tion of stack ore. Virtually all zones of rock weakness are subjected to some mineralization near this front, and the sulfide-sulfate equilibria cause many of these stack deposits to resemble roll fronts. Roll geometry of some of this ore is due to encroachment of the front on reduced ground after the Laramide. Younger, but very local, solutions result in ore in oxidized ground, some of which is indicated by primary uranophane. Roll geometry is present for some of these deposits. The superimposition of the redox front on the older trend ore allows both carbon and sulfur to act as reductants, and ore-body geometries are similar to Wyoming-type rolls in terms of uranium distribution but not necessarily for trace-element distribution.

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Periods of Mineralization in Grants Mineral Belt, New Mexico

Geologic observations coupled with laboratory studies indicate several periods of mineralization in the Grants mineral belt. The earliest mineralization is from trend ore in the Ambrosia Lake and Smith Lake districts; Rb-Sr radiometric ages on chlorite formed penecontemporaneously with primary uranium minerals range from 135 to 138 ± 8 m.y. This period of mineralization is within the limits of error for the age of sedimentation obtained on barren ground montmorillonite of 140 to 145 ± 10 m.y., but cross-cutting ore indicates early epigenetic as opposed to syngenetic mineralization. Early formed ore in the Laguna district was remobilized and reprecipitated during some mid-Cretaceous event at 110 to 115 m.y. determined on the basis of Rb-Sr dating. Ore was not derived from the overlying Dakota Formation (Cretaceous), as the Rb-Sr dates for the Dakota and Mancos formations are 92 ± 6 m.y. and 85 ± 10 m.y., respectively (in excellent agreement with U.S. Geological Survey K-Ar dating). Mineralization is present in the Dakota Sandstone, but whether the ore was syngenetic or epigenetic is unknown. Much of the stack ore was apparently formed during the Laramide orogeny about 60 m.y. ago, usually in close proximity to a redox front. Post-Laramide ore is proposed for several deposits in reduced ground at this redox front, some of which is apparently Tertiary although remobilized Jurassic ore cannot be distinguished from that from much younger sources even though reworked Jurassic ore is supported by high $^{87}Sr/^{86}Sr$ ratios. Ore possibly formed during the Tertiary from a southerly source for some deposits, and some remobilized ore, possibly of Pleistocene age, is common in minor amounts.

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Exploration in Grants Uranium Region Since 1963

The Grants uranium region is the largest uranium area in the United States. From 1951 through 1977, underground and open-pit mines produced 126,537 tons of uranium oxide U_3O_8. This amounts to 40% of the total United States uranium production. Ore reserves estimated by DOE for the region are 366,200 tons U_3O_8, or 53% of the domestic reserves in the $30 forward-cost category. Since 1963, production in the Grants uranium region has expanded to the north and east largely owing to the efforts of exploration programs of major oil companies. During this period, average drilling depths have increased from approximately 200 to nearly 1,600 ft (60 to 960 m). Application of various geologic models is expected to assist in finding additional deposits, and the Grants uranium region is expected to maintain its position as the nation's principal source of uranium for years.

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Geochemical Studies of Grants Mineral Belt, New Mexico

Several hundred clay mineral and whole rock samples of ores and barren rocks from the Grants mineral belt have been analyzed by instrumental neutron activation analysis (INAA) and delayed neutron activation analysis (DNAA). The DNAA method allows high precision and accuracy for uranium and thorium determination, whereas the INAA method allows determination of 20 to 30 trace elements. The trace-element data can only be interpreted properly if the clay-mineral (-2μ) fraction is compared directly with whole-rock samples. The INAA data support mineralization of trend ore as due to southeast-flowing solutions; the DNAA determination of uranium suggests that the source of uranium in the Westwater Canyon Member of the Jurassic was not from the overlying Brushy Basin Formation. Local zonation of trace elements, especially the rare earth elements (REE), indicates fixation of many trace elements when uranium mineralization occurred. Thus, REE-depleted, oxidized ground can, with caution, be used for exploration purposes. Vanadium originally precipitated as V^{3+} in chlorites remains in the original sites after oxidation to V^{5+} and is thus also valuable as a pathfinder. Data for antimony suggest that it, too, may be useful. In general, trend-ore deposits are characterized by a high chlorite + illite, illite + illite-montmorillonite, or illite + chlorite + illite-montmorillonite, whereas ore near the redox front may contain primary kaolinite. The REE are concentrated greatly in all types of ore, primary or secondary, and, coupled with uranium haloes, are useful as ore guides.

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Geology and Ore Deposits of Johnny M Mine, Ambrosia Lake District, New Mexico

The Johnny M mine is one of very few mines in the Ambrosia Lake district with uranium ore in two members of the Jurassic Morrison Formation; these members are the Westwater Canyon sandstone and the Brushy Basin shale. The Westwater Canyon ore is contained in the two upper sandstone units of the member, and the Brushy Basin ore is contained in the Poison Canyon sandstone.

The sedimentary features and structures in the Westwater Canyon sandstone indicate that the sediments were deposited by a system of aggrading braided streams, possibly at the distal end of coalescing alluvial fans. The Poison Canyon sandstone was probably the result of deposition in a complex environment of meandering and braided streams. Paleocurrent direction indicators, such as fossilized-log orientation, foreset azimuths, and the axis of cross-beds and channel scours, suggest that the local paleostream flow was to the east and southeast.

The uranium mineralization is closely associated with (1) local accumulations of carbonaceous (humate) matter derived from the decay of organic material, such as trees and plants; and (2) paleostream channels preserved in the rocks. The ore elements were derived from the leaching of volcanic air-fall tuffs and ash, which were introduced into the fluvial system during volcanic activity in the western United States. The mobile ore element ions were reduced and concentrated by humic acids and bacteria present in the fluvial system, and ultimately remobilized in the system into the forms present today. The uranium is thus envisioned as forming either essentially on the surface as the sediments were being deposited or at very shallow (20 ft; 6 m) depth.

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Exploration for Uranium Deposits in Grants Mineral Belt, New Mexico

Uranium ore deposits in the Grants Mineral Belt, New Mexico, occur in fluvial sandstones in the Jurassic Morrison Formation.

Uranium mineralization is concentrated by a dark-gray to black substance that has been identified as humate derived from decaying vegetation. Black ore is truncated by overlying sandstone in at least two ore deposits, documenting an early age of mineralization. Ore deposits in the Grants Mineral Belt vary greatly in size and shape, generally occur in clusters, and often are difficult targets for drilling.

Current exploration is largely a process of drilling in stages to (1) delineate favorable from unfavorable ground on a wide-spacing, (2) seek mineralization in favorable ground, and (3) conduct closely spaced drilling in mineralized areas. Criteria for favorability differ among exploration groups but generally includes (1) the presence of a host sandstone, (2) anomalous mineralization, (3) color of host rock, (4) presence of carbonaceous matter, and (5) position of area with respect to mineralized trends.

A description of the sequence of drilling, from ore discovery to a mine on a one-square mile area at the Johnny M uranium deposit located in the east part of the Ambrosia Lake District, provides an example of the problem of predicting ahead of discovery where in a certain area, orebodies may occur. A study of the drill data at the Johnny M indicates the uranium ore is not related to specific features other than the presence of humate which is commonly associated with coalified plant fragments in mudstone-rich parts of the host sandstone.

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Radon Emanation Over Orebody: Has Long-Distance Transport of Radon Been Observed?

A major hope for discovering subsurface uranium ore is that measurable concentrations of the radioactive gas ^{222}Rn can be recognized near the surface of the earth. Integrated measurements, made over several weeks, show promise of giving greater reproducibility than short-term measurements, which are more subject to meteorologic variability.

The use of improved methods of integrated radon measurements—free of ^{220}Rn, of thermal-track fading, and of moisture-condensation effects—allow readings to be made that generally are highly stable over time. At a site 16 km north of Thoreau, New Mexico, readings at a depth of 60 cm, taken over a 9-month interval for a set of 55 positions, give different but nearly constant monthly readings at each position, the typical standard deviation being 14%. Superimposed on that stable pattern have been two periods during which spatially grouped radon readings increased by a factor of two or more over their normal values. The simplest tenable description of the source of the increases is sporadic puffs of upflowing gas, originating at as yet unknown depths. The measurements are consistent with an upward velocity of flow of $\sim 10^{-3}$cm/sec.

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Anomalous Orebody Within Ambrosia Lake Trend at Sandstone Mine

At the Sandstone mine, there is an anomalous orebody that lacks the characteristic coloring and gamma counts associated with known uranium ore at Ambrosia Lake. The orebody occurs along the downdip edge of a tongue of hematitic sand in the basal sand unit of the Westwater Canyon Member.

The orebody is white to light gray, most likely because of a lack of indigenous humic material. The abundance of pyrite indicates the uranium is in the tetravalent state, probably coffinite. Preliminary analysis also indicates the presence of uranophane evidently altered from the coffinite. Equivalent U_3O_8 by gamma determination is usually 30 to 60% of actual U_3O_8, indicating that this orebody is relatively recent.

Oxidizing meteoric water, forming a geochemical cell, remobilized the uranium minerals in the preexisting trend orebodies and deposited them downdip from the farthest extent of this cell. Post-Dakota deformation influenced the course of the migrating meteoric water and the extent of the redox interface controlling the orebody.

As lower grades of U_3O_8 become economical, the potential for unknown reserves adjacent to the redox interface should not be overlooked. Areas of low-grade ore should be sampled to become aware of any equilibrium imbalances. An established sampling program coupled with more sophisticated beta-gamma instrumentation should remedy the inaccuracy of present-day gamma evaluations.