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Geology and genesis of the Anderson mine, a carbonaceous lacustrine uranium deposit, western Arizona: a summary report

by

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Abstract

Uranium deposits at the Anderson mine in western Arizona occur largely in debris flow and turbidite sediments deposited in an interfan lake on the northeastern flank of the early middle Miocene Date Creek basin. These lake sediments were deposited during a period of rapid constriction of lakes in the basin, of increasing climatic aridity, and of corresponding increased alkalinity and salinity of ground water and lake water. Alluvial fans marginal to the lake had Precambrian to early Tertiary igneous and metamorphic and older Tertiary volcanic rock sources. Precambrian granitic rocks north of the basin are exceptionally radioactive. Ash falls periodically covered the entire basin. Uraniferous topaz-bearing rhyolites and ultra-potassic rhyolites and trachytes have been found nearby. Palms, grasses, and semi-arid shrubs grew on the alluvial fans and alluvial plains adjacent to the lake, while a temperate deciduous hardwood forest grew in adjacent mountains. Clastic crystalline and tuffaceous detritus, along with entrained plant debris, washed into the lake during episodic floods. Sedimentation was dominated by debris flows. Considerable sorting of the plant debris occurred, with large branches, twigs, and logs remaining in the thick subaerial or subaqueous debris-flow beds while finely macerated plant debris was deposited in thin, laminated distal turbidites. Plant debris in the thick proximal debris-flow facies tended to be silicified, probably because of the greater porosity and permeability of the beds. Plant debris in the more distal facies was preserved and coalified probably because the beds were deposited in a quiet anoxic lake bottom and were low in porosity and permeability.

Shallow ground water from sources in adjacent mountains and within the basin itself leached uranium and silica from the adjacent granitic terrains, from arkosic alluvium, and from ash-falls. This ground water moved into the

lake environment where it also dissolved humic material from degraded plant material in soil horizons or entrained in debris flows. Ground water recharged the lake in the littoral zone around the lake margin. In the quiet, anoxic portions of the lake bottom, uranium, silica, humate, and other species precipitated from solution. Precipitation may have occurred by one or more mechanisms. Increases in salinity by evaporative concentration between periods of fresh water influx may have initiated humate and silica flocculation and precipitation. Alternatively, lower Eh and pH conditions in the lower layers of a stratified lake may have caused coprecipitation of humate, silica, and the associated metal compounds along the interface between water layers.

Uranium deposition occurred in various parts of the lacustrine environment but tended to favor sediments deposited on the anoxic lake bottom, especially the distal laminated carbonaceous turbidites. Uranium minerals coprecipitated with both humate and silica. Grades range from a few hundred to almost 10,000 U_3O_8. Because of the nature of the deposition, orebodies have a thin tabular shape but are stacked so that aggregate thicknesses commonly exceed 10 m.

Introduction

Tertiary alluvial and lacustrine rocks occur throughout much of western Arizona. They range in age from Oligocene to Pliocene. Many uranium occurrences and deposits are known in these rocks, largely in lacustrine or marginal-lacustrine facies of the basinal systems. The largest and most studied deposit occurs at the Anderson mine on the northeastern side of the Date Creek basin 150 kilometers northwest of Phoenix, Arizona (fig. 1).

Reyner and others (1956) first described the Tertiary section and the uranium deposits exposed at the surface at the mine. Otton (1977, 1978) briefly described the deposit. Sherborne and others (1979) gave a detailed description of the deposit, discussing the surface and subsurface stratigraphy, uranium mineralization, mineralogy, alteration, geochemistry, and origin of the deposit. Glanzman and Otton (written commun., 1978) have described a uranium and lithium association at the Anderson mine and offered a geochemical model for uranium transport and deposition. Otton (1981) described the structural setting of the Date Creek basin and the tectonic control of the distribution of lacustrine facies.

The purpose of this paper is to outline the geologic setting of the Anderson mine host rocks, describe the sedimentary processes that formed the host rocks, and discuss a new hypothesis for uranium deposition. The author is indebted to Christopher Hill, William Buckovic, and John Sherborne of Union Minerals and William Schneider and David Hertzke of Urangesellschaft for access to data obtained by the two companies and for their individual published and unpublished observations on the geology of the mine area (Sherborne and others, 1979).

Geologic setting of the Date Creek basin

The Anderson mine is located in lacustrine facies of the Chapin Wash Formation on the northeastern flank of the Date Creek basin. The Date Creek basin is a northwest-trending topographic and structural low (fig. 1), bounded on the southwest by one or more normal faults including the Sandtrap Wash fault, a normal or oblique-slip normal fault (Shackelford, 1980; Otton, 1981). To the north of the basin lies a Precambrian crystalline terrain; to the south and west lies a complex late Mesozoic to mid-Tertiary metamorphic terrain (Shackelford, 1980; Reynolds, 1980). The Precambrian crystalline terrain contains granite that is anomalously radioactive (Loghry and Heinrichs, 1980).

A diverse Tertiary volcanic and sedimentary sequence (fig. 1) is preserved in the basin beneath a thin cover of Pliocene(?) to Holocene alluvium. The sequence is divisible into three gross units: (1) older tilted and faulted Tertiary sedimentary and volcanic rocks, including the Artillery Formation to the west and unnamed volcanic and sedimentary rocks to the east; (2) little-tilted early to mid-Miocene sedimentary and volcanic rocks, including the Chapin Wash Formation and underlying and intertonguing volcanic rocks; and (3) mid-Miocene and younger basin-fill alluvium and basalt flows.

The Chapin Wash Formation is exposed across the Date Creek basin and in some adjacent basins (fig. 1). The formation was deposited in a basin that formed after an initial period of crustal extension and listric normal faulting that tilted the older Tertiary section mentioned above. The Chapin Wash can generally be divided into a western facies consisting of coarse alluvium, slide blocks, and monolithologic breccia and an eastern facies consisting of intertonguing coarse- to fine-grained alluvium and lake

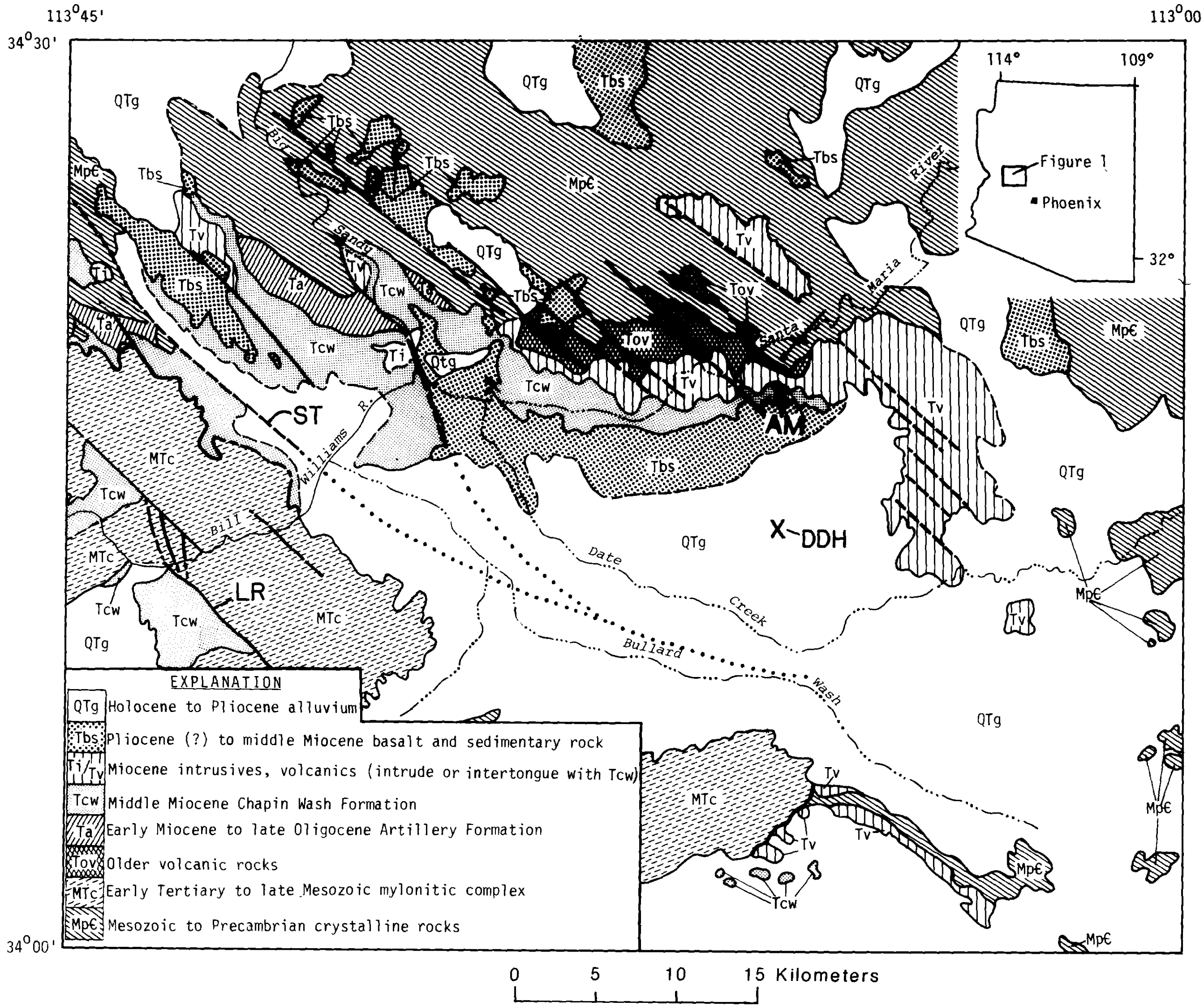

Figure 1.--Geologic map of the Date Creek basin area. Data from Shackelford (1980), Gassaway (1977), J. Otton (unpublished mapping), and W. E. Brooks, Jr. (unpublished mapping). AM - Anderson mine, DDH - El Paso Natural Gas/Brown and Thorp drillhole, ST - Sandtrap Wash Fault, LR - Lincoln Ranch Fault.

sediments. The older tilted volcanic section is composed of andesitic agglomerates and rhyolite flows and domes with a discontinuous basal unit composed of arkose, minor volcanic breccia, and lithic tuff. The older volcanic rocks have yielded K-Ar whole-rock ages of 17.2 m.y. (R. Marvin, written commun., 1979) and 41.5 m.y. (Gassaway, 1977). The younger age can only be considered a minimum age. The older date suggests, but doe not confirm, that this section is late Eocene.

In the vicinity of the Anderson mine, the Chapin Wash Formation rests unconformably on little-tilted biotite-hornblende-plagioclase rhyodacite and associated rocks (dated at 25.7 m.y., K-Ar on plagioclase, N. Suneson, written commun., 1978). West of the mine the Chapin Wash rests with angular unconformity on the older, tilted volcanic section. In the vicinity of the Anderson Mine, which is in the eastern facies of the Chapin Wash Formation, the formation includes the lower alluvial unit, the augite andesite, the mudstone-limestone unit, and the upper alluvial unit of Reyner and others (1956). The lower alluvial unit and the augite andesite are included with the other two units in the Chapin Wash Formation near the mine, because to the south and west in the subsurface the augite andesite is often missing and the rocks above and below the augite andesite horizon are conformable and indistinguishable (Otton, unpublished drilling data, 1979). Sherborne and others (1979) had previously correlated the mudstone-limestone unit and the upper alluvial unit (named by them the Anderson Mine Formation and the Flat Top Formation, respectively) with the Chapin Wash Formation, following Reyner and others (1956).

During deposition of the Chapin Wash Formation, the uranium host at the Anderson mine, the basin was dominated by alluvial fans and only small isolated lakes were present. The lake established in the vicinity of the present mine site appears to have formed in an interfan area (fig. 2). The lake progressively lapped onto a pre-existing volcanic topography including the augite or basaltic andesite and the older rhyodacite sequence.

Stratigraphy at the Anderson mine

The stratigraphy of the Anderson mine section has been described by Reyner and others (1956) and Sherborne and others (1979). Their use of names and the usage in this report are summarized in table 1. Of specific interest are the lower lakebeds, the arkose, the upper lakebeds (the major uranium host), and the upper alluvial unit of the Chapin Wash Formation. Because the basaltic andesite was considered "basement" for drilling purposes in the mine area, these four units of the Chapin Wash Formation were the ones usually penetrated by drilling, described in detail, and cored; thus, they are the best known. A composite stratigraphic section of these four units is shown in figure 3. The lower alluvial unit of the Chapin Wash occurs as discontinuous channels beneath the basaltic andesite in the mine area. In the subsurface to the south, it thickens to several hundred feet. It was seldom penetrated by drilling in the Anderson mine area.

The lower lakebeds, which immediately overlie the andesite, are composed of quartzose, micaceous siltstones, tuffaceous mudstones and siltstones, and fine-grained sandstone. These rocks are gray, greenish-gray, brown, and red. Where highly carbonaceous, they are dark gray to black. Only a few feet of the lower lakebeds are exposed at the surface in one area in the mine. They thicken markedly to the south, to over 150 m. They constitute a minor host for uranium mineralization in the mine area.

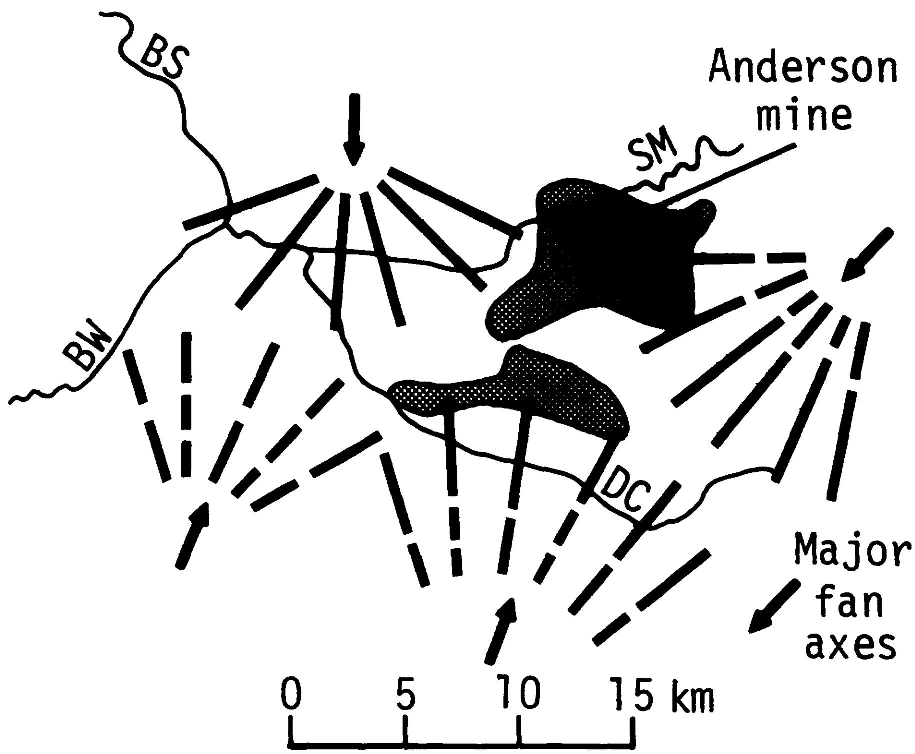

Figure 2.--Schematic diagram of lake-fan relations during deposition of the Anderson Mine host rocks. Shaded areas represent lakes. BW-Bill Williams River, BS-Big Sandy River, SM-Santa Maria River, DC-Date Creek.

Table 1.--Tertiary stratigraphic nomenclature used at the Anderson Mine.

<table>
<tr><th>Reyner and others (1956)</th><th>Sherborne and others (1979)</th><th colspan="2">This report</th></tr>
<tr><td>Undescribed</td><td>Younger alluvium
Older alluvium</td><td colspan="2">Younger alluvium
Older alluvium</td></tr>
<tr><td>Capping conglomerate</td><td>Agglomerate</td><td colspan="2">Sandtrap Conglomerate</td></tr>
<tr><td>Capping basalt</td><td>Basalt</td><td colspan="2">Cobwebb Basalt</td></tr>
<tr><td>Upper alluvial unit</td><td>Flat Top Formation</td><td rowspan="4">Chapin Wash Formation</td><td>Upper alluvial unit</td></tr>
<tr><td>Mudstone-limestone unit</td><td>Anderson Mine Formation
Upper tufaceous member
Lower arkosic member</td><td>Upper lakebeds
Arkose
Lower lakebeds</td></tr>
<tr><td>Augite andesite</td><td rowspan="3">Arrastra Volcanics</td><td>Basaltic andesite</td></tr>
<tr><td>Lower alluvial unit</td><td>Lower alluvial unit</td></tr>
<tr><td>Vitrophyric andesite, basalt</td><td colspan="2">Rhyodacite</td></tr>
<tr><td>Unrecognized</td><td>Basal Tertiary rocks</td><td colspan="2">Arkose, rhyolite, andesite</td></tr>
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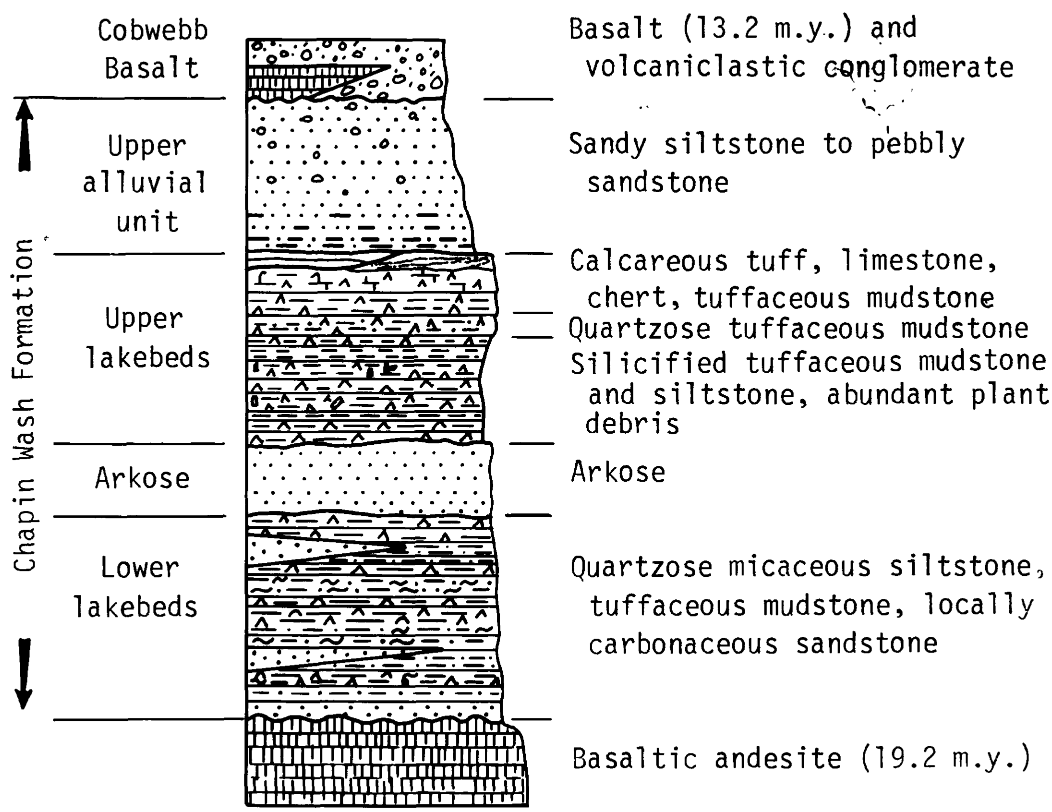

Figure 3.--Composite stratigraphic section, Anderson mine host.

Overlying this unit is the arkose, a gray, medium-grained to coarse-grained, pebbly sandstone. Locally it contains volcaniclastic lenses and pyrite. In some areas the unit has been partly oxidized and contains Fe- and Mn-oxide cement. This unit is locally exposed at the surface in the mine area. The unit has a relatively uniform thickness of about 25 to 35 m, except where it thins as it onlaps the older topography. The arkose, known as the "barren sandstone," appears to represent a major transgression of clastic sediment into the ancestral lake in the mine area.

Above the arkose are the upper lakebeds. They are the major host for uranium mineralization. They constitute most of the lacustrine units exposed in the mine area. At the outcrop, the upper lakebeds can be divided into three units: a lower unit composed of greenish-gray, massive to thinly bedded, silicified, tuffaceous mudstone and siltstone, often containing abundant plant debris; a discontinuous middle unit composed of greenish-gray quartzose, micaceous, tuffaceous mudstone; and an upper unit composed variously of white, silicified, calcareous tuff, tuffaceous mudstone, limestone, and chert. To the south in the subsurface, the upper two units intertongue with sandstone. Much of the lower unit grades laterally into thinly bedded carbonaceous micaceous siltstone, which constitutes the principal uranium host. Farther south, the lower unit also intertongues with sandstones.

The upper alluvial unit overlies and partly intertongues with the upper lakebeds. This unit is a coarsening-upward sequence of sandy siltstone, sandstone and pebbly sandstone. The unit is yellow-gray to gray and commonly contains abundant calcite cement.

Sedimentology

Alluvial and lacustrine sedimentation in the Chapin Wash Formation at the Anderson mine was clearly dominated by debris flows. Where the debris flows entered the lake, they became turbidity currents in which considerable size grading and sorting of the entrained debris took place. In the west-central portion of the mine area, the entire upper lakebed sequence is exposed in a bench cut (fig. 4), and one can reconstruct a prograding turbidite-debris flow sequence.

The arkose crops out at the base of the bench. Overlying the arkose is the lower part of the upper lakebeds which consist, in this locality, of a cyclic sequence of thin, graded beds composed principally of tuffaceous debris. The base of each bed is generally composed of tuff clasts with or without gastropod debris and rip-up clasts of the underlying bed. Upwards in each bed, the tuffaceous material becomes progressively finer grained and, in many beds, darker in color because of increasing content of fine carbonaceous plant debris. The upper fine-grained parts are abruptly terminated by the base of the overlying bed. These units are interpreted as medial turbidites (fig. 5).

Upwards in the section and laterally in outcrop, the thin graded beds abruptly become highly calcareous and poor in carbon, they then give way to thicker, poorly sorted, ungraded, tuffaceous mudstone beds with coarser silicified plant fragments and eventually to beds as much as 1.5 m thick that are choked with silicified plant fragments. These latter beds represent debris flows (proximal turbidites, fig. 5), and it is these massive debris flows which dominate the upper lakebeds exposed at the surface in the mine area.

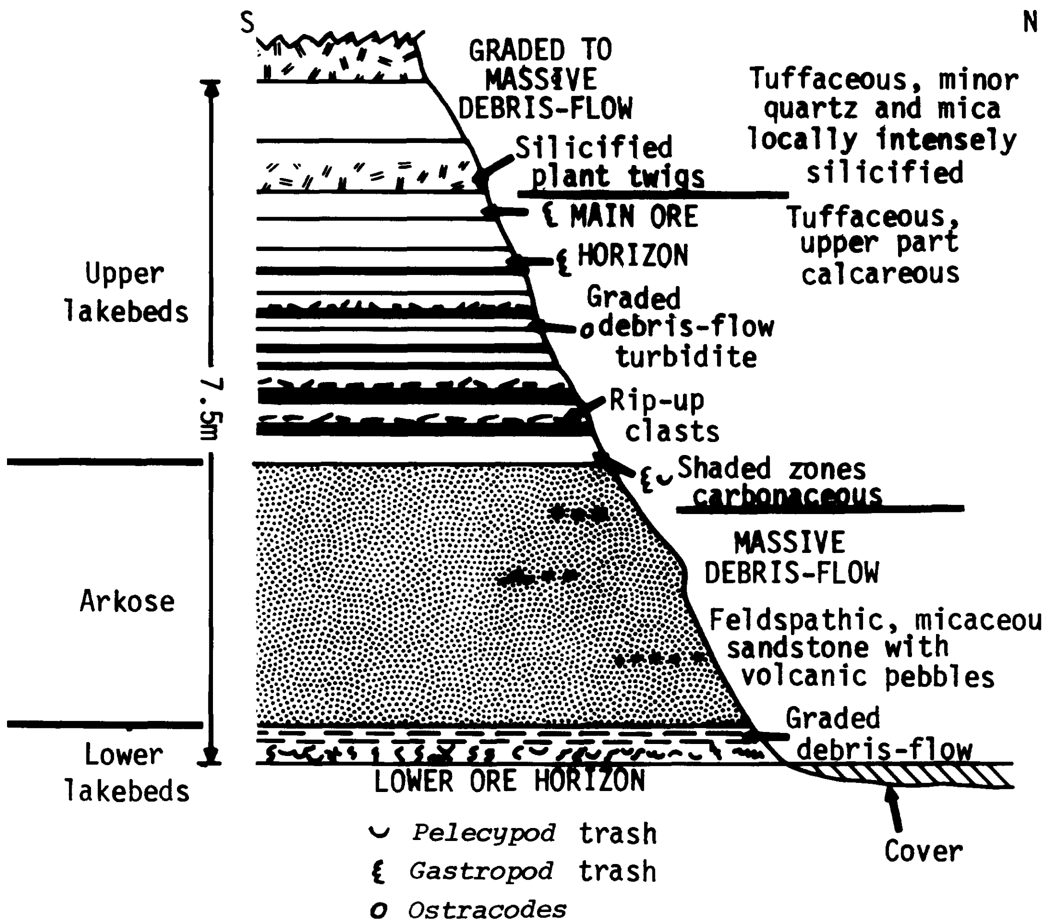

Figure 4.--Measured section in a bench cut, arkose and upper lakebed sequence.

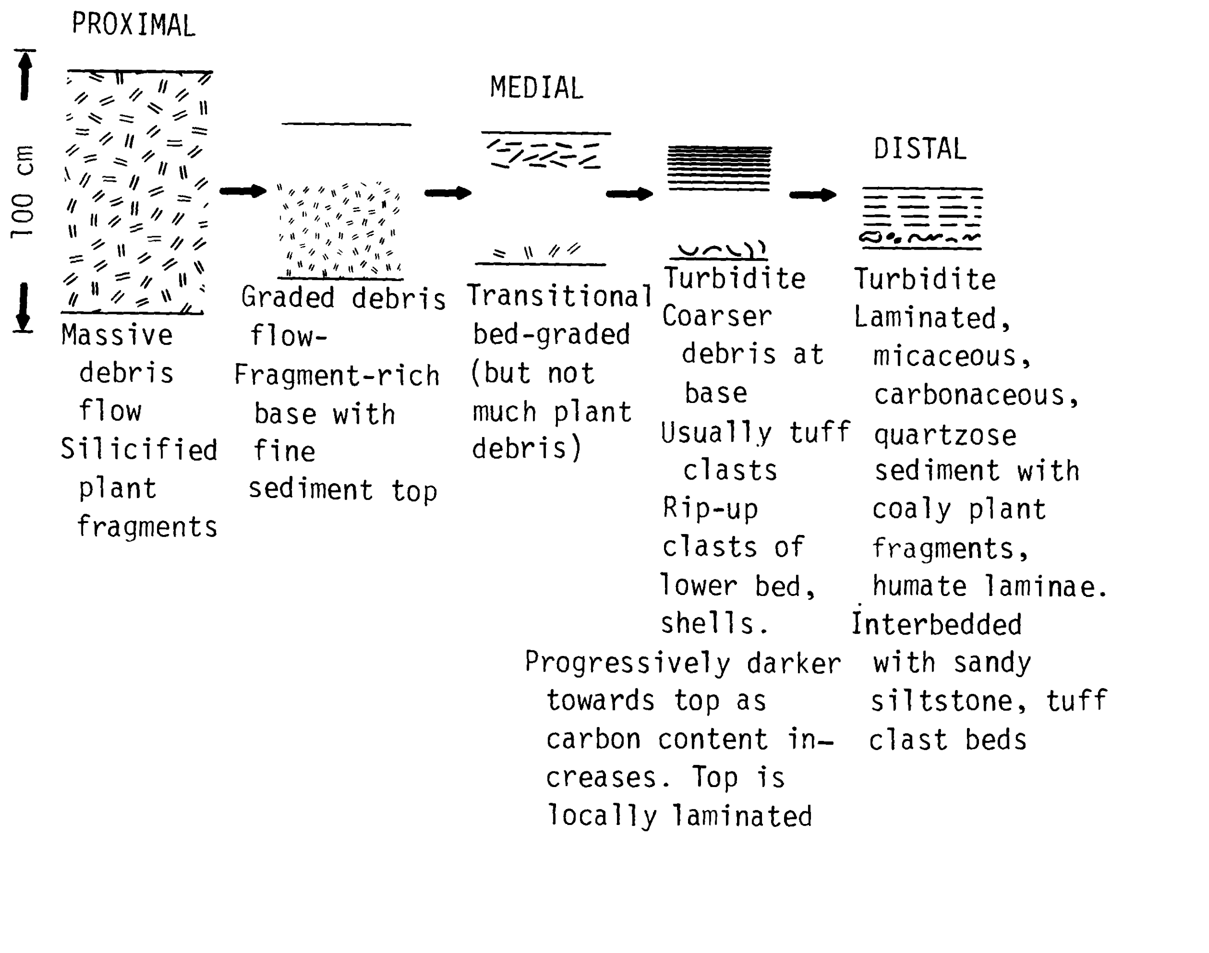

Figure 5.--Schematic diagram, debris flow-turbidites at the Anderson mine.

A distal facies of the turbidite, not seen in outcrop in the mine area, is represented by the thinly laminated carbonaceous siltstones described above. This unit constitutes much of the lower part of the upper lakebeds in the subsurface. The thinly laminated beds are often just above graded tuffaceous beds, but in many drill cores there are stacked sequences of laminated sediment without intervening graded beds. Many of the laminated zones contain thin (1-3 cm), gray, tuffaceous claystones that may represent the featheredge of material transported as a fluidized debris flow and deposited as part of the turbidite sequence.. The laminated layers (described in more detail below) are interpreted as fine material swept from the debris flow during its movement and deposited from suspension shortly after the flow stopped. As noted by Sherborne and others (1979), these carbonaceous siltstone beds are locally as much as 11 m in aggregate thickness. Areas of thick accumulation of this lithology were probably depocenters in the central part of the lake. Because the thin laminae are not disturbed, framboidal pyrite is commonly observed and organic carbon is well preserved, these beds were probably deposited below wave base in an anoxic lake-bottom environment. No burrowing can be demonstrated in these sediments. A schematic diagram of a debris flow-turbidite is shown in Figure 5.

These debris flow-turbidite sequences are believed to have been deposited by sheet floods entering the lake. The sheet floods may have been initiated by episodic heavy storms in the basin or in adjacent mountains. The massive debris flows may have been deposited subaerially or subaqueously on the alluvial plain or nearshore. The medial and distal turbidite facies require deposition in water to achieve the size sorting observed.

Paleoclimatic conditions and geochemistry of lake and ground waters

The formation of the deposits appears to have required a favorable balance between more temperate and humid conditions, which would favor the production of plants to provide organic matter to the system, and more arid conditions, which would create the alkaline waters necessary for mobilizing silica, uranium, and humate. Paleontological, sedimentological, and geochemical evidence all suggest that during deposition of the Anderson mine host rocks conditions were temperate to semi-arid and were becoming progressively more arid. Similarly the lake-water geochemistry appears to have become progressively more alkaline and saline.

Salinities were never high enough during deposition of the Anderson mine host rocks to permit the precipitation of the halide minerals; however, extensive diagenetic carbonate cements and minor gypsum beds are known in the mine area largely in the upper lakebeds and overlying alluvial sandstones. Palynomorphs include forms typical of a temperate deciduous hardwood forest (hickory, oak, linden, pine, spruce), forms likely growing adjacent to a subtropical lake (palm, marsh grass, bullrushes, ferns), and other forms such as grasses, flowering shrubs, coniferous shrubs, and juniper (J. Platt Bradbury, written commun., 1978). This diverse flora suggests considerable physical relief and related climatic zonation in the basin area, with generally warm temperatures and moderate to semi-arid rainfall conditions.

Invertebrate fossils found to date at the Anderson mine include gastropods, ostracods, pelecypods, diatoms, and dinoflagellates (J. Platt Bradbury, R. Forester, written commun., 1978). Most of the specimens are too poorly preserved for generic and specific identifications or are forms not presently known. In general the abundance and diversity are high in the lower part of the lakebed sections at the mine. The diversity decreases rapidly in the upper lakebeds.

A distinctive fauna is present in the middle unit of the upper lakebeds. It contains a single species of ostracod in great abundance (*Heterocypris* cf. salinus) and a single gastropod form also in considerable abundance. This suggests that conditions were becoming more harsh, probably more saline, and that faunal diversity was rapidly decreasing. Two Hemingfordian age vertebrates have been found: *Oxydactylus*, a Miocene tall camelid; and *Diceratherium*, a primitive rhinocerus-like mammal (Lindsay and Tessman, 1974).

Uranium mineralization

Uranium occurs in a wide variety of host rocks at the mine. It is most commonly associated with varying degrees of silicification of the host. The host almost always shows evidence that it contains, or once contained, plant debris and pyrite. Two distinctive ore facies are present: a highly silicified, oxidized facies and a black carbonaceous reduced facies. The oxidized facies is largely restricted to the upper ore horizon at the mine. It consists of uraniferous (uranyl) silica, carnotite, and weeksite in highly silicified, thinly bedded to laminated, plant-debris-rich, tuffaceous siltstone and sandstone. These beds are highly colored with Fe- and Mn-oxides. This ore horizon occurs just below the thick, greenish-gray, quartzose, tuffaceous middle unit of the upper lakebeds. The ore zone is laterally discontinuous but occurs at the same stratigraphic horizon over a distance of 2400 m. It is in this zone that palm fronds, palm logs, vertebrate bones, and mats of twigs (possibly *Ephedra*) have been found. The plant debris is everywhere silicified, although organic carbon is probably still present in some material, judging from the gray to black color. Hematite replacement of framboidal pyrite can be observed in many polished sections from this zone. This ore zone is more areally restricted than lower ore zones although its average grade appears to be higher.

Uranium in the lower ore zones (lower parts of the lower unit of the upper lakebeds) is principally in the dark-gray to black, laminated, carbonaceous, micaceous siltstone. However, it also occurs in weakly silicified tuffaceous sandstone (with or without gastropod debris) and in silicified massive debris-flow beds with abundant, black, silicified plant debris.

This siltstone, as noted above, is interpreted as distal lacustrine turbidite (fig. 5). It is composed of alternating laminae of clastic debris and humate. The clastic debris includes mica flakes (muscovite), quartz grains, clay (probably altered volcanic glass), small shell fragments, coaly plant fragments, and disseminated humate. The uniformly coplanar, horizontal orientation of the mica flakes, fine grain size, and random orientation of linear plant fragments suggest deposition from suspension from the cloudy liquefied tail of the turbidity current.

The humate laminae are about 1-2 mm thick. They are usually internally structureless, although some appear to be horizontally banded. They lack the clastic grains present in adjacent laminae. On fresh surfaces they are black, are glassy, and break with conchoidal fracturing. As core dries, the humate laminae dehydrate and shrink with dessication cracks forming. The humate laminae are usually restricted to the black, laminated, carbonaceous, micaceous siltstone, but they are rarely observed interbedded with the tuffaceous mudstone beds (medial debris flows, fig. 5).

The percentage of humate laminae in a given section varies greatly. The overall grade of the ore appears to increase with increasing percentage of humate laminae present, but this observation has not been confirmed quantitatively. The correlation between organic carbon and uranium content is not strong (Sherborne and others, 1979). This may reflect the fact that two forms of organic carbon are present: coaly plant debris, which appears not to carry uranium; and humate, with which the uranium is associated. Thus the organic carbon content of a given interval may vary greatly if there are variations in the abundance of coaly plant debris, but the uranium content may be relatively constant if the amount of humate is constant.

Detailed studies of polished sections (Sherborne and others, 1979; Schneider, written commun., 1980) of the mineralized carbonaceous siltstones show that uranium is associated with the humate laminae and the disseminated humate in the clastic laminae. The uranium occurs as a silicate usually too poorly crystallized or finely dispersed to give a definitive X-ray pattern. However, in high-grade ore zones, coffinite can be identified in veinlets within the carbonaceous zones. Uranium probably also occurs as a urano-organic complex. One pure humate layer contained about 500 ppm U_3O_8. These polished sections (Sherborne and others, 1979, fig. 15) also show that the coaly plant fragments have no associated uranium. The coaly plant detritus appears to have undergone pre-oxidation (N. Bostick, oral commun., 1980), probably as litter on the land surface next to the lake, which rendered it geochemically inert.

A genetic model

The debris flow-turbidite sedimentologic model, the character of the uranium mineralization, and the evidence for the nature of the aqueous geochemistry of the lake and ground waters suggest a genetic model for uranium mineralization at the mine. This model is shown in figure 6. Uranium was derived from a Precambrian granitic terrain, from arkosic alluvium, and from

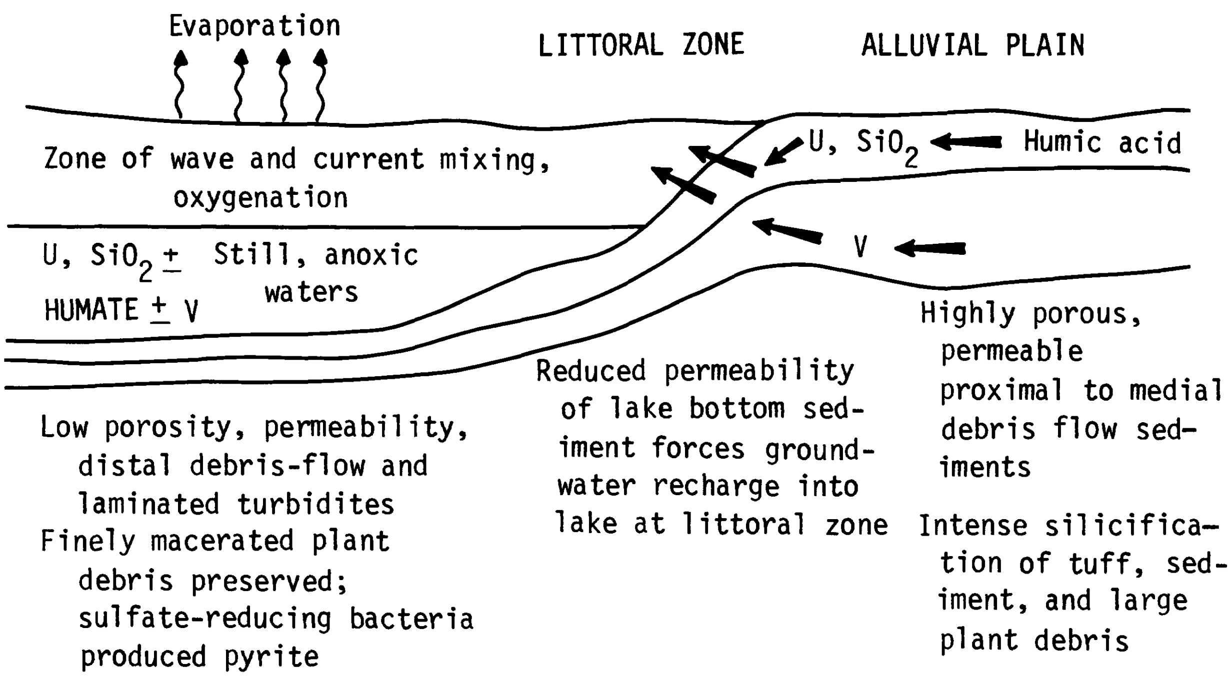

Figure 6.--A model for uranium transport and fixation at the Anderson mine.

the volcanic ash in the basin. Uranium migrated in shallow alkaline ground water down alluvial fans and through the alluvial plain. Where the silicic ash-fall tuffs were encountered, the ground water leached significant volumes of silica. Humic acid also accumulated in this water where the water encountered plant debris in the sediment, or it was added to ground water by degradation and leaching of plant litter in the soils. In the littoral zone around the lake margin, this ground water formed a major recharge source for the lake. Evaporation in the lake concentrated uranium, silica, and humic-acid species in the water. As salinity increased, humate and silica would tend to polymerize and precipitate, forming thin bands on the lake floor or disseminated humate in clastic sediment if it, too, was being deposited. Alternatively, precipitation may have occurred at water-layer interfaces in a stratified lake, with differences in Eh and pH initiating precipitation. These bands were preferentially preserved below wave base in the central part of the lake.

Uranium could have coprecipitated as urano-silica or urano-organic complex. Where uranium concentrations were high enough in the reducing environment of the sediment, coffinite formed.

This mechanism for precipitation was likely cyclic in character as suggested by the stacked, thin, tabular nature of the mineralization. Cyclicity was likely controlled by the relative rates of evaporation and freshwater influx (by surface water or ground-water recharge) or by alternate periods of mixing and stratification in the lake.

Clastic sedimentation was also episodic in nature. Large pulses of fresh sediment likely coincided with a large influx of freshwater. Debris flows generated by sheet floods during large storms would wash fresh clastic sediments and plant detritus into the lake. Between these larger storm events, wave action during smaller storms might carry fine sediment and plant debris from shallow waters nearshore into deeper waters without significantly altering lake-water chemistry. Some turbidite beds, especially those with abundant fossil shell hash but little or no plant debris, may have been caused by slump of lacustrine deltas.

The uppermost ore zone differs from lower zones in that oxidized uranium, vanadium, iron, and manganese species are present. Facies relations suggest that the lake had shrunk to a very small size during deposition of the uppermost ore zone. It seems likely that the entire lake facies may have been flushed by oxidizing, siliceous ground water in early stages of diagenesis of the sediment. Thus all plant debris would have been silicified and would have had large volumes of uraniferous waters flushed past it. This may account for the overall higher grades of uranium seen in the uppermost ore zone.

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