Autunite (hydrated calcium uranyl phosphate), is a fluorescent, radioactive uranium ore mineral.

Uranium Geology of the West

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Understanding how and where uranium deposits form provides the background for considering water quality, hydrologic, and regulatory aspects of uranium mining.

Finch (1996) defined, described, and modeled the North American uranium provinces, including four that cover the western United States: Colorado Plateau Uranium Province (CPUP), Rocky Mountain and Intermontane Basins Uranium Province (RMIBUP), Gulf Coast Uranium Province (GCUP), and Basin and Range Uranium Province (BRUP) (see map right, and table below).

Where Did It Come From?

Uranium occurs naturally within the rocks that form the earth's crust, particularly in granite, volcanic ash, and volcanic lavas with granite-like compositions. Some deposits occur as uranium-rich veins that formed from granitic magmas, but most formed when oxidizing groundwater leached uranium from igneous rocks and transported it to reducing environments where uranium precipitated and became concentrated.

The volcanic activity that provided uranium to the Colorado Plateau deposits was likely located to the west and south, at the edge of the North American tectonic plate. Uranium-rich volcanic ash and tuffs derived from what is now the Basin and Range area and the Rocky Mountains covered the intermontane basins of that area. Localized granitic sources also are found in the RMIBUP, as well as magmatic vein deposits in the central Rockies of Colorado. Volcanism near Big Bend National Park, Texas, and Mexico provided uranium for the Texas Coastal Plain deposits.

How Do Deposits Form?

Most uranium deposits in the western United States were formed by one of four mechanisms described below.

Roll-front deposits are aquifer-controlled ore bodies that form in medium- to coarse-grained sandstone. Oxidizing groundwater leaches uranium from its source rock and carries it through sandstone until it reaches a reducing environment, caused by the presence of buried organic material or gases such as hydrogen sulfide. Uranium precipitates at the interface between

Uranium province	% of total uranium in the 4 provinces	Amount already produced	Types of deposits	Size (tons) and grade (U_3O_8)	Potential resource (tons U_3O_8)	Associated ores	Mineralizing solutions
Colorado Plateau (CPUP)	55	two-thirds	tabular sandstone, solution-collapse breccia pipes	500-200,000 at 0.05 to 0.60%	$6x10^5$	vanadium and copper	groundwater
Rocky Mountain and Intermontane Basins (RMIBUP)	32	half	roll-front and volcanic (hydrothermal veins)	roll-front: 500-20,000 at 0.04-0.23%; vein: 500-5,000 at 0.15-0.48%	$3.5x10^5$	vanadium	groundwater (roll-front) and hydrothermal fluids (veins)
Gulf Coast (GCUP)	9	three-fourths	roll-front	500-10,000 at 0.04-0.39 %	$1x10^5$	molybdenum	groundwater
Basin and Range (BRUP)	4	resources are increasing	volcanic (hydrothermal vein and tabular sandstone composite)	500-20,000 at 0.05 to 0.10%	$4x10^4$	molybdenum, vanadium, fluorite, and mercury	hydrothermal fluids, meteoric waters; and geothermal groundwater

Characteristics of the uranium provinces of the western United States (after Finch, 1996).

Photo: AREVA Inc.

oxidizing and reducing conditions, often forming a curved "roll-front" ore body. This reduction/oxidation front can migrate over time, creating an ore trend that extends for miles. Numerous ore bodies are sometimes stacked parallel to one another at intervals along this trend, reflecting preferential flowpaths in the aquifer.

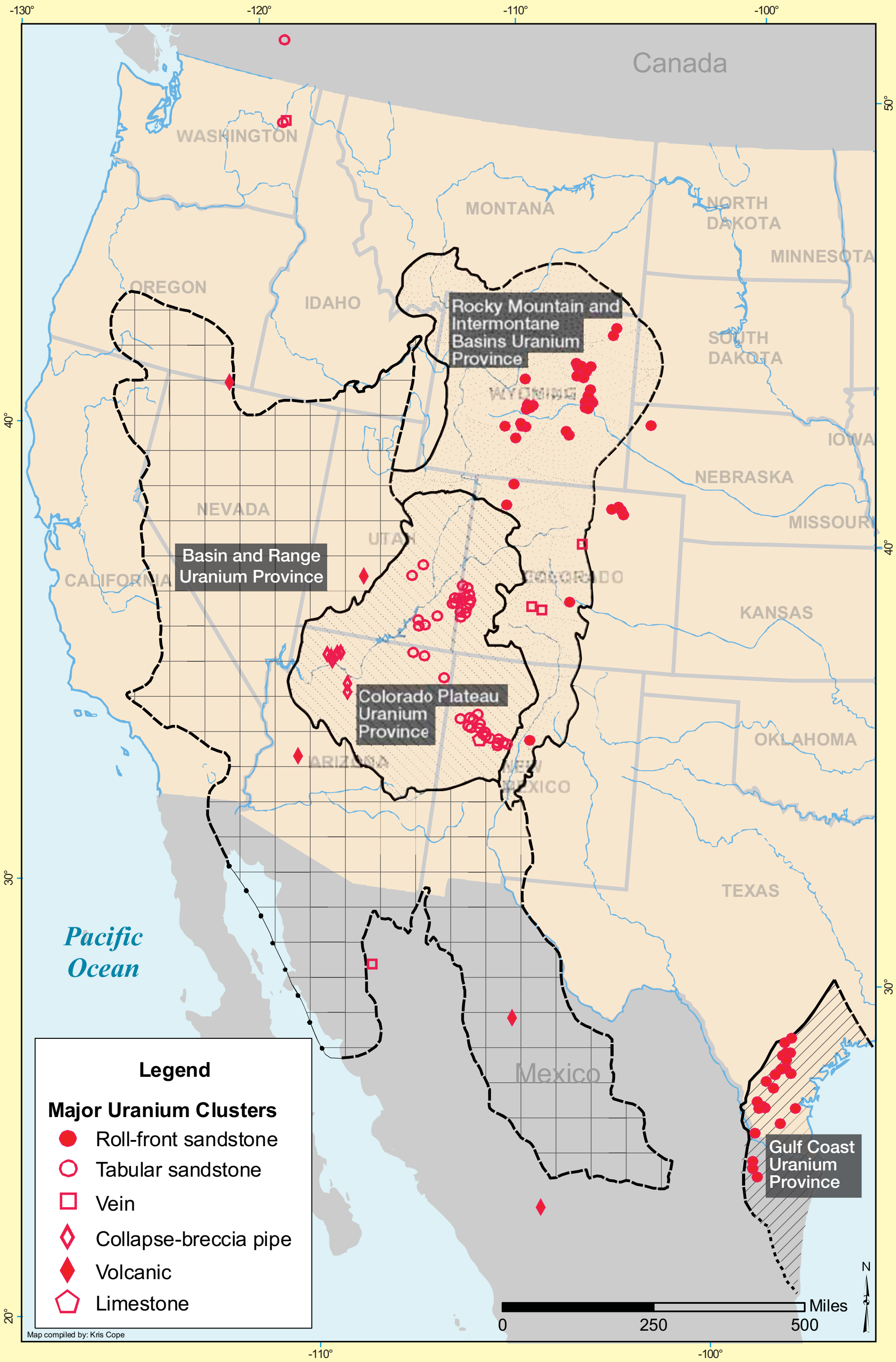
Roll-fronts are the predominant uranium deposit in the RMIBUP and the CPUP, and the only type found in the GCUP. The uranium is typically deposited as uranium oxides and, to a lesser extent, uranium silicates. Uranium concentrations range from 0.04 to 0.25 percent; the deposits generally range in size from 0.5 to 20 million pounds.

Most roll-front deposits that are below the water table can be mined through in-situ recovery (ISR, see pages 28 and 30). This is particularly true of well-defined, well-graded, and well-sorted fluvial sandstones that have good porosity and permeability and are in confined aquifers bounded by impermeable clays. These conditions make it easier to manage the fluids and retrieve the uranium economically. Roll-fronts that are not saturated are typically near the surface and can be mined by open-pit methods; most such deposits were mined during previous mining booms.

Tabular sandstone deposits are elongated, blanket-like deposits usually less than 8 feet thick, average more than 0.17 percent uranium, and have sharp ore-waste rock boundaries. The largest deposits in New Mexico contain more than 30 million pounds of uranium oxide (U_3O_8). Uranium minerals in these deposits are intimately associated with organic detritus, often humates, an insoluble organic material that makes the deposit unsuitable for recovery by ISR. Thus most of these deposits are mined by conventional open-pit or underground methods. Some tabular deposits are reworked over time by groundwater, resulting in the formation of redistributed ore bodies that may be amenable to ISR. Tabular sandstones occur mainly in the CPUP; some deposits also are found in the BRUP.

Solution-collapse breccia pipes form in karstic terrain consisting of limestone and calcium-rich sandstone and shale. Dissolution caused portions of the rocks to collapse, forming vertical pipes. A mineralized breccia pipe ranges from 1,000 to 1,800 feet deep, has a vertical height of up to 600 feet, and is typically 200 to 400 feet in diameter. They are highly fractured and filled with rock fragments from the collapsed overlying layers. Uraninite, a reduced uranium oxide ore mineral, accumulates within the permeable column of broken rock, forming a cylindrical, vertical deposit. Mineralizing fluid apparently flows upward, but the precipitation front remains stationary, unlike the often-migrating roll-front deposits.

see Geology, page 34



Location of uranium provinces in the West (modified from Finch, 1996).

Geology, continued from page 21

Solution-collapse breccia pipe uranium deposits occur in the CPUP, particularly in the Grand Canyon region.

The surface disturbance that results from mining this type of deposit historically has been remarkably small because of the high-grade, compact nature of the mineralization and use of underground waste rock backfill techniques during mine development. A 1,000- to 1,600-foot-deep shaft is usually required to access the deposits unless the pipe occurs near a deep canyon.

Breccia pipe ore grades are at least as high as any other global uranium-deposit type, at 0.4 to 1 percent, because the limited size of the pipe concentrates the uranium. Average ore reserves for an individual mineralized pipe are about 3.5 million pounds U_30_8, with an average grade of about 0.6 percent uranium.

Volcanic uranium deposits are found in volcanic and volcaniclastic rocks. Volcanic deposits and hydrothermal veins occur in rhyolitic flows and tuffaceous ash flows, formed by hydrothermal, hot springs, or meteoric waters. Tabular lacustrine sandstone deposits occur in carbonaceous tuffaceous sandstone and mudstones, deposited by cooler groundwaters.

Several major uranium deposits in the RMIBUP occur as veins in metamorphic and sedimentary rocks, primarily within the Front Range and central Rocky Mountains of Colorado. Here, hydrothermal fluids directly deposited the uranium in fracture systems. Most of the BRUP deposits are volcanic, occurring as vein deposits and tabular ore bodies in paleolake sediments associated with volcanic activity. Volcanic deposits generally are developed by conventional mining methods.

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Remediation, continued from page 23

several hundred years. This isn't good news as far as restoring geochemical conditions to premining conditions, but it provides assurance that contaminated groundwater will not migrate and contaminate new areas.

Future Operations

The Grants uranium district still contains several hundred million pounds of uranium, now worth $60 per pound of U_3O_8. This elevated price will only raise interest in renewed mining and milling in the area. Conventional, open pit, and stope leach mining have historically been conducted in the Grants uranium district; all these methods, along with in-situ leaching, may be proposed in the future.

Environmental regulations that were absent during most of the past mining activities are now in place, along with more stringent mining regulations that will protect human health and the environment to a much greater degree. If water produced during new dewatering activities will be discharged to the surface, it will have to be treated to groundwater and possibly drinking-water standards prior to discharge. This will help prevent additional contamination, but water discharged to the surface could remobilize any contamination still present in the soil from the previous operational period if not addressed before new operations begin. This and continued exposure and oxidation of the ore body above the water table will continue to present challenges in managing potential contamination. However, the current regulations include flexibility to require protective engineering controls during operations and adequate financial assurance to address closure requirements.

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In Situ, continued from page 29

Aquifer Impacts?

Before ISR even begins, the uranium ore-bearing aquifer contains naturally occurring ^{226}radium, ^{222}radon, and other uranium-decay products at concentrations exceeding EPA drinking water standards (see table below). Nonpotable water such as this can be exempted as an underground source of drinking water under EPA's Safe Drinking Water Act, and the field of injection and extraction wells can be permitted for Class III underground injection control (UIC) activity. UIC regulations require ISR operations to be designed to produce only from the exempted area, and monitoring must demonstrate that the leach solution is contained within the ore zone. Monitoring parameters are typically chosen that are high in concentration compared to surrounding ambient groundwater, are robust, and may be rapidly analyzed at site laboratories. Parameters such as conductivity, chloride, bicarbonate, sulfate, and uranium are common. Restoration must be completed before monitoring ceases, to prevent regional contamination.

Construction, operation, monitoring, and reporting at ISR sites in the United States have been highly successful in ensuring that leach solution remains confined to the exempted ore zone, as required by UIC regulations. As a result of these practices and the fact that the ore bodies are not in drinking-water-quality aquifers, ISR uranium operations have caused no adverse impact to underground sources of drinking water in the United States.

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Parameter	Average	EPA MCL
uranium (ppb)	488	30
^{226}radium (pCi/l)	215	5.0
^{222}radon (pCi/l)	207,133	300
gross alpha (pCi/l)	865	15

Water quality data from 89 baseline wells, collected prior to initiation of ISR operations, in the mineralized portion of the Oakville aquifer at the URI Inc. Vasquez ISR project in Duval County, Texas. EPA's maximum contaminant levels (MCLs) are shown for comparison.