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CHARACTERISTICS OF TRIASSIC AND JURASSIC URANIUM-BEARING HOST ROCKS OF THE COLORADO PLATEAU

By

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CHARACTERISTICS OF TRIASSIC AND JURASSIC URANIUM-BEARING HOST ROCKS OF THE COLORADO PLATEAU

By Robert A. Cadigan

ABSTRACT

Uranium deposits in the sedimentary rocks of the Colorado Plateau are distributed throughout most of the lithologic units which make up the regional stratigraphic column. The Morrison formation of Jurassic age and the Shinarump conglomerate and the basal sandstone beds of the Chinle formation of Triassic age yield at least 90 percent of current uranium ore production. The Todilto limestone and Entrada sandstone of Jurassic age together yield about 5 percent of current production.

The host rocks of the Morrison and Chinle formation and the Shinarump conglomerate are noted for ledge-forming lenticular fine- to coarse-grained, cross-stratified sandstone bodies which occupy trough-shaped erosional features known as channels. Associated with the channel sandstones, particularly in the lower parts, are green clay strata and pellets, petrified, carbonized and coalified plant material, bone, and pebbles derived from metamorphic, igneous, and sedimentary rocks. Interbedded with the sandstones are red, green, or variegated siltstone and claystone strata.

The sandstones vary regionally in composition and can usually be classified as arkoses, sedimentary tuffs, or orthoquartzites depending on the location. The clay minerals of the sandstones as well as of the siltstones and claystones belong to the hydromica, montmorillonite and kaolinite groups. The kaolinitic clays are mostly of detrital origin. The montmorillonite and hydromica clays were mostly derived from volcanic ash.

The Todilto limestone is a 10- to 30-foot thick moderately pure limestone unit, extending throughout the southeastern part of the Colorado Plateau. The Entrada sandstone, typically a 50- to 300-foot thick massive partly cross-stratified, fine-grained sandstone varies regionally in composition, but in western Colorado is an orthoquartzite or a feldspathic orthoquartzite.

Generally, ore deposition in the Morrison formation, Shinarump conglomerate, and basal sandstone beds of the Chinle formation appears to be influenced locally by the sedimentary structures, plant material, bone, clay, and certain textural zones in certain parts of the sandstone strata. Ore deposition appears to be favored regionally in the Salt Wash member of the Morrison formation by certain lithofacies characteristics.

Ore deposition in the Entrada sandstone appears to be related to the Dolores-Entrada and Entrada-Pony Express contacts. Ore deposition in the Todilto shows a relationship to joints and fractures.

INTRODUCTION

Stratigraphic location of major uranium-ore deposits

The uranium deposits in the sedimentary rocks of the Colorado Plateau region are distributed throughout most of the lithologic units which make up the regional stratigraphic column. At this time (1955) the major part, at least 90 percent, of the production of ore is from the Morrison formation of Jurassic age, and the Shinarump conglomerate and the basal sandstone beds of the Chinle formation of Triassic age. An additional 5 percent of the production is from the Todilto limestone and underlying Entrada sandstone of Jurassic age (Fischer, R. P., 1955, oral communication). Figure 1 illustrates the regional distribution of ore deposits in excess of 1,000 tons for each of the stratigraphic units named above.

Methods and definitions

The petrographic study of the uranium ore-producing formations has been carried on by means of thin section study, grain-size analyses and the field examination of sedimentary structures. Most of the work has been done on the major producing formations and lithologic types.

Classification of the rocks generally follows the system proposed by Krynine (1948) but was modified as illustrated by table 1. The rocks studied represent various intermixtures of three end products: arkoses, orthoquartzites, and tuffs. Some sandstone strata of restricted occurrence could be classified as graywackes on the basis of their hydromica content, but due to a lack of other essential components such as basic rock fragments and alkalic-calcic feldspars, these rocks are not considered as true graywackes.

The classification of sandstones in specific stratigraphic units was based on point count analyses of an aggregate of 119 thin sections, including 66 for the Morrison formation, 28 for the Shinarump conglomerate, and 25 for the lower sandstone beds of the Chinle formation. The Entrada composition studies were restricted to the examination of few thin sections

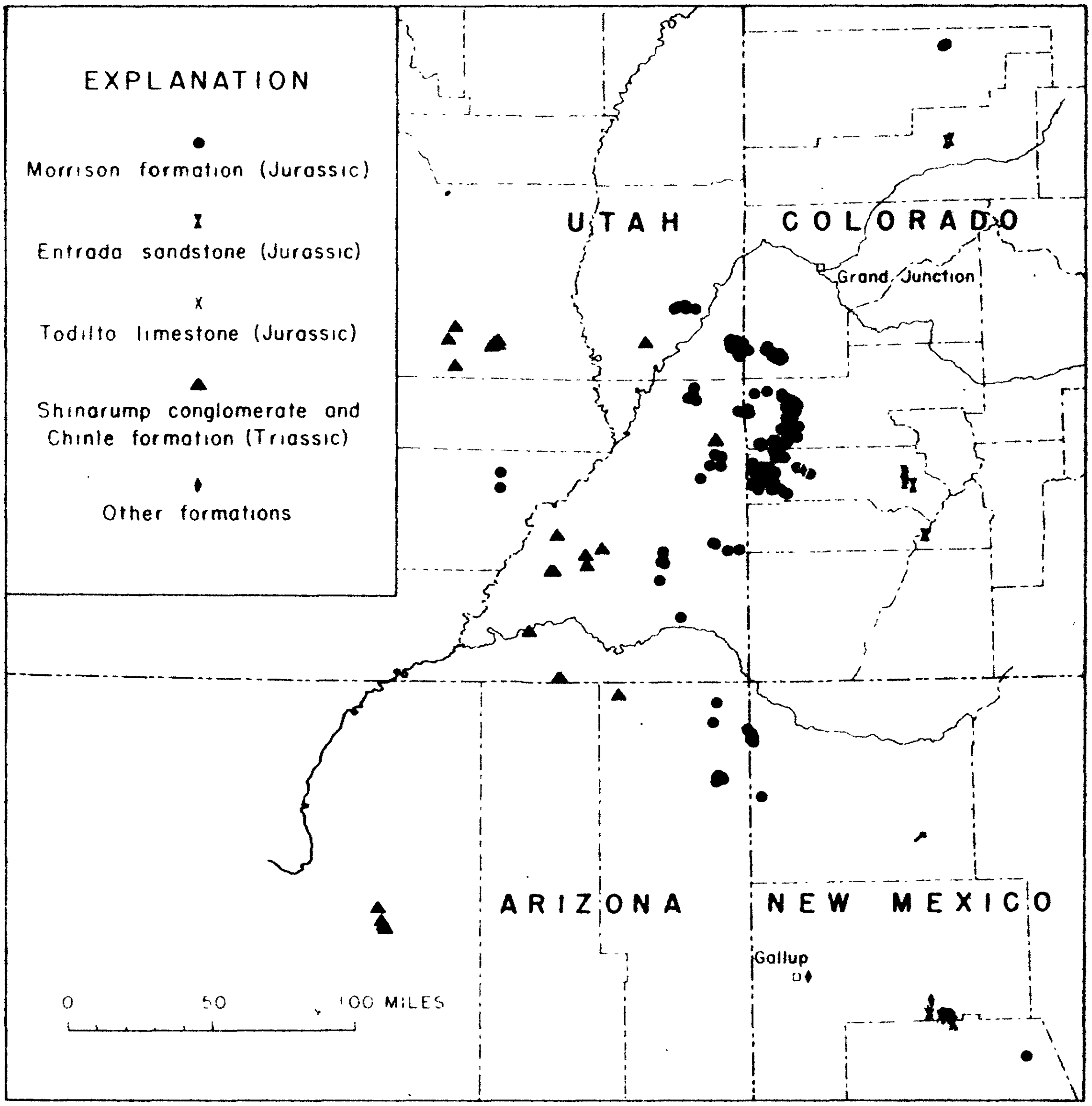

Figure 1. REGIONAL OCCURRENCE OF URANIUM ORE DEPOSITS OF 1,000 TONS OR MORE IN THE MAJOR AND MINOR PRODUCING FORMATIONS OF THE COLORADO PLATEAU. (PREPARED BY R.P. FISCHER, R.T. CHEW, III, AND H.S. JOHNSON FOR THE PAPER, "URANIUM-VANADIUM-COPPER DEPOSITS ON THE COLORADO PLATEAU," INTERNATIONAL CONFERENCE ON PEACEFUL USES OF ATOMIC ENERGY, GENEVA, SWITZERLAND, 1955. FROM A MAP BY W.I. FINCH, 1955.)

supported by loose grain studies including mineral grain counts on 15 samples. The Todilto limestone and the correlative Pony Express member of the Wanakah formation composition studies were restricted to examination of a few thin sections and insoluble residue studies of two samples (one each).

The data on clay minerals in the formations studied were obtained from the thin section studies, from X-ray diffraction analyses of clay and silt separates, and from unpublished work of and informal communications with Alice Weeks, W. D. Keller, and others of the U. S. Geological Survey, and J. C. Griffiths of the Pennsylvania State University.

Microscopic arrangements of the grains, matrix, and cement of the sandstones as they appear in thin section were termed the microstructure of the rock. If the detrital grains are in contact with each other to a maximum extent, with a minimum of interstitial cement and matrix, the microstructure is classified as homogeneous. If the detrital grains are suspended in matrix and cement, with some grains in contact, but most separated from other grains by intervals of varying widths, the microstructure is classified as heterogeneous.

The ore-producing formations were studied on the outcrop to determine small-scale lithologic relationships, to obtain information pertinent to stratigraphic problems, and to collect representative samples for laboratory investigations. The conspicuous bedding features and forms produced by the sedimentation processes of cyclic deposition which included intervals of erosion, are referred to by the general all-inclusive term, sedimentary structures. The erosional features are referred to in this paper as erosion surfaces, cuts, or channels in ascending order of magnitude of relief. The writer was fortunate to be associated with a number of geologists who have done detailed studies of sedimentary structures and their orientations. These include L. C. Craig, G. W. Weir, G. A. Williams, and O. B. Raup of the U. S. Geological Survey.

Table 1. The petrologic classification of detrital sedimentary rocks.[1/]

Classification	Quartz plus tuff[2/] (percent)		Feldspar plus kaolin (percent)	Mica (percent)
Orthoquartzite	Limits:	70 to 100	0 to 10	0 to 20
	Typical:	85	5	10
Feldspathic orthoquartzite	Limits:	55 to 90	10 to 25	0 to 20
	Typical:	75	15	10
Graywacke	Limits:	0 to 70	10 to 80	20 to 75
	Typical:	50	20	30
Subgraywacke	Limits:	15 to 80	0 to 10	20 to 75
	Typical:	60	5	35
Arkose	Limits:	0 to 75	25 to 100	0 to 20
	Typical:	50	40	10

1/ After Pettijohn, 1949, and Krynine, personal communication, 1952; exclusive of the treatment of tuff.

2/ The amount of tuff present affects the rock classification in the following manner:

1. If there is less than 10 percent tuff, the rock classification is not affected.

2. If there is 10 to 25 percent tuff, the rock name is modified by the word "tuffaceous," i.e., tuffaceous arkose.

3. If there is 25 to 75 percent tuff, the rock name designates a variety of tuff, i.e., graywacke tuff.

4. If there is 75 percent or more tuff, the rock is an unmodified tuff.

This chapter is aimed at describing the petrographic framework of the ore deposits. That the ore is stratigraphically controlled is quite obvious; for that reason rocks of the favored strata are referred to as host rocks whether or not they contain ore.

In the following pages, the stratigraphic and lithologic units defined above as host rocks are described so as to emphasize the more general or average characteristics. No attempt is made to give the detailed petrography or sedimentary structure characteristics of any unit in these descriptions. The general outline to which all the descriptions are fitted seeks to bring out the following points for each unit: 1) stratigraphic relations, 2) textural types present and their arrangement, 3) structural features of erosion and deposition, 4) rock composition and classification, and 5) microscopic arrangement of constituents. These are variations of the three main properties of rocks: composition, texture, and structure.

TRIASSIC HOST ROCKS

Shinarump conglomerate

Stratigraphic relations

The white to pale-brown Shinarump conglomerate of Late Triassic age occupies a position in the stratigraphic column of the Colorado Plateau between the Chinle formation and the Moenkopi formation, both of Triassic age. The Shinarump is restricted in occurrence to the southern half of the Colorado Plateau region (Stewart and Williams, 1954). The lower contact of the Shinarump is an erosional disconformity; the upper contact is conformable at most places but is disconformable or indefininte at a few places.

Textural types and their arrangement

The Shinarump conglomerate is in most places a medium-grained sandstone unit with persistent and conspicuous zones of very coarse-grained sandstone, pebbly sandstone, and pebble conglomerate. The sandstones and conglomerates are usually moderately well to poorly sorted. This general texture is characteristic throughout the whole area in which the formation is present. Green claystone or mudstone strata are above, below, and within the sandstone strata. In many places in the southern and central parts of the Plateau region, as the result of a lateral facies change, the Shinarump is represented by green claystone strata containing a 1- to 3-foot thick clay and pebble zone. Where the sandstone facies is locally absent, the greenish kaolin mudstone (Keller, W. D., written communication) equivalent will, in most instances, contain coarse sand grains and granules dispersed throughout. The sandstone facies and siltstone facies contain the same mineral components, but in different proportions.

A variegated red, purple, and white mudstone facies is found in the upper part of the Shinarump in many areas of the northern part of the Plateau including the Moab, White Canyon, and San Rafael Swell areas in Utah. Beyond the range of the sandstone facies it may be a regional equivalent of the Shinarump conglomerate. However, this coarse-sand-filled kaolinitic mudstone stratum is referred to as the "purple-white zone" (Finch, 1953) in areas where it separates the Chinle and the Moenkopi formations, and is usually assigned to the Chinle.

Structural features of erosion and deposition

The sandstone strata of the Shinarump tend to form a single composite ledge-forming sandstone bed which extends many square miles laterally, but which is elongated in the direction parallel to the channel trends in the area. The broad areal extent is the result of the junction or coalescence of adjacent channel fills to form a uniform upper surface for the single conspicuous ledge. The channel fills of the Shinarump conglomerate may have an average cross-sectional area in the order of magnitude of 2,500 to 10,000 square yards. The deeper channels contain abundant petrified, coalified and crushed logs, and disseminated plant material (Witkind, 1954).

Rock composition and classification

The Shinarump conglomerate is typically an arkose, although in some areas it grades into orthoquartzites and tuffs. The common detrital components are grains of quartz, potash feldspar, plagioclase, altered tuff, and quartzite; the kaolinite, illite, and montmorillonite groups of clays; and included pebbles of quartz, quartzite, feldspar, chert, granite, and silicic-alkalic volcanic rocks (Stewart, J. H., and Albee, H. F., 1955, (oral communication).

The chief interstitial clay minerals are of the kaolinite group with minor amounts of hydromica. Where there is a significant increase in the proportion of tuff, the chief clay minerals are of the montmorillonite group. Many of the bedded clays in the Shinarump are of the hydromica group.

The clay minerals in the sandstone are well crystallized. The kaolinite clays appear as detrital clay in white interstitial wads and as decomposition products in the cleavage cracks of weathered feldspar grains.

The main cementing materials of the Shinarump consist, in order of importance, of silica in the form of overgrowths on quartz grains, iron oxides, and calcite and other carbonates. The rocks are, on the average, only moderately indurated. Other nondetrital components include ore and gangue minerals and authigenic silica present in the altered tuff.

The major regional change in composition occurs in the southwestern part of the Colorado Plateau, in north-central Arizona and south-central Utah, where the sandstones can be classified as tuffaceous arkoses or tuffs. The rocks contain enough potash feldspar to support a hypothesis that they were derived from silicic-alkalic igneous rocks. Regional variations in feldspar content are also present with recognized high feldspar areas in the southeastern and northern parts of the Plateau.

Microstructure

The sandstones of the Shinarump contain both heterogeneous and homogeneous microstructures. The kaolin and matrix comprises about 10 percent of the moderately sorted sandstones and about 30 percent of the poorly sorted sandstones. The mud is distributed throughout the rock in interstitial films or in wads of about 1 millimeter in size.

Basal or Lower Chinle sandstone beds

Stratigraphic relations

The light-colored sandstone beds of the basal or lower part of the Chinle formation occupy a position in the stratigraphic column directly above the Shinarump conglomerate. They are easily confused with the Shinarump where it is absent. The sandstone beds are in the Monitor Butte, and the overlying so-called Moss Back (Stewart and Smith, 1954) members of the Chinle formation. Certain types of sandstone considered to be typical of the respective units are not confined within the member boundaries. Thus the Moss Back-type is frequently found in the Monitor Butte member and vice versa. For this reason the lower and basal sandstone beds of the Chinle will be referred to as the Monitor Butte-type or the Moss Back-type sandstones.

The Monitor Butte type of sandstone is similar in composition to the Shinarump type of sandstone but differs greatly in texture and structure. The Monitor Butte type is pale green to gray, fine- to very fine-grained, and tightly cemented with calcite or silica. The greenish beds are in most cases only a few feet thick and are evenly bedded with parallel ripple-laminations in which thin laminae of well-sorted sand are separated by laminae of greenish chloritic or illitic clay. On weathering, the beds are much subjected to jointing, slumping, and separating along their laminae (like shale). Penecontemporaneous slumping is abundant; however, the general bedding and depositional structures are commonly preserved. The Monitor Butte type sandstones are associated with hydromica or bentonitic claystone strata.

The white to pale-brown Moss Back type of lower or basal Chinle sandstone more nearly resembles the type of sandstone in the Shinarump and is almost exclusively the host rock for ore deposits in the lower part of the Chinle. The Moss Back type is the host rock in those areas in the northern and northwestern parts of the Colorado Plateau where the sandstone and conglomerate facies of the Shinarump is absent.

Textural types and their arrangement

The Moss Back-type sandstones are fine-grained with pebbly and conglomeratic zones. They contain claystone and mudstone seams, lenses, and fragments. Individual samples show predominantly moderately good sorting with poor sorting in the coarse-grained parts.

Structural features of erosion and deposition

The erosional and depositional structures of the lower Chinle sandstones are generally of the same scale and frequency as those of the Shinarump sandstones. The sandstone strata of the so-called Moss Back member tend to form a single thick composite ledge-forming sandstone bed or a closely spaced sequence of beds, averaging about 50 feet thick. The unit extends over an area of about 9,000 square miles (Stewart and Williams, 1954). The unit fills erosion channels which, in extreme cases, increases the thickness of the sandstone strata to 100 to 150 feet. Thick-bedded ledge-forming channel-filling sandstone strata of the Moss Back type are frequently found below and separated by thick mudstone strata from the prominent sandstone unit of the so-called Moss Back member.

Lithified, mineralized, or coalified logs and wood fragments may be found in the bottoms of channels in the same manner as those found in the Shinarump, or scattered throughout bedded gray claystones or mudstones associated with the channel deposits.

Rock composition and classification

The Moss Back-type sandstone is an arkose but shows enough variation in composition to be classified as a feldspathic orthoquartzite in some locations. The common detrital components are grains of quartz, potash feldspar, plagioclase feldspar, altered tuff, quartzite fragments, and clays of the kaolinite, montmorillonite, and illite groups. Pebbles of chert, quartz, and quartzite are also present. The Moss Back-type sandstone shows an increase in feldspar to the north or northwest.

The chief interstitial clay minerals in the sandstones are of the kaolinite group with minor amounts of hydrous mica and montmorillonite. Montmorillonite clays increase with the amount of tuff. The bedded clays in and around the Moss Back-type sandstones are illites, montmorillonites, and mixed layer clays. The clay minerals in the sandstones are well crystallized. The kaolinite clays appear as detrital clay in white interstitial wads and as decomposition products in the cleavage cracks of weathered feldspar grains. The "purple-white" mudstone zone underlies the so-called Moss Back member in the absence of the Monitor Butte member and the sandstone-conglomerate facies of the Shinarump.

The suite of clay minerals present in the basal and lower Chinle lithologic units is influenced by larger amounts of altered alkalic-silicic volcanic ash in the southern and western part of the Colorado Plateau and becomes dominantly montmorillonite.

The cementing material of the Moss Back-type of sandstone consists, in order of importance, of silica in the form of overgrowths on quartz grains, calcite and other carbonates, and iron oxides. The sandstones range from highly indurated to poorly indurated. Other nondetrital components include ore and gangue minerals.

Microstructure

The microscopic arrangement of the Moss Back-type sandstones is heterogeneous, becoming more so in the coarse-grained sandstones and conglomerates.

General comparison of Shinarump and basal Chinle ore-bearing sandstone beds

Sandstones of the Shinarump conglomerate and of the so-called Moss Back member of the Chinle formation are similar in average composition. Pebble assemblages of the two show a significantly higher percentage of quartz for the Shinarump (Albee, H. F., oral communication). The main differences in appearance between the two types of sandstone are due to the finer texture of the Moss-Back type, and the multiple ledges in the lower part of the Chinle formation where the Monitor Butte member is present as compared with the single composite ledge commonly observed in the Shinarump conglomerate.

JURASSIC HOST ROCKS

Morrison formation

Stratigraphic relations

The Morrison formation of Jurassic age is made up of light-colored, lens-shaped, cross-stratified sandstones and reddish, greenish-gray, and variegated claystones, siltstones, and mudstones. On the Colorado Plateau, the Morrison is divisible into four members. The uppermost member, the Brushy Basin, is composed dominantly of variegated, red, green, and purple bentonitic mudstone strata and lesser amounts of pebbly sandstone. The basal member, which lies just below the Brushy Basin in the northern half of the Plateau, is the Salt Wash member. The Salt Wash is characterized by light-gray and light-brown ledge-forming sandstones interbedded with red and green siltstone and mudstone strata; the Salt Wash is the chief uranium ore-producing member of the Morrison formation.

In the southeastern part of the Plateau, the Westwater Canyon and underlying Recapture members tongue in between the Brushy Basin and the Salt Wash members and replace the Salt Wash member and the lower part of the Brushy Basin member (Craig and others, 1955). The Westwater Canyon member is characterized by moderately lensing, moderately cross-stratified pale-yellow ledge forming sandstones and brown and brownish-gray siltstone and bentonitic mudstone strata.

Facies changes

Facies changes of both local and regional scale are the rule in members of the Morrison formation. The host rock favored by uranium ore deposits in the Salt Wash member of the Morrison formation in southwestern Colorado and southeastern Utah seems closely related to certain local lithologic facies characteristics (Mullens and Freeman, 1952). Significant facies characteristics include: an optimum ratio of sandstone to mudstone in a vertical sequence (about 50 percent), an optimum thickness "stream deposit-type" to "nonstream deposit-type" sedimentary units (90 to 200 feet), and an optimum degree of average size and continuity of sandstone strata.

In localities in an area from south to southwest of the Four Corners area (juncture of the four states, Colorado, Utah, Arizona, and New Mexico, see fig. 1), the Morrison consists of a sequence of convex weathering, massive Westwater Canyon and Recapture sandstone beds separated by silty sandstone partings. This sandy facies apparently is not a favorable host rock for uranium ore in the Morrison formation. The favorable facies appears to be the sequence of lenticular ledge-forming sandstone units interstratified with mudstone, siltstone, and claystone units to the west, north, and southeast of the Four Corners area.

Brushy Basin member

Stratigraphic relations

The Brushy Basin member is the most regionally extensive stratigraphic unit within the Morrison formation and forms the top of the formation except in areas where pre-Dakota erosion has removed it.

Textural types and their arrangement

The texture of the Brushy Basin sandstones is generally fine- to medium-grained with coarse to conglomeratic zones in the basal parts; thick lenses of sandy coarse conglomerate are common in many localities. The bedded mudstone, which is the dominant lithology in the average exposure of the Brushy Basin member, characteristically contains granules and coarse sand grains of red chert or silicified tuff scattered throughout.

Structural features of erosion and deposition

The resistant sandstone beds are ledge-forming and were deposited in erosional scours. One or two of these sandstone units are commonly present in the lower third of the member. The basal contacts show erosion surfaces. Pertified wood, bone, mud and clay lenses, disturbed bedding, and conglomerates are characteristic of the first sediments deposited above the eroded surfaces. The bedded mudstone contains some thinner, evenly bedded very fine-grained limy sandstones which are seldom of the ledge-forming type, except in the southeastern part of the Plateau region. In northeastern and central New Mexico, thick lenses of medium-grained kaolin-rich arkose are present in the middle and upper parts of the Brushy Basin. The Jackpile ore-bearing sandstone, (Hilpert, L. S., and Freeman, V. L., 1955, written communication) in New Mexico is a ledge-forming composite arkosic sandstone unit that was deposited in close association with the mudstone strata occurring in the middle of the Brushy Basin member.

Rock composition and classification

The Brushy Basin is a tuffaceous unit composed chiefly of montmorillonite-rich mudstones, fragments or grains of silicified altered tuff, and lesser amounts of thick lensing ledge-forming pebbly sandstone and conglomerate beds. The sandstone strata vary over the Colorado Plateau region from arkose to orthoquartzite to tuff with many gradations and modifications. From the center of the Plateau the tuffaceous material increases northwestward, and the arkosic material increases southeastward.

The sandstone units are composed of detrital grains of quartz, altered tuff, potash feldspar, plagioclase, quartzite, and a volumetrically insignificant amount of heavy minerals. Clay minerals include illite, montmorillonite, and mixed layer clays; some kaolinite clays are present in the southeastern part of the Plateau region. The nondetrital constituents include secondary silica in the form of overgrowths on quartz grains, zoned interstitial chalcedony, calcite and other carbonates, localized occurrences of gypsum, and iron oxides in the form of interstitial cement and staining on grains. The white angular sand grains observed in hand specimens in the central, northern, and western parts of the Plateau are probably silicified tuff; they are generally slightly coarser than accompanying quartz grains. Red and green pebbles of chert, which also are probably derived from material of volcanic origin, dominate the pebble assemblage which includes also fragments of quartzite, silicified limestone, and silicified metamorphosed shale. Bones and bone fragments are common in both mudstone, sandstone, and conglomerate units.

Microstructure

The Brushy Basin sandstones contain both homogeneous and heterogeneous microstructures.

Salt Wash member

Stratigraphic relations

The Salt Wash member is the basal member of the Morrison formation in the central, northern, and western part of the Plateau.

Textural types and their arrangement

The Salt Wash member, like the Brushy Basin member, is composed of mudstone strata and ledge-forming sandstone beds; however, in most localities there is much more sandstone in proportion to mudstone than is observed in the Brushy Basin member. Volumetrically, the Salt Wash contains more sandstone than any other member (Freeman, V. L., oral communication).

The sandstones of the Salt Wash member are, on the average, fine-grained and well to moderately sorted. The basal or lower parts of the "channel" sandstones are of coarse sand, moderately to poorly sorted and contain green clay chip conglomerates, quartzite, silicified tuff, chert, and silicified limestone pebbles, wood, and bone.

Structural features of erosion and deposition

The ledge-forming sandstone beds are lenticular composite cross-stratified units. The Salt Wash in any one locality commonly has from 3 to 6 ledge-forming sandstone units separated by silty sandstone or mudstone.

The larger resistant beds form composite ledges that are less continuous than the single composite ledge of the Shinarump and are of smaller dimensions with an average cross-sectional area in the order of magnitude of 1,000 to 5,000 square yards.

Rock composition and classification

The sandstone strata of the Salt Wash vary in classification over the Plateau region, and include orthoquartzites, tuffs, and arkoses, together with all possible modifications. The sandstones are composed of quartz, potash feldspar, sodic feldspar, silicified and altered tuff, chert, metamorphic rock fragments, and rhyolitelike igneous rock fragments and hydromica, montmorillonite, and kaolinite clay minerals. The dominant clay minerals in both the mudstone and in the sandstone strata are of the hydromica group, but with a high proportion of hydromica-montmorillonite mixed layer clays which were possibly derived from montmorillonite or volcanic ash. Analyses of the tuff suggest a silicic-alkalic igneous source. Heavy minerals represent less than 0.5 percent, by weight, of the average sandstone and consist largely of varieties of zircon, tourmaline, garnet, staurolite, epidote, rutile, apatite, magnetite-ilmenite, miscellaneous titanium minerals, and minor amounts of biotite. This general assemblage is common for all sandstones of the Morrison formation but with regional variations in proportions.

The composition of Salt Wash sandstones varies over the region similarly to the Brushy Basin member sandstones, with high feldspar content to the southeast and high tuff content to the northwest.

Wood in the form of petrified, mineralized, or coalified logs or fragments is present at the base of channels. Bone in various degrees of alteration or replacement is present in the Salt Wash mudstone and sandstone strata.

Nondetrital components are calcite, dolomite, and other carbonates, iron oxides, silica, and gangue and ore minerals. Calcite is the dominant cement, but much silica cement is present as overgrowths on the quartz grains. Iron oxides are not significant as cements.

Microstructure

The arrangement of components as observed under the microscope shows the sandstones to have microstructures of two general types, the heterogeneous type where a significant amount of clay matrix and little cement is present and a homogeneous type where the sandstone is made up of grains and cement with a minimum of matrix. The heterogeneous type appears to be the microstructure in which primary uranium ore mineralization is more often found.

Westwater Canyon member

Stratigraphic relations

The Westwater Canyon member is an arkosic facies of the Morrison formation and underlies and is interbedded with the Brushy Basin member in the southeastern part of the Colorado Plateau region. The Jackpile ore-bearing sandstone, although assigned to the Brushy Basin member, is essentially the same facies as the Westwater Canyon member.

Textural types and arrangement

The sandstones of the Westwater Canyon member are, on the average, moderately sorted, medium-grained and contain zones of granule conglomerate and pebbly sandstone which are characterized by fresh-looking cleavage fragments of pink feldspar. Like other members of the Morrison, the sandstone units are associated with bedded mudstone, siltstone, and claystone strata.

Structures of erosion and deposition

Erosional and depositional structures in the sandstones are similar to those of the thick ledges of the Brushy Basin and Shinarump but show less scouring and are less lenticular. The channels are few and inconspicuous, contain little woody material in the Four Corners area, but become more prominent and more "trashy" to the southeast. The erosional and depositional structures of the Jackpile ore-bearing sandstone resemble those of the Salt Wash member of the central part of the Plateau region in that they are highly lenticular and show more erosion and truncation surfaces.

In much of the Westwater Canyon outcrop, the sandstone beds form composite ledges which pile up in closely spaced vertical sequence to form a single massive bed or a thick sandstone interval of 2 or 3 ledges separated by thin yellowish-green and rare red mudstone strata. These thick composite sandstone strata appear in continuous exposures over wide areas.

Rock composition and classification

The yellowish sandstones of the Westwater Canyon member may be classified as arkoses and are composed of detrital grains of quartz, potash feldspar, altered and silicified tuff, plagioclase, igneous rock, quartzite, heavy minerals, and clay minerals of the kaolinite, montmorillonite, and hydromica, or illite groups. Much coarse material is present as pebble-sized fragments of quartz, potash feldspar, granite, quartzite, and chert. Nondetrital components include calcite and other carbonates, silica in the form of overgrowths on quartz grains, and in silicified tuff.

Although hydromica or mixed layer clays are probably dominant, kaolin forms the matrix of many sandstone units, and in this respect the sandstones of the Westwater Canyon differ in composition from the other sandstones of the Morrison formation.

Microstructure

The sandstones of the Westwater Canyon member have both homogeneous and heterogeneous microstructures. The sandstones of heterogeneous texture, which are in the minority, are characterized by abundant kaolin in the matrix. Sandstones with the more homogeneous structures have much less matrix which is in most cases dominantly illite or hydromicaceous clays with some montmorillonite and kaolin.

Recapture member

Stratigraphic relations

The Recapture member intertongues with the Salt Wash member in the Four Corners area of the Plateau and replaces it to become the basal member of the Morrison formation in the south and southeast. In contrast to the pale yellow of the overlying Westwater Canyon member, the Recapture member is characterized by browns and whites in both claystones and sandstone facies.

Textural types and their arrangement

The Recapture member sandstones are, on the average, moderately sorted and very fine-grained but contain some medium- and fine-grained sands with granules and small pebbles of quartz, feldspar, granite, and chert. In general it is finer textured than the overlying Westwater Canyon member and contains a much higher proportion of bedded mudstone, siltstone, and claystone. Nondetrital components include calcite and other carbonates, secondary silica, and iron oxides.

Structural features of erosion and deposition

Structures of erosion and deposition in the Recapture member are similar to those of the Salt Wash member, particularly in the Four Corners area, with similar debris-filled, deep channels, and lenticular ledge-forming sandstone units. Although the size and shape of individual sandstone units are similar to those of the Salt Wash, there are fewer of them in the average vertical sequence of Recapture member strata, and they show less resistance to weathering.

Rock composition and classification

The sandstones of the Recapture member may be classified as feldspathic orthoquartzites and arkoses with the feldspar and kaolin content increasing to the southeast. They contain detrital grains of quartz, potash feldspar, plagioclase, silicified altered tuff, igneous rock, quartzite, and heavy minerals. The clay minerals present are of the illite, montmorillonite, and kaolinite groups, with the illite group dominant. Most of the sandstones contain the hydromica-montmorillonite mixed layer clays common to many of the sandstone units described as host rocks. The bedded mudstones, siltstones, and claystones in the Recapture member contain these same clay minerals. In many localities the Recapture is characterized by thick strata of montmorillonite- rich swelling grayish-green and brown mudstone. Woody debris is present particularly in the Four Corners area.

Microstructure

The sandstones of the Recapture member show both homogeneous and heterogeneous microstructure. The detrital grains are associated with different amounts of hydromica and montmorillonite clays, which form the matrix and are cemented by varying amounts of carbonate minerals, iron oxide, and silica in the form of secondary overgrowths on quartz grains. Kaolinite is present chiefly as the alteration product of weathered feldspar grains.

Todilto limestone

Stratigraphic relations

The Todilto limestone, a formation in the San Rafael group of Jurassic age, is restricted in extent to the southeastern part of the Colorado Plateau region. It is conformable with underlying Entrada sandstone and may be separated from the Summerville by a disconformity. The Pony Express limestone of southwestern Colorado is probably equivalent to the Todilto and has generally the same stratigraphic relations.

Textural and structural features

The Todilto is characterized in outcrop by a 10- to 30-foot thick limestone ledge and has a gypsiferous facies in some localities. The depositional structures are dominantly flat bedded. The flat-bedded features may be emphasized by a banded appearance; the horizontal parallel bands are in the order of magnitude of 1 to 4 inches or less thick. Parallel distorted bands may be seen in the upper part of the limestone unit. The formation exhibits typical limestone jointing influenced by the closely spaced bedding and degree of local structural activity. The Todilto limestone contains crystalline textures ranging from microcrystalline to macrocrystalline. Ore deposits in the Todilto show some relation to structure and jointing (Bucher, 1953).

Rock composition and classification

The Todilto and the Pony Express limestones are composed of an acid-soluble carbonate fraction, which comprises about 90 percent of the rock, and an insoluble fraction. The insoluble fraction consists of authigenic quartz crystals with many bubblelike inclusions, allogenic grains of quartz, orthoclase, microcline, chert, and in very small proportions barite, tourmaline, apatite, biotite, muscovite, rutile, and others. Considering the heavy minerals as index minerals, the proportion of apatite is higher in the Todilto and the Pony Express than in adjacent rocks. The color of the limestone facies changes from dark gray in Colorado to pale yellowish-gray in New Mexico. The color is believed related to the amount of fine carbon disseminated in the rock. A gypsum facies assigned to the Todilto makes up most of the unit in parts of northwestern and north-central New Mexico.

Microstructure

Microscopic examination shows the banded appearance to result from layers of macrocrystalline mosaic-structured euhedral calcite crystals separated by bands of microcrystalline anhedral sutured calcite crystals. Scattered within the microcrystalline bands are parallel-oriented lenses of mesocrystalline to macrocrystalline subeuhedral calcite crystals in mosaic arrangement. Detrital grains are scattered throughout but are more plentiful in the microcrystalline bands.

Entrada sandstone

Stratigraphic relations

The Entrada sandstone, a formation in the San Rafael group of Jurassic age, extends with various facies changes over almost the entire Colorado Plateau region. It immediately underlies the Todilto limestone in the southeast, the Curtis formation in the north, the Cow Springs formation in the south, and the Summerville formation in much of the rest of the Plateau. In western Colorado, where uranium ore is produced from the Entrada, it overlies the Dolores formation of Triassic age (Fischer, 1942), which is equivalent at least in part to the Chinle formation. Elsewhere it overlies the Carmel formation conformably where this unit is present, or it forms the base of the San Rafael group and disconformably overlies the Glen Canyon group.

Textural types and their arrangement

The sandstone units that make up the Entrada are well to moderately sorted and range from fine- to very fine-grained. Some strata contain medium and coarse well-rounded grains of chert, quartz, and potash feldspar. These coarse grains are concentrated along laminations or disseminated throughout the sandstone in some parts of the formation. In west-central Colorado, east of the Plateau, the basal Entrada is medium- to coarse-grained, similar to the underlying Pennsylvanian sediments.

Structural features of erosion and deposition

The Entrada sandstone consists of a number of very thick to thin cross-stratified and horizontally stratified sandstone beds separated by what may be referred to as horizontal truncation planes or partings. In most areas the formation weathers on exposure to form a white, gray, or pale-brown to orange massive convex sandstone ledge 50 to 300 feet thick which is colloquially called the "slick rim." Cross-stratification in some of the beds is of the dimensions associated with eolian deposition.

Rock composition and classification

In the northeastern part of the Plateau where the Entrada is a host rock for uranium deposits, it may be classified as an orthoquartzite or a feldspathic orthoquartzite. It is composed of quartz, chert, potash and sodic feldspar, and a heavy mineral suite consisting of zircon, tourmaline, rutile, anatase, muscovite, epidote, ilmenite, magnetite, and leucoxene. The Entrada is highly feldspathic in west-central Colorado where it appears to contain material derived from underlying arkoses and possibly Precambrian granites. The feldspathic Entrada contains clays formed of ground-up mica and hydromica. In southwestern Colorado, the Entrada contains much less feldspar and more clays formed of recrystallized hydromicas such as illite and chlorite. Nondetrital minerals include calcite and barite, and euhedral anatase crystals probably of authigenic origin.

Microstructure

The microstructure of the sandstones is nearly all of the homogeneous type. The clay matrix is interstitial especially when the rock is rich in ground-up mica but also forms authigenic rims around the quartz and feldspar grains. Feldspar grains, particularly albite, are speckled with calcite and illite which may be accepted as evidence of replacement of the detrital grains by carbonates and authigenic clay minerals. Some unidentified hydromica clay minerals occupy positions which strongly suggest ghosts of detrital grains. The rock is only moderately well cemented by carbonates and clay matrix.

Miscellaneous features of the major uranium-producing host rocks

Detrital minerals

Quartz, the principal detrital mineral, is of two main types, igneous and metamorphic. The grains are usually rounded to subrounded, but the shape is changed in most samples by euhedral overgrowths which form perfect terminations on many grains. The original rounded quartz grains show moderate to slight replacement by calcite; however, the quartz overgrowths on the original grains are replaced readily.

The feldspar varieties are, in order of quantity, orthoclase, microcline, albite, oligoclase, and andesine. The feldspars show various degrees of alteration and weathering, but albite appears as the most weathered of the varieties. In many calcite-bearing sandstones albite grains are commonly replaced in part or wholly by calcite leaving peculiarly oriented ghosts.

The three major varieties of tuff are present, including vitric, crystal, and lithic tuffs, each in various degrees of alteration and silification. The typical vitric tuff grain contains a mixture of amorphous and slightly hydrous silica, spherical microgranular crystals of quartz, and voids. The outside surfaces of the angular grains are, in most instances, white and soft, like chalk. Variation in the proportions of the mixture mentioned above results in variation of the index of refraction from that of opal to that of quartz. The more highly silicified vitric tuff may be highly colored and may comprise the red or green "chert" pebbles and granules found in the Morrison formation.

The crystal tuff grains differ from the vitric only in that they include a fourth component which consists of microphenocrysts of potash feldspar, biotite, quartz, and other minerals.

The lithic tuffs are the most difficult to recognize; they resemble very fine-grained rhyolite, or at worst, a practically unclassifiable rock fragment.

The heavy mineral suites present are moderately large; however, they compose only 0.1 to 1.0 percent of the rock. Exclusive of unique occurrences of unusual minerals, the suites are composed of varieties of the nonopaque minerals zircon, tourmaline, staurolite, epidote apatite, rutile, anatase, brookite, garnet, biotite, muscovite, and spinel, and the opaque minerals magnetite, ilmenite, leucoxene, magnetite-ilmenite, and ilmenite-leucoxene-anatase intermixtures.

Clay minerals include the hydromica, montmorillonite, and kaolinite groups. The term hydromica is used to include illite, sericite, chlorite, and other mica-type clays. In addition to the conventional groups, there are also illite-montmorillonite inter-mixtures and other undefined clay minerals which suggest instability in many of the clays. The clays occur in both well-crystallized and poorly crystallized form. The hydromica clays are well crystallized when they form the borders around detrital grains of quartz. The kaolinite clays that occur in isolated interstitial wads are usually well crystallized. Some kaolinite crystals occur in well-developed accordion-shaped systems in the matrix. Montmorillonite is usually poorly crystallized.

The evidence suggests that recrystallization of some clays has occurred or is occurring. The well-crystallized detrital kaolinite in the interstitial wads may be allogenic and not due to recrystallization; however, the accordion-shaped crystals in the matrix appear to be the result of recrystallization. The hydromica clays are probably nearly all authigenic.

Aside from the kaolinite composing parts of weathered feldspar grains, the clays are nearly all a part of, or were derived from the matrix. At the time the host rocks were deposited, it is conceivable that the matrix consisted of a mixture of detrital clays, fine volcanic ash, and ground-up feldspar, quartz, and igneous and metamorphic rock fragments.

The nondetrital compounds of the host rocks include much material which acts as a cement and some that does not. Isolated euhedral calcite crystals commonly seen in the matrix or in grains of albite, exert little influence as a cement; when calcite is an effective cement, it forms continuous bands or zones which fill the interstices and extend through the rock. Siderite, dolomite, barite, gypsum, and the iron oxides are volumetrically less important than calcite but also have respectively similar roles as isolated crystals and cement. Silica cement takes two forms: as overgrowths on quartz grains and as zoned interstitial chalcedony. The ore and gangue minerals in the uranium-ore deposits are also among the nondetrital minerals.

Summary of lithologic characteristics

The lens-shaped cross-stratified sandstone units of the Morrison and Chinle formations and Shinarump conglomerate characteristically weather to form conspicuous ledges which contrast with the less resistant strata above, below, and lateral to them. The associated red and green claystone and mudstone strata, where sufficiently thick, form variegated, slightly concave slopes. If the fine-textured strata contain bentonite, the slopes are slightly convex. In most cases the ledge-forming sandstones have an erosional disconformity at the base but are conformable with the sediments above; however, the upper contact may be a disconformity if overlying conformable siltstones have been removed by subsequent erosion prior to another depositional cycle.

Most of the ledge-forming sandstones are a composite of many smaller cross-stratified units which are nearly all separated from each other by erosional truncations. The bottom of a typical ledge-forming unit is coarse textured and poorly sorted and may contain a conglomerate zone of clay galls and chips, and pebbles of sedimentary, metamorphic, and igneous rocks. Pebbly zones may be observed also along some truncation planes within the major unit. Other accumulated material found in the basal part of many of the units includes disturbed claystone strata, petrified wood, and various kinds of carbonaceous material either concentrated in pockets or disseminated in the accompanying nonorganic sediments.

The dimensions of each of these major sandstone lenses are a function of the dimensions of the respective erosional cut or cuts which they occupy. The cuts resemble erosional features produced by present day water currents and for this reason the deeper parts of the erosional cuts are referred to as "channels." The size of single continuous ledge-forming sandstone units range in order of magnitude from several miles to 100 feet or less in breadth and from 1 foot to 200 feet in thickness.

Any single major unit may include a large number of complex sedimentary and erosional structures or may consist entirely of a single cross-stratified set. The average size of the units and average scale of structures of deposition and erosion vary from formation to formation and within formations vary from area to area.

Interpretation of environment which produced the host rocks

The majority of geologists who have worked in the Plateau region believe that the rocks discussed above were formed by sediments deposited in an alluvial environment in a broad continental basin. This hypothesis is supported by evidence of contemporaneous deposition and erosion, the widespread extent of the dominant facies, the nature of the interbedding of mudstone strata with lenses of sandstone strata, the high degree of cross-stratification in the sandstone units, the plant remains in the bottoms of channels, and the overall resemblance to present day stream deposits of the sedimentary deposits which form the Morrison formation, the Shinarump conglomerate, and basal sandstone units of the Chinle formation.

CONCLUSIONS

The sedimentary rocks which rank as the major producers of uranium ore have certain characteristics which are believed to be related to the occurrence of uranium ore.

Unique characteristics of composition are: 1) a combination of potash and soda feldspar-rich sands, and 2) large quantities of silicic -alkalic tuff and ash, wood, vegetable material, and bone, all of which produce a wide variety of chemical environments and the resulting variety of clay minerals and other alteration products.

Unique characteristics of combined composition and structure are: 1) the presence of channels, 2) sedimentary traps and confined aquifers, 3) the presence of clays, vegetable material, and conglomerates concentrated in the bottoms of channels, and 4) the region-wide association of restricted permeable sandstones with impermeable chemical-rich claystone strata.

Critical features of the minor producing formations are less apparent. Uranium production from the Entrada sandstone and Todilto limestone is restricted to a narrow 60-foot thick zone in the stratigraphic column which straddles the Entrada-Todilto contact, and to a 20- to 30-foot zone above the Entrada-Dolores formation contact (Fischer, 1942). The special characteristics of these zones include jointed limestone, well-sorted sandstone, and evaporite lithologies. The Entrada-Todilto contact, though inconspicuous, is wide in extent and represents an important stratigraphic reference plane in the southeastern part of the Colorado Plateau region. All, some, or none of these factors may be related to the deposition of uranium in these two formations.

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