Introduction

By Andrea E. Alpine and Kristin M. Brown

Introduction to

Hydrological, Geological, and Biological Site Characterization of Breccia Pipe Uranium Deposits in Northern Arizona

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Plate

[In pocket]

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047	square meter (m^2)
	Flow rate	
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

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Background

In the late 1940s and early 1950s, uranium was discovered in association with many of the old copper mines in the Grand Canyon region, hosted by geologic features called breccia pipes. Discovery of high-grade uranium ore in the Orphan Lode (breccia pipe) deposit led to uranium mining on patented claims within the Grand Canyon National Park from 1956 to 1969 (plate 1). In the 1970s, breccia pipes became the subject of intense exploration in the Grand Canyon region, sought for their uranium ore potential; several were found exposed in the plateaus and the walls of the Grand Canyon and its tributaries. In the 1980s and early 1990s, uranium was mined from seven breccia pipes in the northern Grand Canyon region. Today, some of the highest grade uranium ore in this country is believed to be located in the many mineralized breccia pipes scattered across the Grand Canyon region.

On July 21, 2009, U.S. Secretary of the Interior Ken Salazar proposed a two-year withdrawal of about 1 million acres of Federal land near the Grand Canyon from future mineral entry. These lands are contained in three parcels: two parcels on Bureau of Land Management (BLM) land to the north of the Grand Canyon (North and East Segregation Areas) and one on the Kaibab National Forest south of the Grand Canyon (South Segregation Area) (fig. 1). The purpose of the two-year withdrawal is to examine the potential effects of restricting these areas from new mine development for the next 20 years, "to protect the Grand Canyon watershed from adverse effects of locatable mineral exploration and mining, except for those effects stemming from valid existing rights" (U.S. Bureau of Land Management, 2009, p. 43152). Dissolved uranium and other major, minor, and trace elements occur naturally in groundwater as the result of precipitation infiltrating from the surface to water-bearing zones and, presumably, to underlying regional aquifers. Discharges from these aquifers occur as seeps and springs throughout the region and provide valuable habitat and water sources for plants and animals. Uranium mining within the watershed may increase the amount of radioactive materials and heavy metals in the surface water and groundwater flowing into Grand Canyon National Park and the Colorado River, and deep mining activities may increase mobilization of uranium through the rock strata into the aquifers. In addition, waste rock and ore from mined areas may be transported away from the mines by wind and runoff.

This proposed withdrawal initiated a period of study during which the effects of the withdrawal must be evaluated. At the direction of the Secretary, the U.S. Geological Survey (USGS) began a series of short-term studies designed to develop additional information about the possible effects of uranium mining on the natural resources of the region. These studies include:

1. Estimation of the amount of uranium resources within the proposed withdrawal areas and previously withdrawn areas,
2. Investigation of the effects of the 1980s uranium mine development and extraction operations to determine if mining operations affected local environments,
3. Examination of whether these previous operations were detrimental to the water quality of surface water and groundwater and estimation of the potential effect of future mining operations,
4. Compilation of the available toxicological information on exposure pathways and biological effects of uranium and associated decay products relevant to species occurring in the region, and
5. Completion of a geologic map of the House Rock Valley area (East Segregation Area), Coconino County, Ariz., providing detailed strata and structural information (published separately as SIM 3108 [Billingsley and Priest, 2010]).

Description of the Study Area

The study area is larger than the proposed withdrawal areas and is bounded on the north by the Arizona-Utah border, on the south by Valle, Ariz., on the east by Lees Ferry, and on the west by Iceberg Canyon at Lake Mead (fig. 1). The Secretary of Interior's proposed withdrawal area includes three segregation areas north, east, and south of the Colorado River and encompasses about 1 million acres of BLM, National Forest, State, and private lands; all are contained within the study area (fig. 1).

Climate

The climate of northern Arizona is semiarid to arid with spatial and temporal extremes of temperature and precipitation. The broad range of climate is strongly correlated with altitude resulting in moderate summers and severe winters at higher altitudes and intense summer heat and mild winters at lower altitudes (fig. 2). Microclimates are common to northern Arizona, especially along the Colorado River and at high elevation uplands, as the slope and exposure of mountains and

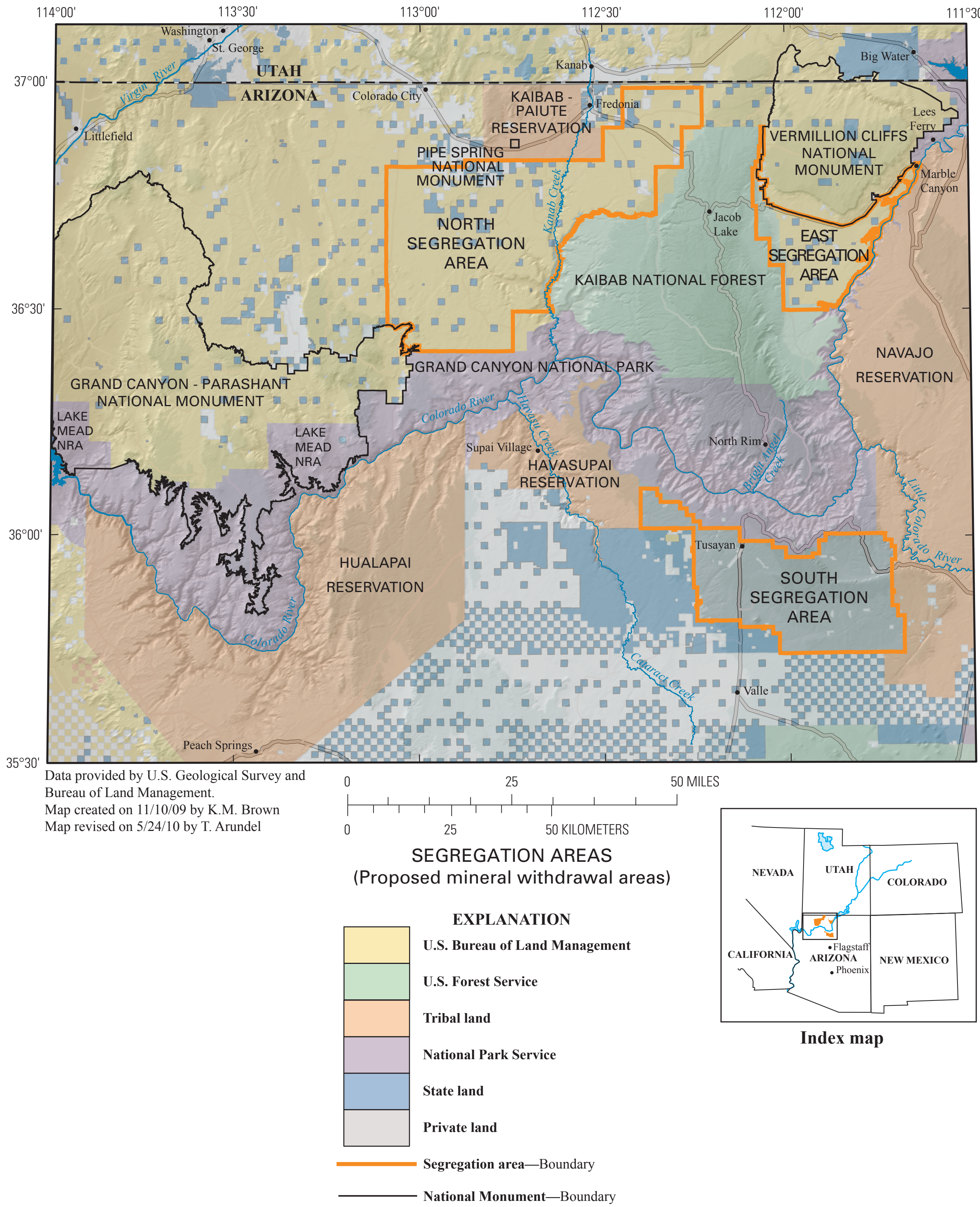

Figure 1. Map showing study area, segregation areas, and land ownership. NRA, National Recreation Area.

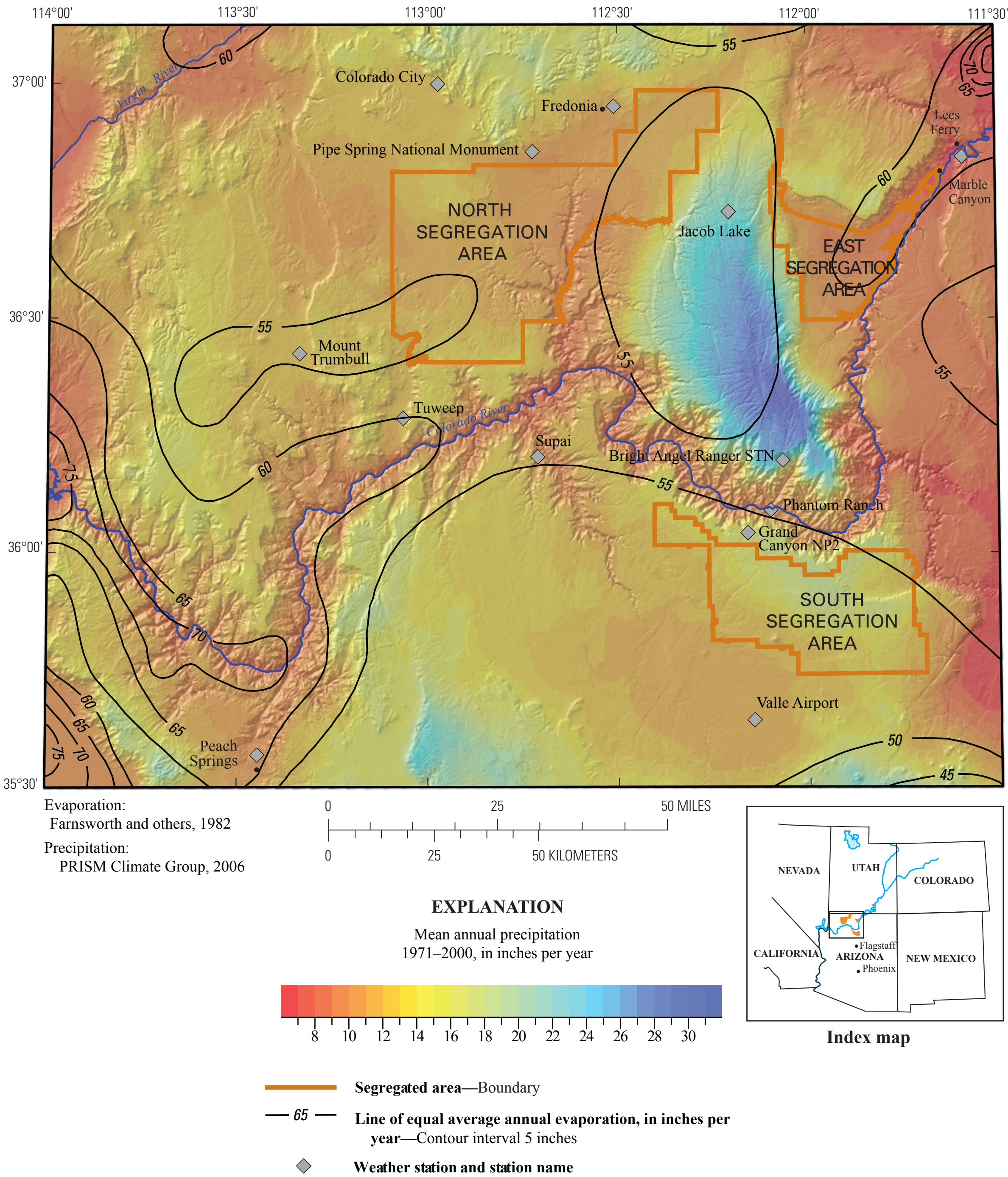

Figure 2. Map showing mean annual average precipitation and evaporation for northern Arizona.

deep canyons control circulating air masses and the amount of solar radiation that reaches land surface. Average annual evaporation rates are large, more than 20 times the average annual precipitation for much of the area (fig. 2), creating a net annual water deficit for most of northern Arizona. However, water is available on the landscape because most of the precipitation falls in the winter months when evaporation processes are at their lowest.

Winter storms (those occurring from October through April) provide about 60 percent of precipitation to the study area, with summer storms providing about 40 percent (Western Regional Climate Center, 2004). This bimodal precipitation pattern is characteristic of Arizona. The winter and summer wet periods have different effects on the occurrence and availability of water in northern Arizona. In winter, large storm systems that originate in the Pacific Ocean pass over the state bringing rain and heavy snows to higher altitudes and less frequent rain and snow to lower altitudes. Deep snow accumulations in the mountains and on the Kaibab anticline can result in significant spring runoff to lower elevations. Because of low evapotranspiration in winter, a greater portion of winter precipitation is available for runoff and infiltration than summer precipitation. Summer rainfall is controlled by moisture-laden air masses that move into Arizona from the Gulf of Mexico and the Gulf of California. In middle to late summer, regionally called the monsoon season, the orographic effect of the high altitude areas of northern Arizona results in frequent, intense, short-duration thunderstorms. The amount of precipitation derived from these thunderstorms is sporadic both spatially and temporally, but intense downpours can produce flash flooding and debris flows. The high summer temperatures also result in evaporation far in excess of precipitation. The ratio of annual evaporation to precipitation is about 2:1 at higher altitudes on the Kaibab anticline and mountains to the south. It ranges from about 6:1 at lower altitudes in western and northwestern parts of northern Arizona to more than 8:1 in eastern and northeastern parts of northern Arizona.

The average annual temperature ranges from about 60ºF on the rim of the Grand Canyon to about 80ºF at the canyon's bottom (Western Regional Climate Center, 2004), with average annual temperatures about 5ºF lower on the higher North Rim. Winter extremes of subzero temperatures can occur in deep canyons and the plateaus to the east and west but are more common at higher altitude areas of the Kaibab anticline. Summer temperatures commonly exceed 100ºF on the east and west plateau north of the Colorado River and reach 110–120ºF in the inner canyons.

Average annual precipitation ranges from 6 in along the river in the eastern edge of the area to 21 in at Jacob Lake on the Kaibab anticline and 16 in at the South Rim of the Grand Canyon. Some of the largest precipitation events north of the Colorado River have occurred as local summer thunderstorms (Webb, 2002). Extreme runoff events are most often driven by rain-on-snow during the early and late winter. The maximum annual precipitation was recorded at the Bright Angel Ranger Station at the North Rim of the Grand Canyon at 45 in (fig. 2). Over 60 percent of that total fell as snow in the winter months. As with areas to the north of the Colorado River, precipitation south of the Colorado River is strongly correlated with altitude. Generally less than 15 in/yr fall on higher altitude areas and 10 in/yr or less fall on the lower elevation plateaus and inner canyon areas; more than 25 in/yr fall on elevations above 7,000 ft (fig. 2) (Bills and others, 2007). In general, climate south of the Colorado River is more arid owing to the generally lower elevations.

Data from the National Weather Station (NWS) at Flagstaff, Ariz., show that the prevailing wind direction is bimodal from the south-southwest for February to September and from the north-northwest for October to January (*http://www.wrcc.dri.edu/summary/lcd.html*, accessed December 2009). The average annual wind speed is 6.4 mph and varies little from month to month. The Grand Canyon National Park Airport reports similar trends (*http://www.wrcc.dri.edu/htmlfiles/westwind.final.html*, accessed December 2009). None of the NWS sites north of the Colorado River consistently reports wind speed and direction, but extreme weather data reported by the U.S. Forest Service and NWS in support of fire condition reports suggest that wind patterns are similar in this area (*http://www.spc.noaa.gov/products/fire_wx/*, accessed December 2009).

Geologic and Hydrologic Setting

The study area is located within the southwest portion of the Colorado Plateau, a unique physiographic province roughly centered on the Four Corners region of the southwestern United States (plate 1). This portion of the Colorado Plateau is characterized by nearly flat lying sedimentary rock layers that are exposed in canyons and by a series of high plateaus (Bues and Morales, 2003); the highest plateau in the study area is the Kaibab Plateau north of the Colorado River between the North and East Segregation Areas. The study area has seven major structural trends that significantly affect the regional geology and hydrology. The western part of the study area has several north-south trending major faults: the Grandwash fault on the west, the Dellenbaugh fault, the Hurricane fault, and the Toroweap fault with offsets down to the west (plate 1). The structural features dominating the eastern portion of the study area are the Kaibab anticline (bordered on the east by the East Kaibab monocline, distinguished by east-dipping sedimentary rocks responding to movement of reactivated basement faults), the Mesa Butte fault, and the Havasu-Cataract Basin south of the Colorado River, northeast and northwest trending with westerly dips. Tectonic features such as faults, folds, fractures, and dip angles of sedimentary layers affect the subsurface groundwater flow.

The primary hydrologic feature found in the study area is the Colorado River that flows from the northeast end of the study area winding westward into Lake Mead (plate 1). The flow of the Colorado River today is primarily controlled by the operation of Glen Canyon Dam and is supplemented with unregulated surface flows from tributaries draining higher elevations of the Grand Canyon region. Elevations north of the Colorado River reach over 9,200 ft on the Kaibab Plateau; the high elevations and steep gradient of streams facilitate rapid surface runoff with high sediment loads toward the Colorado River. Elevations south of the Colorado River reach over 7,000 ft along the South Rim of the Grand Canyon. The south-sloping topography of this area causes surface water to flow away from the South Rim; it is eventually captured by the larger north-flowing drainages of the Little Colorado River and Cataract Canyon and returned to the Colorado River. The Little Colorado River also drains the surface flows southeast of the Grand Canyon into the Colorado River in the eastern Grand Canyon (plate 1).

Springs located throughout the study area support some of the most diverse habitat on this part of the Colorado Plateau and are a critical source of water for humans, fish, and wildlife. Geologic structures such as joints, fractures, faults, folds, and bedding planes control and direct groundwater movement toward spring discharge areas. Fine-grained sedimentary rocks, such as the Hermit Formation and the lower part of the Supai Group, can prevent the downward movement of groundwater, resulting in locally perched water-bearing zones. Perched water-bearing zones can occur from several hundred to more than 2,000 feet above the underlying regional aquifers. Fractures and faults in the fine-grained rock units provide pathways for vertical movement of groundwater from the perched water-bearing zones deeper into the subsurface. Dissolution of the Redwall and Muav Limestones from groundwater flow through joints and fractures causes caves, caverns, and solution channels to form within these rock layers. The collapse of some of these caves and caverns over time has led to the formation of breccia pipes, some of which host uranium ore deposits. Many of the seeps and springs in the Grand Canyon region emerge from the base of these rock layers. Joints and fractures associated with the caves and solution channels in these rock layers provide pathways that preferentially direct groundwater flow to these discharge areas.

Recharge Estimates

Water migrating from the surface to the subsurface is an important transport mechanism for the remobilization of trace and radiochemical elements. Since most of the orebodies associated with breccia pipes are located several hundred to more than 1,000 ft above the regional groundwater flow systems of northern Arizona, natural recharge of water from the surface through these orebodies is one of the few ways of naturally adding to the radiochemistry of the regional groundwater flow systems. Estimated recharge potential for the Desert Southwest has been determined based on temporal and spatial variations in precipitation, air temperature, root zone and soil properties and thickness, faults and fractures, and hydrologic properties of geologic strata in the unsaturated zone (Flint and others, 2004; Flint and Flint, 2007). The most significant recharge potential occurs on the Kaibab anticline with significant secondary areas of recharge occurring along the South Rim and at areas of structural weakness through the northern Arizona area. Breccia pipes in these areas would have the greatest potential for remobilization of radiochemical elements found in the subsurface.

Biologic Setting

Habitats in the Grand Canyon and its environs support a diverse flora and fauna including culturally significant, threatened, and endangered species. Three main ecosystems occur in the study area: Great Basin grassland, Great Basin woodland, and Great Basin desert scrubland (Brown and Lowe, 1982; Olson and others, 2001). High elevation areas of the Kaibab anticline are a mix of Rocky Mountain subalpine conifer forest, montane conifer forest, and subalpine grassland. The canyon lands in the region consist almost entirely of Mohave desert scrub with isolated areas of riparian habitat that support most of the species diversity in the region (Brown and Lowe, 1982; Olson and others, 2001; Grand Canyon Wildlands Council, 2004). Vegetation has a significant effect on the occurrence and flow of water both on the surface and in the subsurface. Plants can intercept and store precipitation and thus delay and (or) prevent overland flow that would lead to runoff. They also transpire moisture that has seeped into the soil and deeper root zones as it becomes available and before it has an opportunity to seep deeper into the subsurface to become part of a groundwater flow system.

In general, the ecosystems and habitats of this area are primarily influenced by precipitation, slope, and elevation. Elevations below about 4,900 ft generally support sparse sagebrush and other desert bushes, grasses, and cactus. Elevations between 4,900 and 6,900 ft support thicker brush and grasslands transitioning into pinyon pine,[1] juniper, and Gambel oak stands on hills and higher elevation areas. While most of these vegetation types require little water, they exist primarily in fracture zones and depressions where water accumulates. Elevations above 6,900 ft are dominated by dense ponderosa pine forest and smaller stands of aspen, firs, spruce, and juniper. Native hardwoods can be found in riparian areas of drainages and include cottonwood, oak, willow, and ash. These species have always been excellent markers on the landscape for locations of water sources. Invasive species such as tamarisk, Russian olive, and Siberian elm have come to dominate and crowd out native species in some drainages and riparian areas where water is available. Land management practices have affected both the vegetation coverage diversity and geomorphic characteristics of drainages north of the Grand Canyon since the early 20th century, changing runoff and recharge patterns (Webb and others, 1991).

In the study area, desert grassland is found on north-facing slopes within the Grand Canyon but is rare, whereas intermediate grassland found at a higher elevation is more

[1]See appendix 1 of the Introduction for a list of scientific names.

common in the study area, specifically in the western Grand Canyon, as well as on the North Rim in the Arizona Strip area. Typical animal species in these grasslands include herbivorous rodents, insects, elk, mule deer, and antelope and predatory golden eagles, red-tail hawks, and coyotes.

Shrubland is characterized by open areas where shrubs are dominant or co-dominant with grasses (Brown and Lowe, 1982). Unique steppe habitat on the Colorado Plateau includes low desert bajadas, slope failure fans, bedrock canyons and fans on the Arizona Strip, inner canyon terraces, Marble and Coconino Plateau steppe habitats, riparian terraces, and chaparral vegetation on steep slopes (Nabhan, 2002). Common plant species in shrubland include banana yucca and snakeweed at high elevations, blackbush and mormon tea at middle elevations, creosotebush and white bursage at low elevations, and snakeweed, rabbitbrush, and big sagebrush in the plateau. Ants, prairie dogs, gophers, raptors, and coyotes are common fauna in the shrublands.

Desert woodland is distinct depending on elevation, with mesquite, catclaw, and netleaf hackberry along stream channels at low elevations. Intermediate woodland is dominated by the pinyon pine, juniper, rabbitbrush, and sagebrush throughout the study area at middle elevations.

Predominant species in the ponderosa pine forest include squirrels, mule deer, and elk. Goshawk and Mexican spotted owls can be found nesting in the ponderosa pine and higher elevation forest. Other common vertebrates found in desert woodland include raccoon, skunk, long-tailed weasel, raven, and several species of owls and other birds (jays, nuthatches, chickadees, warblers, woodpeckers, etc.) Old growth ponderosa pine forest is found in the North Kaibab National Forest and can be identified by yellowed bark and large red-yellow bark plates.

The barrenland ecosystem has been identified as a unique habitat characterized by bare bedrock or soil common of the badlands, canyon country, and alpine habitats (Grand Canyon Wildlands Council, 2004). Barrenland ecosystems are abundant within the segregation areas and are typified by cactus and sparse desert bushes or grasses. Common cliff dwelling vertebrates of the barrenlands include chuckwallas, a variety of other lizards, canyon wrens, raptors, ravens, and swallows.

Areas of riparian habitat occur within each of the above areas around lakes, ponds, springs, seeps, streams, and rivers. These riparian habitats have exceptional biodiversity and are critical for the plants and animals that live in the area. Several springs have National significance and are linked to important components of Native American culture. Many of the springs originate in water-bearing zones in the Redwall and Muav Limestones and flow into canyons of the greater Grand Canyon area. These spring habitats support a species diversity that is 100 to 500 times greater than that of the surrounding landscape (Grand Canyon Wildlands Council, 2004). Common vegetation includes monkey flower, redbud, willow, cottonwood, and maidenhair fern. Spring habitats can also host frogs and invertebrates, such as the endangered Kanab ambersnail. Many bird species, both native and migratory, nest and feed along riparian areas of the Colorado River. Common birds found in the Colorado River riparian zone include finches, hummingbird, swifts, swallows, warblers, phoebe, flycatchers, and wrens. Predatory birds include the great blue heron, red-tail hawk, osprey, kestrel, Peregrine falcon, raven, golden eagle, and bald eagle. Other common vertebrate fauna found along the Colorado River include snakes, lizards, frogs, salamanders, rodents, ringtail cat, skunk, coyote, and fox. Raccoons, bobcat, mountain lion, bats, mule deer, and bighorn sheep occur but are rarer in the riparian corridor of the Colorado River. Multiple species of fish utilize the flowing water of the Colorado River. Current fish populations are dominated by introduced species including carp, rainbow trout, brown trout, and catfish. Native species including bluehead suckers and flannelmouth suckers, speckled dace, and the endangered humpback chub are still present, but many are listed as Federal or State species of concern (Grand Canyon Wildlands Council, 2004). Invertebrates are important components to the aquatic food chain of the Colorado River. Descriptions of important species in the mainstem have been documented (for example, Blinn and Cole, 1991; Stevens and others, 1997, 1998). However, aquatic invertebrates in the tributary streams of the Grand Canyon region have not been studied to the same extent (Oberlin and others, 1999).

Mining activity can result in changes to these habitats that may increase exposure of the biological resources to chemical elements including uranium, radium, and other radioactive decay products. Uranium and other radionuclides can affect the survival, growth, and reproduction of plants and animals. The identification of biological pathways of exposure and the compilation of the chemical and radiological hazards for these radionuclides are important for understanding potential effects of uranium mining on the northern Arizona ecosystem.

Breccia Pipes and Uranium

Breccia Pipes

The uranium deposits of northwestern Arizona are hosted by geologic features described as “solution-collapse breccia pipes,” or simply “breccia pipes.” The features, formed by solution and collapse, are named for their vertical, pipe-like shape and the broken rock, or breccia, that fills them (fig. 3). Breccia pipes generally form through a sequence of steps: (1) dissolution and karst (cave) development in the Redwall Limestone rock unit; (2) collapse of the cavern ceiling (which forms the broken rock rubble); and (3) progressive collapse moving upward into overlying formations through time, forming a broken rock or rubble-filled column. The region surrounding the Grand Canyon hosts hundreds, possibly thousands, of breccia pipes, some of which contain concentrated deposits of uranium, copper, silver, lead, zinc, cobalt, and nickel minerals (Wenrich, 1985; Wenrich and others, 1989; Finch and others, 1992). Exploration in the region has shown

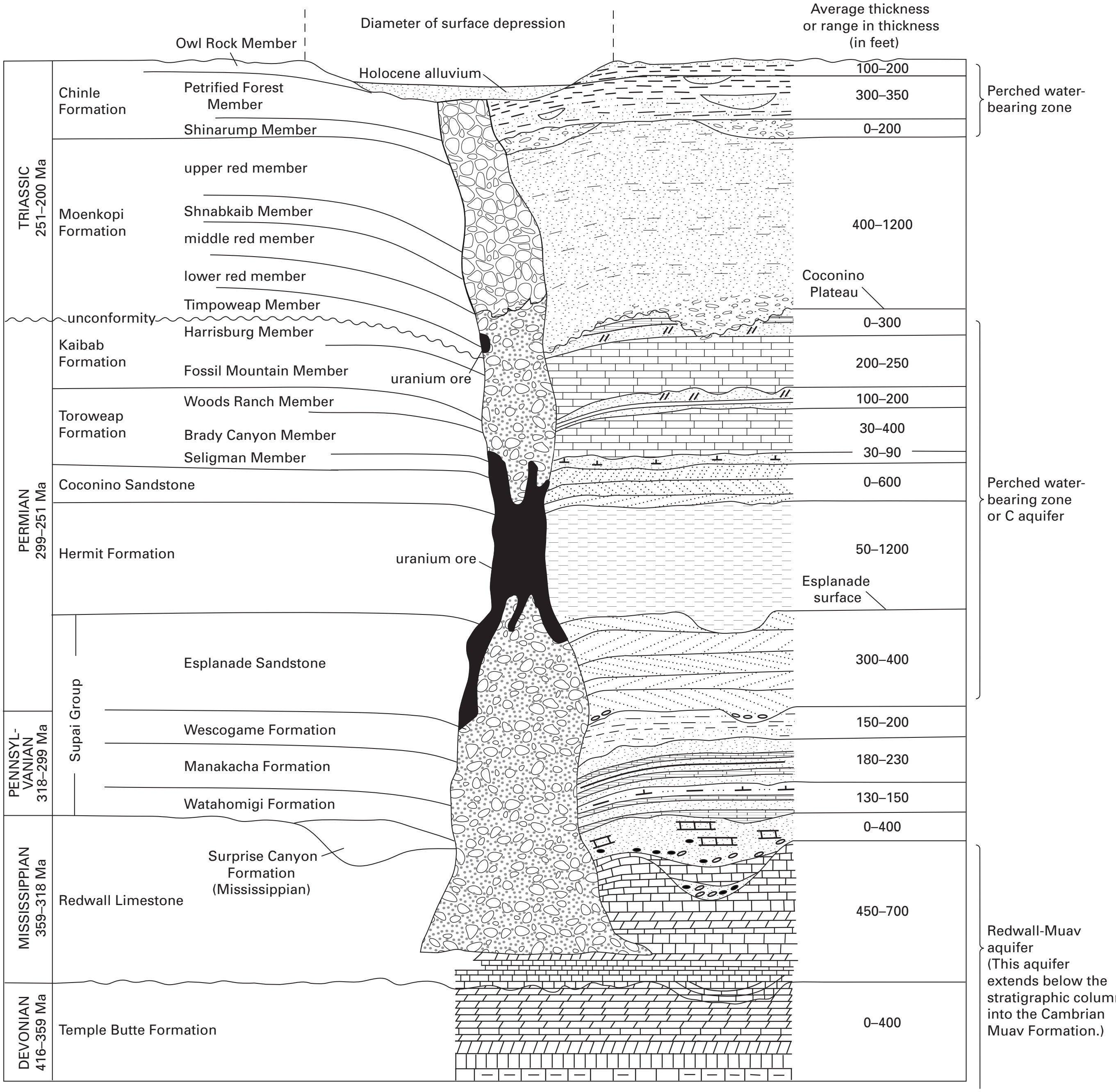

Figure 3. Stratigraphic column of a breccia pipe showing relation of breccia pipe to surrounding rock, orebodies, and perched water-bearing zones and aquifers.

that a small percentage of the identified breccia pipes do contain an economic uranium deposit. The USGS has mapped more than 1,200 possible solution-collapse breccia pipes in the northern Arizona region.

Breccia pipes have not been observed in rock units younger than about 200 million years old (Triassic age). The breccia fragments that form the pipes are consistently blocks and pieces of rock units found below their normal position in the wall rock; that is, all rocks within the breccia column (pipe) have fallen downward and are never found above their original level. In contrast to many other types of breccia pipes, no igneous rocks are associated with the northern Arizona breccia pipes and no igneous processes have contributed to their formation.

The pipe-shaped structures average about 300 feet in diameter and can vertically extend from the Redwall Limestone to the Chinle Formation. Because the thickness of the host sedimentary strata varies across the Grand Canyon region, the depth to an orebody within a breccia pipe varies from area to area. The upper part of the uranium orebody in breccia pipes often occurs within the horizon of the Coconino Sandstone or the Hermit Formation, with the ore often extending down into the Esplanade Sandstone (fig. 3). The three segregated areas are located in the central and eastern areas of the Grand Canyon region, which are mostly capped by the Kaibab Formation. Thus, the uranium orebody in a breccia pipe within the three areas is typically 900–1,000 ft (or more) below the plateau surface (capped by the Kaibab Formation).

Some breccia pipes are exposed in the canyon walls within the Grand Canyon and its tributaries (fig. 4), but because they are exposed to erosion and weathering processes, much of the uranium ore material has dissipated. Although no single exposure in the Grand Canyon region exposes an entire breccia pipe from bottom to top, exposures of many hundreds of feet appear at several locations and encompass various stratigraphic formations. These exposures illustrate that an individual breccia pipe can cover a vertical range of at least 3,000 ft, from the Redwall Limestone through the Chinle Formation.

The breccia pipe column abuts against sedimentary rocks. The plane of contact between the breccia column and the surrounding flat-lying rock is formed by a zone of concentric, circular, near vertical fractures ("ring fractures") and inward-dipping strata. The mineral deposits, including uranium, occur in the fracture zone and in the brecciated column; the mineral deposits do not generally extend into the surrounding sedimentary wall rocks. An orebody, if present, is typically located several hundred to more than a thousand feet (150–350 m) above the regional water table in brecciated sandstones and siltstones in the pipes. It is possible, however, that a number of orebodies may be in contact with perched groundwater above the Redwall-Muav aquifer.

While the breccia pipe column is typically only a few hundred feet in diameter, its expression on the plateau surface is often a shallow structural basin (fig. 5) that can be as much as a half mile in diameter. Some pipes form a prominent circular depression with inward-dipping strata (Wenrich and Sutphin, 1988), but others are difficult to decipher and show little surface expression on the plateau surface. Buried, "blind" breccia pipes also exist; these pipes have their roots in the Redwall Limestone and do not extend to the plateau surface. Some geophysical techniques, such as airborne vertical time-domain electromagnetic surveys (Spiering, 2009), have shown promise in locating buried breccia pipes, which have then become potential drilling targets. Once geologic, geochemical, and (or) geophysical indicators suggest that a breccia pipe structure exists at a site, exploratory drilling is conducted to test for uranium deposits at depth. At this time, because the uranium deposits occur deep inside the pipe, usually several hundred feet below the plateau surface, only drilling and sampling of the drilled material can determine if a collapse feature is mineralized at depth.

Figure 4. Photo showing an exposed breccia pipe column (indicated by arrow) in the Grand Canyon area. Note the bending of strata toward the breccia pipe. (Photo by George Billingsley, U.S. Geological Survey.)

Figure 5. Photo showing the surface expression of a collapse structure, specifically the Grand Pipe in the western Grand Canyon near the Colorado River and Grand Wash Cliffs. The structure measures approximately 2,500 feet in diameter. Note circular inward dipping strata with no breccia exposed at the center. (Photo by George Billingsley, U.S. Geological Survey.)

Orebodies

Most of the uranium deposits in the northern Arizona breccia pipes are high grade by U.S. standards. Breccia pipe deposits in this region that were mined or thoroughly drilled during the 1980s revealed average grades of 0.42 to 1.08 percent uranium oxide (U_3O_8) (Pool and Ross, 2007; Moreton and Ross, 2009) in ore bodies containing about 430,000 pounds to 7 million pounds U_3O_8. From breccia pipes of this region, combined uranium production has totaled 23.3 million pounds of ore (to November 2009); this includes past production from the Orphan Mine and the Hack 1, Hack 2, Hack 3, Pigeon, Hermit, Kanab North, and Pinenut pipes/mines in the North Segregation Area.

The primary uranium ore mineral in the breccia pipe deposits is uraninite (UO_2). It is complexly intergrown with numerous sulfide and oxide minerals (Wenrich, 1985; Wenrich and others, 1989). The ore minerals are confined to the breccia pipe column (fig. 3) and the enclosing fracture zone (ring fractures). The principal form of alteration in the rocks surrounding the deposits is nearby bleaching of iron-oxide minerals, thereby turning red sandstones and siltstone to a bleached white color. The uraninite and associated ore minerals are generally fine grained in size, less than 1/32 of an inch across.

Uranium Mining

Mining in breccia pipes of the Grand Canyon region began in the 1860s. Prior to 1940, all of the mineral production was for copper, lead, zinc, and silver. The discovery of high-grade uranium deposits in the Orphan Lode (breccia) pipe led to uranium production at this site in 1956, about two miles west of Grand Canyon Village on the South Rim of Grand Canyon National Park. Though the Orphan Lode deposit seemed to be unique (an "orphan"), discovery of uranium there led to the discovery of uranium in breccia pipes in the region. The Orphan Mine produced 4.3 million pounds of U_3O_8 from 1956 to 1969 (Chenoweth, 1986) and was by far the largest uranium producer in this region during the early era of uranium production of the 1950s and 1960s. Modest uranium production came from a few other breccia pipe mines during this period, including the Hacks (or Hack Canyon), Ridenour, and Chapel Mines (Chenoweth, 1988). The Hack Canyon Mine produced only about 5,000 pounds of U_3O_8 from 1951 to 1954 and in 1961. Mining is no longer permitted within the national park, nearby national monuments, or protected areas of Kaibab National Forest on the North Rim.

Exploration for these kinds of deposits occurred throughout the 1970s, and uranium mining resumed in 1980. During the 1980s and early 1990s, nine pipes were mined or developed, including eight in the North Segregation Area (Kanab Creek area)—the Hack 1, Hack 2, Hack 3, Pigeon, Hermit, Kanab North, Arizona 1, and Pinenut pipes—and one in the South Segregation Area (Kaibab National Forest)—the Canyon pipe. Mining at the Hack 1, Hack 2, Hack 3, Pigeon, and Hermit pipes was completed by 1989 and the sites were then reclaimed. All of the modern breccia pipe mines (1980s forward) in northern Arizona have been underground operations. Auxiliary surface operations at these kinds of sites typically occupy about 15–20 acres. The uranium ore is not milled on site; since 1980, uranium ore from these mines has been shipped to a mill near Blanding, Utah, for processing.

Sulfide minerals associated with orebodies have the potential to produce acidic waters. However, the rock fragments (breccias) that host the orebodies, as well as the sedimentary rock units that surround the breccia pipes, include limestone and calcareous sandstone that have a high capacity to buffer acid waters (Wenrich and others, 1995). The breccia pipe mineral deposits are porous and weather rapidly. Based on experiences with newly mined deposits in the region, the uranium ores can oxidize within six months when exposed to surface conditions (Wenrich and others, 1995), indicating rapid leaching and chemical reaction of these materials, even in the arid environment of northern Arizona.

Overview of This Report

Chapters in this report provide an overview of geological, geochemical, hydrological, and biological issues related to uranium mining and natural resources of the designated segregation areas in the Grand Canyon region. Each chapter provides a detailed discussion of the focus area and, where relevant, identifies additional scientific research that would increase understanding and reduce uncertainty for the issues. The summaries that follow provide a general description of the contents of each chapter.

Chapter A, "Uranium Resource Availability in Breccia Pipes in Northern Arizona," estimates the amount of available uranium resources in the segregation areas. The authors compare uranium endowments from these segregation areas with endowments from other favorable uranium mining areas in northern Arizona.

Chapter B, "Effects of 1980s Uranium Mining in the Kanab Creek Area of Northern Arizona," provides a summary of the geochemistry of surface soils and sediments from a 2009 field assessment of several reclaimed and inactive breccia pipe uranium mines on the plateau north of the Grand Canyon. Stream sediments were also evaluated at a site with no mining history and no known uranium deposits. Chemical analysis for uranium and co-occurring trace metals and measurements of gamma radiation were completed at each site. Samples from breccia pipe sites were analyzed to determine historic wind and water dispersion, and some mine waste samples were evaluated for effects of weathering.

Chapter C, "Historical and 2009 Water Chemistry of Wells, Perennial and Intermittent Streams, and Springs in Northern Arizona," provides an evaluation of available historic water-chemistry data and water-chemistry data collected in 2009 for wells, springs, and streams in the Grand Canyon region. Historical data were used to evaluate effects of legacy mining and provide a baseline concentration for dissolved uranium in water in northern Arizona. New data were collected in the three segregation areas.

Chapter D, “Biological Pathways of Exposure and Ecotoxicity Values for Uranium and Associated Radionuclides,” compiles available chemical and radiation toxicity information for plants and animals from the scientific literature on naturally occurring uranium and associated radionuclides. Exposure pathways are described and a food web specific to the segregation areas is developed. This chapter summarizes pertinent information that will aid in the development of an ecological risk assessment, but it does not estimate or derive guidance thresholds for uranium or radionuclides associated with uranium.

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