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**BRECCIA-PIPE URANIUM MINING IN THE GRAND CANYON
REGION AND IMPLICATIONS FOR URANIUM LEVELS IN COLORADO
RIVER WATER**

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April 2011

ARIZONA GEOLOGICAL SURVEY

Breccia-pipe uranium mining in the Grand Canyon region and implications for uranium levels in Colorado River water

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Abstract

The Grand Canyon region contains over 1300 known or suspected breccia pipes, which are vertical, pipe-shaped bodies of highly fractured rock that collapsed into voids created by dissolution of underlying rock. Some breccia pipes were mineralized with uranium oxide as well as sulfides of copper, zinc, silver, and other metals. Renewed exploration during and following a steep rise in uranium prices during 2004-2007 led some to concerns about contamination of the Colorado River related to uranium mining and ore transport. Total breccia-pipe uranium production as of Dec. 31, 2010 has been more than 10,700 metric tons (23.5 million pounds) from nine underground mines, eight of which are north of Grand Canyon near Kanab Creek. Colorado River water in the Grand Canyon region currently contains about 4 µg/l (micrograms per liter) of uranium (equivalent to 4 ppb [parts per billion by mass]), with approximately 15 cubic kilometers annual discharge. Thus, approximately 60 metric tons of dissolved uranium are naturally carried by the Colorado River through the Grand Canyon in an average year. We consider a hypothetical, worst-case accident in which a truck hauling thirty metric tons (66,000 pounds) of one-percent uranium ore is overturned by a flash flood in Kanab Creek and its entire ore load is washed into the Colorado River where it is pulverized and dissolved during a one-year period to become part of the dissolved uranium content of the river (such a scenario is extremely unlikely if not impossible). This addition of 300 kilograms (660 pounds) of uranium over one year would increase uranium in river water from 4.00 ppb to 4.02 ppb. Given that the EPA maximum contaminant level for uranium in drinking water is 30 ppb, this increase would be trivial. Furthermore, it would be undetectable against much larger natural variation in river-water uranium content.

Breccia-pipe uranium deposits

Paleozoic strata of the southwestern Colorado Plateau are spectacularly exposed in the walls of the Grand Canyon. This approximately 1 km-thick sedimentary sequence rests on Proterozoic schist, granite, and tilted sedimentary rocks visible in the bottom of the eastern Grand Canyon. The Mississippian Redwall Limestone, one of the cliff-forming Paleozoic sedimentary rock units exposed in the Canyon, is located several hundred meters (up to several thousand feet) below the Canyon rim. After the Redwall Limestone was deposited (between about 359 and 318 million years ago), it was slightly elevated above sea level, leading to dissolution of the limestone and formation of a rubble zone called a dissolution breccia (McKee and Gutschick, 1969; Beus, 1989; Troutman, 2004). Some of these breccias remained highly porous and permeable while overlying strata were deposited, and are now an excellent source of potable groundwater in some areas, and contain significant dissolved solids in others.

A breccia pipe is a vertical, pipe-like mass of broken rock (breccia), typically a few tens of meters across and hundreds of meters in vertical extent (Fig. 1). Breccia pipes formed within Paleozoic and Triassic strata over a broad area around the Grand Canyon. They were created when groundwater, flowing through Redwall Limestone dissolution breccias and along fracture zones, dissolved more limestone, causing collapse of overlying rocks and possibly creating sink holes. Some pipes extend many hundreds of meters upward into the Chinle Group (formerly Chinle Formation; Heckert and Lucas, 2003), indicating that some pipes are at least as young as this Upper Triassic rock unit (Brown and Billingsley, 2010). Some pipes are blind and never broke through to the surface. Breccia pipes are abundant in the Grand Canyon region, with approximately 1300 pipes or suspected pipes identified (Fig. 2; Sutphin and Wenrich, 1989; Brown and Billingsley, 2010).

Cover Illustration. The high plateaus above Kanab Creek are barren of most vegetation except sagebrush. Within these plateaus lie thousands of breccia pipes. Some of them contain the highest grade uranium in the U.S. and some are dissected by the canyons and tributaries of northern Arizona, exposing them to oxidation and weathering. The Kanab North breccia pipe, which contains high-grade ore and is incised along the west wall of Kanab Creek, is shown in the center of this aerial view over Kanab Creek (see insert). Note the small area of red Moenkopi Sandstone within the amphitheater eroded into the breccia pipe. Much of the ore from this dissected breccia pipe has been mined (2.7 million pounds of U_3O_8) through the shaft below the headframe in photo. This block of sandstone was downdropped 700 feet into the pipe during breccia-pipe collapse over 200 million years ago. Photos by K. Wenrich.

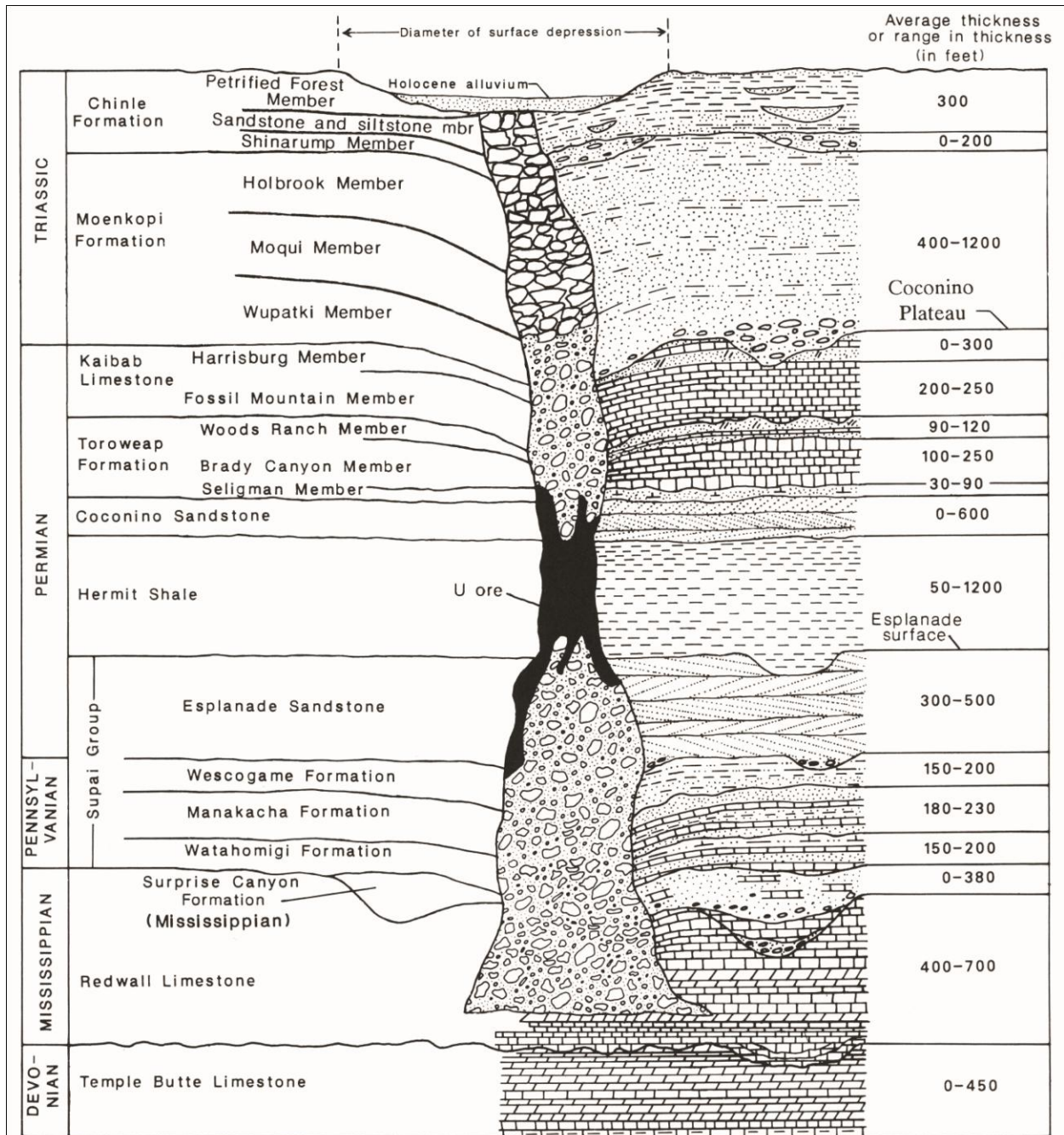
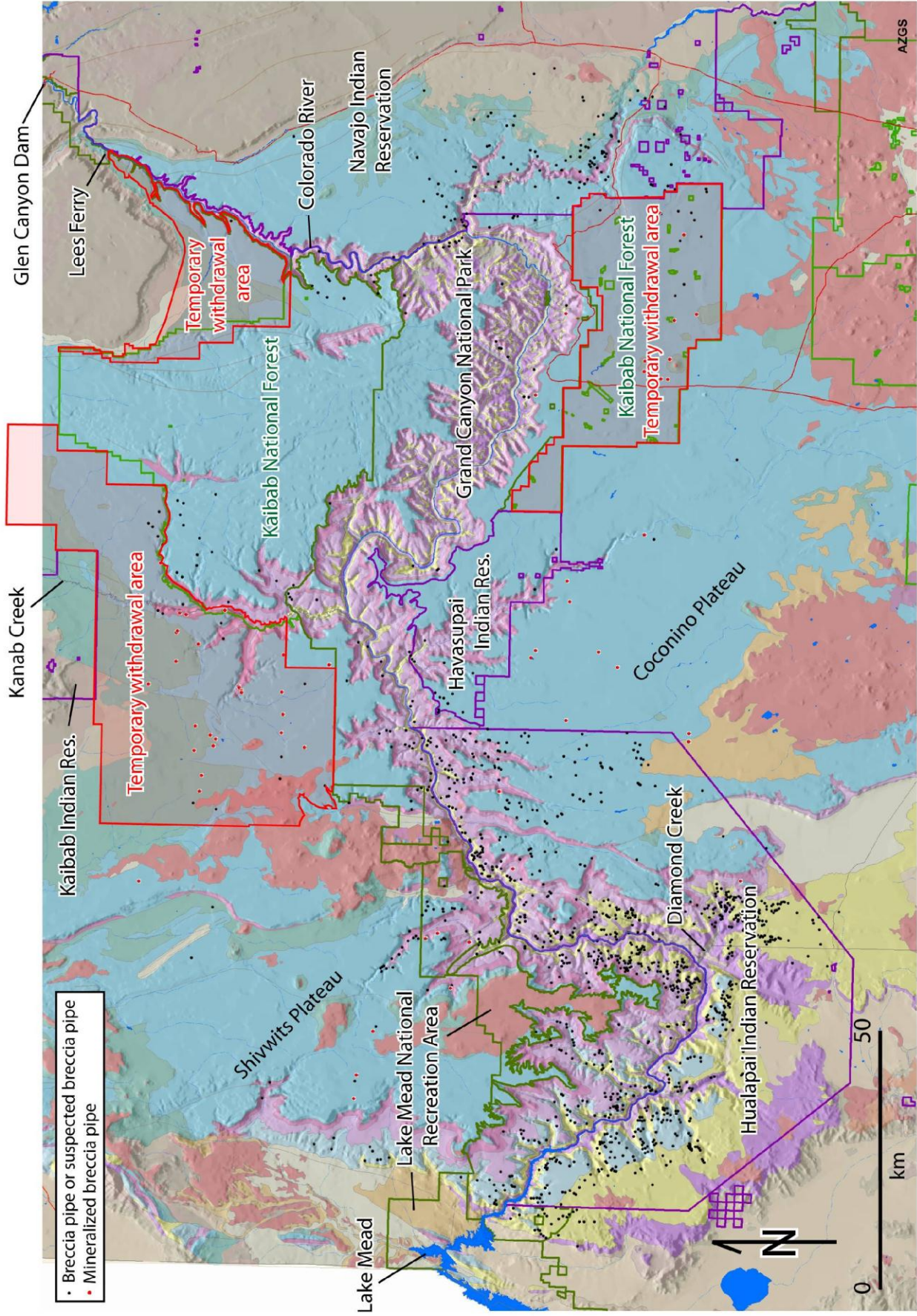


Figure 1. Simplified cross section of a breccia pipe and host uranium mineralization (modified from Finch et al., 1990).

Figure 2 (next page). Geologic map of the Grand Canyon area in northwestern Arizona showing the many areas that are off-limits to uranium mining (all labeled areas except parts of the Shivwits and Coconino Plateaus), including the three 2009 temporary withdrawal areas. Blue represents the Kaibab Limestone that forms most of the rim of the Grand Canyon and surrounding plateaus. Red represents late Cenozoic volcanic rocks. Thin red lines represent highways.



Warm to hot brines migrated through the Redwall solution breccia and up the breccia pipes at about the time, or shortly after, the pipes formed, and may have contributed to some late-stage pipe dissolution and collapse. Abundant sulfide minerals were precipitated from these brines, including pyrite (FeS), chalcopyrite (CuFeS₂), galena (PbS), and sphalerite (ZnS), and a great variety of other minerals, including Ni-Co sulfides. Fluid-inclusion analysis of some of the precipitated minerals indicates that mineralizing solutions were brines with salinities commonly >18 wt% NaCl equivalent and homogenization temperatures of, generally, 80° to 173°C (Wenrich and Sutphin, 1989).

Uranium, in the form of uraninite (UO₂), is abundant in some breccia pipes. Because uranium is soluble and hence mobilized by oxidizing aqueous solutions, such as most shallow groundwater, and is immobile in reducing aqueous solutions, such as those associated with sulfide mineral precipitation, it is generally believed that breccia-pipe uraninite was derived from different solutions than were the sulfide minerals. This inference is supported by the observation that uranium minerals were precipitated after most sulfide minerals. Most likely, oxidizing aqueous solutions carrying dissolved uranium flowed laterally through the Esplanade Sandstone Member of the Supai Group, entered the breccia pipes, and mixed with ascending, reducing brines (Wenrich and Titley, 2008). Mixing of solutions caused chemical reduction of the uranium and immediate precipitation of uraninite, typically in the pipe breccia adjacent to the Hermit Shale or Coconino Sandstone (Fig. 1). Alternatively, oxidizing, uranium-bearing solutions reacted with previously precipitated sulfide minerals, similarly causing prompt uraninite precipitation (oxidation/reduction front in figure 19 of Wenrich and Titley, 2008). Uranium-lead isotopic analysis of uraninite indicates uraninite precipitation at 200-260 Ma (Ludwig and Simmons, 1992).

Breccia-pipe uranium exploration and mining

As noted above, the Grand Canyon region contains at least 1300 known or suspected breccia pipes (Sutphin and Wenrich, 1989; Wenrich and Titley, 2008). Exploration for mineralized breccia pipes over the flat to gently sloping plateaus around the Grand Canyon is directed at finding a set of features, as follows: (1) a circular depression a hundred meters to 1.5km across, (2) inward-dipping beds that may indicate collapse into an underlying pipe, (3) brecciated rock, (4) sulfide minerals or altered sulfide minerals, and (5) radioactivity anomalies. In most cases, it is necessary to drill into the underlying rock to determine if a breccia pipe is mineralized, and necessary to drill hundreds of meters to determine if the breccia pipe contains uraninite ore. Electromagnetic techniques that identify electrically conductive minerals deep below the surface have been successfully used in the search for uranium ore.

By 1989, over 71 breccia pipes had been drilled and were found to contain ore-grade mineralized rock (Sutphin and Wenrich, 1989). As of 2010, nine of these breccia pipes had yielded approximately 10,653 metric tons (23.5 million pounds) of uranium. Eight of these breccia pipes produced approximately 10,522 metric tons (23.2 million pounds) of uranium between 1980 and 1994 (Wenrich and Titley, 2008). The ninth has produced an additional 132 metric tons (0.29 million lbs.) of uranium over a 13-month period between Dec. 1, 2009 until Dec. 31, 2010 (Harold Roberts, Denison Mines (USA), written communication, 2011). These small, deep uranium deposits are mined by way of conventional underground mining rather than

by open-pit methods. Generally, two shafts are used, with a second shaft to provide ventilation and an alternative escape route in case of emergency. Remediation and mine closure are done by filling the shafts with waste rock and re-grading and re-vegetating the land. This can be, and has been, done with essentially no long-term environmental consequences.

Dissolved uranium in the Colorado River

Concerns about adverse environmental consequences of uranium mining led to temporary withdrawal from mineral entry of approximately one million acres of public land in the Grand Canyon region encompassing three different sub-areas (“Temporary withdrawal area” on Figure 2). This was done in spite of the fact that there had been no environmental accidents or significant events during the 1980-1995 period of breccia-pipe mining, nor during the following 15 years of mining inactivity. This temporary withdrawal was placed into effect on July 21, 2009, by the U.S. Secretary of the Interior, Ken Salazar, for period of time “up to two years”. During this time the U.S. Bureau of Land Management (BLM) was instructed to prepare an Environmental Impact Statement (EIS) evaluating the consequences of various alternatives for a 20-year withdrawal period. BLM retained SWCA Environmental Consultants (SWCA) to prepare the EIS under BLM’s direction. The Arizona Geological Survey is one of the many Cooperating Agencies in the EIS development process.

One concern about adverse environmental consequences of uranium mining was expressed by then Governor of Arizona Janet Napolitano in a letter, dated March 6, 2008, to U.S. Secretary of the Interior Dirk Kempthorne (Appendix 1). That letter stated that “the dramatic rise in prices for uranium over the last three years has created a ‘boom’ that has the potential to seriously harm the Grand Canyon National Park and the water quality of the lower Colorado River.” Concern about contamination to the Colorado River was reiterated by environmental groups such as the Sierra Club: “Mining would have ... threatened to contaminate the Colorado River, the source of drinking water for tens of millions of people.”

(<http://sierraclub.typepad.com/scrapbook/2008/10/club-allies-sto.html>, accessed Dec. 10, 2010 under the heading “Club, Allies Stop Uranium Mining Next to Grand Canyon”).

An evaluation of potential contamination of the Colorado River due to uranium mining requires consideration of the natural uranium concentration in river water. Two hundred and seventy uranium analyses of river water from three sites along the Colorado River between Glen Canyon Dam and Lake Mead, summarized by Bills et al. (2010, Figure 15 and Appendix 4), indicate average dissolved uranium concentration of generally between three and eight parts per billion (ppb), with significant variability (Fig. 3; Table 1). One hundred measurements during a nine-year period (1963-1972) from a site below Page, Arizona, show decreasing dissolved uranium concentrations after the first ~1.5 years, possibly because of increasingly significant effects of water impoundment by Glen Canyon dam directly upstream (Fig. 3). Dissolved uranium concentration during this initial measurement period varied from six to twelve ppb, but then dropped below approximately eight ppb. The average concentration for the entire nine year measurement period was 6.46 ppb uranium (U) (n=100), while the average concentration following the first 18 months of the measurement period was 5.57 ppb U (n=73) (Table 1). Measurements at Lees Ferry during 1996 to 1998 averaged 3.24 ppb U (n=19), while measurements near Peach Spring (1997-2007), near the head of Lake Mead, averaged 3.57 ppb U (n=78). On the basis of these data sets, we consider modern Colorado River water to have a dissolved uranium concentration of 4 ± 1 ppb uranium.

Table 1. Uranium concentration in Colorado River water, Grand Canyon area*

site	time period of survey	n	average U (ppb)	standard deviation	source
Page	5-1963 to 5-1972	100	6.46	2.24	USEPA (1973)
Page	7-1965 to 4-1972	73	5.57	1.49	USEPA (1973)
Lees Ferry	1-1996 to 8-1998	19	3.24	0.38	USGS (2009)
Near mouth of Diamond Creek	11-1996 to 8-2007	78	3.57	0.46	USGS (2009)

*table derived from Bills et al., 2010, Appendix 4

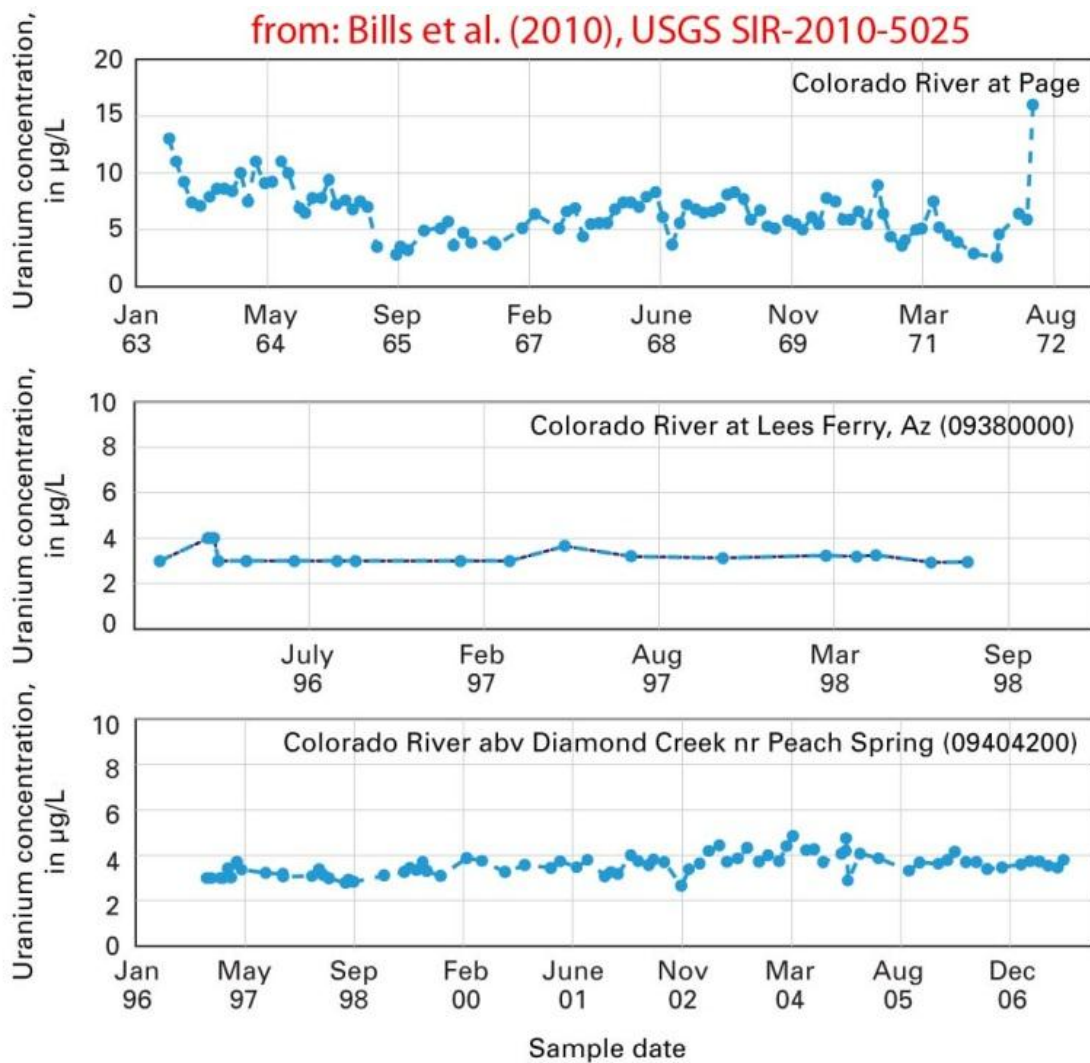


Figure 3. Dissolved uranium concentration in Colorado River water from measurements at three sites in the Grand Canyon area (modified from Bills et al., 2010, Figure 15). Sample locations are shown in Figure 2 (Page locality is just below Glen Canyon dam).

The 4±1 ppb uranium level considered to be representative of Colorado River water is below the 5.57 ppb average for a long set of measurements made during the period 1965-1972 (Table 1; Fig. 3). We consider this acceptable partly because analytical methods improved considerably by the time later measurements yielded generally lower levels, and consider it likely that earlier measurements were less accurate. This is indicated by much greater variability of earlier measurements, with a standard deviation of the older data set that is considerably higher than for later data sets (Table 1).

The 4±1 ppb uranium level estimated for the modern Colorado River probably underestimates natural Colorado River water conditions, as indicated by higher levels recorded below Glen Canyon dam immediately after initial water impoundment. We speculate that Colorado River uranium levels were naturally higher before river water was impounded and suspended sediment removed by settling to the reservoir floor. While 4±1 ppb uranium in Colorado River water may be an underestimate of pre-reservoir, natural water conditions, it is more relevant to evaluating potential contamination from future mining.

Colorado River water flux in the Grand Canyon region averages 13 to 16 cubic kilometers per year (km³/yr), depending on the measurement site and set of years over which measurements were made (Table 2, note that 1.29E+07 = 1.27 x 10⁷). A cubic kilometer of water, corresponding to a cube of water 1000 m along each side, contains a billion cubic meters, each of which has a mass of one metric ton (a tonne). Thus, if one cubic kilometer of water contains one ppb of uranium, it contains one tonne of uranium (one tonne = 1000 kg = 2205 lbs). As outlined above, uranium concentration of Colorado River water is estimated at 4±1 ppb. Thus, 13 to 16 km³/yr of river water carrying 4±1 ppb dissolved uranium correspond to a uranium flux of 39 to 80 tonnes (86,000 to 176,400 lbs.) carried by the Colorado River each year. We represent this as 60±20 tonnes/year uranium.

Table 2. Colorado River water volume, Grand Canyon area

Source	ac-ft / yr	gal / ac-ft	m³/gal	m³/yr	km³/yr
Smith et al., 1997, p. 49*	1.29E+07	325851	0.003785	1.59E+10	15.95
Irelan, 1971, p. E9**	1.21E+07	325851	0.003785	1.50E+10	14.96
Anning, 2002, Table 3***	1.08E+07	325851	0.003785	1.33E+10	13.26

*Discharge at Lees Ferry (1912-1962) before Lake Powell began filling in March, 1963

**Discharge at Grand Canyon 1926-1962

***Discharge at Davis Dam, 1995-1999

A worst-case uranium-ore spill

We now consider a maximum credible uranium-ore spill into the Colorado River that assumes a sequence of worst-case events. We consider this scenario as bordering on impossible, but consider it nevertheless in order to address concerns about contamination of a vast and enormously valuable water resource. Any real uranium spill is likely to be much smaller than the scenario outlined here.

Uranium ore is hauled in trucks with loads up to 30 tons (about 27.2 tonnes), usually in a 20 ton trailer with a second trailer containing 10 tons (Kris Hefton, Vane Minerals LLC, personal communication, 2010). We represent this as 30 tonnes of ore, recognizing that this is slightly larger than a likely real full load. Most breccia-pipe uranium ore varies from 0.4 to 0.8% uranium oxide, but we represent this as 1.0% uranium for analytical simplicity (again, recognizing that this is a modest overestimate). Consider a hypothetical truck hauling 30 tonnes of uranium ore at 1% uranium grade (300 kg U). If this ore truck was overturned by a flash flood while crossing Kanab Creek, and its entire load of uranium ore was washed 60 km down Kanab Creek, completely pulverized in the riverbed, and dissolved into Colorado River water over a one-year period, then 0.3 tonnes of uranium would be added to the river over this time period. Against a natural background of 60 ± 20 tonnes/year of uranium dissolved in the Colorado River, this amounts to an approximately 0.5% increase in river-water uranium concentration, or a change from 4.00 ppb to 4.02 ppb (an increase of 0.02 ppb, or 20 parts per trillion). This change would be trivial, especially when considered in light of the EPA Maximum Contaminant Level for drinking water of 30 ppb uranium.

Standard deviation of uranium measurements at Lees Ferry and near Peach Spring is 0.38 and 0.46 ppb, respectively (Table 1). Thus, in our worst-case uranium-spill scenario, uranium concentration in the Colorado River would be increased by about one twentieth of one standard deviation of uranium measurements in these two data sets. If deviation primarily represents natural variation, which seems likely, then uranium added to the Colorado River in this hypothetical situation would be undetectable against much larger natural variation.

Our deliberately exaggerated, worst-case scenario for a uranium-ore spill into the Colorado River can be applied to even more unlikely environmental situations. Consider the entire 132 tonnes of uranium production from the Arizona 1 mine that occurred during 13 months in 2009-2010. Then consider that, for some reason, the ore containing this uranium was not trucked to a distant uranium mill, but was stockpiled on site in a location vulnerable to flash flooding. At a grade of 1% uranium, this stockpile would consist of 13,200 tonnes of uranium ore. If a flash flood washed the entire 13,200 tonnes of uranium ore into the Colorado River, and all of the ore was pulverized and its 132 tonnes of uranium dissolved in the Colorado River over one year, then the annual uranium flux in the Colorado River would increase from approximately 60 tonnes to 192 tonnes. Uranium concentration in river water would increase from 4.0 to 12.8 ppb for one year, which is still far below the 30 ppb EPA Maximum Contaminant Level. Thus, even in this implausible scenario, with approximately 20% of the entire ore body washed into the Colorado River and completely dissolved in river water, the water would still be considered safe to drink by the EPA under current regulations. In reality, any such flash-flood mobilization of uranium ore would result in mixing of ore with stream-bed sediment, in the Colorado River as well as in tributaries, and a much more gradual addition of uranium to river water.

Conclusion

Uranium, present in typical crustal rock at about 3 ppm (Spencer, 2002), is one of the many chemical elements in Earth's crust that are gradually washed away by weathering and erosion and dissolved in very small concentrations in river water and groundwater. The seemingly large amount of naturally occurring uranium in the Colorado River (tens of tonnes per year) reflects the large water flux in the river, not unusually high uranium concentration. Colorado River water is consumed by millions of people in Arizona, California, and Nevada. Uranium concentration in

river water, at about 4 ppb, has been consistently well below the EPA Maximum Contaminant Level (MCL) of 30 ppb for drinking water. Under the conditions modeled here for a uranium ore-truck accident, designed to represent an extremely unlikely, worst-case, mining-related uranium spill into the Colorado River, an increase of 0.02 ppb uranium would be trivial in comparison to the EPA drinking water MCL of 30 ppb uranium. Furthermore, such an increase of uranium in river water would be undetectable against natural variation as revealed by variability in past uranium measurements of river water.

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APPENDIX A: Letter from Arizona Governor Janet Napolitano regarding uranium mining



STATE OF ARIZONA

JANET NAPOLITANO
GOVERNOR

OFFICE OF THE GOVERNOR
1700 WEST WASHINGTON STREET, PHOENIX, AZ 85007
March 6, 2008

MAIN PHONE: 602-542-4331
FACSIMILE: 602-542-7601

The Honorable Dirk Kempthorne
Secretary of the Interior
Department of the Interior
1849 C Street, N.W.
Washington DC 20240

Dear Mr. Secretary:

I am writing to you on behalf of the citizens of the State of Arizona to express concerns regarding the impact of uranium development on the Grand Canyon National Park. As you know, the Grand Canyon is not only an Arizona treasure, it is a National one and we must fully understand environmental impacts before moving forward with uranium mining or millsite activities. Therefore, I request that you exercise your emergency withdrawal authority under the Federal Land Policy and Management Act (FLPMA), 43 U.S.C. Section 1714 to stop new claimstaking and conduct an overall environmental impact analysis of uranium development around the Grand Canyon. It is imperative that we fully understand impacts to the land and water in the Canyon region before moving forward with mining and millsite activities. Should the analysis determine a negative impact to the Canyon, you should exercise your authority to withdraw the lands from mineral entry for twenty years. The attached map shows the areas of concern.

As you may be aware, the dramatic rise in prices for uranium over the last three years has created a "boom" that has the potential to seriously harm the Grand Canyon National Park and the water quality of the lower Colorado River. According to a report by The Environmental Working Group, 2,215 new mining claims have been filed within 10 miles of Grand Canyon National Park since 2003, and that 805 of those claims are within 5 miles of the Grand Canyon National Park. As those claims are further developed, the industrial development in the vicinity of the Park and along its watersheds would have significant negative economic, cultural, and environmental repercussions for the residents of Northern Arizona and for the citizens of the State of Arizona.

On Tuesday, February 5, 2008 the Board of Supervisors for Coconino County passed a resolution opposing uranium development in the vicinity of the Grand Canyon National Park and its watershed. The resolution reflects the sentiment of citizens in the local communities around the Grand Canyon and calls for the withdrawal of mineral entry that I am now requesting.

These efforts have resulted in stories and editorials in the New York Times and other newspapers. These reflect the high level of public concern, both here in Arizona, and nationally, about the prospect of uranium mines opening on the rim of the Grand Canyon. This is not just an Arizona concern; this has national implications.

The Honorable Dirk Kempthorne
March 6, 2008
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There are places where uranium might be appropriately mined, but I think that almost every American can agree that the Grand Canyon is not one of those places. As President Theodore Roosevelt, who created what is now Grand Canyon National Park, said:

In the Grand Canyon, Arizona has a natural wonder which, so far as I know, is in kind absolutely unparalleled throughout the rest of the world...

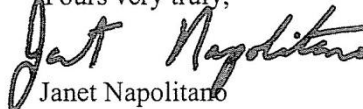
Leave it as it is. You can not improve on it. The ages have been at work on it, and man can only mar it. What you can do is to keep it for your children, your children's children, and for all who come after you...

In 1906, President Roosevelt put his words into action and removed the land from mineral entry that is now largely encompassed by the North Kaibab Ranger District of the Kaibab National Forest. Since that time, additional lands in the region, including those that fall within the boundaries of the Grand Canyon Parashant and Vermillion Cliffs National Monuments were protected from new mineral entry. The Navajo Nation has prohibited uranium development on their tribal lands bordering the Grand Canyon and other tribes are considering doing the same. Indeed, the Navajo Nation just passed Tribal Superfund legislation to specifically help address the large number of abandoned and unreclaimed uranium sites on their land.

The withdrawal from mineral entry of the three areas that I have indicated will complete the process of protecting the Grand Canyon from the adverse affects of mineral development that President Roosevelt began more than a century ago. On behalf of the citizens of the state of Arizona, I, therefore, petition and request that you remove those federal lands identified on the attached map. Should you need additional information, please contact Lori Faeth, Sr. Policy Advisor for Natural Resources, Agriculture and Environment at 602-542-1334, lfaeth@az.gov.

I thank you for your consideration of this very important issue.

Yours very truly,


Janet Napolitano
Governor

cc: Congressman Rick Renzi
Congressman Raul Grijalva
Congressman Nick Rahall
Senator John McCain
Senator John Kyl
Senator Jeff Bingaman
The Honorable Ed Schafer Secretary U.S. Department of Agriculture
Chairwoman Ono Segundo, The Kaibab Paiute Tribe
Chairman Don Watahomigie, The Havasupai Tribe
Chairman Ben Nuvamsa, The Hopi Tribe
Chairman Charles Vaughn Sr., The Hualapai Tribe
President Joe Shirley Jr., The Navajo Nation