

Groundwater processes and sedimentary uranium deposits

D. K. Hobday · W. E. Galloway

Abstract Hydrologic processes are fundamental in the emplacement of all three major categories of sedimentary uranium deposits: syngenetic, syndiagenetic, and epigenetic. In each case, the basic sedimentary uranium-enrichment cycle involves: (1) leaching or erosion of uranium from a low-grade provenance; (2) transport of uranium by surface or groundwater flow; and (3) concentration of uranium by mechanical, geochemical, or physiochemical processes. Although surface flow was responsible for lower Precambrian uranium deposits, groundwater was the primary agent in upper Precambrian and Phanerozoic sedimentary uranium emplacement. Meteoric or more deeply derived groundwater flow transported uranium in solution through transmissive facies, generally sands and gravels, until it was precipitated under reducing conditions. Syndiagenetic uranium deposits are typically concentrated in reducing lacustrine and swamp environments, whereas epigenetic deposits accumulated along mineralization fronts or tabular boundaries.

The role of groundwater is particularly well illustrated in the bedload fluvial systems of the South Texas uranium province. Upward migration of deep, reducing brines conditioned the host rock before oxidizing meteoric flow concentrated uranium and other secondary minerals. Interactions between uranium-transporting groundwater and the transmissive aquifer facies are also reflected in the uranium mineralization fronts in the lower Tertiary basins of Wyoming. Similar relationships are observed in the tabular uranium deposits of the Colorado Plateau.

Résumé Les processus hydrologiques sont déterminants dans la localisation des trois principaux types de

dépôts sédimentaires d'uranium: syngénétique, syndiagénétique et épigénétique. Dans chaque cas, le cycle fondamental d'enrichissement en uranium sédimentaire met en jeu: 1) le lessivage ou l'érosion de l'uranium à partir d'un matériau à faible teneur, 2) le transport de l'uranium par un écoulement d'eau de surface ou souterraine, et 3) la concentration de l'uranium par des processus mécaniques, géochimiques ou physico-chimiques. Bien que les écoulements de surface aient été à l'origine des dépôts d'uranium au Précambrien inférieur, les eaux souterraines ont été l'agent principal de la mise en place des formations uranifères sédimentaires du Précambrien supérieur et du Phanérozoïque. Des écoulements souterrains proches de la surface ou même plus profonds ont transporté l'uranium en solution au travers de faciès à forte transmissivité, en général des sables et des graviers; l'uranium a ensuite précipité sous des conditions réductrices. Les dépôts d'uranium syndiagénétiques sont habituellement concentrés dans des environnements réducteurs de lacs et de marais, alors que les dépôts épigénétiques se sont accumulés le long de fronts de minéralisation ou suivant des limites tabulaires.

Le rôle des eaux souterraines est très bien montré dans les systèmes alluviaux fluviaux de la province uranifère du sud du Texas. La migration vers le haut de saumures réductrices d'origine profonde a conditionné la formation hôte avant l'oxydation; l'écoulement d'eau météorique a concentré l'uranium et d'autres minéraux secondaires. Les interactions entre l'eau souterraine vecteur de l'uranium et les faciès transmissifs de l'aquifère se manifestent aussi dans les fronts de minéralisation des bassins du Tertiaire inférieur du Wyoming. Des relations du même type sont observées dans les dépôts uranifères tabulaires du plateau du Colorado.

Resumen Los procesos hidrológicos son de una importancia fundamental para la distribución geográfica de las tres grandes clases de depósitos sedimentarios de uranio: singenéticos, sindiagenéticos y epigenéticos. En cada uno de los casos, el ciclo sedimentario básico de enriquecimiento de uranio incluye: (1) filtración o erosión de uranio procedente de una fuente de bajo contenido; (2) transporte de uranio por flujo superficial o subterráneo; y (3) concentración de uranio

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mediante procesos mecánicos, geoquímicos o físico-químicos. Aunque el flujo superficial fue el responsable de los depósitos de uranio formados durante el Precámbrico Inferior, el agua subterránea fue el agente principal en la formación de depósitos sedimentarios correspondientes al Precámbrico Superior y Fanerozoico. Agua subterránea, meteórica o profunda, transportó el uranio en disolución a través de facies transmisivas, generalmente arenas y gravas, hasta que éste precipitó bajo condiciones reductoras. Los depósitos de uranio sindiagenéticos se encuentran normalmente concentrados en ambientes reductores asociados a lagos o pantanos, mientras que los epigenéticos se acumulan a lo largo de frentes de mineralización o de depósitos tabulares.

El papel de las aguas subterráneas se ilustra particularmente bien en los sistemas fluviales de la provincia uranífera al Sur de Texas. La migración hacia la superficie de salmueras, situadas a gran profundidad y en condiciones reductoras, acondicionaron la roca matriz antes de que un flujo meteórico de carácter oxidante produjese la concentración de uranio y de otros minerales secundarios. Las interacciones entre el agua subterránea, transportadora de uranio, y las facies transmisivas del acuífero se reflejan también en los frentes de mineralización de uranio en cuencas del Terciario Inferior localizadas en Wyoming. Relaciones similares se observan en los depósitos tabulares de la Meseta de Colorado.

Key words uranium · groundwater processes · paleohydrology · sedimentary rocks

Introduction

Sedimentary rocks host a large proportion of the world's uranium reserves, and hydrologic processes are fundamental in the emplacement of this resource. Siliceous igneous rocks such as granites and rhyolite are comparatively enriched in uranium, averaging 3.6 and 5.0 ppm uranium, respectively; such rocks and their pyroclastic equivalents are a primary source of sedimentary uranium. The U^{6+} valency of uranium is highly soluble in surface water and groundwater, which are capable of concentrating uranium to economic grade.

Major time-bound categories of global uranium resources represent particular geologic and hydrologic settings, coupled with specific stages in evolution of the earth's atmosphere. Uraniferous quartz-pebble conglomerates are predominantly Archean to Early Proterozoic in age (2800 to 2200 Ma) and are rich in pyrite and, in some regions, gold. The ores comprise uraninite and pitchblende paleoplacers that predated evolution of a highly oxygenated atmosphere, so that reduced uranium minerals survived surficial weathering and transport. Geologically younger, unconformity-

related, uranium vein deposits are associated with fault breccias or fracture zones beneath regional unconformities. These deposits apparently required high uranium mobility in aqueous solution, a condition that arose with the evolution of a more strongly oxygenated atmosphere around 1500 Ma. Sandstone-type uranium deposits are typically of Permian, Mesozoic, or Cenozoic age, with smaller amounts in older Paleozoic rocks. Nearly all such deposits reflect solution transport of uranium in the oxidized form, and concentration of intergranular uranium in mineralization fronts and lenses. This article focuses on the interactions between groundwater processes and geologic framework that lead to economic concentrations of uranium in sedimentary rocks.

Classification of Uranium Deposits

Three broad genetic classes of sedimentary uranium deposits are recognized. These classes are based on the timing of primary mineralization relative to deposition of the host sediment and relative importance of surface flow or groundwater systems in transporting uranium to the site of accumulation. Their gross geologic and hydrologic framework is illustrated in *Figure 1*.

Syngenetic deposits are contemporaneous with sedimentation (*Figure 1*). Archean and Proterozoic quartz-pebble conglomerate deposits originated as detrital placers of uranium minerals. Quartz-pebble conglomerate ores in the Witwatersrand Goldfields of South Africa and the currently nonproducing Elliot Lake uranium district, Canada, are the prime examples. Emplacement required an elevated granitoid provenance, high-energy bedload transport over relatively short distances, hydrodynamic sorting, selective deposition, and winnowing in an oxygen-deficient atmosphere. Surface hydrodynamics, rather than groundwater, controlled the distribution of uranium and other metals such as gold, and syngenetic ores are not considered further here. Nor are uraniferous black shales, peats, and phosphorites, which constitute a younger and economically insignificant subclass of syngenetic uranium extracted from solution in surface waters.

Syndiagenetic deposits are the product of circulating shallow, but partially confined, meteoric groundwater within sediments, and involve extreme variations in Eh and pH. Flow direction reflects regional topography and stratification of the host depositional system. Syndiagenetic calcrete uranium deposits (*Figure 1*) form in areas of meteoric discharge, generally along the lower reaches of fluvial systems incised into bedrock. Discharge of uranium-enriched waters through organic-rich sediments of lacustrine or marsh origin results in stratabound and locally stratiform uranium mineralization.

Epigenetic deposits are produced by meteoric groundwater flow following burial of the host depositional system, which serves primarily as passive

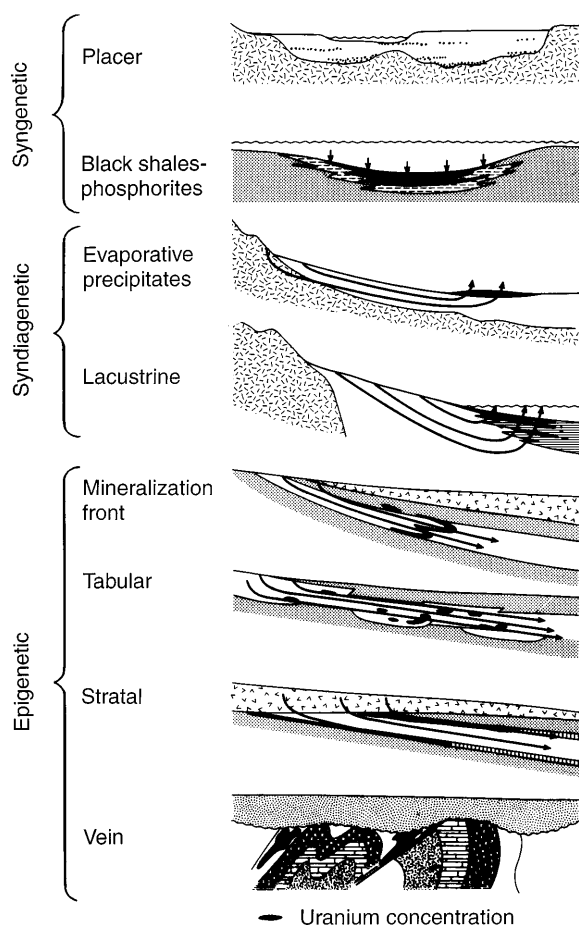


Figure 1 Principal genetic classes of sedimentary uranium deposits and their stratigraphic and hydrologic settings. (After Galloway and Hobday 1996)

plumbing for the mineralizing fluids. Such groundwater flow systems are typically confined, and the waters tend to evolve geochemically along the flow paths. Resultant deposits are commonly stratabound, reflecting preferred conduits for fluid flow, but are rarely stratiform. Epigenetic deposits assume a range of morphologies, as illustrated in *Figure 1*. Their geometry and distribution are a function of the permeability configuration, the localization of regional recharge, lateral flow and discharge zones, and the distribution of geochemical traps for dissolved uranium.

Syndiagenetic Uranium in Lacustrine, Swamp, and Pedogenic Environments

Uranium concentrations, locally attaining economic grades and volumes, are present in basin-center lacustrine and swamp/marsh depositional facies, ranging from the upper Quaternary lowmoor peats of Russia and North America to the Miocene interval of the Date Creek Basin, Arizona, and the Permian Lodeve Basin of France.

Lowmoor peats and interspersed lakes occupy groundwater discharge centers with prolific plant growth. Uranium mobilized in groundwaters and surface flow is concentrated by adsorption and direct reduction and precipitation of reduced uranium minerals within organic-rich facies (Lisitsin et al. 1967). The concentration of uranium increases in dry climates, where circulating oxidized and mineralized groundwater encounters the slightly acidic, reducing peat beds. Uranium enrichment in the Anderson Mine Formation of the northern Date Creek Basin took place in fluvial arkoses overlain by volcanoclastics deposited in a restricted lake embayment. Lake levels and geochemistry fluctuated markedly in the prevailing semi-arid climate. Dispersed, poorly crystalline coffinite is concentrated to form low-grade, stacked stratiform ore bodies that individually are less than 3 m thick and underlie areas of about 2.6 km². Most aspects are directly comparable to mineralization in lowmoor peats.

Calcrete uranium ores, best known from the Yeelirrie district of Australia, offer another variant of syndiagenetic mineralization produced by genetically interrelated depositional and groundwater processes (Mann and Deutscher 1978a, 1978b; Morgan 1993). Yeelirrie and similar calcretes of the Yilgarn Craton occur in a closed, cratonic basin floored by Archean granitoids and greenstones. Mineralization was a product of intense chemical weathering of a low-relief terrain in an increasingly arid climate during late Tertiary and Quaternary time. Groundwater transported uranium in solution, converged on drainage axes, and discharged in the lower channels, as illustrated in *Figure 2*. Uranium in the oxidized form, carnotite, is concentrated in calcrete distributed along surface drainage axes of ephemeral streams and around the margins of playa lakes.

Epigenetic Sandstone Uranium Deposits

Until recently, approximately 40% of the world's uranium reserves were in sandstone ores (Robertson et al. 1978). United States production from epigenetic sandstone uranium ores peaked around 1980. By 1990, the bulk of historical uranium production was from sandstone and quartz pebble conglomerate (Dahlkamp 1991, p. 9). Major sandstone-hosted epigenetic ores are also present in the former Soviet Union, Canada, Niger, and elsewhere. Orebodies are typically small and reflect the distribution and internal facies geometry of the host sandstones. Sandstone uranium deposits are products of epigenetic mineralization in a spectrum of fluvial, alluvial-fan, and shore-zone depositional systems. Today, however, unconformity-related uranium deposits have assumed greater economic importance (Cumming and Krstic 1992; Bruneton 1993).

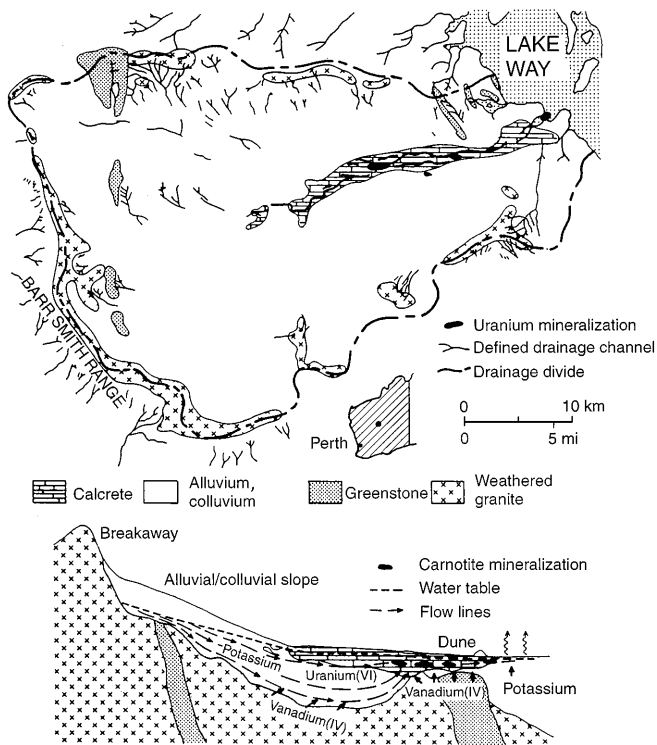


Figure 2 Map and section of the Yeelirrie drainage basin, Western Australia, showing the distribution of calcrete and contained uranium deposits. Mineralized groundwater converges on the drainage axis, flows down the channel trend, and discharges along lower reaches of the channel in response to bedrock ridges or the flattened topography of the lake margin. (Modified from Mann and Deutscher 1978b; after Galloway and Hobday 1996)

Terrestrial Systems: Wyoming Tertiary Basins, USA

Large uranium districts in upper Paleocene and Eocene strata of Wyoming include the Fort Union, Wind River, Wasatch, and Battle Spring Formations (Galloway et al. 1979; Harshman and Adams 1981). The Wyoming uranium resource is second in the United States to the Colorado Plateau (Dahlkamp 1991, p. 290).

Uranium deposits of the Gas Hills and Shirley Basin districts occur in alluvial-fan and proximal fluvial deposits. This large drainage network extended along the Wind River Basin, across the Casper Arch, and then northward along the axis of the Powder River Basin. Regional patterns and local front trends, for example within the Puddle Springs Arkose Member (Soister 1968), indicate oxidation/alteration tongues centered around the transmissive, conglomeratic sand lobes enclosed within the main body of the alluvial-fan system. Classic C-shaped mineralization fronts tend to be concentrated within muddy sand intervals along the margins of the coarsest facies. In the Powder River Basin, a broad belt composed of multiple alteration tongues occupies the fluvial axis. Examples of ore bodies and oxidation tongues are illustrated in *Figures 3 and 4*.

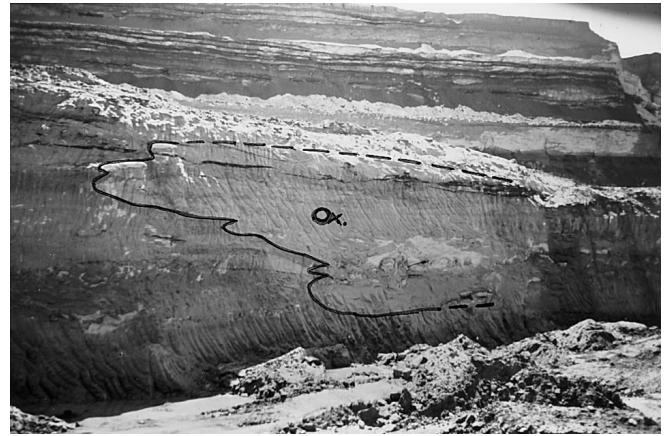


Figure 3 Ore deposits in the southern Powder River Basin, Wyoming. A light-colored oxidation tongue in the center of the photograph terminates left in a darker ore roll



Figure 4 Aerial view of Highland Mine, southern Powder River Basin, Wyoming. The horseshoe-shaped pit outlines a plan view of an ore roll, with an oxidation tongue extending into it from the left

Upon burial, the alluvial-fan and fluvial systems became highly transmissive to groundwater flow. Late Eocene tectonism disrupted the drainage network, placing portions of the alluvial-fan and channel-fill deposits in structural and topographic positions amenable to active meteoric recharge along basin-margin outcrop belts. Burial of the basins, subsequent uplift, and mantling with volcanic debris during Oligocene and Miocene Epochs resulted in aquifer recharge by mineralized fluids, representing the dominant episode of alteration and ore genesis.

Coastal Plain Systems: South Texas Uranium Province, USA

Uranium is present within several formations that compose the lower to middle Tertiary clastic wedge of the Gulf Coastal Plain. Productive units include the upper Eocene Jackson Group barrier-lagoon and



Figure 5 Jackson Group lagoonal mudstones overlying uranium ore, Karnes County, Texas

deltaic systems, illustrated in *Figure 5*, Oligocene to lower Miocene Catahoula Formation fluvial systems, lower Miocene Oakville Formation fluvial systems, and Miocene Goliad Formation fluvial systems (Riggs et al. 1991).

Gulfward meteoric groundwater flow followed fluvial depo-axes occupying structural troughs such as the Rio Grande Embayment of South Texas. Growth faults, initiated largely in Eocene time, affected both structure and facies patterns in the overlying uraniferous fluvial systems (Galloway 1977). The influence of fault zones on fluid migration is reflected in the suite of unusual diagenetic features, including uranium mineralization, adjacent to fault zones. Compactional and thermobaric flow regimes also played major roles in multiple epigenetic alteration events that have substantially modified the simple mineralization-front model.

The Oakville Formation provides a prime example of these complex events (Galloway 1982). Epigenetic Oakville uranium deposits, shown in *Figure 6*, cluster along laterally continuous, sinuous mineralization fronts that developed at or near margins of fluvial axes. This relationship is illustrated in *Figure 7*. Major mineral districts lie near shallow projections of deep-seated fault zones rooted in Cretaceous carbonates and geopressed Tertiary muds, but faulting is not a prerequisite. District reserves are directly proportional to the size and relative transmissivity of the host fluvial axis. Dispersive sand depocenters form the core of the Oakville system (*Figure 7*) and are bounded by flood-plain muds and silts, which include volcanic ash. Analysis of water-well pumping-test results demonstrates a correlation between fluvial channel facies type and aquifer permeability.

The role of upward-migrating, reducing groundwater is indicated by alteration patterns. Reducing, sulfidic deep-basin fluids were driven up fault zones by the pressure head, interacting with the supergene environment in the mineralization process. Specific alteration zones are defined by the oxidation state of the



Figure 6 Highly reduced, ore-bearing, basal Oakville sand down-faulted against Catahoula shale, Ray Point, Texas

contained iron and by textural features of the oxidized or reduced iron mineral phases present. The idealized zonation produced by groundwater oxidization and uranium mineralization of a regionally reduced aquifer and reduction by deep-seated brines of an oxidized aquifer is illustrated in *Figure 8A*. The typical alteration zonation of middle Tertiary Texas coastal-plain uranium deposits is more complex, as illustrated in *Figure 8B*, and records the superimposition of multiple oxidation and sulfidization events.

Tabular Sandstone-Hosted Uranium Deposits

The Jurassic Morrison Formation of the Colorado Plateau, USA, contains world-class reserves in bedload fluvial and alluvial-fan systems that grade distally into lacustrine facies (Galloway 1980; Tyler and Ethridge 1983; Turner-Peterson et al. 1986). Referred to as the Grants Uranium Region, this includes Ambrosia Lake, the largest uranium producing area in the United States (Dahlkamp 1991, p. 250). The highest degree of mineralization is associated with the most highly transmissive facies assemblages. Organic material and vanadiferous clays provided potential reductants capable of concentrating uranium from oxidizing groundwaters.

The distinctive geometry and enigmatic geochemistry of the tabular deposits has led many authors to consider them as a distinct style of mineralization. Some tabular deposits formed at an interface between meteoric and saline groundwaters. Like those in South Texas, certain tabular uranium occurrences may record the sequential or contemporaneous interaction of oxidizing meteoric waters with fluids of the deeper ground-

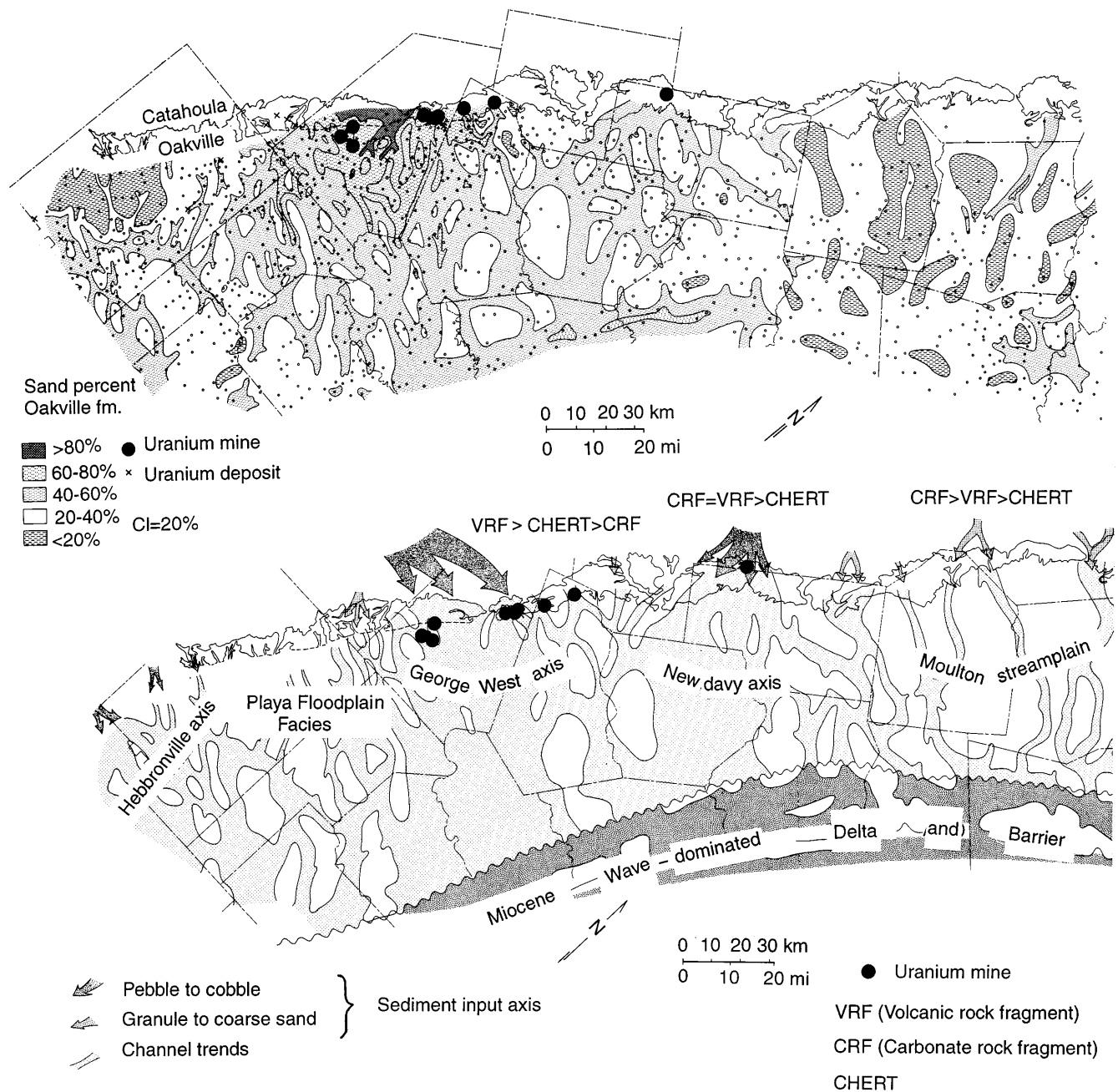


Figure 7 Sandstone-percentage map of the Oakville (Miocene) bedload fluvial system, South Texas Coastal Plain, illustrating coarse fluvial entry points of the George West and New Davy Axes and the distribution of uranium mines and deposits. (Modified from Galloway et al. 1982; after Galloway and Hobday 1996)

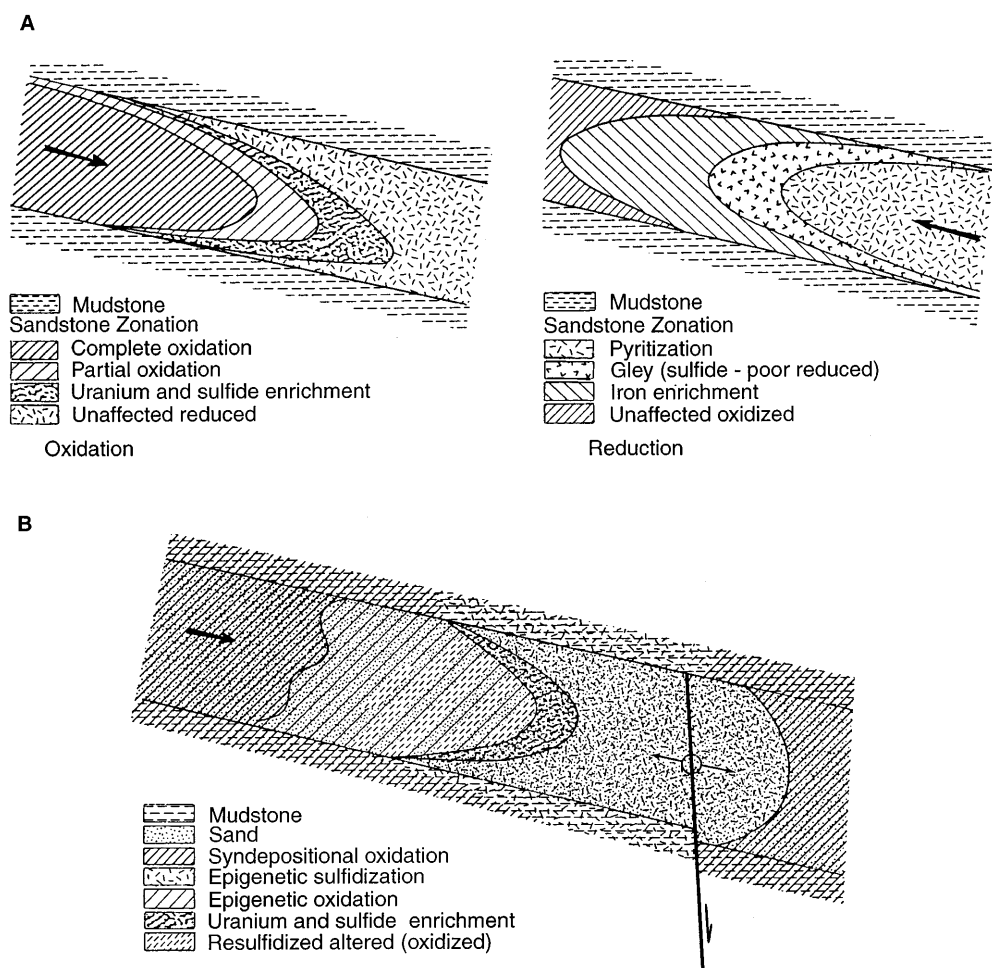
redistribution of primary Mesozoic mineralization can be related to multiple phases of meteoric circulation in Tertiary time (Saucier 1980). The uranium may have been derived from intraformational, tuffaceous acid volcanics or from a more distant, altered igneous source (Dahlkamp 1991, p. 262–264).

water regimes. Alteration histories were further complicated by the variety of postmineralization hydrologic systems within these geologically old aquifers. As illustrated by the deposits in the Westwater Canyon Formation of the southern San Juan Basin, large-scale

Incised Valley-Fill Deposits: Lake Frome, South Australia

A further class of epigenetic sandstone ores is present in paleovalley fill, commonly incised into granite or other crystalline basement. In such highly confined aquifers, the ore bodies are characteristically tabular

Figure 8A,B Geochemical zonations produced by epigenetic oxidation and reduction of an aquifer. **A** Idealized zones produced in a reduced aquifer by circulating, oxidizing, uranium-bearing meteoric water and in an oxidized aquifer by intrusion of sulfide-bearing groundwater. **B** Idealized geochemical zonation typical of mineralized parts of the Oakville aquifer of the South Texas uranium province. (From Galloway 1982)



and dispersed. The style of mineralization is illustrated by uranium deposits of the Lake Frome area, South Australia, where the ore bodies are distributed as isolated masses within paleovalley systems such as the lower Tertiary Yarramba channel. The valley fill consists of up to 50 m of interbedded sand and mud, which grades from bedload fluvial facies at the base to finer grained, mixed-load stream deposits at the top (Harshman and Adams 1981) and which is almost entirely oxidized. Cross sections indicate that the uranium ore occurs as irregular masses and pods, poorly defined stacked rolls, and tabular beds, largely within the lower part of the valley fill. The shape and location are commonly determined by the geometry of unoxidized, less permeable remnants within the valley fill. Patterns of mineralization are reminiscent of the tabular Colorado Plateau deposits.

Genesis of Epigenetic Uranium Deposits: A Model

Mass transfer in groundwater results in a cyclic arrangement of geochemical trapping mechanisms. Primary mineralization is followed by a modification phase, involving alteration or redistribution of uranium.

Uranium migration and concentration during the constructional mineralization phase establishes regional mineralization patterns. Uranium is most effectively liberated from fresh volcanic ash in the aquifer recharge area, a process that is accelerated by soil-forming processes (Walton et al. 1981). Uranium-bearing, oxidizing groundwaters enter the meteoric flow system, interacting with regionally reduced portions of the aquifers. A schematic plan view of an oxidation tongue showing the downdip-migrating active front, the more stable passive flank along the margin, and groundwater flow divergence and bypass, is illustrated in Figure 9. Uranium and associated metals are concentrated where flow crosses from oxidized to reduced portions of the aquifer. Mineralization follows elongate margins of reductant-rich pods or islands within pervasively oxidized ground, or where extrinsic reductants are present. Reducing conditions prevail at permeability boundaries where flow crosses from massive sand into finer grained facies. Uranium mineralization associated with the constructional phase of an idealized uranium roll-front deposit is shown in Figure 10.

The modification phase (Figure 10) of the primary uranium mineralization is brought about by changes in

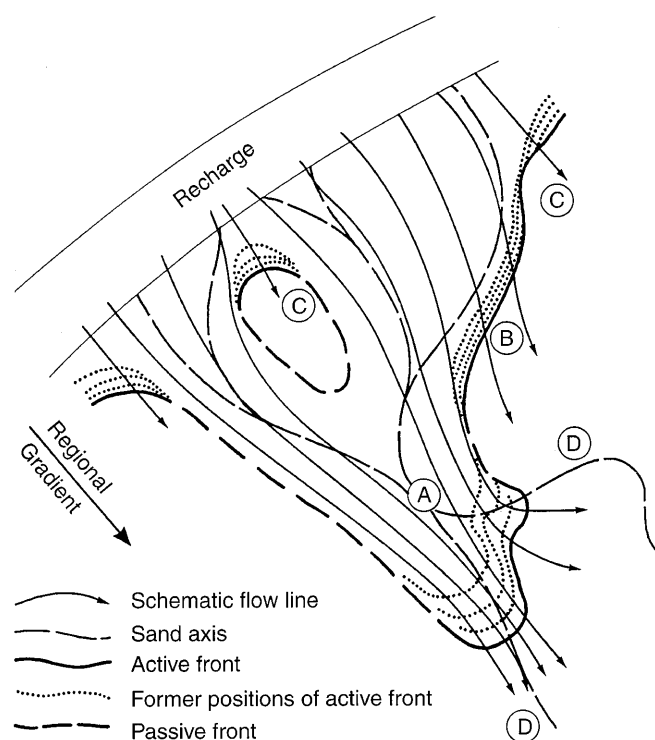


Figure 9 Idealized oxidation tongue produced by the flux of reactive, oxidizing groundwater through a uniformly reduced aquifer. A, convergent flow and oxidation salient; B, flow deflection; C, flow divergence; D, bypassed permeable zone. (From Galloway 1977; Galloway and Hobday 1996)

the hydrologic system. Permeability reduction by compaction or secondary mineralization, elevation of the ore deposits above the water table, meteoric rejuvenation, or invasion by deeper groundwaters cause re-reduction of parts of the oxidation tongue and redistribution or destruction of deposits that are elevated above the water table.

This generalized mineralization cycle is consistent with the known distribution and geologic relationships of most sandstone-type uranium ores. Application of the conceptual framework allows prediction of the extent and probable nature of potential mineralization, provided that the depositional framework and groundwater flow history of the system can be reconstructed.

Criteria for Geologic and Hydrologic Exploration

The epigenetic, roll-type uranium cycle within a depositional basin can be compared to an ore-processing mill (Galloway et al. 1979), which extracts a dispersed element from a large volume of rock and concentrates it into a potentially commercial resource. The amount of enriched product (U_{tot}) is equal to the product of the volume of uranium-transporting fluid moved through the system per unit time (Q), multiplied by the duration of the flux (T), the concentration of the desired

element in the fluid (C), and the efficiency of the extraction process (E):

$$U_{\text{tot}} = Q \times T \times C \times E$$

Any positive change in Q , C , E , or T has positive implications for uranium exploration. For example, air-fall volcanic ash in the aquifer recharge area potentially liberates a large quantity of uranium in its soluble form. Silicic plutonic rocks such as granite provide lower concentrations of uranium in the transporting fluid, but this may be compensated for by the very long time interval (T) of mobilization and recycling that occurs in the stable repository basins.

Semiconfined, highly transmissive aquifers deposited as bedload fluvial or alluvial-fan systems promote efficient recharge, downgradient flow, and discharge of meteoric water. The three-dimensional distribution of such aquifers determines the volume of groundwater (Q) that can later be transmitted. Uranium mineralization by solution-transport processes is most effective in dry or strongly seasonal climates that facilitate recharge through a thick, aerated phreatic zone. The organic-rich, reducing, biologically active soils and saturated aquifers of more humid regions are less favorable.

Entrapment (E) of dissolved uranium in most aquifer systems requires an efficient downdip reducing environment. Reductants may be intrinsic to the depositional system, for example disseminated organic matter, primarily in finer-grained facies. In such environments, uranium is concentrated at a geochemical boundary that is coincident with a permeability barrier. Alternatively, the reducing conditions may have been introduced into the system after deposition, for example by way of reducing fluids moving up faults. In this latter situation, the most permeable facies are most subject to reduction.

The Role of Localized Groundwater Flux: A Summary

Aquifer transmissivity is a product of aquifer thickness and hydraulic conductivity, which is in turn controlled by texture and bedding. The three-dimensional water-bearing capacity of a sedimentary sequence is therefore closely related to facies distribution. Framework facies define the highly transmissive "plumbing." Bounding lithologies form a confining but leaky matrix around permeable, transmissive elements. Transmissivity tends to be a highly directional property, reflecting the trend of framework sand bodies. Although fluvial channel and barrier sand bodies may have comparable permeabilities and thicknesses, only the fluvial sand body produces a highly transmissive element oriented in the direction of the basinward hydraulic gradient. This situation is illustrated in Figure 11. Flow across depositional grain, for example shore-zone barrier/lagoon complexes, is much less efficient.

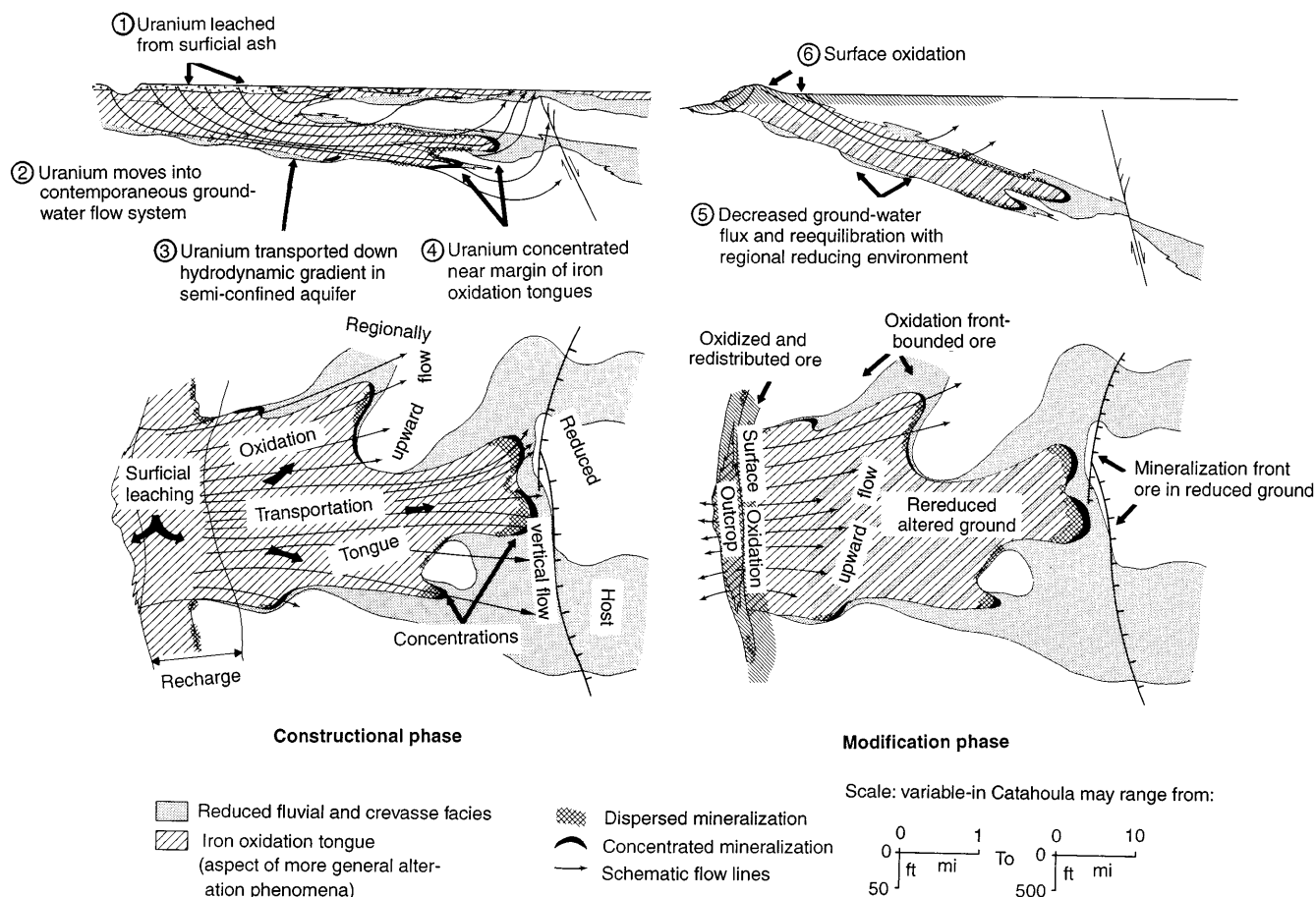


Figure 10 Two principal phases of the uranium mineralization cycle typical of many epigenetic roll-type uranium deposits. Constructional events include primary mobilization, migration, and concentration of uranium within a semiconfined aquifer system during or soon after deposition of volcanic ash (or alternative uranium source) in the regional recharge area. Possible modifications of the primary mineralization trends include rereduction of parts of the alteration tongue and local remobilization or destruction of shallow deposits by surface oxidation at or above the ambient water table. *Scale of the cycle is a function of the size of the aquifer system.* (After Galloway 1977)

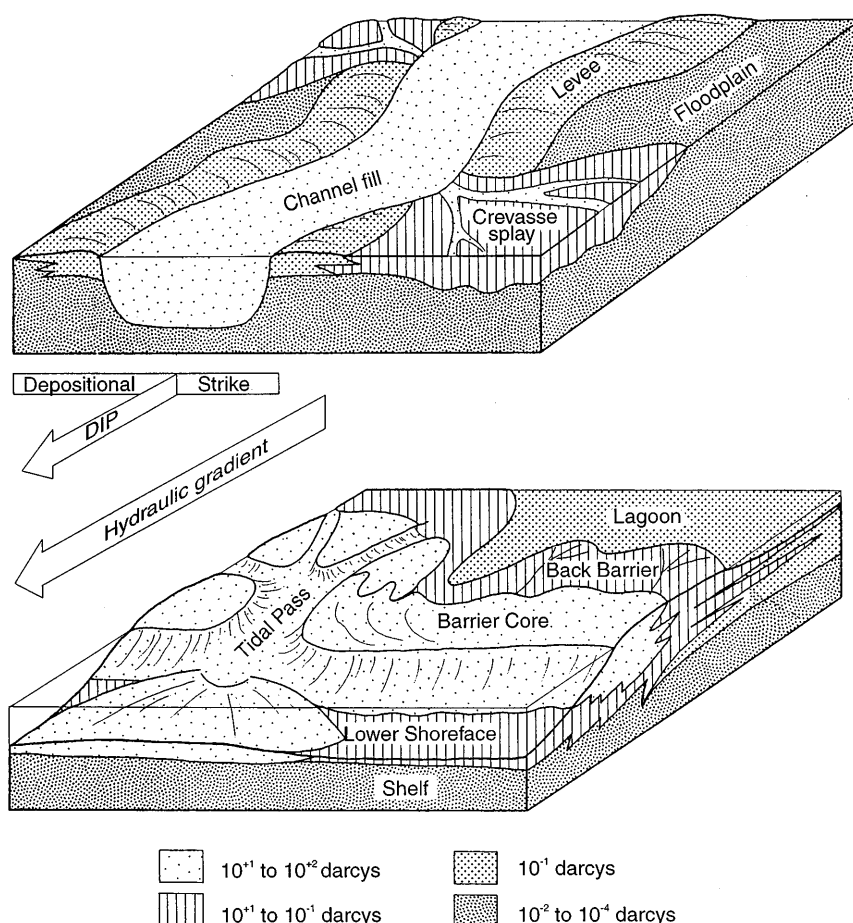
The distribution of epigenetic uranium within a single depositional system is primarily a function of spatial variations in surface or groundwater flux Q . High groundwater flux produces well-developed, laterally extensive alteration tongues. This provides potentially large concentrations of uranium for the prevailing C , T , and E of the system. Ore deposits tend to follow predictable patterns that can serve as guides for exploration.

Major, dip-oriented sand bodies that parallel the regional hydrodynamic gradient may develop mineralized tongues that extend into unaltered sediments. The largest deposits are likely to be along the nose or distal margins of such salients, which define areas of maximum Q (and therefore maximum incursion of oxidant and uranium). Clusters of small to medium-sized deposits tend to form where groundwater flow is

deflected by local stratigraphic or structural features. Fault zones and basement highs modify flow patterns of both surface flow and groundwaters. Vertical flux of groundwater along a fault zone may distort the ideal roll geometry of a mineralization front by accentuating the upper or lower wing, or it may lead to syndiagenetic mineralization in shallow, reduced, or evaporative facies. Fault zones are likely conduits for discharge of compactional or thermobaric waters into the shallow aquifers, resulting in the production of geochemical traps within shallower aquifers.

The geometry of framework, high-energy, permeable facies is commonly reflected in the geometry of mineralization. Ore bodies tend to parallel mapped facies boundaries, scour surfaces, paleotransport directions, or isolith contours. For example, *Figure 12* illustrates the geometry of an epigenetic alteration front associated with uranium mineralization. The front extends from the channel into the body of the crevasse splay. Local fingers over 60 m long project along the diverging splay channel sands. Early recognition of such facies-related patterns or trends in alteration or distribution of uranium concentration allows interpretation or extrapolation of ore bodies using limited data.

Figure 11 Contrasting geometry, lateral relationships, and trends of equally transmissive sand facies of a fluvial and barrier/lagoon system. The dip-oriented fluvial channel fill is the more effective aquifer for the regional basin-ward hydraulic gradient. (After Galloway et al. 1979)



Representative order-of-magnitude permeability of unconsolidated deposits

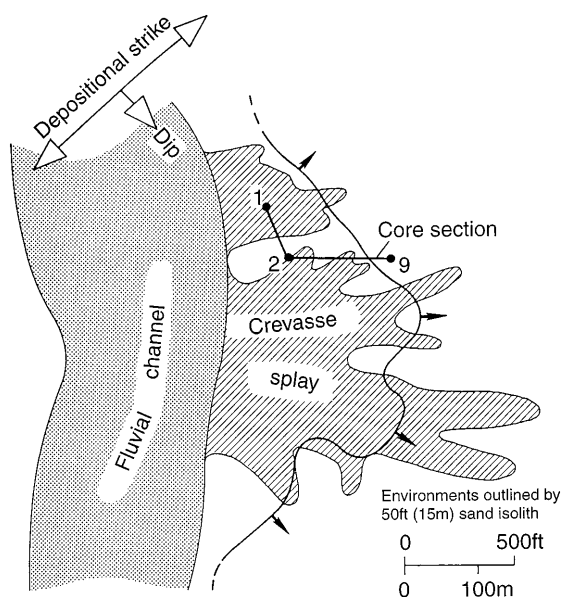


Figure 12 Localized expansion of a mineralization tongue from its host mixed-load channel fill unit into the adjacent permeable crevasse-splay deposits. The crevasse sandstones are dominantly oxidized in wells 1 and 2 but entirely reduced in well 9. The diverging splay channels offer secondary axes of higher transmissivity producing minor down-dip salients along the front. (After Galloway and Kaiser 1980)

Applications to Commercial Uranium Extraction

Careful analysis of host depositional facies in relation to reconstructed groundwater flow patterns can significantly improve uranium recovery and reduce cost. Understanding the depositional and hydrologic framework can also help anticipate problems in mining. For example, extracting uranium from sand bodies that are oriented parallel to hydraulic gradient may present greater problems for mine dewatering than do strike-parallel sands. In the South Texas Coastal Plain, open-pit mines in fluvial or deltaic channel facies predictably produced much greater volumes of water than did pits in the strike-parallel barrier systems that graded up and downdip into mudstone facies.

In-situ leach mining of uranium is a specialized application of hydrogeology that reverses the mineralization process. Carefully designed lixiviants are introduced down injection wells and flow through the mineralized sandstones, taking uranium into solution. The pregnant liquor is extracted by production wells. Solution mining of uranium commenced in the Shirley Basin of Wyoming in 1961, with experimentation relating to well-completion methods, well patterns and spacing, and lixiviant composition, followed by commercial extraction in 1963. Rising uranium prices

during the 1970s led to 48 pilot projects by 1983. This resulted in 21 in-situ leach mining operations, which by 1986 accounted for 11% of United States uranium production. Since that time, some plants have been decommissioned. In 1996, however, in-situ operations expanded in Wyoming, a trend that is expected to continue well into the next century.

In summary, epigenetic sandstone uranium ore bodies result from the concentration of dissolved uranium from moving groundwater. Groundwater flow patterns, which reflect the geometry and distribution of permeable framework facies, determine sites of accumulation. Furthermore, the geochemical preconditioning necessary for uranium concentration is controlled in many cases by syndepositional hydrogeology. For example, preservation of dispersed organic material within fluvial channel-sand facies is most likely determined by the depth of the water table during deposition. Organic debris and early diagenetic iron disulfide provide the matrix reducing conditions necessary to precipitate dissolved uranium from meteoric groundwaters that may subsequently intrude the sands.

Conclusions

Groundwater processes are responsible for the emplacement of both syndiagenetic and epigenetic uranium ores. Syndiagenesis involves solution transport of uranium and its precipitation by organic-rich reducing facies such as peat. The Miocene Date Creek ores of Arizona are an example. Here, uranium mineralization is hosted by fluvial arkoses, overlain by volcanoclastics of a shallow, restricted lake environment.

Epigenetic uranium mineralization ideally involves air-fall volcanic ash in the recharge area, which liberates uranium in soluble form. This uranium is transported down semiconfined aquifers until it encounters reducing conditions, where it is precipitated or adsorbed, for example in the South Texas uranium province, Tertiary strata of Wyoming, and the Colorado plateau. Any change in the hydrologic system results in modification of the ore bodies. Application of this model in exploration needs to take into account the volume and duration of groundwater circulation, concentration of dissolved uranium, and efficiency of fixation processes.

The largest uranium-producing districts of this type are represented by a relatively limited suite of depositional systems, including alluvial-fan and bedload fluvial systems, and less commonly, shore-zone and mixed-load fluvial systems. Alluvial-fan and bedload fluvial systems are highly transmissive to groundwater flow because of their coarse grain size, dip orientation, and topographic gradients parallel to depositional trends. Understanding and predicting the distribution of epigenetic uranium deposits therefore requires

reconstruction of depositional environment as well as groundwater flow history.

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