SILTSTONES, MUDSTONES & CLAYSTONES	
	Salt Wash Member (26 Samples)	Brushy Basin Member (12 Samples)	Salt Wash Member (5 Samples)	Brushy Basin Member (8 Samples)
Ag	0	< 0.00001	< 0.00001	0
As	0	< 0.01	0	< 0.01
B	0.002	0.002	0.007	0.006
Ba	0.03	0.002	0.03	0.05
Be	0	0	0	< 0.0001
Co	< 0.0007	< 0.001	0.001	0.002
Cr	0.002	0.002	0.009	0.008
Cu	0.002	0.002	0.008	0.003
Ga	< 0.001	< 0.001	0.001	0.003
La	0	< 0.01	0	< 0.01
Mo	< 0.0015	0	0	0
Nb	< 0.0015	0	0	0
Ni	0.0005	< 0.001	0.003	0.003
Pb	0.002	< 0.001	< 0.001	0.002
Sc	< 0.007	< 0.001	0.002	0.003
Sn	< 0.01	0	0	0
Sr	0.007	0.02	0.03	0.03
V	0.004	0.004	0.004	0.005
Y	0.001	0.001	0.003	0.003
Yb	0.0001	0.0001	0.0002	0.0003
Zr	0.03	0.01	0.02	0.03

red-bed facies sandstones of the Salt Wash is about 10 percent, but the red-bed facies of the ore-bearing sandstone contain only about 2.5 percent calcite.

Heavy mineral content of the red-bed facies in the upper Salt Wash sandstone is tabulated in Table 11. Heavy mineral content and the amount of black opaque minerals are highest in red-bed facies sandstone.

Shawe (1976a) believes that the red-bed facies formed as a result of diagenetic processes which permitted at least partial oxidation of the iron-bearing detrital minerals to hematite, the source of the red color in the sediments.

Table 10. Average chemical composition of Salt Wash sandstones of the red-bed facies, carbon facies, and altered facies from the Slick Rock district (modified from Shawe, 1976a).

Semiquantitative spectrographic analyses, in weight percent.

M = Major. 0 = Below Limit of Detectability. Tr = Trace.

	RED-BED FACIES (7 Samples)	CARBON FACIES (1 Sample)	ALTERED FACIES (18 Samples)
Si	M	M	M
Al	1.7	1	1.5
Fe	0.8	1	0.5
Mg	0.5	0.1	0.9
Ca	2.3	0.3	2.5
Na	0.2	0.1	0.3
K	0.9	0	0.8
Ti	0.11	0.01	0.10
Mn	0.02	0.01	0.02
Ag	0	0	0
As	0	0	0
B	0.003	0	0.002
Ba	0.04	0.03	0.03
Be	0	0	0
Co	0	0	0.0007
Cr	0.003	0.001	0.001
Cu	0.002	0.003	0.002
Ga	< 0.001	0	< Tr
Mo	0	0	< 0.0015
Nb	< 0.0015	0	< 0.0015
Ni	0.0005	0.001	0.0005
Pb	0	0.003	0.003
Sc	0	0	< 0.0007
Sn	0	0.01	0
Sr	0.007	0.03	0.005
V	0.005	0.001	0.004
Y	< 0.0015	0	0.001
Yb	< 0.00015	0	0.0001
Zr	0.012	0.01	0.02

Table 11. Average relative abundance of heavy minerals from the upper sandstone unit of the Salt Wash Member (modified from Bowers and Shawe, 1961; and Shawe, 1976a).

Tr = trace, less than 0.001 percent of total rock and 0.5 percent of heavy mineral fraction

MINERAL	RED-BED FACIES		CARBON FACIES		ALTERED FACIES	
	% of Total Rock	% of Heavy Mineral Fraction	% of Total Rock	% of Heavy Mineral Fraction	% of Total Rock	% of Heavy Mineral Fraction
Black Opaque Minerals	0.183	59	0.067	42	0.002	2
Zircon	0.045	14.5	0.032	20	0.034	31
Tourmaline	0.012	4	0.010	6	0.009	8
Apatite	0.005	1.5	0.002	1.5	0.002	2
Rutile	0.003	1	0.002	1	0.001	1
Garnet	Tr	Tr	Tr	Tr	0.001	0.5
Leucoxene	0.020	6.5	0.014	9	0.015	13.5
Barite	0.037	12	0.029	18	0.033	29.5
Anatase	0.003	1	0.002	1.5	0.004	4
Spinel	Tr	Tr	Tr	Tr	Tr	Tr
Pyrite	Tr	Tr	0.002	1	0.008	7
Other Minerals	0.002	0.5	Tr	Tr	0.005	1.5
Number of Samples	66		32		74	
Average Heavy Mineral Content of Samples in Weight Percent	0.31		0.16		0.11	

Carbon-Facies Rocks

Carbon-facies rocks of the Salt Wash include reduced sandstones, siltstones, and mudstones. As the name implies, carbonaceous debris is commonly present. The carbon-facies rocks are generally light gray below the zone of oxidation and tan to light brown in outcrop and near-surface exposures. Megascopically, they are indistinguishable from altered-facies rocks. The chemical composition of a single sample of carbon-facies sandstone is listed in Table 10.

Carbon-facies rocks of the Salt Wash Member are widely distributed in the Slick Rock district. They are less abundant than red-bed facies rocks but, presumably, are more abundant than Salt Wash rocks of the altered facies.

Clay minerals and calcite content in the carbon-facies rocks are similar to those in the red-bed facies rocks. Silica cement is common in rocks of the carbon facies, where it makes up about 10 percent of the sandstones. Much of the silica is present as overgrowths on detrital quartz grains. Barite and anatase are widely distributed in small amounts; pyrite is sparse and erratically distributed.

Heavy mineral content of carbon-facies rocks is shown in Table 11. The heavy mineral content of carbon-facies sandstone is approximately half as abundant as in red-bed facies sandstone but slightly more abundant than in sandstones of the altered facies of the Salt Wash. Black opaque oxides, inferred to be mainly magnetite and ilmenite, are less abundant in carbon-facies sandstones than in sandstones of the red-bed facies but are much more abundant in carbon-facies sandstones than in altered-facies sandstones.

Shawe (1976a) believes that the light gray color of the carbon-facies rocks formed diagenetically in reducing environments associated with carbonaceous material. Some of the original black opaque minerals were destroyed by reduction in connate solutions. The released iron was precipitated as pyrite, but no hematite was formed.

Altered-Facies Rocks

Altered-facies rocks of the Salt Wash, like the carbon-facies rocks, are reduced rocks. They are light gray below the water table and tan or light brown in the zone of oxidation. Uranium-vanadium deposits in Salt Wash sandstones, at least in the Slick Rock district, are confined to the altered facies (Shawe, 1976a). Altered-facies rocks appear to have formed by the action of post-depositional solutions which reacted with rocks of the red-bed and/or carbon facies. Average chemical composition of 18 samples of altered-facies Salt Wash sandstones is shown in Table 10.

Clay minerals in altered-facies rocks of the Salt Wash are similar to those in the red-bed and carbon facies. Silica cement is widely distributed, amounting to 5 to 15 percent of the sandstones. Some detrital quartz grains and some authigenic silica overgrowths have been partly dissolved, suggesting to Shawe that there may have been at least two stages of post-depositional silica solution and precipitation. Calcite is a common constituent of altered-facies rocks; in some areas it replaces detrital grains of quartz, chert, and feldspar.

Heavy mineral content of altered-facies Salt Wash sandstones is summarized in Table 11. Black opaque minerals are very sparse, but pyrite is relatively abundant. Barite is common but is no more abundant than in red-bed or carbon-facies rocks.

Shawe's data indicate that altered-facies sandstones of the Salt Wash contain approximately four times more uranium than red-bed facies or carbon-facies sandstones. The average uranium content of 40 red-bed facies sandstone samples is 0.0001 percent U_3O_8; 150 samples of carbon-facies sandstones also average 0.0001 percent U_3O_8; but 100 samples of altered-facies sandstone average 0.0004 percent U_3O_8 (Shawe, 1976a). The altered-facies rocks of the Salt Wash also appear to be enriched in lead and perhaps slightly enriched in cobalt, nickel, vanadium, yttrium, ytterbium, niobium, and manganese. Metals which may have been leached from altered-facies rock include iron, magnesium, boron, and calcium.

Interpretation and Significance

Red-bed facies, carbon-facies, and altered-facies rocks are altered derivatives of a single-parent sediment assemblage of uniform composition. Red-bed facies rocks were produced by diagenetic alteration of oxidized sediments. Carbon-facies rocks were produced by diagenetic alteration in a reducing environment favoring the preservation of carbonaceous material. Altered-facies rocks formed by epigenetic alteration of both red-bed and carbon-facies rocks. Ore deposits formed only in carbon-facies rocks which were epigenetically altered.

Mineralogically and chemically the Salt Wash rocks of the red-bed facies, the carbon facies, and the altered facies are very similar. The red-bed facies can be differentiated easily from the rocks of the two reduced facies by color alone. Rocks of the carbon facies and altered facies are megascopically indistinguishable, but significant differences exist in the relative abundance of black opaque minerals and pyrite. The amount of black opaques present in carbon-facies rocks is considerably less than in red-bed facies rocks, but black opaques in altered-facies rocks have been almost completely destroyed. Pyrite is absent in red-bed facies rocks, sparse in carbon-facies rocks, and moderately abundant in altered-facies rocks. Small, but perhaps important, differences in the amounts of trace elements have been cited.

Reduced and oxidized facies in the Salt Wash have long been recognized, and the association of ore with reduced rocks has been used as a broad-scale exploration guide for many years. However, all of the reduced rocks within the major producing Salt Wash areas were considered to be equally favorable, provided that such reduced rocks were more than 40 feet thick, contained carbonaceous material, and were associated with interbedded and underlying gray clays. Drilling within these favorable areas was continued until ore was found or until the project was terminated unsuccessfully, but no attempt was made to differentiate between unfavorable reduced sandstone (Shawe's carbon facies) and favorable reduced sandstone (Shawe's altered facies). The successful efforts of Shawe and his co-workers to differentiate between megascopically similar reduced rocks of the carbon facies and altered facies provide not only a better understanding of the alteration, but also a possible criterion for evaluating potential ore-bearing areas with relatively few drill holes.

As was emphasized at the beginning of this section, it is not known if the three sandstone types recognized by Shawe in the Slick Rock district are typical of the other ore districts. The relative proportions of the sandstone types and their distributions are also unknown. Even the genetic significance of the altered facies, which is characterized by the virtual destruction of ilmenite and magnetite, is not understood. As the abundance of carbonaceous material is similar in the carbon-facies and altered-facies sands, it seems most likely that the difference is due to the transmissivity of the altered-facies sands and the more thorough leaching of ilmenite and magnetite by reduced ground waters. The position of the vanadium-uranium ores within the altered-facies sands and the distribution of other associated rock alterations are also unexplained.

GENETIC MODEL

Introduction

A genetic model for a sandstone-type uranium deposit must consider the source of sediments and ore metals, characteristics of the host rocks, transportation and precipitation of ore metals, age and timing of mineralization, and subsequent geologic events which may have modified or redistributed the orebodies. The geological characteristics of the deposits were presented in the preceding sections of this report. In this section we review published interpretations of ore controls and genesis and then present a working model which we feel best fits the existing data. The model should help to identify the geologic characteristics most useful for resource studies and exploration.

Evolution of Thought and Previous Models

Theories on the genesis of Salt Wash ore deposits have been proposed since shortly after the first orebodies were discovered. An excellent review and summary of many of the various theories which were proposed between 1900 and 1961 is published in Finch (1967). Much of the following information is based on this review.

Most of the genetic hypotheses advanced between 1900 and 1961 fall within either a syngenetic or epigenetic classification. The syngenetic hypothesis assumes that uranium and vanadium minerals were transported and concentrated mechanically, or that the ore minerals were precipitated from surface solutions at the time the sediments were deposited. Epigenetic hypotheses, which can be divided into supergene or hypogene classes, suppose that the ore metals were deposited after deposition of the host rock.

One of the earliest theories of genesis of Salt Wash ore deposits was proposed by Hillebrand and Ransome (1900), who had seen only the secondary carnotite deposits. They believed that the carnotite ores formed only at or near the outcrop, apparently as a result of precipitation from solutions which leached disseminated ore metals from the host sandstone.

Syngenetic Hypotheses

The earliest recorded proponents of the syngenetic theory were Fleck and Haldane (1907), who suggested that the ore deposits resulted from the decomposition of vanadiferous pitchblende which had been mechanically concentrated within the host sandstones as placers. A variation of the syngenetic theory was proposed by Hess (1914), who believed that the ore deposits formed in shallow seas by reduction caused by decaying organic material. He suggested that the ore metals may have been derived from the weathering of veins in the sediment source areas. It is interesting to note that Hess apparently recognized the carnotite deposits as concentrations of secondary minerals which had oxidized in place from primary deposits. This was an astute speculation in 1914, considering that the presence of the unoxidized primary ores was not to be verified until nearly 40 years later.

Syngenetic theories were popular early, but few geologists would subscribe to them today. The cross-cutting nature of the orebodies with respect to bedding clearly precludes a strict syngenetic interpretation.

Epigenetic Hypotheses

Epigenetic theories include both hypogene and supergene hypotheses. Hypogene theories propose that the ore metals were derived from deep-seated magmatic sources; the hydrothermal solutions may have mixed with ground waters, which transported the ore metals to depositional sites. Supergene theories assume that ground waters moving downward and/or laterally leached the ore metals from disseminated sources in the host rock or adjacent sediments and transported them to depositional sites (Fischer, 1968).

Hypogene theories were advocated mainly during the 1950s. Waters and Granger (1953) proposed that laccolithic rocks of the Plateau were underlain by deep-seated masses of igneous rocks which supplied ore metals to hydrothermal solutions during crystallization of the magma in Tertiary time. Ascending telethermal solutions mixed with ground waters, and the ore metals were precipitated by reduction near organic matter and clays. Waters and Granger (1953) also suggested that some of the ore metals may have been derived from the leaching of volcanic ash beds. Other proponents of the hydrothermal hypothesis, according to Finch (1967), included McElvey et al (1956), Cater (1955), Kerr (1958), and Page (1960). Because many Plateau-type deposits are far removed from known igneous rocks, and few, if any, deposits contain mineral assemblages or alteration patterns typical of hydrothermal mineralization, few geologists today support a strict hydrothermal concept of origin for Salt Wash ore deposits.

Supergene theories involving some concept of leaching ore metals from disseminated sources in the source area, host sediment, or adjacent sediments are now commonly accepted, although the exact source or sources of the ore metals and the timing of mineralization remain subjects of continuing controversy.

One of the first to recognize the Salt Wash deposits as epigenetic was Lindgren (1911), who concluded that the uranium and vanadium in the sandstones of Colorado and Utah were products of concentration by surface waters below the zone of oxidation at temperatures less than 100°C. Burwell (1920) suggested that uranium and vanadium migrated downward from overlying clay beds and impure sandstone beds and that the ore minerals were precipitated from sulfate waters by carbonaceous material. Koeberlin (1938) may have been the first to single out pyroclastics, ash beds in particular, as the source of the ore metals. He believed that the metals in such beds could be leached by surface or ground-water solutions. Coffin (1921), one of the first to investigate the uranium-vanadium ore deposits in detail, proposed that the ore metals were dispersed in the sediments and were redistributed by ground waters which traveled along the beds rather than across them.

Fischer (1937, 1942, 1949, 1957, and 1974) believed that the ore metals were concentrated within the host rocks by dilute solutions at the time of sedimentation, but that the ore minerals were epigenetic. This concept, referred to as the penesyngenetic hypothesis, supposes that the ore minerals were precipitated from ground water soon after deposition of the sediments, before deep burial or compaction. Although the penesyngenetic theory involves aspects of both the syngenetic and epigenetic hypotheses and is treated as a separate class by Finch (1967), we include it here because Fischer clearly recognized the deposits as epigenetic. The penesyngenetic theory is mainly concerned with the time of ore formation, but the assumption is that the metals were derived from the host beds or associated beds and carried to sites of deposition by circulating ground water.

In connection with their work on vanadium deposits in the Entrada sandstone near Placerville, Colorado, Fischer et al (1947) introduced the suggestion that the vanadium ore deposits there may have formed at the contact of ground waters of two different types after the sediments accumulated. Shawe (1956a) applied the two-solution concept to roll-type orebodies in the Salt Wash, suggesting that both the roll-type and tabular orebodies in the Salt Wash had similar origins.

In contrast to Fischer, who believed that the ore deposits formed after the sediments were deposited but before deep burial and compaction, Gruner (1954) suggested that marine waters from Late Cretaceous seas contained uranium and vanadium in solution. Circulation of these waters was initiated by Laramide deformation, allowing the solutions to penetrate carbonaceous or hydrocarbon zones in the underlying Triassic and Jurassic rocks, where the metals were precipitated.

Many other authors have published theories which conform to the general parameters of an epigenetic supergene hypothesis. Finch (1967) summarizes several theories not reviewed above under the heading of lateral secretion hypotheses. The following papers, reviewed by Finch, relate to Salt Wash ore deposits: Moore and Kithil (1913); Butler et al (1920); Lindgren (1933); Wright (1955); Garrels (1957); Shawe et al (1959); and Noble (1960). These authors, and many others, believe that the Salt Wash ore deposits are epigenetic (supergene), but there is no unanimity concerning the source of the ore metals or the time of mineralization. Most commonly mentioned as sources of the ore metals are the host sandstone or overlying tuffaceous beds. The time of mineralization is variously interpreted to be soon after deposition, after deposition but before regional deformation, Laramide, or Tertiary.

Based on geologic settings, habits of deposits, and geochemical relations, as well as a review of the various genetic hypotheses, Finch (1967) concluded that the ore metals were derived from dispersed sources within the host rocks or associated sediments and that the metals were soluble in alkaline carbonate pore fluids. Compaction of the sediments, especially the clays, forced the metal-bearing waters into the more permeable portions of the sandstones, where they migrated down the sandstone beds until they encountered a reducing environment of sufficient strength to precipitate the ore minerals. Precipitation of the primary ore minerals ceased when the mineralizing solutions were flushed and replaced by normal ground water.

Current Epigenetic Hypotheses

Several papers have been published on the genesis of Salt Wash ores since Finch (1967) summarized and reviewed the various hypotheses advanced to that time. At least three differing epigenetic theories are in vogue today, and each has its advocates. The two-solution hypothesis, first applied to Salt Wash ore deposits nearly 25 years ago by Shawe (1956a), has withstood the test of time, and his concept is generally accepted by many geologists today (Granger, 1976; Granger and Warren, 1979; and others). There are, however, variations on the basic theme. The two-solution theory presumes that precipitation of the ore minerals occurred at the interface of two solutions of different composition and character. Proponents of this theory do not necessarily agree on the time of precipitation of the ore minerals, the source of the ore metals, or the nature and composition of the two solutions. While Fischer (1947) believed that the ore deposits formed soon after the deposition of the sediments, Shawe (1976a) proposed a much later time of ore formation. He believed that compaction of the Mancos Shale in Early Tertiary time expelled pore waters containing uranium and vanadium in solution. These solutions presumably penetrated fractured or permeable zones in the overlying and underlying sediments, altering (reducing) large volumes of rock, but ore minerals were precipitated only within sediments containing carbonaceous debris.

The compositions and characteristics of the two solutions have been subjects of much speculation, but there appears to be some agreement that one of the solutions may have been stagnant reducing connate water. A later-introduced mineralizing solution contacted connate water along the boundaries of more and less permeable sediments. The introduced metal-bearing solution may have been an alkaline bicarbonate solution in which uranium and vanadium were soluble. The introduced solution may have been pore waters expelled from compacting clays within or adjacent to the host sediments (Finch, 1967; and others), or much younger sediments (Shawe, 1976a). In either case, the ore deposits formed in the vicinity of carbonaceous debris, where, presumably, the connate waters were most strongly reducing.

A lacustrine-humate model has been proposed for the Salt Wash deposits in the Henry Mountains of Utah (Peterson, 1977, 1980; Peterson and Turner-Peterson, 1980; Turner-Peterson and Peterson, 1978) and for the Poison Canyon sandstone deposits in the Grants mineral belt (Turner-Peterson et al, 1980). According to the authors (Peterson and Turner-Peterson, 1980),

> The basic premise of the model is that humic and fulvic acids generated in the offshore muddy sediments of humus-bearing lakes were expelled by compaction or seepage into nearby sandstone beds where the organic acids were fixed as tabular humate deposits. Subsequently, uranium-bearing ground water passed through the sandstones where humate fixed and concentrated the uranium, forming tabular sandstone uranium deposits.

The description of the favorable clays and their association with orebodies in the Henry Mountains has been reviewed in an earlier section of this report. The pore waters expelled from the favorable clays are considered to have been alkaline, reducing, and humate rich. The source of the uraniferous ground water may have been tuffaceous units within the Morrison Formation. Formation of the ore deposits was early diagenetic. Although the lacustrine-humate model incorporates aspects of the two-solution model, it is much more specific as to the source of the uranium precipitant (the humate mass) and the composition of the solutions derived from the favorable clays. It differs from some of the earlier models in that it suggests that the humic substances were locally derived and that they migrated only short distances from their sources.

The lacustrine-humate model may well be applicable in some form to the uraniferous humate deposits of the Grants region. The large deposits in the Henry Mountains are more like the Grants deposits than other Salt Wash deposits in some important respects, in particular their lower vanadium/uranium ratios and broad tabular ore continuity. The lacustrine-humate model may be applicable to deposits in the Henry Mountains and elsewhere in the Salt Wash, but thus far they have been found to be essentially void of redistributed humates. Whether the lacustrine-humate model is applicable to Salt Wash deposits remains to be demonstrated, but work should be pursued to test its validity.

Since the middle 1970s, a number of geologists have concluded that the sandstone uranium deposits of the Colorado Plateau, the Wyoming basins, and South Texas are more similar than different (Rackley, 1976, 1980; Galloway, 1978; Gabelman, 1977). Under this theory, the deposits are considered to be epigenetic in that they formed after the sediments were deposited, but the timing of mineralization is conceded to be debatable. Disseminations of easily leachable ore metals within the sediment are believed to be adequate sources from which the ore deposits were derived. The process of mineralization is considered to result from precipitation of ore minerals at an oxidation-reduction interface as oxygenated, uranium-bearing ground water invades and penetrates a reducing environment (the geochemical cell concept). Differences in the shapes of orebodies between different districts (rolls vs. tabular) are thought to result from differences in the geometry and permeability of the enclosing sandstone bodies.

A novel concept has recently been proposed by Granger and Warren (1981). They note the generally poor correlation between uranium and carbonaceous material and/or pyrite, suggesting these potential reductants were probably not responsible for uranium precipitation in the Uravan mineral belt ores. They suggest, instead, that ore formation resulted from the mixing of two ground waters, one containing organic complexes together with vanadium (III) derived from altered magnetite and ilmenite and the other containing uranium (VI). The proposed mechanism of precipitation was the reduction of uranium (VI) by vanadium (III) which produced uranium (IV) minerals and vanadium (III), principally as montroseite. We find this mechanism appealing as it is consistent with many characteristics of the ores and associated alterations and it is discussed further in the following section on a working model.

Working Model

Sources of Uranium and Vanadium

Malan (1972), Silver et al (1980), and others have noted that Salt Wash ore deposits, as well as other significant uranium deposits in Mesozoic and Tertiary sediments outside of Texas, are co-extensive with a partially exposed region of Precambrian rocks which are enriched in uranium. Sampled Precambrian igneous and metamorphic rocks from this region contain significantly higher concentrations of radioelements than do similar Precambrian rocks outside this region (Fig. 24). This 300-mile wide belt of anomalous Precambrian rocks extends northeasterly from the common boundary of Arizona, California, and Nevada through southern Wyoming and northern Colorado and may be present in the subsurface farther to the northeast, along the transcontinental arch.

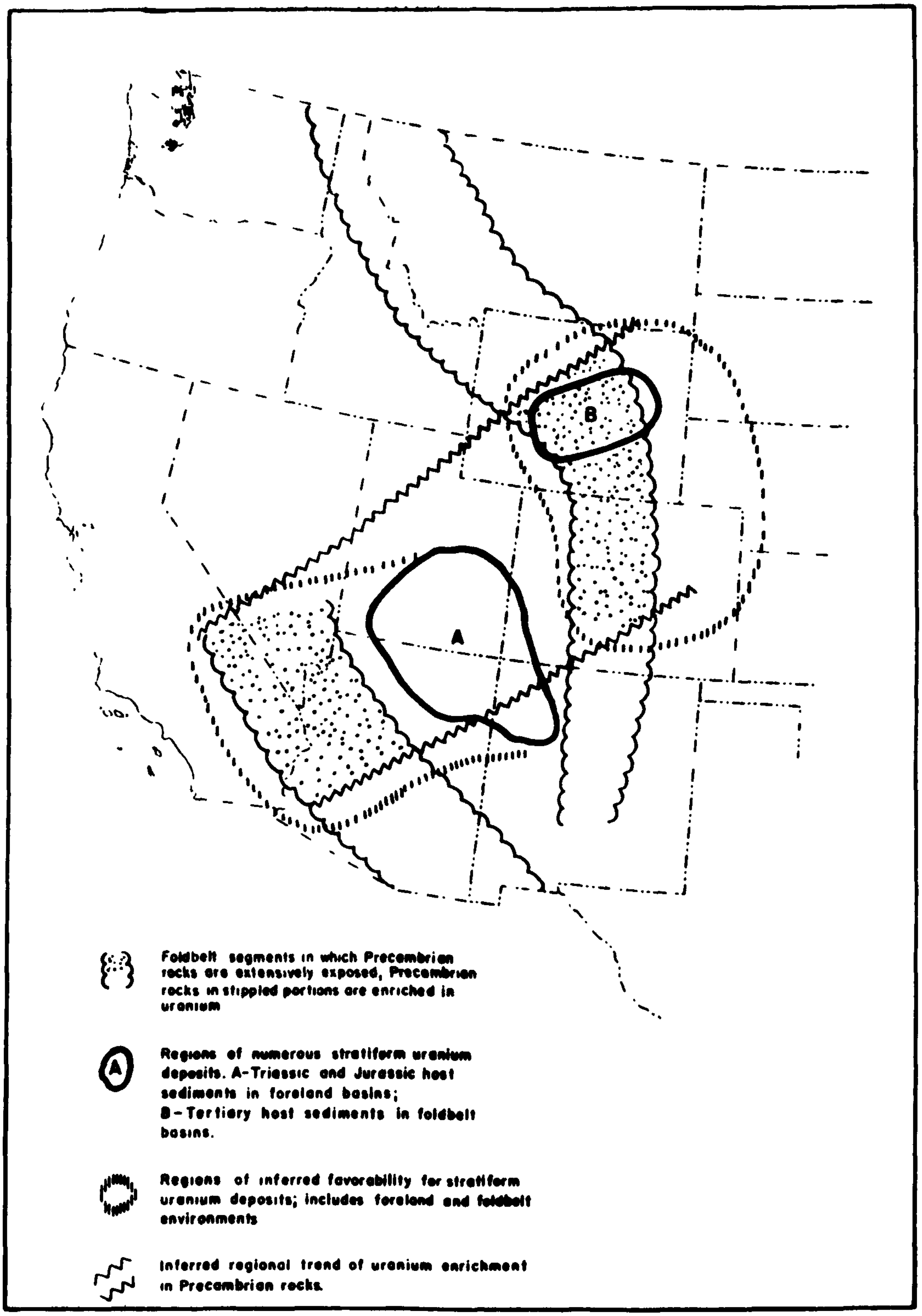

Figure 24. Regional patterns of uranium enrichment in the western United States (from Malan, 1972).

The uranium-enriched Precambrian rocks, or younger igneous or volcanic rocks formed by subsequent remelting of the enriched Precambrian rocks, were possible source rocks for much of the uranium now found in the sandstone deposits. Although the clasts in the Salt Wash were derived largely from pre-existing sediments, the volcanic ash incorporated within the host sandstones and the overlying Brushy Basin shales presumably contained anomalous amounts of uranium, and we prefer this material as the source for the uranium in the deposits.

The source of vanadium in Salt Wash ores is not known, but at least two possibilities have been presented. Vanadium may have been derived (a) from the breakdown of detrital magnetite and ilmenite within the host sediments or (b) liberated by chemical weathering of sedimentary rocks within the source area. Fischer and Stewart (1961) pointed out that the vanadium-rich sandstone deposits of the Colorado Plateau are confined to second-cycle sandstones, one of which is the Salt Wash. Vanadium may have been preserved in ilmenite and magnetite which might be expected to be more concentrated in second-cycle sands than, for example, arkosic sandstones. If most of the vanadium was derived from the alteration of magnetites and ilmenites, the question arises as to why the Grants deposits contain so little vanadium, for magnetite-ilmenite destruction on a large scale has been documented in that district. It seems to us difficult to derive the required vanadium from heavy mineral alteration, but we prefer this source if it can be demonstrated that it provided adequate vanadium.

Sediment Depositional Environment

The Salt Wash was deposited as part of a thick fluvial sequence of Late Jurassic age within a large continental interior basin. The sediments were deposited as braided and meandering stream and floodplain deposits on an aggrading alluvial plain building to the north and east from multiple source areas lying southwest and west of the depositional sites. The area of deposition probably was a broad plain where vegetation was abundant along the watercourses; the climate was semi-arid, but supported both animal and plant life.

Major depositional axes from southwestern and western source areas extended northward and eastward into the Green River area, northeastward or eastward into the Uravan area, and southeastward into the Lukachukai-Carrizo area. The Uravan lobe was separated from the Lukachukai-Carrizo lobe by a structural high which diverted major drainage systems around it to the north and south. Other existing or growing structures, such as the salt anticlines of the Uravan area, the Monument Upwarp, small anticlines in northeast Arizona and northwestern New Mexico, and transverse structures in the Henry Mountains area probably diverted or impeded sedimentation.

Clay lenses rich in volcanic debris were locally deposited as bottom muds in shallow ponds or lakes, perhaps in areas sheltered in the lee of growing structures. Gray mudstones deposited above, below, or lateral to reduced bodies of sandstone may have become important sources of humic and fulvic acids expelled during compaction of the sediments (Peterson, 1980).

In the Uravan area, a restricted but significant increase in the thickness of the sediments developed, perhaps in response to a local downwarp within the

Paradox Basin. A thick sequence of Salt Wash sediments accumulated in the Henry Basin due to tectonic subsidence in that area. In general, the Salt Wash alluvial plain gradually advanced across the area as a series of coalescing alluvial plain complexes derived from sources to the south and west (Peterson, 1980).

Proximal facies of the alluvial complex were characterized by high sandstone to mudstone ratios and braided stream deposits. The proximal facies was deposited under high flow rates as thick, massive sandstone units containing only a few thin interbeds of clay. Farther to the east, in the more distal facies of the Uravan area, a much lower sandstone to mudstone ratio prevailed in the meandering stream deposits of that area. Much of the channel sediments subsided below the water table, preserving accumulations of detrital plant debris which subsequently contributed to the formation of the carbon-facies sandstones. Adjacent overbank muds were oxidized above the water table and are now represented by the hematitic-rich sediments that bound many ore trends. The distal facies was deposited under conditions of low flow as discrete channel sandstones and floodplain clays. Still farther to the east, the sediments were deposited in standing water as horizontally laminated sandstones and mudstones which contain little carbonaceous material. Presumably, most of the carbonaceous debris was deposited within the fluvial channel and floodplain sequence as the streams gradually slowed and lost carrying capacity eastward.

Sedimentation continued to the close of the Salt Wash time and on into Brushy Basin time without interruption. The fluvial environment of the Brushy Basin carried large volumes of silicic volcanic ash from sources of contemporaneous volcanism to the south and west. These sediments are dominantly oxidized and were presumably deposited under floodplain conditions. Brushy Basin deposition was followed by a cycle of erosion, then by deposition of the Burro Canyon and Dakota sandstones and the thick black shales of the Mancos.

Sediment Diagenesis and Mineralization

Oxidized and reduced sandstones and mudstones of the Salt Wash developed early in the depositional history of the sediments. Presumably, the dominantly red color of the floodplain deposits formed by oxidation of magnetite and ilmenite to hematite under alternately wet and dry conditions of deposition. Carbonaceous debris which probably was deposited in the floodplain regions was destroyed by oxidation. The gray pyritic sandstones and mudstones of the channel facies were deposited under conditions which favored the preservation of a reducing environment; otherwise, the carbonaceous material within them would have been destroyed. As individual small channels within major channel systems were diverted or abandoned, the trapped pore water in the sands became stagnant and reducing from the decay of buried organic debris. Reduced zones could have been small or quite large, depending on the size of the abandoned channels and the amount of carbonaceous debris within them. Larger channels with abundant organic debris underwent more intense reduction, leading to the leaching of iron from magnetite and ilmenite. This type of alteration, the altered facies described by Shawe (1976a), is analogous to alteration associated with the deposits of the Grants Uranium Region (Adams and Saucier, 1981). Completely destroyed ilmenite and magnetite probably indicate ground-water flow within the altered-facies rocks because relict grains are present elsewhere in even strongly reduced sands that are hydrologically isolated (Adams et al, 1974). The carbonaceous-rich carbon-facies rocks of the Salt Wash also contain incompletely altered ilmenite and magnetite.

The more intensely reduced portions of the channel sands tend to be concentrated near the base of the thicker sandstones along one margin of a major channel system. These zones were presumably more favorable for the deposition and preservation of carbonaceous debris. There is no obvious explanation, however, as to why these highly reducing areas, in which the vanadium-uranium orebodies subsequently formed, are preferentially oriented along one side of a major channel.

Ultimately, the Salt Wash channel-sandstone systems were covered by the dominantly oxidized tuffaceous siltstones and shales of the Brushy Basin Member. As these overlying, fine-grained sediments and the oxidized flood-plain deposits marginal to the channel systems began to compact, they expelled oxidizing pore waters into the channel-sandstone aquifers. These waters probably contained significant uranium derived from the alteration of tuffaceous clasts. Some of the pore water forced out of the Brushy Basin clays may have found access to the underlying Salt Wash sandstones through discontinuous basal Brushy Basin conglomerates. These waters would have tended to move above, laterally past, and into the deeper reduced ground waters oxidizing the outer margins of the reduced sands as they advanced. Dominant ground-water flow was probably in the same direction as the sediments were deposited, and the size of the reduced zone was progressively diminished. The boundary between the reduced ground water and a more oxidizing, but not necessarily hematite-producing, ground water was the site of vanadium-uranium precipitation.

The mechanism of precipitation of the vanadium-uranium ore, occurring as it does entirely within the reduced altered-facies sands, has evaded interpretation. We visualize the ore-forming process as follows. Preserved plant trash in the deeper channel sands was partly dissolved, contributing humic acids to the ground water. This developed a reducing environment, which led to the dissolution of iron and vanadium from ilmenite and magnetite.

The hydrolysis of the volcanic glasses released silica and alumina and produced a rise in pH, which further promoted dissolution of plant material. The contact of these reduced solutions with the uranium (VI)-bearing, more oxidized solutions, derived from adjacent red beds, the overlying Brushy Basin, and recharge areas up hydrologic gradient, was, we believe, the site of ore formation. The most plausible mechanism of precipitation is that proposed by Granger and Warren (1981) which suggests that the reduction of uranium (VI) by vanadium (III) led to the precipitation of insoluble uranium (IV) and vanadium (IV) minerals. They believe, however, that this required a ground water other than that derived from the Morrison sediments. They propose that this solution, possibly derived from underlying evaporites, contained uranium and sufficient magnesium to displace complexed vanadium and aluminum from the soluble humates. The coupled precipitation of uranium, vanadium, and aluminum as hydroxide gels co-precipitated Mg^{++} and K^{+}, which subsequently aged to form the clay-bearing assemblages characteristic of the ores. We prefer a mechanism of vanadium-uranium precipitation that requires only the simple mixing of two solutions, a relatively oxidized and a relatively reduced ground water but with precipitation resulting from the coupled oxidation-reduction reaction they propose.

The interface between the oxidized and reduced ground waters within the sandstones probably oscillated from time to time. The dominant ground-water movement was in the same direction as the sediments were transported with the oxidized ground water, which was under hydrologic head from the compacting shales above and marginal to the channel axes, moving tangential to and into the reduced sands. In more uraniferous, thicker sand sequences, such as occur in the Henry Mountains region, the interface assumed a simple tabular habit and produced the more consistent, tabular deposits of the Tony M and related deposits. Where the sediments consisted of complexly interbedded sand-shale sequences, the interface became contorted between shales, leading to mixed tabular-roll patterns mapped by Shawe et al (1959). Vanadium-uranium precipitation at the interface between an overlying oxidized and an underlying reduced ground water would have produced element zoning that proceeded from selenium and vanadium at the top, through uranium to molybdenum at the bottom of the mineralized zone. This is the pattern most commonly observed, but as noted earlier, ore rolls will produce inverted patterns on the overturned limbs.

The vanadium-uranium mineralization most commonly occurs within altered-facies sandstones, as defined by Shawe (1976a), commonly adjacent to carbon-facies sandstones, both of which contain carbonaceous material and no evidence of the type of altered (oxidized) sandstone tongues that are associated with most roll-type deposits. It appears, therefore, that the uraniferous solutions were sufficiently oxidizing to carry uranium in the oxidized state but were sufficiently low in oxidation capacity to leave unaltered the majority of the detrital carbonaceous material. Granger and Warren (1979) have discussed solutions that are capable of retaining uranium (VI) in solution but without free oxygen. The absence of redistributed humates within the vanadium-uranium ores suggests that the pH of the two mixing solutions was sufficiently similar to prevent the precipitation of humates from an alkaline-reduced ground water.

Granger and Warren (1981) have verified the reactions they propose by laboratory experiments. Aware of the tendency to prematurely embrace new hypotheses, particularly where previous interpretations have proved so unsatisfactory, we nonetheless suggest that their mechanism was probably important in the formation of the Salt Wash ores. It now remains to be tested, and the many unresolved problems explained.

Post-Ore Changes

Once deposited, the ores remained essentially in the positions in which they formed. There is no evidence that changes in ground-water patterns resulting from regional folding, faulting, or local intrusions caused significant migration of the ore elements, especially in those ores of high vanadium content. It is possible that some of the uranium migrated away from vanadium-poor deposits, but no conclusive evidence has been presented. The majority of the primary Salt Wash orebodies oxidized in place and the uranium was fixed because of the insolubility of the secondary minerals.

COMPARISON OF SALT WASH DEPOSITS TO DEPOSITS IN OTHER AREAS

Several papers have emphasized the similarities or the differences between the tabular, uniform deposits in the Salt Wash and the roll-type deposits of Wyoming and Texas. Rackley (1976, 1980) includes all the major sandstone uranium deposits under a general heading of "Western States-Type Uranium Deposits." He concludes that the apparent differences between deposits of the Colorado Plateau and the Wyoming basins are local variations within a larger model, citing similarities in tectonic conditions, sedimentation, sedimentary environments, paleoclimate, diagenesis, mineralization, and alteration (see Table 12). Similarities in the shape of the ore zones and in the zoning of metals within the deposits are stressed.

Brooks et al (1978), in applying the geochemical cell concept to Salt Wash ore deposits of the Uravan mineral belt, state,

> The interface between connate ground water and the uranium-bearing water advanced at varying rates along the different permeability conduits resulting in an extremely irregular front, rather than in a regular front as in the Wyoming uranium roll-front deposits. However, the flow was stable and consistent with ground-water flow through the braided stream deposits of an alluvial fan system. Tabular as well as tubular ore deposit morphologies are readily explained by such a flow pattern. The uranium and associated metals are zoned around these tubes in a manner analogous to the zonation of metals in the roll-front uranium deposits of Wyoming and Texas.

These authors imply that the invading uranium-bearing waters were oxidizing and that precipitation of ore minerals occurred at an oxidation-reduction interface similar to those of typical roll-type deposits.

Fischer (1970), while recognizing the similarities between Wyoming roll-type deposits and the peneconcordant deposits of the Colorado Plateau, also pointed out several apparent differences (Table 13).

We agree that sandstone uranium deposits in all districts are similar in many respects, and that many of the differences could indeed be considered as variations on a central theme rather than characteristics of distinctly different ore types.

We do not agree that the conventional geochemical cell concept involving uraniferous ground waters can be applied to most Salt Wash deposits. The typical Salt Wash deposit is surrounded by apparently reduced rock, a situation not compatible with the roll-type genetic theory. It seems more likely that the ore metals were carried to sites of deposition by solutions mainly depleted in free oxygen which were not capable of oxidizing pyrite (Granger and Warren, 1979). Precipitation of the ore minerals could have occurred along areas of contact between an epigenetic, mildly oxidizing (relative to uranium) solution containing uranium and a reducing water containing vanadium. Mineralogical studies are inadequate to determine if the rocks surrounding Salt Wash deposits have been re-reduced from a previously oxidized state.

Table 12. Common features of Western States-type uranium deposits (modified from Rackley, 1976).

Tectonic conditions

(1) Host rock is part of a thick, extensive continental sequence, much of which may be red beds.
(2) Host rock is feldspathic to arkosic, micaceous, or cherty sandstone.
(3) Volcanic material is present in or overlying the host rock.
(4) Upstream erosion of host rock.
(5) Burial and preservation.

Sedimentation

(1) Sedimentation by stream flow of braided or meandering streams on local or regional unconformities.
(2) Sandstones and conglomerates tend to be lenticular and relatively restricted.
(3) Siltstone and mudstone are interbedded with and in erosional relationship to sandstones and conglomerates.
(4) Mudstone clasts are common constituents of sandstone and conglomerates.

Sedimentary environment, paleoclimate, and diagenesis

(1) Light-gray or green to dark-gray sandstones with gray and green mudstone, all commonly pyritic; pink or red mudstones present but minor in amount.
(2) Gypsum crystals in mudstones.
(3) Reptilian fauna.
(4) Bioturbation.
(5) Vegetal carbonaceous material from logs, stumps, and roots in place, detrital fragments to bacterial residue and/or asphaltic material.

Mineralization and alteration

(1) Uraninite and coffinite are principal uranium minerals in non-weathered deposits.
(2) Mineralization is both discordant and concordant with sedimentation.
(3) Mineralization occurs in sharp contact with carbonaceous-free or oxidized zones.
(4) Epigenetic minerals occur in same relative spatial positions when present.
(5) Mineralization is most common in thicker sandstone-facies belts where mudstone facies make up 20 to 50 percent of the sequence.

Table 13. Summary of characteristics of the Wyoming roll-type and the Colorado Plateau peneconcordant-type uranium deposits (modified from Fischer, 1970).

Similarities	Differences: Wyoming Type	Differences: Colorado Plateau Type
	HOST ROCKS	
Continental, stream-laid, lenticular sandstone; containing shaly layers and carbonized fossil wood, and confined between beds of low permeability.	Cenozoic. Highly arkosic, unlithified; deposited in intermontane basins.	Mesozoic. Slightly to moderately arkosic, lithified; deposited in broad basins or foreland areas.
	DISTRIBUTION OF DEPOSITS	
Moderately wide, in favored stratigraphic zones.	Scattered along miles-long interfaces between altered rock, like widely spaced beads on a string, with a little uranium along these interfaces between orebodies.	Discrete, like raisins in raisin bread; barren altered rock may pervade a mining district, or it may merely envelop individual deposits.
	COMPOSITION	
Similar suite of elements and minerals.	Consistent--U deposits with considerable Se and in places Mo; generally little V, and sparse Cu.	Varied--U, VU, and V deposits with Se and Mo conspicuous in only a few places.
	HABITS OF OREBODIES	
Ore minerals mainly impregnate sandstone.	Dominantly crescent-shaped rolls, discordant to bedding, extending vertically through or partly through a sandstone unit, and asymmetric in composition from concave to convex side; in places thin peneconcordant layers project from the limbs of the rolls.	Dominantly tabular layers, peneconcordant to bedding, thin and occupying only a small part vertically of a sandstone unit, and without recognized "fronts" or "backs"; rolls are only small parts of most orebodies and are more common in the V-rich bodies.
	ALTERATION	
Consistently associated, though somewhat varied among mining districts in both the Wyoming and the Plateau regions.	Oxidizing, with destruction of pyrite and carbonized fossil wood; only on the concave side of ore rolls and interfaces.	Reducing, with formation of pyrite, destruction of red (ferric oxide) color, and preservation of carbonized fossil wood; envelops deposits.
	ORE DEPOSITION	
In a reducing environment, associated with organic material, mostly carbonized fossil wood.	As a dynamic (moving) body--the multiple migration-accretion idea of Gruner (1956)--along a self-sustaining oxidation-reduction interface.	As a static (stationary) body--the "'one shot' affair" of Garrels (1957)--apparently localized by intensive reducing "patches" in a mildly reducing environment (area of alteration).
	ORE-BEARING SOLUTIONS	
Ground waters moving along sandstone beds.	Moving through the oxidation-reduction interfaces and the roll orebodies.	Moving through masses of altered rock, but generally parallel to the tabular orebodies.
	RELATIVE AGE OF MINERALIZATION	
Probably before significant regional deformation.	Present orebodies may have formed fairly long after the host rocks accumulated.	Deposits may have formed shortly after the host rocks accumulated.

Salt Wash uranium deposits are similar in many respects to some of the primary uranium deposits in the Grants district, but significant differences also exist. Both types of deposits are within similar tectonic, structural, and regional geologic settings, and both are associated with similar sediments of the same age. The composition of the host sandstones is similar, and both contain interbedded gray reduced clays. Pre-existing or growing structures were important in influencing depositional patterns in each area. The ore deposits in both areas are surrounded by apparently reduced pyritic sandstones which have been leached of magnetite and ilmenite. Deposits of both types are thought to have formed as tabular and lenticular orebodies along the contact between ground waters of different composition. In both districts one of the solutions probably contained dissolved humates which transported alumina and silica to form clays in the ore zones. In the case of the Grants ores, the humates produced widespread silicate alteration (Adams et al, 1978; Adams and Saucier, 1981) which has not been reported in the Salt Wash deposits.

The ore-bearing sandstones of the Salt Wash Member, the Wyoming basins, and the Grants district all contain detrital carbonaceous material. The abundant humates of the Grants ores have not been identified in Salt Wash deposits. The thicker and more continuous sandstones in the Grants district probably account for the larger size of the ore deposits.

RECOGNITION CRITERIA

Introduction

The geologic characteristics of Salt Wash vanadium-uranium deposits have been reviewed and discussed in the context of ore-forming processes in the preceding sections of this report. We now proceed to identify those geologic characteristics related to these deposits that would seem to be most diagnostic for the presence or absence of Salt Wash-type deposits in unexplored areas. The geologic characteristics selected are referred to as recognition criteria and have been chosen because of their close association with the Salt Wash-type deposits. These recognition criteria should be useful in resource studies and exploration for estimating the geologic favorability of areas of study for occurrences of Salt Wash-type deposits.

The selection, definition, and ranking of recognition criteria are routinely performed by the experienced exploration geologist. The material presented in this section and in the Appendix is intended to be used as an aid by geologists involved in exploration or resource studies. This material is not presented as a "cookbook" to be perfunctorily applied to prospective areas. Considerable geologic judgement is required in the use of the recognition criteria, and inexperienced geologists will encounter much difficulty. The recognition criteria are merely guides to be used by geologists as they conduct exploration or resource studies in unexplored areas, within the Salt Wash and elsewhere.

To be useful in resource studies or exploration, recognition criteria are chosen so that: (a) when they are present or favorable, the chances of a deposit being present are significantly increased, i.e., they are important "good news"; or (b) when they are absent or unfavorable, the chances of a deposit being present are significantly decreased, i.e., the negative criteria are important "bad news". Some recognition criteria have both attributes and are thus particularly useful. By using only criteria that significantly affect the likelihood of a deposit being present or absent, one avoids the distraction of including geologic observations which are too ubiquitous or undiagnostic to be useful guides to the favorability of an area.

Considerable subjectivity is involved in the selection, definition, and use of the recognition criteria. Because geologic observations do not lend themselves to rigorous numerical treatment, the use of such data unavoidably involves subjective judgement. In our opinion, it is far better to use the data and the judgements, carefully documenting where and how subjectivity has been used, than simply to leave the reader to make the most of geologic information such as was presented in the preceding sections of this report. In the following paragraphs, therefore, we subjectively select and define those criteria which, based upon our experiences and the data contained in the preceding sections of this report, we consider to be most useful for evaluating areas for Salt Wash-type deposits. We make no pretense that these are the only criteria and definitions that could have been chosen; they are simply the best ones we were able to devise. The reader may prefer other criteria and/or other definitions which, if they reflect geologic facts, may improve our list. We acknowledge that such improvements will be needed and solicit constructive comments and contributions. Only through a consensus of careful observations and informed opinions will the criteria become reliable and useful.

Recognition criteria may be defined so that they are general or specific. For example, permeability might be chosen as a criterion and defined to incorporate observations on relevant geologic characteristics, such as sorting, rounding, and sphericity. Conversely, each of these could be chosen as a criterion. For simplicity, we prefer to lump criteria and, therefore, have subdivided them only as far as seems necessary to avoid ambiguity and to identify the most important geologic observations. Here again, subjective judgement and personal preference enter the process.

The detail or scale of each recognition criterion deserves special mention. As exploration and resource studies are conducted on areas of vastly different size and degree of geologic definition, it is appropriate to include recognition criteria that range from regional in scale (i.e., "regional tectonic setting", "uranium content of basement rocks", etc.) to local (i.e., "alteration in the sandstone", "color of interbedded shales", etc.). We have attempted to do this in the accompanying criteria, but some readers may consider certain criteria too general or too detailed to be useful or may wish to include criteria yet more general or more specific. These options, where supported by geologic data, may improve the list of recognition criteria.

In Figure 25, the criteria we have selected for the Salt Wash-type deposits are arranged by scale of observation, proceeding from the broadest and most regional on the left to the most local on the right. The criteria also are arranged in a hierarchical format, with the more general criteria, located at the top of the diagram, progressively subdivided into more detailed, "modifying" criteria toward the bottom of the recognition criteria net. This format, patterned after Hart et al (1978), permits the lowest level criteria (terminal criteria), which are based on field observations, to be combined to evaluate the favorability of the higher level criteria above them. In the evaluation of an area, this combining process continues up through the recognition criteria net until the favorability of the area of study for Salt Wash deposits is determined. A rigorous method for combining information on the criteria has been presented by Hart et al (1978). In the Appendix, we present a much-simplified method for combining geologic observations to reach favorability estimates. The reader is cautioned that the individual criteria are used only to establish the favorability of intermediate level criteria. The ultimate favorability estimate for a Salt Wash-type deposit is the composite effect of many criteria, and it is not necessarily equivalent to the probability of a deposit being present, as will be discussed in the Appendix.

With recognition criteria identified and organized as in Figure 25, it is now possible to geologically define each criterion and establish its relative importance in determining the favorability of the criteria above it in the net. The selection and definition of criteria are subjective, as discussed earlier, but the estimation of the relative importance of criteria is even more so. The justification for assigning a relative importance or weight to each criterion is that intuitively we feel some criteria are more important than others. As with the criteria themselves, we have assigned the best set of weights we could develop, but they are entirely subjective, and the reader may be justified in modifying our estimates to reflect his data. Weights assigned

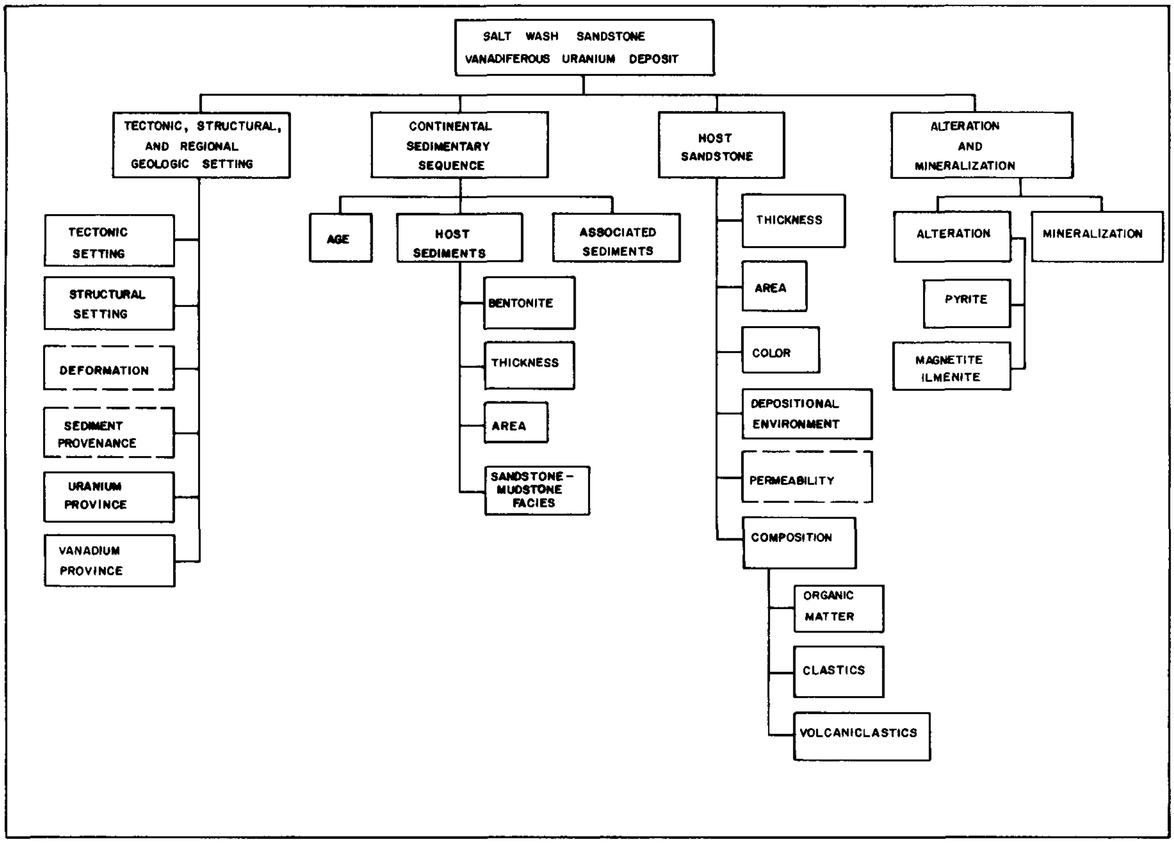

Figure 25. Recognition criteria net for Salt Wash-type sandstone uranium deposits. Numerical estimates of relative favorability are not assigned to recognition criteria shown in dashed lines.

are obviously only approximations to indicate the relatively encouraging or discouraging nature of a particular definition of a criterion. An estimate of +65, for example, might as well have been +75 or +50. We are simply attempting to capture the geologist's approximate estimate of the relative importance of geologic observations as an additional aid in the evaluation of unexplored areas. The system is subjective and imprecise and likely to remain so, but the subjective information is useful if we can learn to collect and use it properly. It is toward that end that the subjective, relative importances are assigned to all criteria in the following section, and a simple method for accumulating this information is presented in the Appendix.

Evaluation of Recognition Criteria

The assignment of importance or weight to recognition criteria may be conveniently explained by referring to the criteria at the left side of Figure 25 which evaluate Tectonic, Structural, and Regional Geologic Setting (TSRS). Of the six criteria shown, four are considered the most useful for evaluating TSRS. The other two criteria, in dashed lines, are not used as will be explained below. Each of the four criteria embodies, in the geologist's mind, numerous considerations which relate to geologic observations, the processes they reflect, and their importances to the presence or absence of a uranium deposit. With respect to evaluating TSRS, which in turn will be used with three other criteria to evaluate the likelihood of occurrence of a deposit, these are presumably the four most important criteria that could have been selected, and we assume no important criteria have been omitted.

In most cases, any four such criteria will have different importances in establishing the intermediate criterion above them. Therefore, importance or weight is assigned to each recognition criterion with the aid of the relation shown in Figure 26. Weights are assigned to each criterion independently of the others based on how sufficient the presence of the criterion by itself is for establishing the presence of favorable TSRS or how sufficient the absence of the criterion is by itself to establish the absence of favorable TSRS. For example, if one knows the tectonic setting in some area under consideration but knows nothing about the four other criteria, how favorable is TSRS? The types of tectonic settings one might consider include:

continental interior basin
intermontane basin
graben
coastal plain
miogeosyncline
eugeosyncline

The favorability of TSRS decreases from continental interior basin to eugeosyncline (additional depositional environments might have been chosen, but, as with all the criteria, no attempt is made to be inclusive, merely to provide enough examples so that the geologist can use his judgement in applying the criteria to other geologic conditions). Therefore, the likelihood of favorable TSRS being present is highest if the tectonic setting is a continental interior basin and lowest if it is a eugeosynclinal depositional environment.

Suppose the tectonic setting is known to be a continental interior basin. Since this is the type of depositional environment in which Salt Wash-type deposits occur, this is suggestive or "good news" for the presence of the proper TSRS, but how suggestive is it? In Figure 26, modifying expressions have been arranged along arbitrary scales from 0 to +100 and 0 to -100 as an aid to the geologist in estimating the importance or weight for a particular criterion. The positive scale is used when geologic observations confirm the presence of a recognition criterion, i.e., it is encouraging or "good news" for the occurrence of the higher level criteria. The negative scale is used when the criterion is absent, i.e., it is discouraging for the presence of favorable TSRS. Zero is used when the available data neither increases nor diminishes the favorability of TSRS. The scale ranges and modifying expressions might have been chosen quite differently, for example 0 to 1.0 or 0 to 500, and with different words such as "favorable" and "very favorable" for the positive scale and "unfavorable" and "extremely unfavorable", etc., for the negative scale. The conventions used were arbitrarily chosen but seemed suitable for this application.

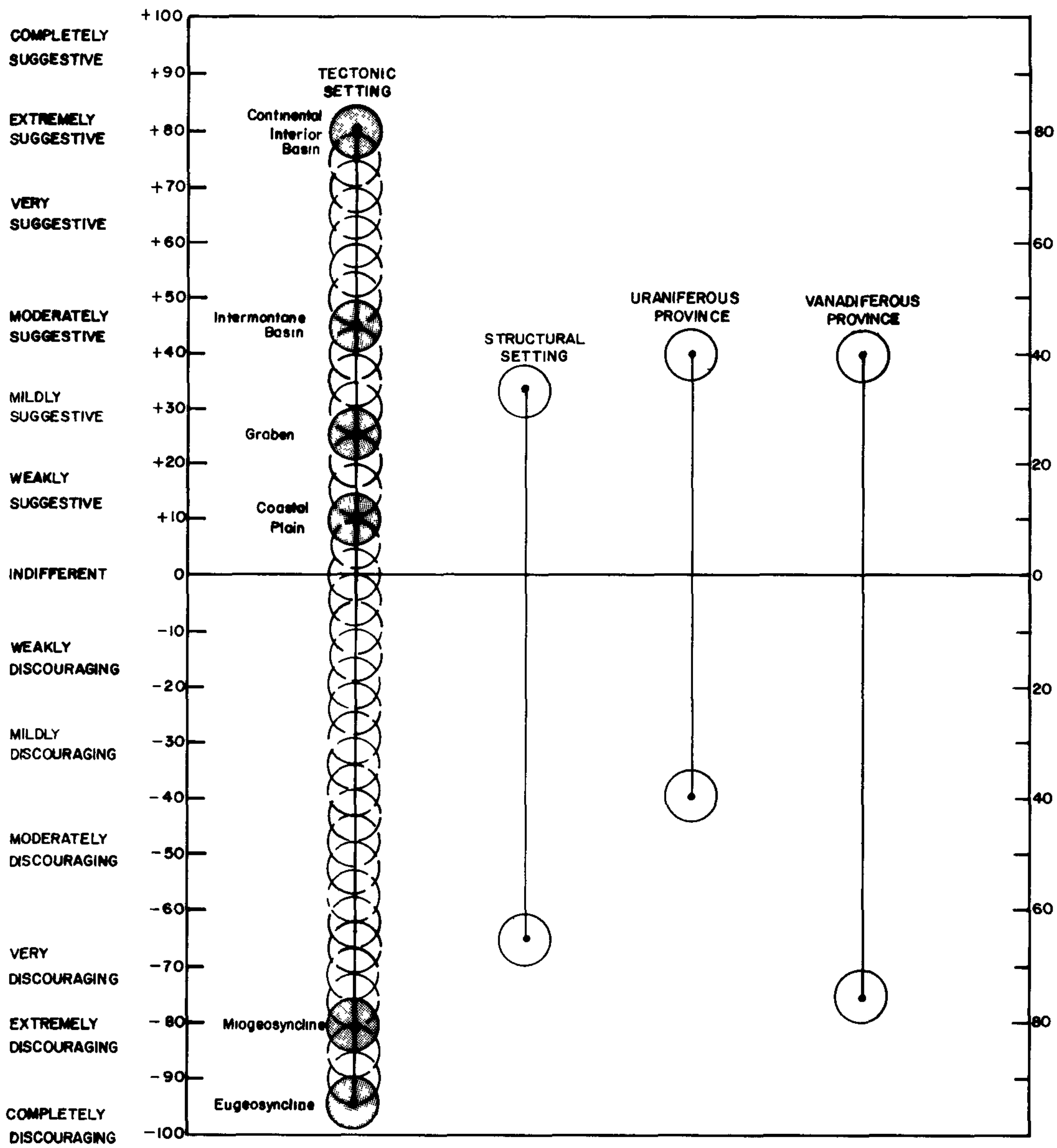

Figure 26. Example of the assignment of weights to recognition criteria using the four criteria that determine Tectonic, Structural, and Regional Geologic Setting.

To assign weights to a criterion, the geologist asks, "If the criterion is absolutely perfect, i.e., if the area under evaluation is a perfect intracratonic basin, how suggestive is it that favorable TSRS is present?" In the case of tectonic setting, we feel the presence of a continental interior basin is extremely suggestive that the TSRS is perfect, i.e., the criterion by itself is so important that if present with no information on other criteria, it provides 80 percent certainty that the TSRS is perfect.

If, on the other hand, the tectonic setting is in a eugeosyncline, it effectively rules out the possibility of a proper TSRS; thus we have designated it almost completely insufficient and assigned it a value of -95. We might have assigned a value of -100 but, out of respect for the vagaries of the earth, we have left some room for surprises. The result is essentially the same. The presence of a eugeosynclinal environment essentially destroys the potential not only for a favorable TSRS, but for a Salt Wash-type deposit. It is up to the geologist using this system to place proper weights on environments not specifically included using his judgement and the examples provided.

The tectonic setting is not the only criterion for evaluating TSRS. Structural trends such as faulted or folded basin margins against basement uplifts and fracture patterns extending out into the basin sediments also have their impact. When considered without any other information, the presence of such favorable structures is, however, only mildly suggestive (+35) for the presence of favorable TSRS. Similarly, if such favorable structures are absent and unfavorable ones are present, they are believed to be moderately discouraging; hence, they are assigned a -65. The other two criteria which affect the favorability of TSRS, Uraniferous Province and Vanadium Province, have similarly been assigned suggestivity values for when they are present and perfectly favorable, and negative values for when they are absent or completely discouraging for the presence of favorable TSRS. Values have been assigned for all the lowest level criteria and for the intermediate level criteria for evaluating the yet higher level criteria, and they are tabulated in Table 14. The "model" is now ready to use in the evaluation of real data.

The reader perhaps will have made two observations from the foregoing discussion. First, it is assumed that each recognition criterion is independent of all others, i.e., each is used separately to evaluate the criterion above it. In fact, many criteria are not independently variable and would affect the likelihood of the higher criterion differently in combination than they do by their simple sum. However, error or bias due to non-independence of variables probably becomes insignificant in the accumulated uncertainties of the geologic data and the conclusions we make about them. Secondly, there is a continuous range of decreasing favorability for each criterion starting at the maximum weighting and extending down to the most discouraging, "worst case". In applying the method, the geologist should use his judgement in selecting the favorability values for his field observations. For example, he may believe his area is a graben but that it is a very large graben system, which would increase its favorability up toward intermontane basin (Fig. 26). He might, for example, assign a value of +45 in contrast to our value of +25 and be justified in doing so. This method is to be used with geologic judgement and good sense and is not a substitute for them.

Table 14. Estimates of the values (Scale +100 to -100) for recognition criteria for Salt Wash-type deposits for establishing the favorability of the criteria above them in the recognition criteria net (see Fig. 25).

Criterion		Estimate of Suggestivity When Present or Favorable	Estimate of Discouragement When Absent or Unfavorable
Salt Wash-type uranium deposit			
Tectonic, Structural and Regional Geologic Setting		+30*	-95*
Continental Sedimentary Sequence		+40*	-95*
Host Sandstone		+40*	-95*
Alteration and Mineralization		+50*	-95*
		+160	-380
Tectonic, Structural and Regional Geologic Setting			
Tectonic Setting		+80	-95
Continental interior basin	(+80)		
Intermontane basin	(+45)		
Graben	(+25)		
Coastal plain	(+10)		
Miogeosyncline	(-80)		
Eugeosyncline	(-95)		
Structural Setting		+35	-65
Favorable	(+35)		
Unfavorable	(-65)		
Uraniferous Province		+40	-40
Present	(+40)		
Absent	(-40)		
Vanadiferous Province		+30	-40
Present	(+30)		
Absent	(-40)		
		+185	-240
Continental Sedimentary Sequence			
Age		+30	-80
Mesozoic	(+30)		
Upper Paleozoic	(+25)		
Cenozoic	(+20)		
Pre-Devonian	(-80)		

Criterion		Estimate of Suggestivity When Present or Favorable	Estimate of Discouragement When Absent or Unfavorable
Associated Sediments		+40	-75
Favorable	(+40)		
Unfavorable	(-75)		
Host Sediments		+60*	-95*
Bentonite			
Thickness			
Area			
Sandstone-mudstone facies		____	____
		+130	-250
Host Sediments			
Bentonite		+60	-75
Present	(+60)		
Absent	(-75)		
Thickness		+20	-30
Several hundred feet	(+20)		
Few hundred feet	(-30)		
Area		+30	-50
10,000 square miles	(+30)		
1,000 square miles	(-50)		
Sandstone-mudstone facies		+40	-30
Continuous sedimentation	(+40)		
Erosional breaks	(-30)	____	____
		+150	-185
Host Sandstone			
Thickness		+40	-40
> 50 feet	(+40)		
25-50 feet	(+20)		
< 25 feet	(-40)		
Area		+40	-50
> 5 square miles	(+40)		
< 1 square mile	(-50)		
Color		+50	-70
Gray with nearby red zone	(+50)		
Gray or reduced	(+20)		
Red or oxidized	(-70)		
Depositional Environment		+50	-60
Lacustrine clays present	(+50)		
Lacustrine clays absent	(-60)		

Criterion		Estimate of Suggestivity When Present or Favorable	Estimate of Discouragement When Absent or Unfavorable
Composition		+60*	-95*
Organic Matter			
Clastics			
Volcaniclastics			
		+240	-315
Composition			
Organic Matter		+30	-70
Present	(+30)		
Absent	(-70)		
Clastics		+50	-70
Orthoquartzite	(+50)		
Arkose	(+10)		
Graywacke	(-70)		
Volcaniclastics		+40	-60
Present	(+40)		
Absent	(-60)		
		+120	-200
Alteration and Mineralization			
Mineralization		+50	-50
Favorable	(+50)		
Unfavorable	(-50)		
Alteration		+60*	-70*
Magnetite-Ilmenite			
Pyrite			
		+110	-120
Alteration			
Magnetite-Ilmenite		+70	-70
Altered	(+70)		
Unaltered	(-70)		
Pyrite		+50	-20
Abundant	(+50)		
Traces	(+15)		
Absent	(-20)		
		+120	-90

* Values assigned to intermediate level criterion

Description of Recognition Criteria

In order to apply the recognition criteria net (Fig. 25) to the evaluation of field areas, it now remains to (1) describe the recognition criteria so that they can be evaluated with field geologic observations, and (2) assign numerical value to various states of the criteria depending upon how suggestive or discouraging the states are for the intermediate criterion above them. In the following pages, the criteria are organized by the major second level criterion shown in Figure 25. The subjective weights for the various criteria, estimated according to procedures described in the preceding paragraphs, accompany the definitions.

Tectonic, Structural, and Regional Geologic Setting

Tectonic Setting

Of the possible tectonic settings in which a favorable sedimentary sequence might accumulate, the broad intracratonic basin is by far the most favorable because of its size and the associated geologic conditions which promote both the accumulation of the Host Sediments and a proper diagenetic history. The favorability of potential environment may be arranged as follows:

(1)	Continental Interior Basin	+80
(2)	Intermontane Basin	+45
(3)	Graben	+25
(4)	Coastal Plain	+10
(5)	Miogeosyncline	-80
(6)	Eugeosyncline	-95

Structural Setting

Pre-existing and actively growing structures exerted a pronounced effect on patterns of sedimentation within the Salt Wash depositional basin. Such structures as recurrently active salt anticlines which diverted or impeded major drainage patterns, or local downwarps in which thicker deposits of sediments were accumulated, were important in localizing favorable environments for later ore-forming processes. Structures of Laramide and younger ages or local intrusive bodies of Tertiary age disrupt the previously formed orebodies, affecting exploration and mining, but were not important ore controls, unless they were active structures at the time of Salt Wash sedimentation.

The relative importance of large-scale structures which influenced depositional patterns is rated below:

(1) The depositional basin contains numerous structural elements which influenced depositional patterns. +35

(2) The depositional basin contains few or no structures which influenced depositional patterns. -65

Deformation

Post-ore deformation affects the economics of exploration and mining, but it is not effective in creating conditions under which the vanadiferous uranium deposits of the Salt Wash are chemically destroyed or remobilized. Obviously, some deposits have been physically removed by erosion. Presumably, the deposits would be chemically stable even under conditions of moderate metamorphism. Therefore, no relative weights are assigned to deformation.

Sediment Provenance

A source area capable of supplying stable detrital minerals such as quartz and feldspar together with silicic volcaniclastics and tuffaceous material is considered most favorable. Because the Salt Wash was derived from multiple source areas which are not now identifiable, a type source area cannot be adequately quantified.

Uraniferous Province

Most of the significant uranium deposits in sandstone are within a known or suspected "uraniferous province". Exposed granitic and metamorphic rocks of Precambrian age within this province are anomalously high in radioelements compared to Precambrian rocks in other areas. Younger intrusives and extrusive rocks derived from the remelting of these rocks are also anomalously high. Granite basement rocks, even though leached of some uranium at or near the surface, may be useful in assessing the potential of a region or district. Numerical weights are derived as follows:

(1) Source area of sediments is known to be within a uraniferous province. +40

(2) Source area of sediments is known to be outside of uraniferous province. -40

Vanadiferous Province

It cannot be demonstrated conclusively that Salt Wash sediments were derived from a vanadiferous province, although certain Paleozoic black shales within the generalized source area are highly enriched in vanadium. Vanadium may have been liberated by weathering of these shales or other vanadiferous sources or transported in detrital grains such as ilmenite and magnetite to become incorporated in the Salt Wash depositional environment.

Perhaps equally important, the vanadiferous uranium deposits of the Salt Wash occur in second-cycle sandstones. This may have permitted the accumulation of a higher concentration of vanadiferous ilmenite and magnetite than would have occurred, for example, in an arkose. Although the presence of a second-cycle sandstone by itself is at best only a weak indication of the possibility for finding a vanadiferous uranium deposit, its absence is somewhat more discouraging. First-cycle arkosic sandstones are judged to be less likely host rocks for vanadiferous uranium deposits, even though they may contain large uranium deposits in some areas. The relative favorability of a source area for vanadium can be summarized as follows:

(1)	The source area was composed mainly of quartzitic and pelitic sedimentary rocks but also included potentially vanadiferous sources within a known or suspected vanadiferous province.	+30
(2)	The source area was composed mainly of silicic igneous or volcanic rocks without evidence of vanadiferous ilmenite and magnetite.	-40

Continental Sedimentary Sequence

Salt Wash-type deposits appear to be related to thick and laterally extensive continental fluvial sequences which include relatively thin sections of reduced sandstones (the host rocks) containing carbonaceous material and silicic volcanic ash. A discussion of continental sedimentary sequence touches on age, host rocks, and associated sediments, each of which is considered separately.

Age

Favorable carbonaceous sedimentary sequences older than Silurian probably were not formed because of the relative scarcity of land plants prior to that time. Terrestrial rocks of Devonian or younger ages may contain abundant plant fossils, reflecting the evolution and proliferation of land plants. From the standpoint of availability of plant material only, continental sequences younger than Silurian may be equally favorable.

From a tectonic standpoint, the large intracratonic basins formed during Upper Paleozoic and Mesozoic time may be most favorable.

Age favorability is rated below:

Mesozoic	+30
Upper Paleozoic	+25
Cenozoic	+20
Pre-Devonian	-80

Associated Sediments

The sediments associated with vanadiferous uranium deposits of the Salt Wash-type are continental fluvial sequences of the "red beds" type. Within the "red beds" sequence are relatively thin but widespread units of reduced sandstones containing interbeds of gray clays and carbonaceous debris. Continental fluvial sediments several hundred to a few thousand feet thick extending over hundreds of thousands of square miles would be most favorable.

Associated sediments are:

(1)	Dominantly of continental fluvial origin, several hundred to a few thousand feet thick, and deposited over an area of at least 10,000 square miles.	+40
(2)	Not dominantly of continental fluvial origin, or if so, they were deposited only over small areas as thin sequences.	-75

Host Sediments

Host Sediments are the particular rock units being evaluated for the presence of uranium deposits, but units immediately overlying or underlying the host rock (usually a sandstone) are also included. In the case of Salt Wash deposits, the overlying Brushy Basin Member is thought to be an important contributor of uranium and is therefore considered as an integral part of the Host Sediments.

Bentonite

Overlying and underlying units dominantly of clay or siltstone composition could have formed upper and lower permeability boundaries to the host sandstone and may have contributed uranium to the mineralizing system if they contained significant amounts of volcanic ash.

The relative favorability of depositionally continuous overlying or underlying units from the standpoint of bentonite content is assessed below:

(1)	The sediments overlying or underlying the Host Sandstone are composed dominantly of mudstones or siltstones containing significant amounts of bentonite.	+60
(2)	The sediments overlying and underlying the Host Sandstone contain only non-bentonitic clays.	-75

Thickness

Thick sequences of favorable Host Sediments containing interbeds of reduced carbonaceous sandstones are more favorable than thin sequences of limited areal extent. Thick accumulations generally indicate widespread depositional conditions over a large area and greater possibilities for the accumulation and subsequent introduction of larger amounts of uranium to the system. Reduced to generalities, the evaluation of thickness is:

(1) The favorable Host Sediments are several hundred feet thick. +20

(2) The favorable Host Sediments are not more than a few hundred feet thick. -30

Area

Like increasing thickness, a larger area of favorable Host Sediments enhances the possibilities of finding larger or more numerous ore deposits. The influence of area, in very general terms, is:

(1) Potentially favorable Host Sediments occupy an area larger than 10,000 square miles. +30

(2) Potentially favorable Host Sediments occupy an area of less than 1,000 square miles. -50

Sandstone-Mudstone Facies

Favorable Host Sandstones and their immediately adjacent overlying and underlying Host Sediments should exhibit depositional continuity within the total sequence. For example, the Brushy Basin mudstones grade upward from the underlying Salt Wash sandstones without a major break in the depositional sequence.

(1) The Host Sediments were deposited without major breaks in the sedimentary sequence and are interbedded at their boundaries. +40

(2) Major depositional breaks occur within the Host Sediment sequence. -30

Host Sandstone

Potentially favorable Host Sandstones for Salt Wash-type vanadiferous uranium deposits can be identified and evaluated by specific recognition criteria which measure their relative importance. The area and thickness of the sandstones are important criteria because thicker units of large areal extent are more transmissive. Permeability of the sands is influenced by the composition of the sandstone and by the amount of interbedded mudstone. Certain types of mudstones and carbonaceous debris are important in supplying a source of reductant, and volcaniclastic and tuffaceous material within the Host Sandstones can be likely sources of at least some of the uranium.

Thickness

Thickness, by itself, is not an important criterion. For example, a thick oxidized red sandstone is very unfavorable, while a thick gray reduced sandstone can be very favorable, but only if other favorable criteria exist also. Abrupt transitions to a thick favorable sand are more significant than uniformly thick areas or areas where the sand thickness changes gradually. Considering only the favorable reduced sands, it is usually true that the thicker and more continuous reduced sands will host larger orebodies:

(1) The favorable reduced sandstone is more than 50 feet thick. +40

(2) The favorable reduced sandstone is 25 to 50 feet thick. +20

(3) The favorable reduced sandstone is less than 25 feet thick. -40

Area

Area, like thickness, is important mainly as a measurement of the amount of favorable reduced sandstone. A sandstone may have great thickness as well as wide areal extent yet have few, if any, other favorable characteristics. In terms of the area of favorable reduced sand, the following relative weights are applicable:

(1) The favorable reduced sandstones are continuous over an area larger than 5 square miles. +40

(2) The favorable reduced sandstones are continuous over an area smaller than 1 square mile. -50

Color

Color of the Host Sandstone may be the most important single criterion for determining the favorability of a sandstone for hosting Salt Wash-type vanadiferous uranium deposits. Red oxidized sandstone is very unfavorable and will host only very small and widely scattered orebodies. Gray sandstone is an indication of a potentially favorable environment, but large areas of gray sandstone are barren or host only widely scattered orebodies of modest size. The largest and most significant Salt Wash orebodies appear to be concentrated in elongated zones of reduced favorable sand near and parallel to a contact with oxidized sediments. Favorability ratings are, then:

(1) The sandstone is gray and reduced and parallels an adjacent contact of red oxidized sediments. +50

(2) The sandstone is gray and reduced. +20

(3) The sandstone is red and oxidized. -70

Depositional Environment

An alluvial fan complex derived from a single source area can be divided into proximal, medial, and distal portions, each of which can be rated separately for uranium favorability. Usually the medial facies is most favorable because of the more likely preservation of carbonaceous material and intermediate permeability.

A series of coalescing alluvial plains derived from multiple source areas is more difficult to assess. For example, Figure 4 of this report divides the Salt Wash sediments into conglomeratic sandstone facies, sandstone and mudstone facies, and mudstone and lenticular sandstone facies. As a broad generalization, these facies might be construed as proximal, medial, and distal facies, and to some extent this is probably correct. Most of the uranium deposits are within the sandstone-mudstone facies, but significant deposits also have been found within the area previously mapped as conglomeratic facies on Figure 4. Peterson's detailed work within this area identified braided stream deposits, meandering stream deposits, eolian, evaporite, deltaic, and lacustrine deposits, indicating that the so-called conglomeratic facies is actually composed of several depositional environments.

While we agree that the medial portion of an alluvial fan complex is the most favorable facies, coalescing alluvial plain complexes may be more difficult to categorize. Following the lead of Peterson (1980), we conclude that the best indicator of a favorable depositional environment is measured by the presence or absence of "favorable" gray lacustrine clays within a permeable sandstone sequence.

(1)	The Host Sandstone is overlain, underlain, or interbedded with "favorable" gray lacustrine clays.	+50
(2)	"Favorable" gray lacustrine clays are not intimately associated with the Host Sandstones.	-60

Permeability

While it is obvious that an epigenetic uranium deposit cannot be formed in impermeable sandstone, the complex internal geometry of sandstones like those of the Salt Wash makes a favorability assessment of permeability difficult. Differences of permeability within a single sand package appear to be more favorable than a uniformly permeable system. Connate waters as well as introduced solutions appear to be important in the formation of Salt Wash-type deposits. Because of the difficulty in assessing this criterion, we have not rated permeability.

Composition

Factors influencing composition of a favorable Host Sandstone include the nature and stability of the clastic fraction and the presence or absence of volcaniclastics and organic material.

Organic Material

Plant debris in the Host Sandstone or in associated clays is essential as a source of humic acids and for the formation of sulfides. Many rock units contain carbonaceous material but host no uranium deposits, making the presence of plant material alone only weakly suggestive. Conversely, the absence of carbonaceous matter or other suitable reductants is very discouraging for a favorable Host Sandstone.

(1)	Carbonaceous material (plant debris), or other sources of reductants, present in more than trace amounts in the Host Sandstone or associated clays.	+30
(2)	Plant material or other reductants are absent.	-70

Clastics

A framework of stable detrital grains, mainly quartz and feldspar, is necessary to insure porosity and permeability of the Host Sandstone. Poorly sorted sands, or sands containing a high percentage of clays or detrital minerals which break down to clay minerals, would be unfavorable.

We have discussed before that vanadiferous uranium deposits in sandstone appear to be confined to second-cycle sandstones, and this was considered under the heading of Vanadiferous Province. Composition of the Host Sandstone for deposits of the Salt Wash type is also affected by that consideration. Arkosic sandstones may be the most favorable type to host vanadium-poor uranium deposits, but they appear to be less favorable as a host for vanadium-rich uranium deposits.

(1)	The Host Sandstone is a tuffaceous or feldspathic orthoquartzite derived mainly from pre-existing sedimentary rocks.	+50
(2)	The Host Sandstone is an arkose.	+10
(3)	The Host Sandstone is a graywacke with unstable detrital minerals and abundant interstitial clay.	-70

Volcaniclastics

The presence of a moderate amount of volcanic material within the Host Sandstones or in interbedded or adjacent clay beds indicates a potential local source of uranium. Diagenetic alteration of the fine-grained or glassy fraction may have destroyed the original volcanic components, but the presence of high-temperature beta-quartz crystals or the volcanic feldspar sanidine may indicate an original volcanic fraction.

(1)	Volcaniclastic material is a recognizable but subordinate constituent of the detrital fraction of the Host Sandstone, and bentonite is a major constituent of interbedded clays.	+40
(2)	There is little or no indication of volcaniclastics or bentonite within the Host Sandstone.	-60

Alteration and Mineralization

Specific evidence of alteration or mineralization may not be observed without conducting drilling programs and detailed laboratory investigations, but presumably a potential Host Sandstone has been identified which meets the recognition criteria defined for Tectonic, Structural, and Regional Setting, and for Continental Sedimentary Sequence. Alteration may be confined to small portions of the Host Sandstone, and mineralization may be restricted to a small fraction of the altered sandstone.

Alteration

Altered reduced sandstone is not megascopically distinguishable from unaltered reduced sandstones, nor are their oxidized equivalents recognizably different. The altered sandstone, however, contains more pyrite, and the magnetite and ilmenite have been almost completely destroyed by intense reduction in the district studied.

Magnetite-Ilmenite

Altered areas within the normal reduced facies of the Salt Wash are characterized by an almost complete destruction of the heavy minerals magnetite and ilmenite. Thick and extensive zones of alteration would be most favorable. Possibly these altered areas, essentially devoid of magnetite and ilmenite, could be detected by outcrop or drill hole magnetic susceptibility measurements, but to our knowledge such tests have not been conducted in the Salt Wash.

(1)	The gray reduced and carbonaceous Host Sandstone contains intervals in which magnetite and ilmenite have been totally destroyed.	+70
(2)	There is evidence that magnetite and ilmenite have not been destroyed.	-70

Pyrite

The concentration of pyrite within the Host Sandstone increases with the intensity of alteration. Unaltered reduced sandstones are sparsely pyritic, while altered reduced sandstones may contain 0.5 percent or more pyrite.

(1)	The gray reduced carbonaceous Host Sandstone contains significant concentrations of pyrite (or limonite in weathered outcrop).	+50
(2)	The Host Sandstone contains only traces of pyrite. (Limonite in weathered outcrop)	+15
(3)	The Host Sandstone contains no pyrite. (Limonite in weathered outcrop)	-20

Mineralization

Indications of uranium and vanadium mineralization in the proper host environment certainly are significant and encouraging. Anomalous concentrations of the ore metals may be detectable on the outcrop at sandstone-shale interfaces or in residual concentrations of carbonaceous material. Anomalous ground waters or stream sediments may help to isolate more favorable areas, as would anomalies detected by airborne or ground radiometric surveys. Radon or helium anomalies within or adjacent to the Host Sandstone can be equally favorable indicators of buried targets in favorable sediments.

(1) Compared to other potentially favorable Host Sediments or Host Sandstones, the rock units under investigation contain more numerous or more intense anomalies indicative of uranium-vanadium mineralization. +50

(2) The Host Sandstone and Host Sediments contain few if any indications of uranium-vanadium mineralization. -50

REFLECTIONS AND CONTINUING STUDIES

The vanadium-uranium deposits of the Salt Wash sandstone in the Colorado Plateau have been exploited longer than any other uranium deposits in the United States. In spite of this, there is no generally accepted concept which explains the formation and controls of these deposits or identifies those geologic characteristics most useful for exploring untested areas. This reflects (a) the early preoccupation with oxidized, near-surface deposits and the much later recognition of the primary black ores at depth, and (b) the generally smaller size of individual deposits, which has discouraged broad-scale, systematic exploration and geologic studies. In fact, the deposits are relatively unimportant in terms of domestic production and reserves, constituting less than 10 percent of the former and less than 7 percent of the latter. Regional exploration was probably also somewhat discouraged by the occurrence of most significant deposits within the Uravan mineral belt, causing exploration efforts to focus heavily within that area.

The recent discovery of major new deposits in the Henry Mountains, and the recognition of inadequately explored sandstone channel systems, suggests that exploration potential outside of the Uravan mineral belt may still prove successful. Furthermore, studies by the U.S. Geological Survey are once again beginning to contribute information on ore deposit characteristics and modes of ore formation, which may prove useful in exploration and resource studies. In light of these activities, and the data and interpretations presented in this report, some obvious shortcomings in our data and understanding, and hence directions for fruitful research, are apparent. The more important of these are briefly enumerated below.

(1) The process of ore formation is still uncertain, although promising new concepts are being developed. In few cases is adequate information on the chemical and mineralogic composition of the ore <u>and</u> the unmineralized host rocks in <u>all</u> directions from the deposits available. Until such data bases have been developed for a representative number of deposits, even an accurate ore-formation model will be untestable. Not only should the composition of the Salt Wash sands be established, but so also should that of its shales and those of the Brushy Basin, in terms of such factors as thorium-uranium ratios and minor element contents.

(2) The source of the uranium is presumed to have been in the shales of the Salt Wash and Brushy Basin Members, but there are no data which convincingly demonstrate that this was the case. Geochemical data on the concentrations of uranium in the Morrison sediments and other elements that will indicate the degree of uranium leaching need to be collected.

(3) Most uraniferous deposits within the Salt Wash Sandstone Member are essentially vanadium deposits with associated uranium. In spite of this, most studies of these deposits have focused on the uranium characteristics and similarities with other sandstone uranium deposits, rather than confronting the source, transport, and mode of precipitation of the vanadium. The answers to these questions are the most likely to provide information on the formation, control, and distribution of these types of uranium deposits. Among other things, the vanadium content of ilmenite and magnetite in the sands, a common proposed source of vanadium, should be representatively determined.

This will permit estimates of the adequacy of altered sandstone (sands in which ilmenite and magnetite have been destroyed) to provide the large amounts of vanadium now found in the deposits. Companion studies of other vanadiferous deposits such as at Rifle, Colorado, and in the Southern Black Hills, South Dakota, could provide useful comparisons. Studies by Spirakis (1977), LaPoint and Markos (1977), and others on the Rifle deposit present concepts which may be applicable to the Salt Wash ores and need to be tested. Other investigators have favored a vanadium source outside the Morrison Formation, in which case the conditions of vanadium transport in oxidizing solutions must be established. The possibility that vanadium was transported as humate or other complexes to the site of the ore formation and precipitated without the precipitation of the humic material deserves investigation.

(4) The sources of the sediments which now comprise the Salt Wash Member are more diverse and complicated than they are generally represented to be. As the deposits are closely related to thicker sandstones and specific channel sandstone axes, more detailed regional sedimentologic and facies studies of the Salt Wash are justified. Studies of the clastic components, in particular ilmenite and magnetite, could prove useful to investigations of both provenance and vanadium source.

(5) On a more detailed scale, the changes in depositional environments across the Uravan mineral belt have been hypothesized but not well documented. As the characteristics of the sediments presumably exert a strong influence on ore controls and distribution, these regional characteristics are of paramount importance, as are the changes produced in the sediments of the different depositional environments by diagenetic and ore-forming processes.

POTENTIAL FOR NEW DEPOSITS IN THE UNITED STATES

The potential of the United States for Salt Wash-type deposits was not investigated extensively for this report. Finch (1967) lists more than 100 formations containing uranium deposits in continental sandstones. Many of these are of Mesozoic age and may warrant a thorough review. An additional 55 formations containing continental sandstones not known to contain uranium deposits are also included (Finch, 1967). Annual reports on uranium reserves and potential resources are provided by the U.S. Department of Energy (1980a). These reports contain much useful information on geologically favorable areas. The recently released report by the U.S. Department of Energy (1980b), An assessment report on uranium in the United States of America, identifies areas containing reserves and potential resources in each of 116 1° by 2° topographic quadrangles. A careful review of these reports might well identify Salt Wash-type targets. A recent open-file report by Nilsen and Moore (1980) identifies ancient and modern alluvial fan deposits throughout the world and contains selected bibliographic references for each. Again, a review of this information may prove to be rewarding.

The Morrison Formation may contain a significant uranium potential in areas which have not been intensively prospected to date. The discovery of moderately large uranium deposits in the Henry Mountains within the mapped conglomeratic facies of the Salt Wash shown in Figure 4 of this report strongly suggests that this facies is more favorable than had been considered previously. The exploration guidelines provided by the lacustrine-humate model (Peterson, 1980) should prove useful in exploration.

The discovery of moderately large vanadium-uranium deposits in upper Salt Wash sandstones in the La Sal area, more than 50 miles west of the Uravan mineral belt, indicates that other major tributaries should be present north or south of the La Sal trend (Butler and Fischer, 1978). The upper Salt Wash sandstones within the Uravan mineral belt have been extensively prospected for more than 30 years; small deposits will continue to be found, but the chance for discovery of significant new deposits probably is small. Lower Salt Wash sandstones within the mineral belt have not been thoroughly explored, and some potential exists for finding deposits of small to moderate size.

About 850,000 tons of Salt Wash ore were mined during the 1950s and 1960s from part of the Navajo Reservation in northeastern Arizona and adjoining parts of New Mexico. Very little ore has been mined since that time, and little exploration has been done. Although several government drilling programs were conducted in this area during the 1950s, most of the drilling was done behind known mineralized outcrops. Little wide-spaced exploration was done for stratigraphic information. A careful review of the drilling data and available geologic' information might locate target areas of possible interest.

Measured sections of thick gray Salt Wash sandstones containing interbeds of gray clay have been described from Dinosaur National Monument, near Vernal, Utah (Bilbey et al, 1974). These thick sandstones are far to the north of the limits of the sandstone-mudstone facies shown on Figure 2 and may be derived from a separate source area to the west. A few small Salt Wash prospects are known in northeast Utah and northwestern Colorado in this general area, but no significant production has been recorded. Nevertheless, a careful search of the literature might point out areas worth field checking.

Finally, we are convinced that large-scale oxidation-reduction boundaries are important guides to Salt Wash orebodies and ore districts. Transitional areas between oxidized and reduced facies of the Recapture, or areas where oxidized Recapture sediments intertongue with reduced Salt Wash sediments, may be worth further investigation. Changes of these types may be present in northeastern Arizona within the area shown on Figure 2. The Recapture has not been an important uranium producer to date, but perhaps it deserves more attention.

APPENDIX

ESTIMATION OF GEOLOGIC FAVORABILITY FOR THE OCCURRENCE OF SALT WASH-TYPE DEPOSITS

Introduction

Numerous methods have been used for estimating the geologic favorability or expected resource endowment of an area for various types of ore deposits (Cargill and Clark, 1978; Singer and Ovenshine, 1979; Voelker et al, 1979; Harris and Carrigan, 1980). In this section we present a simplified method for estimating the favorability of an area for the occurrence of Salt Wash-type deposits using the recognition criteria net (Fig. 25) and the weights assigned to the recognition criteria (Table 14). It must be emphasized that the favorability estimate reflects only the general geologic similarities between known deposits, as defined by the recognition criteria, and the geologic characteristics of an area in which similar deposits might occur. A higher degree of geologic similarity yields a higher favorability estimate, suggesting a greater likelihood that the type of deposit for which the recognition criteria were developed is present in the untested area. No attempt is made to estimate the number of deposits or their geologic size, grade, and continuity. These characteristics require information about the known deposits which, in many cases, is not yet available.

The use of this method presumes that sufficient geologic information is available for the area of study, so that weights can be confidently assigned to the recognition criteria. In most cases, geologic data are incomplete and values cannot be assigned to all criteria. Using the method described below, the absence of a value for a criterion is analogous to assigning it a value of zero. This could introduce a significant error in the interpretation of the favorability estimate if the geologist fails to note where data were lacking. If the true favorability of the criterion is significantly higher than zero, the absent data lead to a fallaciously low estimate of the area's favorability. This is a common situation, particularly in resource evaluation of Federal lands where adequate geologic information is customarily unavailable for the systematic evaluation for all types of deposits. Geologic favorability simply cannot be estimated until an adequate data base is available. Where data are lacking, the large negative and positive weights indicate those recognition criteria for which data must be acquired. The assignment of a weight of zero may also significantly overestimate favorability if that criterion is in fact very discouraging. There is no substitute for a sufficient data base.

Calculation of Estimated Favorability

The procedure for calculating an estimated favorability may be conveniently explained by returning to the discussion of Tectonic, Structural and Regional Geologic Setting (TSRS), considered under Evaluation of Recognition Criteria. Weights were assigned to various favorable and unfavorable states of the four criteria that determine TSRS. To evaluate the favorability of TSRS for field areas, favorability values, based on field observations, are assigned to the four criteria. Table 15 presents hypothetical results for four imaginary field areas. In accumulating the values of the recognition criteria, negative and positive values are accumulated separately but in like fashion.

Table 15. Hypothetical recognition criteria values, from four imaginary field areas, for the four criteria that determine Tectonic, Structural, and Regional Geologic Setting (TSRS).

	Estimated Favorability Values (Fe)				Maximum and Minimum Favorability Values	
	Area A	Area B	Area C	Area D	(Fm+)	(Fm-)
Tectonic Setting	+ 20	+ 10	+ 5	- 70	+ 80	- 95
Structural Setting	+ 30	+ 20	+ 30	- 65	+ 35	- 65
Uraniferous Province	+ 40	+ 20	- 40	+ 10	+ 40	- 40
Vanadiferous Province	+ 20	+ 5	- 40	- 15	+ 30	- 40
	+110	+ 55	+ 35	+ 10	+185	-240
			- 80	-150		

In Test Area A, for example, the Tectonic Setting has been assigned a value of +20. Structural Setting provides an additional 30, and so forth for the other two criteria, yielding an estimated favorability (Fe) for TSRS of +110. However, if all the criteria had been perfect and the maximum favorability values had been used, the sum of the four criteria would have been +185 (Table 15). It is necessary, therefore, to normalize the estimated favorability by dividing it by the maximum favorability (Fm) value to yield a normalized (Fn) value:

$$\frac{Fe}{Fm} = Fn \qquad \text{or,} \qquad \frac{110}{185} = .59$$

The favorability of TSRS for Area A is 59, i.e., moderately suggestive.

For Area C the negative and positive criteria are combined in like manner, but separately, then normalized and summed:

Negative values--

Uraniferous Province		Vanadiferous Province		
-40	+	(-40)	=	-80

$$\frac{Fe}{Fm-} = Fn \qquad \text{or,} \qquad \frac{80}{240} = -.33$$

Positive values--

Tectonic Setting		Structural Setting		
+5	+	+30	=	+35

$$\frac{Fe}{Fm+} = Fn \qquad \text{or,} \qquad \frac{35}{185} = +.19$$

Combining the normalized positive and negative values (-.33 + .19 = -.14) one determines that Area C has a relatively large negative number, hence, a discouraging composition. This is not a very favorable area in which to prospect for a Salt Wash-type deposit. In fact, the large negative values for Uraniferous Province might be sufficient in most geologists' minds to kill the potential of this area. The explorationist might not waste further time in collecting other detailed geological information from this area. This example shows that the geologist making the evaluation must always inspect individual negative numbers, which, if sufficiently discouraging, can destroy the entire potential for the area, even though the accumulation of numerous positive observations may yield a net positive answer.

It can be seen in Figure 25 and Table 14 that, for example, Composition is merely one of five criteria that define the favorability of the Host Sandstone. From Table 25 it will be seen that Composition can contribute a maximum of 60 points, hence, once the favorability of Composition has been determined from its three criteria, as in the example above, the result (x) is multiplied by 60:

(x) x 60 = Applied Normalized Favorability (Fna)

This value can now be used with the values for the four other intermediate criteria in calculating the value of the higher order criterion, namely, the favorability of Host Sandstone. In a similar manner, all other terminal criteria are combined to evaluate intermediate criteria until the favorability for a Salt Wash-type deposit has been evaluated. This favorability is not necessarily equivalent to the probability of a deposit being present, as is discussed in a later paragraph.

Completeness and Confidence of Geologic Data

Assuming that the field geologist has complete geologic data and is equally and completely confident about all his field observations, he may evaluate the favorability according to the preceding paragraphs. In most cases, however, he will lack data and probably have various levels of confidence regarding the data that do exist. His confidence for different observations may range from completely certain that, for example, a uranium source rock is present, to no confidence (i.e., he does not know) that the age of the prospective basin sediments is Mesozoic. In such circumstances, methods can be devised to modify the favorability estimates, but they are not considered in this report.

No calculations can overcome the lack of data or confident observation. Such shortcomings must be carefully documented and the resulting favorability estimate interpreted accordingly.

Interpretation of Results

Favorability estimates prepared by the methods described in the preceding paragraphs should be accepted and used only after review of four important parameters:

(1) The final favorability estimate itself;

(2) Favorability estimates for intermediate level criteria;

(3) Favorability values for individual criteria, particularly large negative values;

(4) Completeness of data and certainty of observations.

Each of these is briefly discussed, with reference to favorability estimates made for three areas in the United States and presented in the next section.

The final favorability estimate reflects the net geologic favorability of an area when compared with the type area (i.e., productive Salt Wash districts of the Colorado Plateau) for which the recognition criteria net and maximum and minimum favorability values were selected. A score of 100 indicates a perfect geologic fit, i.e., virtual assurance that at least one deposit is present. A final score of zero indicates a very low level of favorability, provided the geologic data were complete, and the prospects of finding a deposit would be comparable to hitting a deposit with a dart thrown at a map of North America. A favorability of +50, therefore, is only half as favorable as one of +100. If the score is based on high confidence in the observations and complete data (i.e., no zeros assigned to criteria because of unavailable data), the area may be said to possess only half the favorable attributes necessary for a deposit. This does not mean the area has a fifty percent chance of a deposit being present. In our judgment the likelihood is less, but how much less is difficult to estimate. At a favorability estimate of zero the chances of a deposit being present are vanishingly small, and at negative favorabilities the chances are even worse. Figure 27 is our subjective attempt to relate estimated favorability of an area to the chances of a deposit being present within that area. The relationship suggests that the chances of a deposit being present decrease more rapidly than the estimated favorability. At 75 percent favorability, for example, we feel there is about a 50 percent chance that a deposit is present.

The estimated favorability values for the second level criteria of the recognition criteria net (Fig. 25) for the three areas considered in the next section are also useful for interpreting the favorability estimates. Inspection of these values, which are tabulated below, permits one to determine the contribution of each intermediate level criterion to the final estimated favorability.

Second Level Criterion	Applied Normalized Favorability Values: La Sal District Utah	Shootaring Canyon Utah	San Juan Basin	Maximum Applied Normalized Values (Fm+)
Tectonic, Structural and Regional Geologic Setting	30	30	26	30
Continental Sedimentary Sequence	40	40	40	40
Host Sandstone	36	40	25	40
Alteration and Mineralization	50	50	7	50

The favorability of the deep San Juan Basin (DSB) is substantially less than the other two areas because of low scores for Alteration and Mineralization and Host Sandstone. By similar inspection, one can pursue favorability values down through lower levels of the criteria net and ascertain exactly where favorable and unfavorable observations are originating.

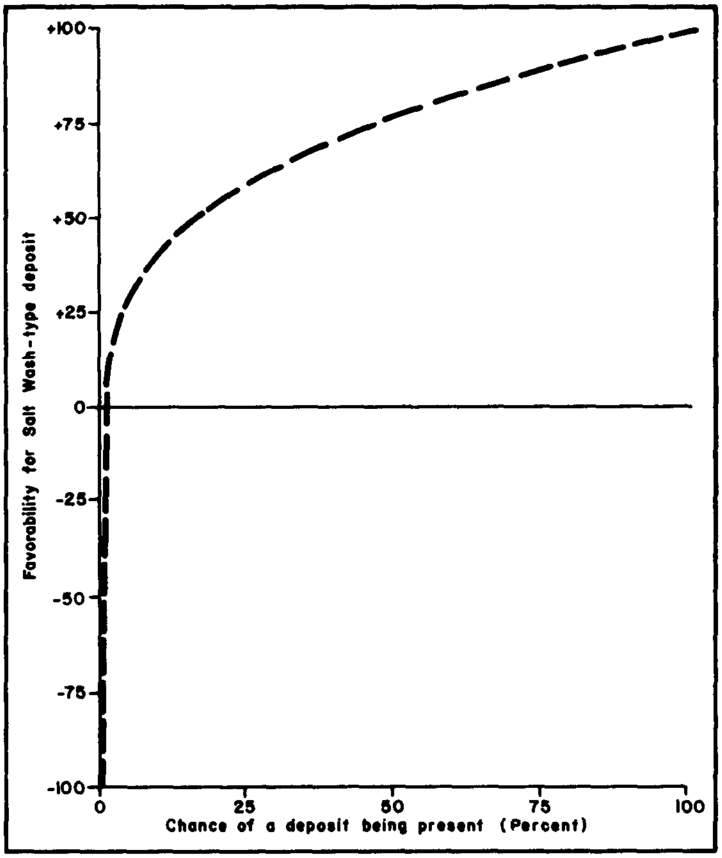

Figure 27. Schematic relation between calculated favorability for Salt Wash-type deposits and the chances of a deposit being present within the area evaluated.

Strongly negative values for individual criteria are, in some cases, sufficient to essentially kill the potential of an area. In the final favorability estimate, a single large negative value may become lost in generally positive criteria values; hence, the geologist must inspect the values of individual criteria.

Finally, the completeness of the data, hence the number of zero values, may produce erroneous estimated favorability values. In exploration, low favorability values due to incomplete and uncertain data are not as unfavorable as low favorability values resulting from negative or low positive criteria values. In resource studies, however, the absence of data could yield an apparent favorability much lower (or higher) than the area warrants. Careful inspection must be made of incomplete and uncertain data and the resulting favorability estimate interpreted accordingly. Where new data or more certain observations are needed, the criteria weights will indicate which observations are most important to obtain.

Examples of Favorability Estimates for Three Areas

In the following pages, recognition criteria are used to estimate the geologic favorability for Salt Wash-type deposits in two areas in the Salt Wash Member in Utah and one in the Westwater Canyon Member of the Morrison Formation in the deeper part of the San Juan Basin, northwest New Mexico. These examples are chosen to illustrate one simple method for developing favorability estimates.

The following abbreviations are used throughout:

LSD = La Sal District, Utah

SHM = Shootaring Canyon area, Henry Mountains district, Utah

DSB = Deep San Juan Basin, Northwest New Mexico
(Townships 19-20 North, Ranges 7-8 West)

Fe = Estimated favorability value

Fm = Maximum favorability value

Fn = Normalized favorability value

Fna = Normalized applied favorability value

Estimated Favorability (Fe) is simply the sum of the favorability values assigned to each of a group of criteria that determines the favorability of a higher intermediate level criterion, based upon field data.

Maximum Favorability (Fm) is the sum of the maximum values that could be assigned to those criteria. There are both positive and negative maximum values.

Normalized Favorability (Fn) is equal to the estimated favorability divided by the maximum favorability. It may be interpreted, therefore, as a percentage of the total possible favorability of the criteria.

Normalized Applied Favorability (Fna) is the normalized favorability of a group of criteria which is then multiplied by the weight assigned to the criterion above; the product is the weight for that higher level criterion that is then used with other criteria to calculate the favorability of the next higher level criterion. For example (Fig. 25), three criteria determine the favorability of Composition of the Host Sandstone. The normalized favorability obtained from these three criteria is not used directly in combination with the four other criteria that establish the favorability of Host Sandstone but is multiplied by the positive or negative value (+60, -95) assigned to Composition (see Table 14). It is necessary to calculate Fna only where higher level criteria have been assigned separate weight values, generally toward the top of the criteria net, and all such assigned weights are indicated by asterisks in Table 14.

I. Tectonic Structural and Regional Geologic Setting (TSRS)

The favorability of TSRS is determined by the geology of four criteria:

(a) Tectonic Setting

LSD +80 (continental interior basin)

SHM +80 (as above)

DSB +80 (as above)

(b) Structural Setting

LSD +35 (perfect score)

SHM +35 (as above)

DSB +35 (as above)

(c) Uraniferous Province

LSD +40 (favorable)

SHM +40 (as above)

DSB +40 (as above)

(d) Vanadiferous Province

LSD +30 (favorable)

SHM +30 (as above)

DSB + 5 (not likely)

(e) TSRS Score

The favorability estimate (Fe) for TSRS is the sum of the individual favorability numbers derived from field data:

$$\text{Fe LSD} = 80 + 35 + 40 + 30 = +185$$

$$\text{Fe SHM} = 80 + 35 + 40 + 30 = +185$$

$$\text{Fe DSB} = 80 + 35 + 40 + 5 = +160$$

Reference to Table 14 shows that the maximum and minimum favorability for TSRS that could be derived from the sum of these criteria are:

$$\text{Fm+} = 80 + 35 + 40 + 30 = +185$$

$$\text{Fm-} = -95 - 65 - 40 - 40 = -240$$

We now want to know the extent to which the estimated favorabilities achieved the maximum potential favorability; hence we divide the estimate (Fe) by the maximum (Fm+) value. One also notes (Table 14) that the maximum values of TSRS for evaluating the favorability for a Salt Wash-type deposit are +30 and -95. We can therefore combine two steps and calculate directly the normalized applied favorability which is the contribution to the favorability for Salt Wash-type deposit:

$$\text{Fna} = \frac{\text{Fe}}{\text{Fm}} \times 30,$$

thus,

$$\text{Fna LSD} = \frac{185}{185} \times 30 = +30 \text{ (a perfect score)}$$

$$\text{Fna SHM} = \frac{185}{185} \times 30 = +30 \text{ (as above)}$$

$$\text{Fna DSB} = \frac{160}{185} \times 30 = +26 \text{ (near perfect score)}$$

II. Continental Sedimentary Sequence

(a) Age

LSD = +30 (Mesozoic)

SHM = +30 (as above)

DSB = +30 (as above)

(b) Associated Sediments

LSD = +40 (extensive continental sediments)

SHM = +40 (as above)

DSB = +40 (as above)

(c) Host Sediments

(1) Bentonite

LSD = +60 (abundant)

SHM = +60 (as above)

DSB = +60 (as above)

(2) Thickness

LSD = +20 (thick sands)

SHM = +20 (as above)

DSB = +20 (as above)

(3) Area

LSD = +30 (broad area)

SHM = +30 (as above)

DSB = +30 (as above)

(4) Sandstone-Mudstone Facies

LSD = +40 (continuous sedimentation)

SHM = +40 (as above)

DSB = +40 (as above)

(5) Host Sediment Score

Fe LSD = 60 + 20 + 30 + 40 = +150

Fe SHM = 60 + 20 + 30 + 40 = +150

Fe DSB = 60 + 20 + 30 + 40 = +150

The assigned weights for Host Sediments are +60 and -95 (Table 14), hence:

$$\text{Fna LSD} = \frac{150}{150} \times 60 = +60 \text{ (a perfect score)}$$

$$\text{Fna SHM} = \frac{150}{150} \times 60 = +60 \text{ (as above)}$$

$$\text{Fna DSB} = \frac{150}{150} \times 60 = +60 \text{ (as above)}$$

(d) Continental Sedimentary Sequence Score

Fe LSD = +30 + 40 + 60 = +130

Fe SHM = +30 + 40 + 60 = +130

Fe DSB = +30 + 40 + 60 = +130

$$\text{Fna LSD} = \frac{130}{130} \times 40 = +40 \text{ (perfect score)}$$

$$\text{Fna SHM} = \frac{130}{130} \times 40 = +40 \text{ (as above)}$$

$$\text{Fna DSB} = \frac{130}{130} \times 40 = +40 \text{ (as above)}$$

III. Host Sandstone

(a) Thickness

LSD +40 (more than 40 feet)

SHM +40 (as above)

DSB +40 (as above)

(b) Area

LSD +40 (> 5 square miles)

SHM +40 (as above)

DSB +40 (as above)

(c) Color

LSD +40 (gray and red sediments)

SHM +50 (as above)

DSB +20 (only gray sediments)

(d) Depositional Environment

LSD +25 (lacustrine clay probably present)

SHM +50 (lacustrine clays present)

DSB 0 (unknown)

(e) Composition

(1) Organic Matter

LSD +30 (adequate plant debris)

SHM +30 (as above)

DSB +30 (as above)

(2) Clastics

LSD +50 (feldspathic orthoquartzite)

SHM +50 (as above)

DSB +30 (subarkose)

(3) Volcaniclastics

LSD +40 (adequate amount present)

SHM +40 (as above)

DSB +40 (as above)

(4) Composition Score

Fe LSD = 30 + 50 + 40 = +120

Fe SHM = 30 + 50 + 40 = +120

Fe DSB = 30 + 30 + 40 = +100

Fna LSD = $\frac{120}{120} \times 60 = +60$ (a perfect score)

Fna SHM = $\frac{120}{120} \times 60 = +60$ (as above)

Fna DSB = $\frac{100}{120} \times 60 = +50$ (out of a possible 60)

(f) Host Sandstone Score

Fe LSD	=	40 + 40 + 50 + 25 + 60	=	+215
Fe SHM	=	40 + 40 + 50 + 50 + 60	=	+240
Fe DSB	=	40 + 40 + 20 + 0 + 50	=	+150

Fna LSD = $\frac{215}{240} \times 40$ = +36 (out of a possible 40)

Fna SHM = $\frac{240}{240} \times 40$ = +40 (a perfect score)

Fna DSB = $\frac{150}{240} \times 40$ = +25 (out of a possible 40)

IV. Alteration and Mineralization

(a) Mineralization

LSD +50 (favorable anomalies)

SHM +50 (as above)

DSB +50 (as above)

(b) Alteration

(1) Pyrite

LSD +50 (significant amount of pyrite)

SHM +50 (as above)

DSB + 5 (very minor pyrite)

(2) Magnetite-Ilmenite

LSD +70 (favorably altered)

SHM +70 (as above)

DSB -50 (largely unaltered)

(3) Alteration Score

Fe LSD	=	50 + 70	=	+120
Fe SHM	=	50 + 70	=	+120
Fe DSB	=	Pos + 5	=	+ 5
		Neg -50	=	- 50

$$\text{Fna LSD} = \frac{120}{120} \times 60 = +60 \quad \text{(a perfect score)}$$

$$\text{Fna SHM} = \frac{120}{120} \times 60 = +60 \quad \text{(as above)}$$

$$\text{Fna DSB Pos} = \frac{5}{120} = +.04$$

$$\text{Fna DSB Neg} = \frac{50}{90} = -.55$$

$$\text{Fna DSB Net} = +.04 - .55 = -.51$$

$$\text{Fna DSB} = -.51 \times 70 = -36 \quad \text{(out of a possible -70)}$$

(c) Alteration and Mineralization Score

$$\text{Fe LSD} = 50 + 60 = +110$$

$$\text{Fe SHM} = 50 + 60 = +110$$

$$\text{Fe DSB} = \text{Pos } +50 = +50$$

$$\text{Neg } -36 = -36$$

$$\text{Fna LSD} = \frac{110}{110} \times 50 = +50 \quad \text{(a perfect score)}$$

$$\text{Fna SHM} = \frac{110}{110} \times 50 = +50 \quad \text{(as above)}$$

$$\text{Fna DSB Pos} = \frac{50}{110} = +.45$$

$$\text{Fna DSB Neg} = \frac{36}{120} = -.30$$

$$\text{Fna DSB Net} = +.45 - .30 = +.15$$

$$\text{Fna DSB} = +.15 \times 50 = +7 \quad \text{(out of a possible 50)}$$

The favorability estimates for the second level intermediate criteria, calculated above, can now be tabulated in preparation for calculating the favorability estimates for Salt Wash-type deposits in these three areas:

Second Level Criterion	Applied Normalized Favorability Values: La Sal District Utah	Shootaring Canyon Utah	San Juan Basin	Maximum Applied Normalized Favorability
Tectonic, Structural, and Regional Geologic Setting	30	30	26	30
Continental Sedimentary Sequence	40	40	40	40
Host Sandstone	36	40	25	40
Alteration and Mineralization	50	50	7	50

The favorability for Salt Wash-type deposits in these three areas is calculated using the data above and the same procedure used in the preceding calculations.

$$Fe\ LSD = 30 + 40 + 36 + 50 = +156$$

$$Fe\ SHM = 30 + 40 + 40 + 50 = +160$$

$$Fe\ DSB = 26 + 40 + 25 + 7 = +98$$

$$Fm+ = 30 + 40 + 40 + 50 = +160$$

$$Fn\ LSD = \frac{156}{160} \times 100 = 97 \text{ percent}$$

$$Fn\ SHM = \frac{160}{160} \times 100 = 100 \text{ percent}$$

$$Fn\ DSB = \frac{98}{160} \times 100 = 61 \text{ percent}$$

These results suggest, not surprisingly, that the La Sal and Henry Mountains areas are favorable for the occurrence of Salt Wash-type deposits. The La Sal district scored slightly lower because of uncertainty about the presence of lacustrine mudstones.

The deep San Juan Basin, however, scored substantially lower, suggesting the area is less favorable for the presence of this type of deposit. The lower favorability is due, principally, to unfavorable magnetite alteration and the paucity of pyrite in the area under consideration. The lack of oxidation zones, the greater abundance of feldspar, and the uncertainty about the presence of lacustrine sediments also lowered the Host Sandstone score. Finally, some favorability was lost due to the perceived lack of an obvious vanadium source. As discussed in the text, the relationship between geologic favorability and the probability of a deposit being present has not been established with any reasonable confidence. Although we have presented a schematic relationship in Figure 27, it should be used with caution because the actual relationship may be quite different and substantially more complicated.

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