SOLUTION-COLLAPSE BRECCIA PIPE U DEPOSITS
MODEL 32e; Finch, 1992)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of pipe-shaped breccia bodies formed by solution collapse and contain uraninite, and associated sulfide and oxide minerals of Cu, Fe, V, Zn, Pb, Ag, As, Mo, Ni, Co, and Se with high acid-generating capacity. Ore minerals are restricted to the near-vertical breccia pipe and surrounding ring fracture zone. Host rocks include limestone and calcareous sandstone, both with high acid-buffering capacity.

Examples

Orphan Lode (Chenoweth, 1986; Gornitz and others, 1988); Hack 1, 2, and 3 (Chenoweth, 1988; Rasmussen and others, 1986); Pigeon (Schafer, 1988); Kanab North (Mathisen, 1987); Canyon (Casadevall, 1989); Ridenour (Wenrich and others, 1990; Verbeek and others, 1988; Chenoweth, 1988); these deposits are located in the northern Arizona breccia pipe district (fig. 1), which is the largest breccia-pipe-hosted uranium province in the world. Similar deposits located elsewhere include Apex, southwest Utah (Wenrich and others, 1987; Verbeek and others, 1987); Temple Mountain, Utah (Hawley and others, 1965); Pryor Mountains, south-central Mont. (Hauptman, 1956; McEldowney and others, 1977; Patterson and others, 1988); Tsumeb, Namibia (Lombaard and others, 1986).

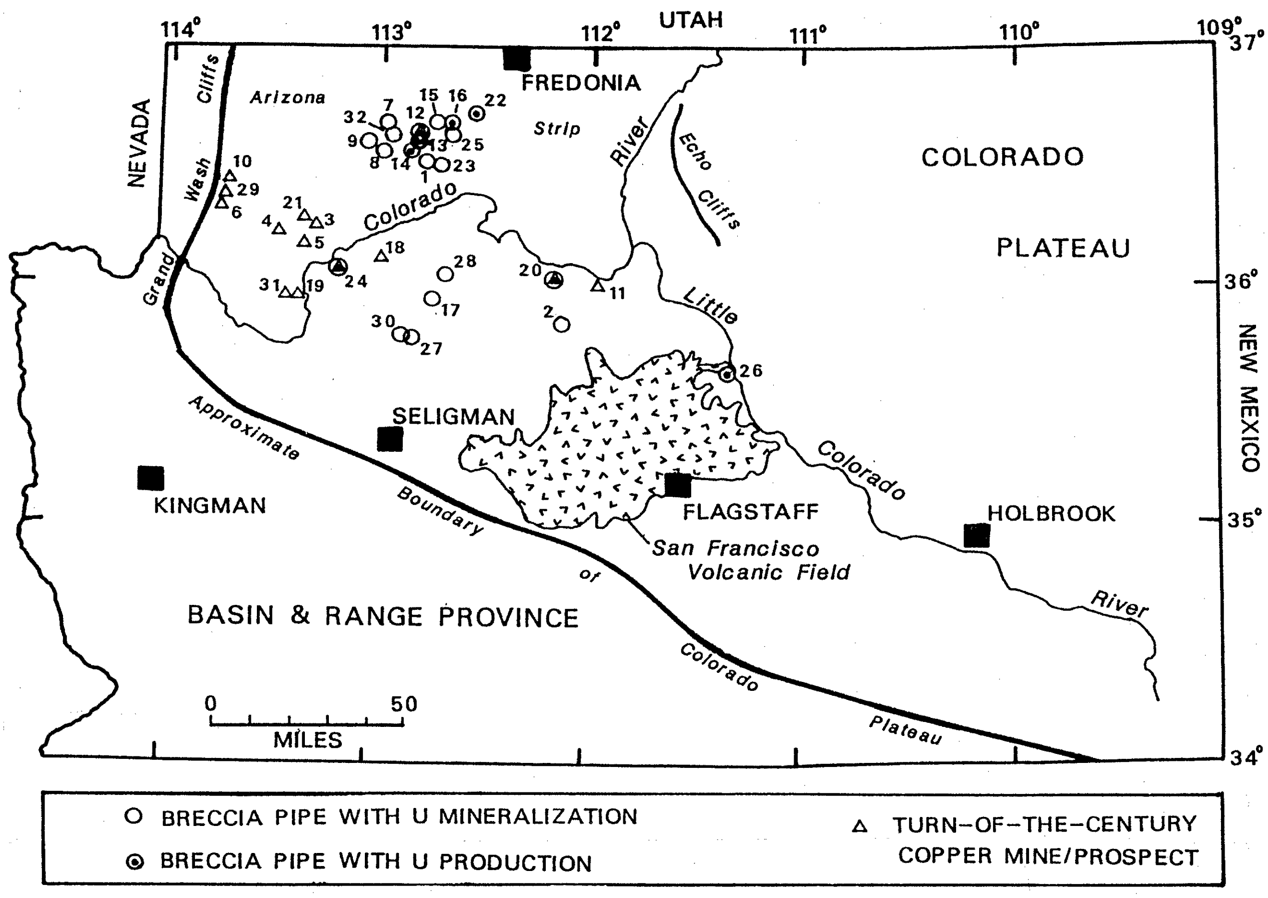

Figure 1. Index map of northern Arizona showing locations of mineralized breccia pipes, and San Francisco volcanic field that buries terrane with high potential for breccia pipes (Wenrich and others, 1989). Numbers refer to the following mines: (1) Arizona 1, (2) Canyon, (3) Chapel, (4) Copper House, (5) Copper Mountain, (6) Cunningham, (7) DB-1, (8) EZ-1, (9) EZ-2, (10) Grand Gulch, (11) Grandview, (12) Hack 1, (13) Hack 2, (14) Hack 3, (15) Hermit, (16) Kanab North, (17) Lynx, (18) Mohawk Canyon, (19) Old Bonnie Tunnel, (20) Orphan, (21) Parashant, (22) Pigeon, (23) Pinenut, (24) Ridenour, (25) Rim, (26) Riverview, (27) Rose, (28) Sage, (29) Savannic, (30) SBF, (31) Snyder, (32) What.

Spatially and (or) genetically related deposit types

None of the Cox and Singer (1986) models are known to be genetically related to solution-collapse breccia pipe deposits. Breccia pipe deposits are, however, spatially associated with uranium concentrations in paleostream channel deposits and Shinarump ore, hosted by the Chinle Formation near Cameron, Ariz. Cameron area ore may be genetically related; it may have been deposited from breccia pipe mineralizing fluids that moved up and laterally outward (Wenrich and others, 1989). Breccia pipe deposits are also spatially associated with Kaibab Limestone stratiform copper deposits (Van Gosen and Wenrich, in press).

Potential environmental considerations

Potential geoenvironmental considerations associated with breccia pipe deposits include:
(1) Radon and gamma radiation associated with active and abandoned mines, dumps, and tailings; radon in caves.
(2) Contamination related to transporting radioactive ore along highways in route to processing facilities.
(3) Radioactive elements and toxic metals in mill tailings.
(4) Acid drainage and toxic metals (such as arsenic, lead, and zinc) could be a problem in the immediate vicinity of mineralized pipes where they are dissected and exposed to flooding and catastrophic precipitation. In general, limestone and calcareous sandstone host rocks efficiently buffer acidic runoff water, and buffer downward percolating water prior to, or during, their transport in aquifer systems.

Exploration geophysics

Electrical conductivity and magnetic properties of the pipes are distinct relative to those of unbrecciated host rocks. Diagnostic differences in conductivity have been identified by scalar audiomagnetotelluric and E-field telluric profile data for at least one ore-bearing pipe (Flanigan and others, 1986). Ground magnetometer surveys show subtle magnetic lows over several pipes, perhaps indicating alteration of detrital magnetic minerals within reduced zones associated with uranium deposits (Van Gosen and Wenrich, 1989). Breccia pipe locations are spatially unrelated to magnetic lineations defined by a high resolution aeromagnetic survey (Flanigan and others, 1986). High-grade uranium ore in northern Arizona breccia pipes is generally deeply buried (>300 m); associated gamma-radiation is essentially undetectable at the surface (Wenrich, 1986). Detailed gamma-radiation surveys of more than 1000 breccia pipe and collapse features indicate that few pipes have associated gamma radiation that is more than five times background levels (Wenrich, 1985). Scarce gamma radiation anomalies detected at the surface are coincident with ring fracture zones and are of limited areal extent (<1 m in diameter) (Wenrich, 1985). The limited size of these anomalies is responsible for the fact that an airborne radiometric survey, flown about 120 m above ground, over this area at 5 (east-west) and 10 (north-south) km flight-line spacings (LKB Resources, Inc., 1979) identified no anomalies associated with known deposits (fig. 1). In limestone karst-hosted uranium-vanadium deposits of the Pryor Mountains, Mont., minor increases in radioactivity (twice background level) were measured directly over mineralized fractures, but no anomalous radioactivity was identified near karst pits (Patterson and others, 1988).

References

Hauptman (1956), Wenrich and others (1989), Wenrich and Sutphin (1989), and Finch (1992), Finch and others (1992).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are of small to intermediate size. Production and reserves associated with northern Arizona pipes include 0.1 to 0.5 million metric tonnes of ore (Finch and others, 1992). Production and reserves from the Tsumeb deposit include 22 million metric tonnes of ore (Lombaard and others, 1986). Deposits in the Pryor Mountains are very small (Hauptman, 1956).

Host rocks

Host rocks include breccias of limestone, sandstone, siltstone, and shale in a finely comminuted sand matrix cemented by carbonate minerals.

Surrounding geologic terrane

These deposits are in alternating sequences of sandstone, siltstone, shale, and limestone strata overlying paleokarst with open and paleo-sandstone-filled channels and caverns.

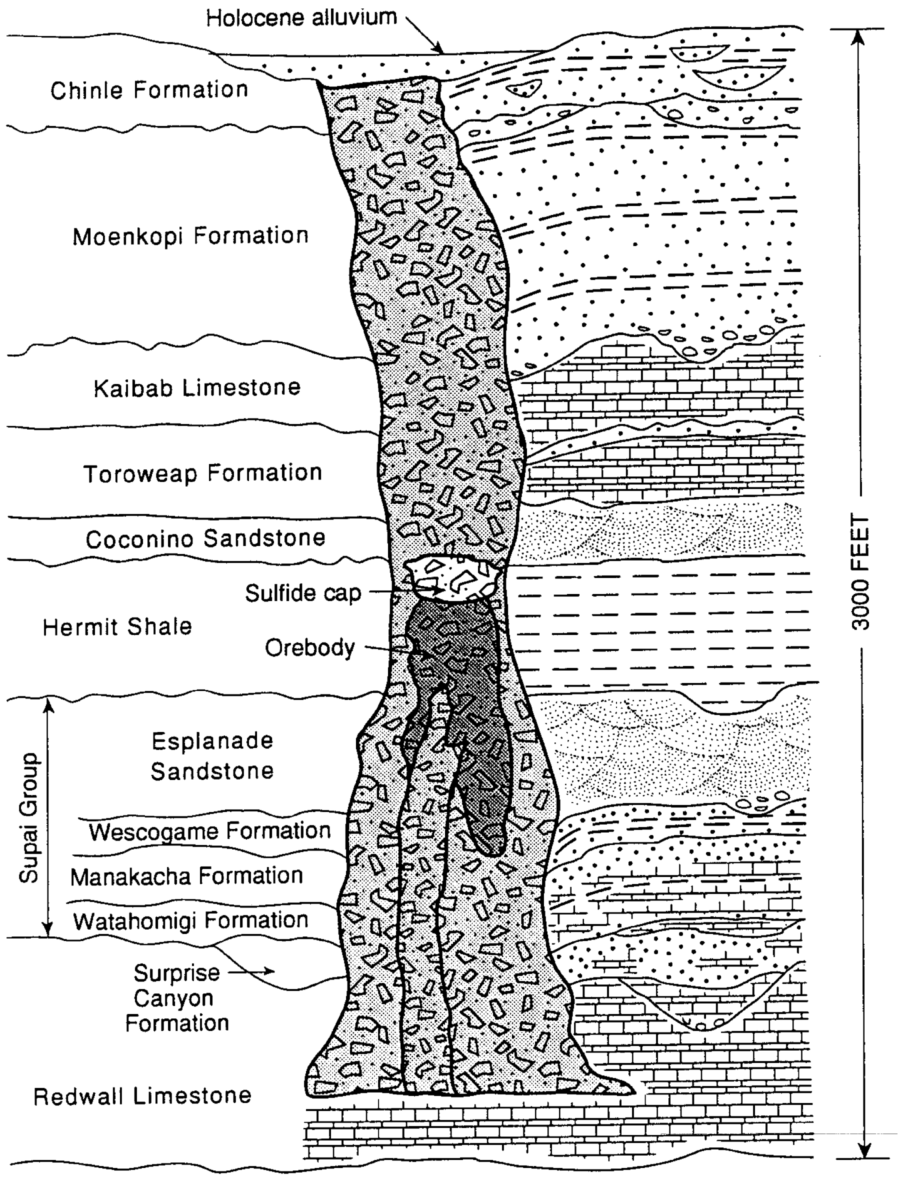

Figure 2. Simplified geologic cross section of northern Arizona breccia pipe showing dimensions and stratigraphic setting of breccia pipe, uranium-sulfide ore, and sulfide mineral "cap" (Wenrich and Aumente-Modreski, in press). Typical diameter of pipe is 100 m.

Wall-rock alteration

The principal form of wall-rock alteration associated with these deposits is bleaching (oxidation) of iron oxide minerals in red sandstone by reducing fluids. Alteration extends 30 to 100 m outward into wall rock of Grand Canyon, Ariz., region deposits and less than 10 m into wall rock of Pryor Mountains, Mont., deposits.

Nature of ore

Nearly all primary ore is confined to breccia pipes (fig. 2); the only major exception is the local presence of ore in ring fracture zones in country rocks surrounding pipes. The vertical position of most primary ore in the Grand Canyon breccia pipe is at the Coconino Sandstone, Hermit Shale, and Esplanade Sandstone (all Permian) stratigraphic horizons.

Deposit trace element geochemistry

Randomly collected breccia pipe rock samples contain elevated abundances of a number of elements, including <2 to 2,400 ppm Ag, 0.5 to 111,000 ppm As, 4 to 100,000 ppm Ba, <2 to 2,900 ppm Cd, 0.66 to 26,000 ppm Co, <1 to 290,000 ppm Cu, <0.01 to 140 ppm Hg, <2 to 24,000 ppm Mo, <2 to 62,000 ppm Ni, <4 to 84,000 ppm Pb, 0.13 to 2,900 ppm Sb, <0.10 to 3,000 ppm Se, 4 to 5,800 ppm Sr, 0.63 to >210,000 ppm U, <4 to 50,000 ppm V, and <4 to 260,000 ppm Zn (K.J. Wenrich, unpub. data, 1995).

Ore and gangue mineralogy and zonation (see Wenrich and Sutphin, 1988, 1989)
Potentially acid-generating minerals underlined. Primary ore minerals include uraninite, sphalerite, galena, nickeline, rammelsbergite, pararammelsbergite, gersdorffite, bravoite, siegenite, vaesite, millerite, skutterudite, Co-gersdorffite, linnaeite, stibnite, molybdenite, enargite, chalcopyrite, lautite, tennantite, tetrahedrite, pyrite, marcasite, arsenopyrite. Primary gangue minerals include barite, quartz, chalcedony, pyrobitumen, kaolinite, calcite, dolomite, ankerite, siderite, anhydrite and fluorite.
Zoning: The only recognized zoning in primary orebodies involves concentration of nickel-cobalt-iron-copper arsenide and sulfide minerals in sulfide caps above ore. Secondary and supergene minerals are present where ore has been exposed to oxidation, including canyon dissection and fracture-controlled oxidation (Verbeek and others, 1988; Wenrich and others, 1990).

Mineral characteristics
Textures: Uraninite, other oxide minerals, and sulfide minerals are very fine grained (generally <1 mm); rarely, primary mineral grains are as large as 1 cm. Secondary mineral grains, commonly as much as 1 cm, tend to be larger than those of primary minerals.
Trace element contents: Primary and secondary minerals can include any of the following: Ag, As, Ba, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sr, U, V, Y, and Zn.
General rates of weathering: These deposits weather rapidly. Primary ore can oxidize within six months when exposed to surface weathering. Within six months of opening drifts in underground breccia pipe mines in the Grand Canyon area, some uraninite has altered to hexavalent secondary minerals, primary cobalt-bearing sulfide minerals to erythrite, and molybdenite to ilsemannite.

Secondary ore and gangue mineralogy
Secondary ore and gangue minerals include tyuyamunite, metatyuyamunite, zippeite, zeunerite, metazeunerite, metatorbernite, uranophane, bayleyite, uranospinite, adamite, smithsonite, aurichalcite, hemimorphite, anglesite, cerussite, wulfenite, rhodochrosite, hewettite, vesignieite, volborthite, calciovolborthite, roscoelite, erythrite, bieberite, ilsemannite, chalcocite, djurleite, digenite, covellite, bornite, cuprite, tenorite, chrysocolla, azurite, malachite, olivenite, chalcanthite, brochantite, cyanotrichite, chalcoalumite, langite, antlerite, devilline, conichalcite, acanthite, naumannite, proustite, scorodite, melanterite, limonite, hematite, goethite, siderotil, coquimbite, jarosite, celadonite, illite, gypsum, hexahydrite, and leonhardtite (Wenrich and Sutphin, 1988).

Topography, physiography
Solution-collapse breccia pipes are distinguished by concentric-inward-dipping beds that generally surround a basin, amphitheater-style erosion, concentric drainage, soil and vegetation patterns, breccia, and altered and mineralized rock (Wenrich and Sutphin, 1988). Locally, breccia plugs are silicified and more resistant to erosion. These plugs form erosional spires or pinnacles in which ore has been oxidized; most trace metals have been leached from these pipes. Ring fractures surrounding the pipes tend to erode readily, which causes development of concentric drainage around pipes.

Hydrology
Ring fracture zones: These zones have high permeability and therefore locally focus ground water flow. Breccia in solution collapse pipes is also relatively permeable where not silicified. However, in the Grand Canyon area, ground water within 600 m of the plateau surface is rare. Consequently, unless canyon dissection has altered this situation or a perched aquifer is present, very little water moves downward into the pipes because orebodies are located, on average, 300 m below the surface.
Aquifers: Major aquifers in the Grand Canyon region are the Mississippian Redwall Limestone and the Cambrian Muav Formation; both lie several hundred feet below the breccia pipe orebodies. However, in the Pryor Mountains, south-central Mont., uranium minerals are oxidized and are within paleokarst and modern karst of the Mississippian Madison Limestone (stratigraphic equivalent of the Redwall Limestone); this karst is a major aquifer in the region,

and therefore plays a major role in uranium oxidation and mobility.

Mining and milling methods

Historic: Typical underground workings followed ring fracture zones in oxidized breccia pipes. Historic mines (fig. 1) produced copper, lead, zinc and silver ore (Billingsley, 1974; Chenoweth, 1988; Wenrich and Sutphin, 1988).
Modern: Uranium was not recognized in the breccia pipes until 1951 (Chenoweth, 1986). All modern mines have been underground operations. During the 1960s, ore from breccia pipes in the Grand Canyon region was shipped to a mill in Tuba City (where copper and vanadium were also extracted); since the 1980s it has been shipped to a mill in Blanding, Utah. Uranium ore is dissolved by either acid or alkaline solutions, and uranium is precipitated by either ion-exchange or solvent extraction; in either case, the product, commonly ammonium diuranate, is called "yellowcake" because of its color (Cooper, 1986).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data: No data available for the Grand Canyon, Ariz., area; no surface water drains the immediate vicinity of mines. Warchola and Stockton (1982) found no significant uranium enrichment in water draining uranium deposits in the Pryor Mountains, Mont. More water sampling adjacent to mine areas is needed in both Arizona and Montana.
Natural-drainage data: Data are available for north Grand Canyon rim springs (Billingsley and others, 1986) and south Grand Canyon rim springs and surface water, including Hualapai Indian Reservation (Wenrich and others, 1994). Grand Canyon area water is primarily of the calcium-magnesium-bicarbonate type, although some is of the sulfate and chloride types, which tend to have higher natural trace metal contents. The few spring water samples collected near mines tend to have metal contents that are similar to, though somewhat more elevated than, those of some sulfate-type water (Billingsley and others, 1986; Wenrich and others, 1994).

Metal mobility from solid mine wastes

Solid waste resulting from mining breccia pipe deposits is very limited. No data pertaining to quantities of metals mobilized by limited quantities of water interacting with these wastes are available.

Soil, sediment signatures prior to mining

Extensive soil sampling surveys in the Grand Canyon region provide elemental abundance levels in (1) regional soil, (2) soil over mineralized breccia pipes, and (3) soil over unmineralized breccia pipes (Van Gosen and Wenrich, 1991; Wenrich and Aumente-Modreski, 1994). In addition, stream sediment samples were collected during the National Uranium Reconnaissance Evaluation (Wagoner, 1979; Koller, 1980). A few additional stream-sediment samples were collected by Billingsley and others (1986). The exceptionally small size (diameters generally less than 100 m) of these deposits, and exceptionally weak associated geochemical halos (commonly less than 2.5 times background) preclude detection of most mineralized breccia pipes using stream-sediment samples (Wenrich, 1986). Similarly, Patterson and others (1988) conducted a stream-sediment sampling program in the Pryor Mountains, Mont., an area known to contain uranium occurrences. Samples collected immediately downstream from known deposits contained less that 4 ppm uranium. Their sampling failed to identify previously unknown uranium occurrences. Consequently, these deposits have essentially no pre-mining geochemical signature.

Potential environmental concerns associated with mineral processing

Mineral processing is not done on site. Ore is sorted from waste on site and shipped to mills for processing. On site environmental concerns include radon from mines and gamma radiation from ore and waste piles. Reclamation entails backfilling mines with waste rock and sealing mine entrances to prevent radon leakage and future entry.

Mill signatures

Tailings at mineral processing sites are a major environmental concern because of their large volume and fine-grain size, which permits redistribution by wind. Large tailing piles emit abundant radon and gamma radiation; if water circulates through tailings and escapes from ponds, local aquifers and drainages may be contaminated. Potential water contamination may be a particularly serious problem during periods of severe weather or from stress failure of dams. For example, "on July 16, 1979, the failure of an earthen dam, which held back uranium-mining and milling wastewater and sediment, released about 94 million gallons of highly acidic liquid and 1,100 tons of uranium-mine tailings to the Puerco River through Pipeline Arroyo....Three months to a few years following the spill, several scientific studies concluded that no trace of sediment containing radium and thorium from the spill could be identified, although the Puerco River was still receiving high amounts of dissolved uranium from mine dewatering" (Wirt, 1994). Although these were not breccia pipe mine tailings, they exemplify the potential problem of uranium tailings. However, although this was the largest single release of uranium mine tailings in United States history, the long term and long distance effects of uranium contamination on the environment in the Rio Puerco, N. Mex. and Ariz., drainage appear to be negligible (Wirt, 1994).

Environmental mitigation

Environmental mitigation should include complete surface reclamation, as done in the area of the Hack and Pigeon, Ariz., mines (see photographs in Finch, 1994). Mines should be sealed, dumps and tailings should be backfilled into mines, and mine areas revegetated.

Climate effects on environmental signatures

In the Grand Canyon region the climate is arid, which greatly retards orebody oxidation and the movement of trace metals in the environment. The effects of other climate regimes on the geoenvironmental signature specific to these deposits has not been documented. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Electromagnetic and direct current resistivity or induced polarization surveys can be used to map acidic drainage and water with increased metal content escaping from mill tailings. Detailed ground or airborne gamma radiation surveys can be used to detect or monitor radioactive contamination related to flooding and ore transportation and processing.

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