The Hydrogeologic Framework and the Impact of High-Grade Uranium Ore Mining on the Grand Canyon Aquifer System

Image of uranium mine operation directly next to the Grand Canyon.
Photo by Michael Collier, Grand Canyon National Trust

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Introduction

Nearly 155 years ago, John Wesley Powell embarked on the first known expedition down the Colorado River through the Grand Canyon (Powell, 1895). The area previously unchartered and unknown to the common settlers in the West, he set out to survey the river cutting through the 5,000 feet vertical rims of Northern Arizona. After his successful voyage down the 277-river-miles of the Grand Canyon, he brought an expansive and lyrical understanding to the people on land:

> *"The Grand Canyon is a land of song. Mountains of music swell in the rivers, hills of music billow in the creeks, and meadows of music murmur in the rills that ripple over the rocks. Altogether it is a symphony of multitudinous melodies. All this is the music of waters." (Powell, 1895)*

Powell's survey and subsequent lessons from the Canyon were globally revered for their geological, geographic and water resource planning impact on the region. He sparked a call to artists, adventurers, scientists and eccentrics to explore the natural wonder and mystery of the Canyon for generations to come. To this day, 6 million tourists visit the Grand Canyon National Park each year (Tillman, 2021). However impactful Powell's first run of the river was for increasing Western understanding and access to the Grand Canyon, the riverbanks had previously been inhabited for thousands of years by the Havasupai Tribe (Hirst, 2006).

Today, the 639 remaining Havasupai people, or the People of the Blue Green Waters, are located within the Havasu Canyon, a large tributary on the south side of the Grand Canyon (Hirst, 2006, Figure 1). The Havasupai Tribe get their name from the gushing spring that acts as the lifeblood for their people. The natural opening in the Redwall Limestone aquifer unit springs out a blue-green water supply directly to the Havasu Canyon, in which the Tribe has used the water for irrigation, drinking supply, and nourishment for centuries (Hirst, 2006). After the development of the Grand Canyon National Park, in thanks to Powell, and the historic inhabitance of the Canyon's riverbanks by the indigenous people, primely the Havasupai People, groundwater is heavily relied upon to sustain tourism, ecosystem health, agriculture, and life in the Grand Canyon. As Powell wrote, the Grand Canyon's beauty lies in "*the music of the waters*." Groundwater is a crucial instrument in the ensemble of the Grand Canyon's water supply.

Approximately 80 years after Powell's first run of the Colorado River, a new category of interested parties zeroed in on the opportunities of the Grand Canyon. Instigated by the United States Government's commitment to expanding their atomic weapons arsenal, the post-World War II economic and nuclear boom launched a "Uranium Frenzy" (Ringholz, 2002). Thousands of uranium prospectors raced to the Southwest in search of uranium deposits to source directly from U.S. domestic soil for atomic bombs and nuclear energy (Amundson, 2001). This quest was supported, and even encouraged, on the national level with the guidance of the Atomic Energy Act of 1947, declaring that nuclear weapon development and nuclear power would be managed by private industry rather than military control (Ringholz, 2002). Less than 10 years later, by 1955, there were over 800 industrial mines producing high grade uranium ore on the Colorado Plateau (Ringholz, 2002). This "Frenzy" ravaged areas surrounding the Grand Canyon (Figure 1). The 1980's showed a steep decline in uranium pricing, the market dropped as the military defensive mindset settled and nuclear power development slowed down (Ringholz, 2002).

Although the mining industry expansion resolved by the late 20th century, the impact of the intense mining operations cuts deep into the aquifers of the Grand Canyon hydrogeologic system, and thus, the people and ecosystems that rely on it. The "*symphony of multitudinous melodies"* that string together the water supply of the Grand Canyon is threatened by impact of historic and current high-grade uranium ore mining in the Grand Canyon.

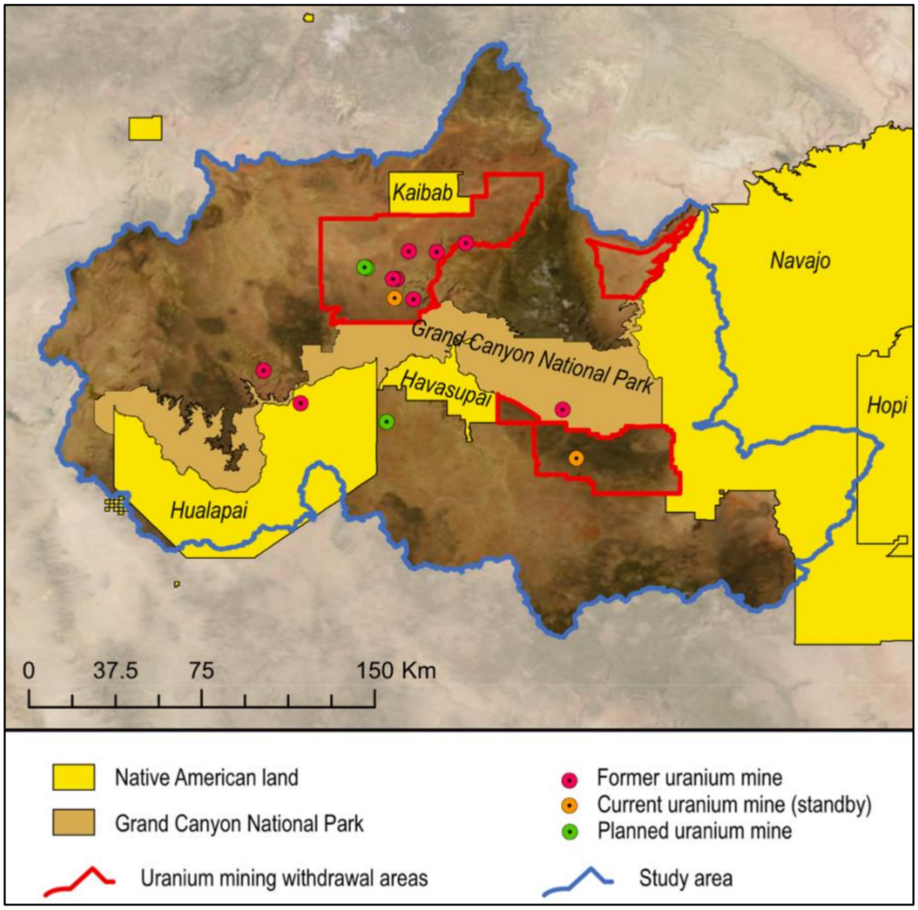

Figure 1. Map of the Grand Canyon region depicting the location of Tribal Nations (in Yellow), the Grand Canyon National Park (beige) and uranium mines and their withdrawal zones (dots and red lines). *Source: Tillman, 2021.*

Groundwater in the Grand Canyon

Hydrogeologic Framework

Powell's bewildered amazement at the geology of the Grand Canyon led to the continued fascination with uncovering the geologic history of the region (Powell, 1895). There are nearly 40 major sedimentary rock units that are exposed on the rims of the Grand Canyon, that range in deposition from the Permian (200 MYA) to the Precambrian (2 BYA) (Knight, 2022). The sedimentary layering of the walls of the Grand Canyon present a unique opportunity for diverse recharge and groundwater flow systems to occur. The primary features of the Grand Canyon geology that govern the flow of groundwater through the region are karst systems, fractures and faults, and the relatively impermeable Bright Angel Shale unit (Cooley, 1976). Given the diversity in recharge regimes of the Grand Canyon Aquifer systems, there is immense variability in age of groundwater. Estimated ages of groundwater in the Grand Canyon range from 6 years old to 20,000 years old, respectively (Solder, 2020). There are two principal aquifers responsible for groundwater storage, flow and distribution in the Grand Canyon (Figure 2).

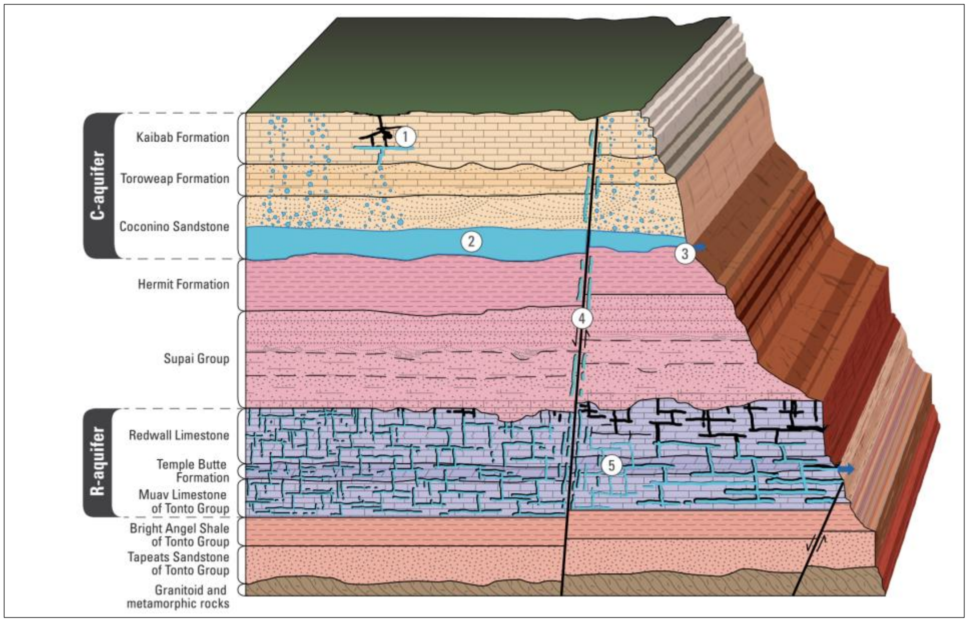

Figure 2. Conceptual cross-sectional diagram of the hydrogeologic units of the rims of the Grand Canyon. Highlighted sections include, (1) recharge to the C-aquifer, (2) storage of the C-aquifer, (3) discharge from the C-aquifer, (4) vertical flow to the R-aquifer, and (5) storage, flow, and discharge of the R-aquifer. *Source: Knight, 2022*.

The C-Aquifer

The Coconino Aquifer (C-aquifer) is a shallow, unconfined system consisting of sandstones and limestones of the Coconino Sandstone, Toroweap Formation, and the Kaibab Formation (Solder, 2020, Figure 2). These rock units are spatially discontinuous and unconfined due to the elevated plateau, well-draining material, and extensional fault zones in the C-aquifer. The water table of the C-aquifer is diverse throughout its extent, including depths of 300 feet to over 1,500 feet, to parts where it is completely dry except for localized perches (Bills, 2016). The Hermit shale Formation and the Supai Group, stratigraphically below the Coconino Sandstone, serve as aquitards to the C-aquifer (Knight, 2022, Figure 2).

Recharge to the C-aquifer occurs via three primary mechanisms, (1) runoff from snowmelt of the nearby elevated peaks of the San Francisco Mountains, (2) alluvial channels leading to vertical soil infiltration in the plateaued region, and (3) diffuse recharge directly from precipitation (Solder, 2020). These recharge regimes are typical of a shallow, unconfined system. Once the water infiltrates into the C-aquifer, the general flow direction through the unconsolidated sediment is towards the Canyon through springs and seepage systems (Knight, 2022). The springs discharging from the C-aquifer are slow-rate, small springs, often home to hanging gardens. Although, the Hermit Shale unit acts as a regional aquitard to the C-aquifer, there are pathways for water to migrate vertically from the C-aquifer (Bills, 2016, Figure 2). Percolation to deeper units into the geologic stratigraphy of the Grand Canyon occurs via faults and fractures, transporting water from the surface, through the C-aquifer to the underlying regional aquifer system, the Redwall Mauv Limestone Aquifer.

The R-Aquifer

The Redwall Mauv Limestone Aquifer (R-aquifer) is a deep, confined system consisting of the Redwall Limestone, Temple Butte Formation, and Mauv Limestone rock units (Knight, 2022, Figure 2). The R-aquifer is situated approximately 1,000 to 3,000 feet below the C-aquifer (Solder, 2020). It is stratigraphically confined by the overlying aquitard of the Supai Group and the underlying aquitard of the Bright Angel Shale formation (Figure 2). The faults and fractures of the Grand Canyon stratigraphy, hydraulically connect the C-aquifer and the R-aquifer in the northeast parts of the Grand Canyon (Bills, 2016). The R-aquifer is primarily a karst system, dominated by the dissolution of limestone to form connected flow paths throughout the stratigraphic units (Knight, 2022). This internal dissolution results in linear passageways for water to move in the general dip direction of the hydraulic gradient, which in the Grand Canyon, is towards the Colorado River from either rim (Solder, 2020).

Recharge into the R-aquifer is dominated by mountain block recharge (Solder, 2020). Mountain block recharge is a process of vertical downward migration of groundwater from high topographic water sources through deep fractures, faults and collapse features of the bedrock to the aquifer unit (Bills, 2016). In the Grand Canyon, the snowcapped peaks of the San Francisco Mountains are comprised of dense bedrock with an integrated regime of fractures and faults that allow for water to percolate through them and reach the R-aquifer. Along the lower contact with the Bright Angel Shale Formation, the R-aquifer discharges water to tributary canyons, which serve as aquifer drainage pathways. These pathways lead to over 200 known springs in the Grand Canyon National Park, over 24 springs to the Havasu Creek, and supply baseflow to multiple tributary streams leading to the Colorado River (Knight, 2022). Importantly, the largest of these springs, the Roaring Springs, acts as the primary drainage for the R-aquifer in the south-central portion of the Grand Canyon. The Roaring Springs serve as the sole source of water supply for the Grand Canyon National Park, including all 6 million of its annual residents and visitors (Solder, 2020, Knight, 2022).

Groundwater Supply

Powell catalyzed the obsession with the natural wonders of the Grand Canyon in the late 1800’s, and the lure has yet to diminish. The Grand Canyon National Park hosts over 6 million residents and visitors every year (Solder, 2020). All 6 million people require water for drinking, food preparation, irrigation, and sanitization, however brief their trip to the Grand Canyon may be. The Grand Canyon National Park pipes water from the Roaring Springs to meet this demand year-round (U.S. National Park Service). The pump house and piping shoot out of the contact of the Redwall Limestone and the Bright Angel Shale formations prior to the R-aquifer’s contact with the atmosphere and deliver the water to the North Kaibab Trailhead (U.S. National Park Service). It is estimated that the National Park Service pumps between 600 -1,000 acre-feet of water a year to meet the demand (U.S. National Park Service).

In addition to the employees and visitors of the park, the surrounding tribal nations, especially the Havasupai People, rely on water from the R-aquifer for the entirety of their supply. The Havasupai People rely solely on water sourced from the spring fed Havasu Creek that runs through their growing reservation (Hirst, 2006). In 1975, Congress returned 185,000 acres of Grand Canyon and Rim territory to the Havasupai Tribe, increasing their geographical extent and thus creating more land for agriculture and domestic uses (Hirst, 2006). The R-aquifer discharges all of the water required to maintain the flow into the Havasu Creek on the southern edge of the Grand Canyon (Figure 1). In addition to providing the physical lifeblood to the Havasupai People, groundwater also holds incredible cultural significance for the Tribe. The Havasu Falls are blue-green waterfalls throughout the Havasu Canyon. The waterfalls exhibit this blue-green color because of the high calcium carbonate concentrations leached out from the karstification of the R-aquifer (Hirst, 2006). The Havasupai People, translating to the "people of the blue-green waters," have dwelled along this canyon for over 1,000 years; their lineage, ancestry, spirituality, and existence are inextricably tied to the groundwater emerging from the Grand Canyon Aquifer system.

Uranium Mining in the Grand Canyon

The Grand Canyon National Park and the Havasupai Tribe share a geographical boundary and a water source. Powell's own account through the Canyon in 1895 spirited a reverence and respect for the indigenous communities he encountered along the way (Powell, 1895). Although there has been a complicated history of land stealing, colonialization, and cultural erasure by the U.S Government to indigenous peoples across the Country, the three bordering tribes of the Grand Canyon now exist peacefully and in cooperation with the National Park Service (Hirst, 2006). That being said, not all of the neighboring parties share this sentiment. The uranium mining industry that has been drilling into the Grand Canyon and Colorado Plateau since the 1950's continues to threaten the groundwater supply of the region (Ringholz, 2002). This region was prospected specifically in search of breccia pipes, an iconic and unique source of high-grade uranium. The development of mines at these breccia pipe locations is dangerous to the surrounding groundwater systems because the perched springs, hydraulic gradient, and collapse features come into contact with the regional supply of the C-aquifer and R-aquifer units (Solder, 2020).

Breccia Pipes

Breccia pipes are the source of high-grade uranium in and around the Grand Canyon. Breccia pipes are a geological product of acidic groundwater intrusion, cave development, clast deposition, hydrothermal fluid intrusion, and preferential mineralization (Sutphin, 1989). Although there continues to be scholarly debate to the exact process of breccia pipe formation, the simplified seven steps of deposition are presented below (adapted from *USGS Report* Sutphin, 1989):

1. The stratigraphic rock layers of the Grand Canyon are deposited from the Permian (200 MYA) to the Precambrian (2 BYA). Resulting in the deep layers of igneous and metamorphic rocks, and the more surficial sedimentary rocks. The C-aquifer and the R-aquifer develop through variable recharge and discharge regimes.
2. Throughout the Permian and Jurassic eras (260-200 MYA) acidic groundwater intrudes into the limestone of the R-aquifer. Intense karstification occurs dissolving

limestone and creating voids and cavities. Carbon dioxide and other dangerous gasses are trapped in the caves.

3. The less dense gasses migrate vertically upward through the rock stratigraphy because of their buoyancy, causing vertical rupturing of the overlying units.
4. The roof of the cave continues to collapse, depositing large, angular boulders (clasts) from the overlying units on the cave floor. Tens of millions of years of vertical migration, roof collapse, and upward climb of the cave, create a vertical pipe, cross-cutting thousands of feet of the Grand Canyon stratigraphy.
5. A period of high intensity mantle convection brings elementally rich hydrothermal fluid to the region. The hydrothermal fluids migrate through the breccia pipes, releasing dissolved minerals, gasses and salts throughout the stratigraphy.
6. The preferential mineralization of uranium occurs under the correct pressure and temperature conditions hosted by the Hermit Shale Formation. Causing high-concentration uranium pockets to deposit in the breccia pipes in line with the Hermit Shale Formation.
7. Lastly, wind and water erode down surficial units to bring the tips of the collapsed breccia pipes to the surface of the earth. The surface appears different than its surroundings because it exhibits fascinating rocks, topographic depressions, and mineralogical anomalies.

The structure of breccia pipes in the Grand Canyon are over 32,000 feet in width, and between 2,600 and 4,600 feet deep (Barnhart, 2019). They cut vertically through the stratigraphy, starting in the Redwall Limestone unit and migrating upwards, some outcropping at the top of the Toroweap Formation (Sutphin, 1989, Figure 3a). Breccia pipes are present throughout the Colorado Plateau, fanning throughout the Southwest of the U.S. (Figure 3b). There are more than 1,300 breccia pipes surrounding the Grand Canyon itself (Barnhart, 2019, Figure 3b). The uranium in breccia pipes is incredibly concentrated and rich, making it especially attractive for mining purposes. The Grand Canyon region holds 1.3% of the U.S.'s uranium supply, yet it makes a severe impact on its surroundings (U.S. National Park Service).

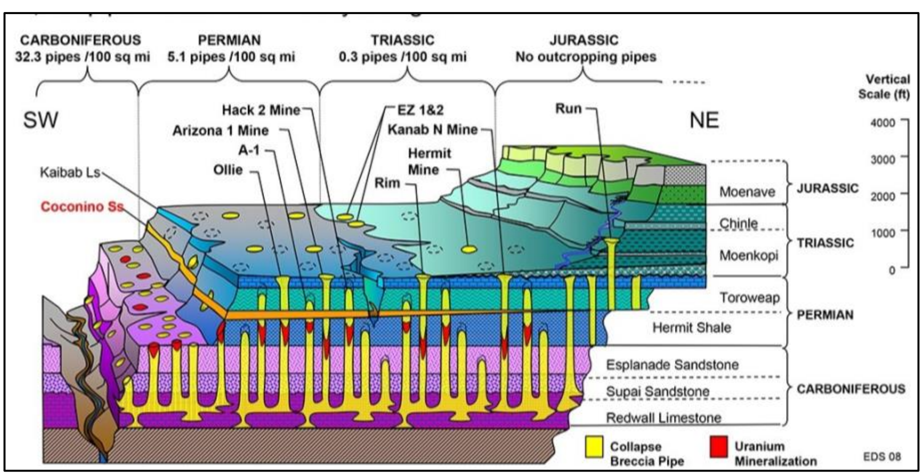

Figure 3a. Cross sectional diagram of the north side of the Grand Canyon. Breccia pipes that have been previously mapped are shown in yellow, uranium mineralization in the Hermit Shale Formation in red. *Source: Sutphin, 1989.*

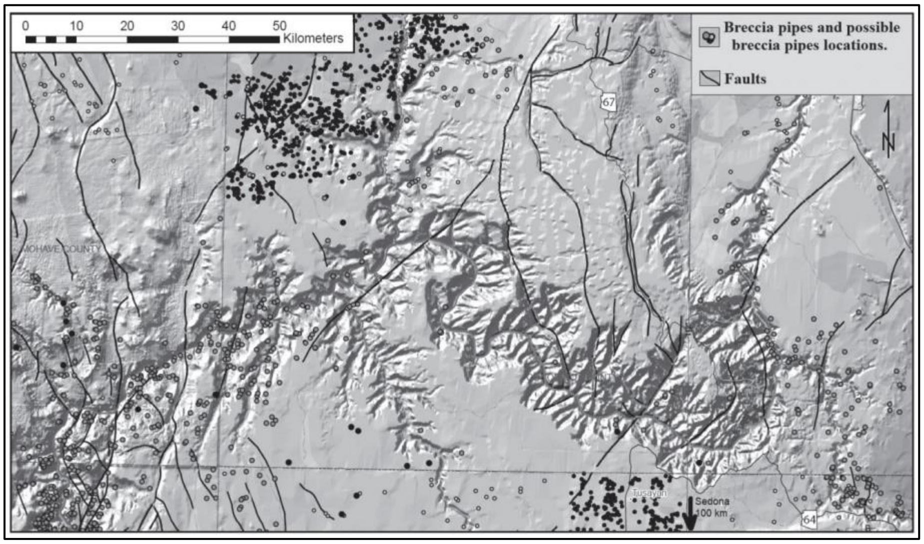

Figure 3b. Map of known or prospected breccia pipe locations surrounding the Grand Canyon in northwest Arizona. Black and grey dots indicated the roughly 1,300 breccia pipe locations on the regional Colorado Plateau. *Source: Barnhart, 2019.*

Groundwater Contamination from Uranium Mining

Out of the 1,300 known breccia pipes around the Grand Canyon, there are currently 598 mining claims filed to them (Tillman, 2021, Figure 1). Uranium is dangerous when it is extracted and mobilized during mining operations to regional groundwater systems through several mechanisms. Figure 4 demonstrates the close proximity of the uranium deposits to the perched C-aquifer and the hydraulic pathways for contaminants to transport to the deeper R-aquifer through fractures, dissolution and infiltration (Tillman, 2021). The process of extraction of uranium, requires a medley of highly acidic, toxic chemicals to dissolve the uranium bulk rock into more manageable entities (Ringholz, 2002). This process not only exposes the uranium during extraction, making it more radioactive, but it also releases the waste from mining into the surrounding aquifer (Amundson, 2001). Additionally, the solutions used to excavate the uranium are then pumped back up through the shaft to sit in surficial ponds and either (a) infiltrate back into the shallow aquifer, or (b) evaporate into the air, both of these processes result in contamination of nearby water and air (Amundson, 2001, Figure 4,). In just 1 year there can be over 10 million gallons of contaminated water leached out from a single mine to the surrounding environment, with the 800 current and historic uranium mines in the Grand Canyon, the impact of this contamination is severe (Tillman, 2021). In addition to disturbing regional *water quality*, mine shafts pierce aquifer layers that then require pumping for no intended use, also putting a strain on *water quantity* in the region.

As deep wells and mine shafts continue to drill into the R-aquifer and pierce through the C-aquifer, the quality of water delivered to both the Grand Canyon National Park and the Havasu Creek are threatened. In 2010, a U.S.G.S survey determined 15 springs and 5 wells near uranium mines within the boundaries of the Grand Canyon National Park watershed, to have dissolved uranium concentrations exceeding the EPA standard of 30 ppb (U.S. National Park Service). The EPA established the abandon mine site, the Orphan Mine, a Superfund Site on the boarder of the Grand Canyon National Park (Chen, 2022, Figure 1). Currently, there is signage throughout the interior of the Park that reads, “water not suitable for drinking,” indicating the increasing levels of uranium concentration in the seeps and springs within Grand Canyon National Park (Chen, 2022).

The Havasupai Tribe are fiercely trying to protect their water source from increased uranium contamination. The Pinyon Plain Mine, located 10 miles south of the Grand Canyon, bordering the Havasu Creek tributary, has pumped over 30 million gallons of contaminated groundwater to date (Chen, 2022, Figure 1). Tillman et al. (2021) published that the groundwater surrounding the Pinyon Plain Mine and recharging the perched aquifers leading to the Havasu Canyon have an average uranium concentration of 15 ppb. The continued use of the mine and radioactive decay of the existing uranium in the aquifers significantly contaminants the sole water supply of the Havasupai People in the Grand Canyon, threatening their livelihood in the region and their cultural and ancestral claim to the land (Marsh, 2022).

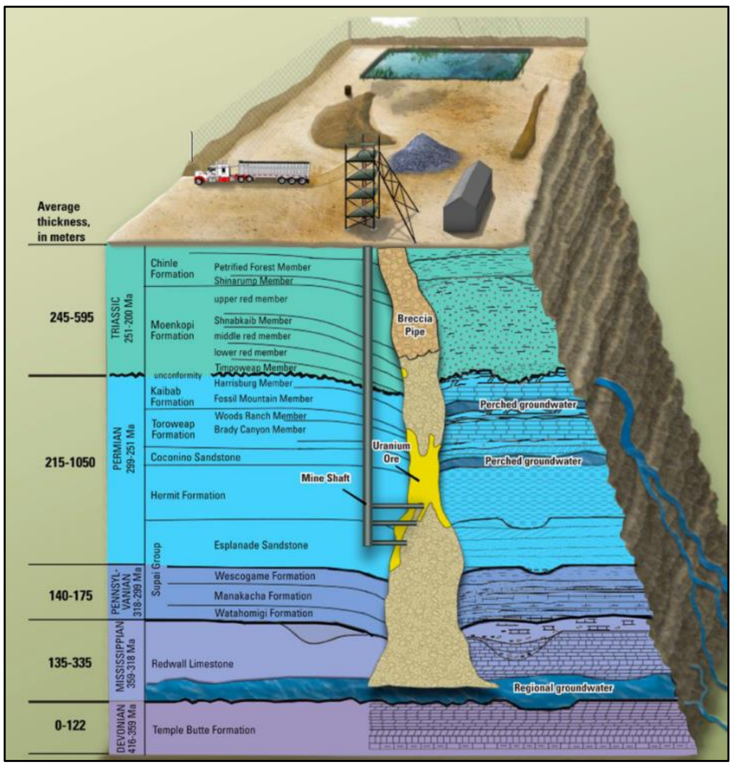

Figure 4. Cross-sectional diagram of the geology, hydrogeology, mining shaft, surface pond, and waste pile of a uranium mine in the Grand Canyon. *Source: Tillman, 2021.*

Current Legal Landscape

The Havasupai People have been in a decade long battle with the U.S. Government to ban mining operations in the region. In 2012, the Secretary of the Interior put a temporary (20 year) pause to future mine exploration but did not halt current production or allocate additional money to clean up abandoned mine sites (Marsh, 2022). In response, the Inter-Tribal Association of Arizona, including 21 tribal nations, passed a resolution titled, "The Grand Canyon Protection Act." This act calls for the banning of new uranium minds in the Canyon forever. The Act has now passed the House of Congress with widespread bipartisan support, only two weeks after it was introduced by Arizona Senators in 2021 (Marsh, 2022). On a visit to the U.S. Congress in Washington D.C. in 2019, Havasupai Tribe councilmember, Carletta Tilousi called for support of the Act, saying, "We are in extinction" as the "mining threatens to poison our waters, harm our economy, and risk our way of life, it is the Havasupai, people of the blue-green water, who must come to the Grand Canyon's defense" (Agoyo, 2019, Figure 5). The current, 118th U.S. Senate, now has the power to vote on the "Grand Canyon Protection Act." An affirmative vote from the Senate would decree a moratorium on the ban of new uranium mines, potentially safeguarding over 1 million acres of public lands surrounding the Grand Canyon, the groundwater supply to the National Park, and most critically, the lifeblood of the Havasupai People (Agoyo, 2019).

Figure 5. Photograph of Carletta Tilousi, Havasupai Tribe council member, speaking in front of the U.S. House of Congress in 2019, presenting on the Grand Canyon Protection Act. *Source: @IndianZ Twitter Account*.

Conclusion

Powell's vision is in danger. Since the 1950's, uranium mining in the Grand Canyon has threatened the melodic harmony of the groundwater supply. The *"land of song"* that Powell experienced on that first voyage in 1869 is still intact, inspiring visitors and inhabitants on the daily, but the looming fear of contaminated waters, and the erasure of culture and significant livelihoods, is infiltrating the beat of the Canyon (Powell, 1895). The future projections of this concern are only worsening with increased climate change and drought. The biogeochemical processes that control the mobility and fate of uranium are heightened with aridification as the aquifers become more vulnerable to extreme events (Chen, 2022). In preserving Powell's fantastical view of the Grand Canyon, the livelihood and importance of the Havasupai People, and the critical water supply to the visitors of the National Park, increased energy and emphasis needs to be applied to the Grand Canyon Protection Act. If this does not happen, we risk replacing the "*murmur in the rills that ripple over the rocks"* with the piercing buzz of pneumatic drills sinking new mine shafts into the aquifers of the Grand Canyon.

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