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Article

Uranium in waters of the southern Colorado Plateau: Implications for the Navajo Nation

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Abstract

Uranium (U) has been observed to be enriched in the waters of the southern Colorado Plateau including waters of the Navajo Nation. The region has naturally occurring U in rocks and a history of mining which may exacerbate U concentrations in waters. Despite past research into the abundance of U in the waters of the Navajo Nation, a regional framework has not been established to understand where U is typically higher and lower. We examined data collected by multiple studies and organizations to establish where and why U is likely to be enriched in waters of the Navajo Nation. Our work shows that U concentrations are related to the presence of U-rich rock bodies, elevation, and the salinity of local aquifers. Additionally, we show that U concentrations in water sources downstream from abandoned U mines are higher than they are in water sources that are not downstream from mines. Our work provides a means for understanding the patterns of U concentration in waters of the Navajo Nation and can act as a guide for local water withdrawal, as well as remediation and mitigation efforts for regional water sources.

Keywords: Uranium; Groundwater; Colorado Plateau; Navajo Nation; Chinle Formation

1. Introduction

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Surface water is scarce on the Colorado Plateau, and elevated uranium (U) in groundwater further complicates water access. Water scarcity is driven by a low annual rainfall that is below 20-30 cm per year (Credo et al., 2019; Jones et al., 2020; Ingram et al., 2020), and enrichments of U in these waters pose health concerns for people and animals (USDHHS 2013; Hund et al., 2015; Rock et al., 2019; Hoover et al., 2020; Ingram et al., 2020; Lister et al., 2021; Nozadi et al., 2022). The southern Colorado Plateau is the ancestral land of the Navajo (Diné) people and the current boundaries of the Navajo Nation are located entirely in the region (Figure 1A). Approximately 30 % of Diné lack access to municipal water sources and rely on hauling water to meet their water needs—in some cases from unregulated sources that have U concentrations above the recommended guidelines of 30 μg/L (EPA, 2018; Credo et al., 2019; Ingram et al., 2020). Despite past work on elevated U concentrations in the region, a framework establishing where and why U is likely to be enriched has not yet been established. Such a framework will help improve the well-being of people in the region.

U occurs naturally in rocks on Earth and common U bearing rocks include shale and granite (Turekian and Wedepohl, 1961). U has a complex redox chemistry, and this chemistry influences the ability of U to dissolve in waters. Waters with low Eh and low pH tend to increase the dissolution of U from minerals. The tailings and materials from U mines are known to contribute to elevated U concentrations in waters, in part through decreasing the pH through the oxidation of sulfides (Hoover et al., 2017; Ingram et al., 2020). Additionally, U is attracted to the presence of the bicarbonate anion in solution forming complexes that can increase its mobility (Campbell and Ingram, 2014).

The naturally occurring U in rocks of the southern Colorado Plateau has led to a history of U mining, and more than 1200 mining related features are located in the region (O'Rear, 1966; EPA, 2006). Past research has shown that the U concentrations of some waters are related to mine drainage (Hoover et al., 2017), but U concentrations in the context of regional aquifers or rock units have not yet been examined. Regional U mining began in the 1940s and continued through the 1980s in support of the efforts of the United States during the Cold War (Wenrich et al., 1989). U mining in the region largely focused on the Shinarump Conglomerate Member of the Chinle Formation (Chinle Fm.), and the Salt Wash Member of Morrison Formation (Figure 1B) (Rosenzweig et al., 1954; Evensen, 1958; Sanford 1982). The Shinarump (occasionally Sinarump) Member is the stratigraphically lowest portion of the Chinle Fm. and tends to be enriched in U compared to other units due to the presence of ancient weathered volcanic debris (Weeks and Garrels, 1959). The presence of similar material in the Morrison Formation (Morrison Fm.) also contributes to the presence of U in this formation (Weeks and Garrels, 1959).

We gathered data from several published sources to better understand the factors determining the abundance of U in the groundwater of the southern Colorado Plateau. We hypothesized that U concentrations in groundwater should be correlated with regional drainage patterns and the presence of U rich rocks in the region. Additionally, we hypothesized that U mining in the region may influence the concentration of U in groundwater. The results from our work present a framework for understanding the geospatial concentrations of U throughout the southern Colorado Plateau.

2. Geological Setting

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The Colorado Plateau is dominated by four major aquifers, the Coconino-De Chelly aquifer, the Mesaverde aquifer, the Uinta-Animas aquifer, and the Dakota-Glen Canyon aquifer. All 4 aquifers are present in the southern Colorado Plateau, but the two most prominent are the Coconino-De Chelly aquifer, and the Dakota-Glen Canyon aquifer. The Coconino-De Chelly aquifer is predominantly hosted in the De-Chelly and Coconino Standstones—units which are lithologically continuous but have different names in different regions (Robson and Banta, 1995). Occasionally, the Dakota-Glen Canyon aquifer is split into the Navajo aquifer (after the Navajo Sandstone) and the Dakota aquifer (after the Dakota Group) (Hoover et al., 2018).

Of the major aquifers of the Colorado Plateau, the Coconino-De Chelly aquifer is present in the oldest rocks and is the deepest aquifer of the Colorado Plateau in some places (Robson and Banta, 1995). In the south of the Colorado Plateau, the Coconino-De Chelly aquifer is present at the surface (Figure 1B). This results in the infiltration and percolation of rain water through the Chinle Fm. and into the Coconino and De Chelly Sandstones in places where the Chinle Fm. outcrops at surface. Thus, in the south of the Coconino-De Chelly aquifer, the entire Chinle Fm.—including the U-rich Shinarump Member—is in hydrological contact with the De Chelly Sandstone. In places where the red, purple, white, and green layers of the Chinle Fm. are not exposed at the surface, the shale-rich formation acts as a barrier between more surficial waters and the Coconino-De Chelly aquifer (Ludington et al., 2007; Robson & Banta, 1995). In some areas, the Shinarump Member directly overlies the De Chelly Sandstone potentially contributing to increased U in this aquifer, but overlies the shale-rich Moenkopi Formation in others (Evensen, 1958).

In its southern portion, the Coconino-De Chelly aquifer experiences its highest elevations in the Chuska Mountains, flows south towards the little Colorado River, and finally discharges through springs in the walls of the Grand Canyon (Robson and Banta,1995). This flow path roughly traces the elevation gradients in the region

(Robson and Banta,1995). Additionally, as the water flows across and through the land, it dissolves solids (Gaillardet et al., 1999; Raymond, 2017). This results in a pattern of increasing salinity from the Chuska Mountains to the region of discharge near the Grand Canyon (Robson and Banta,1995), however the highest concentrations of total dissolved solids (TDS) occur in the southeastern portion of the aquifer (Figure 2A). Since groundwater tends to increase in salinity the longer it spends in an aquifer (Lakey and Krothe, 1996), the salinity of the Coconino-De Chelly aquifer can be used as a proxy for the amount of time that water has spent in the aquifer.

The Morrison Formation is Jurassic in age, and its base is usually represented by an unconformity in the region (Robson and Banta, 1995). Several different members are recognized within the Morrison Fm., including the Salt Wash and Bushy Basin Members (Rosenzweig et al., 1954; Robson and Banta, 1995). The Salt Wash Member is recognized by a light pink to buff colored sandstone with interbedded green and red mudstones and tends to comprise cliffs (Rosenzweig et al., 1954; Ludington et al., 2007). Hydrologically, the Morrison Fm. comprises the Morrison aquifer, which is an isolated aquifer system within the Dakota-Glen Canyon aquifer system (Robson and Banta, 1995).

3. Methods

3.1. Data sources and extraction

We relied on several published data sets to perform the analyses in this study. U concentrations in groundwater were obtained from data published by Credo et al. (2019). Briefly, the dissolved materials in regional waters—including U—were measured from unregulated water sources, namely springs, windmills, water storage tanks, and troughs. The detection limit for U in the samples was 0.047 μg/L. In locations that measured at or below the detection limit, the detection limit was used in the analysis. Water sources where U concentrations varied through time were

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discarded from this analysis. Please see Credo et al. (2019) for more information as to how this data was collected.

Characteristics and data regarding the salinity of the Coconino-De Chelly aquifer were obtained from Robson and Banta (1995). Robson and Banta (1995) identified the locations where the Coconino-De Chelly aquifer is the surface-most aquifer in the region, as well as regions in the Coconino-De Chelly that ranged in concentration of TDS from 0-1 k, 1-3 k, 3-25 k, and > 25 k mg/L (Figure 2A). These regions were pulled from the published maps using the 'countcolors' package in R (Figure 2B) (R Core Team, 2022; Weller, 2019). The outlines of the identified collection of points were identified using the 'concaveman' package in R (Figure 2C) (Gombin et al., 2020), and transformed into polygons using the 'sp' package (Figure 2D) (Pebesma and Bivand, 2005). The digital boundary of the polygons generated for the salinity regions within the Coconino-De Chelly aquifer did not line up exactly with the published boundaries since the boundaries of the regions were marked in black. To account for this, we adjusted the boundaries of the regions of interest by 3 km which approximately corresponded to the missing area.

Information about the geology of the region was also obtained from previously published sources. The locations where the Chinle and Morrison formations outcrop were obtained from the KML versions of the geological maps of Arizona and Utah (Ludington et al., 2007). The boundaries of these formations were expanded by 1 km to account for any imprecision in the plotted boundary of the formation.

Locations of abandoned U mines were obtained from the EPA (2006). Data published by the EPA (2006) and Credo et al. (2019) did not contain elevation data for the abandoned mines and water sources. Elevations for the mines and water sources were obtained by converting the locations

 doi:10.20944/preprints202208.0077.v1

of water sources and mines into kml files and uploading them to GPS Visualizer (https://www.gpsvisualizer.com/elevation). Water sources located within a particular subsection of the Coconino De-Chelly aquifer, or rock unit were identified using the 'sp' package (Pebesma and Bivand, 2005).

3.2. Statistical Analyses

The statistical relations of U concentrations in the study area to the factors of interest were assessed through a variety of techniques. The U concentration in waters sources on the Navajo Nation was not normally distributed and was log-transformed to better approximate a normal distribution for future analysis. Differences in U concentration in water sources in different regions in the Coconino-De Chelly aquifer were assessed using ANOVA and Tukey's honestly significant difference. The relationship between U concentrations and elevation was assessed through linear regression. Differences between U concentration in waters in the Chinle or Morrison Formations were assessed using Wilcoxon tests. These tests are analogous to two-sample t-tests assuming unequal variance.

The presence of mining on U concentration in water sources was assessed over scales from 1 to 5 km. For any particular well, only mines upstream (i.e. at a higher elevation) from the well in question were considered. We restricted the analysis to mines upstream from wells since gravity produces a shear force on water causing it, and its dissolved load, to flow downhill. The total number of mines upstream from a well and the presence of a single mine upstream of a well on U concentrations in samples were assessed through linear regression and Wilcoxon tests, respectively. It is important to note that the location of mining features in the EPA dataset is not entirely accurate

(EPA, 2006; Charley, personal communication, 2021). Our analysis accounts for this by allowing for a larger window (at least 1 km upstream) than the 200 – 300 m uncertainty present in the location data.

Many of the factors that could potentially influence the U concentration in groundwater exhibit some correlation. For instance, the factors 'elevation' and 'presence of a mine upstream from a well' are inherently related because an elevation difference is necessary for the analysis. Additionally, a sample may also exhibit high U concentrations because it was downstream from a mine, but may have simultaneously been located in a U-rich rock formation. To begin understanding the causes between elevated U concentrations and the presence of U-rich rocks in the region, analyses were undertaken where water sources were located within the Chinle Fm. were analyzed separately from water sources that were not located within the Chinle Fm. Additionally, upstream mining features were limited to those that were present within 2 km to minimize the relationship with elevation.

3.3. Data Availability

All figures presented in the manuscript were made using R. All project code and files unique to this manuscript are hosted on GitHub and can be found at (https://github.com/websterkgd/USouthernColoradoPlateau).

4. Results

The U concentration in groundwater of the southern Colorado Plateau appears to exhibit trends across space. U concentrations appear to be low in the vicinity of the Chuska Moutains in the

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region east of Chinle, increase towards the southwest and then increase towards the northwest with the highest concentrations present in the vicinity of Tuba City (Figure 3). This pattern appears to mirror trends in elevation, groundwater flow paths, and the presence of U-rich rocks in the region.

The U concentration in groundwater of the Navajo Nation was higher in regions where the Coconino-De Chelly aquifer is the surface-most aquifer compared to other regions (median $[U]_{Coconino\text{-}De\ Chelly}$ = 7.03 μg/L, median $[U]_{other}$ = 3.24 μg/L, Wilcoxon Rank Sum Test: W = 7389, p = 0.01). Additionally, U concentration in groundwater was higher in regions of the Coconino-De Chelly aquifer that had a greater concentration of TDS (ANOVA: df = 2, f = 12.96; p =$7*10^{-6}$) (Figure 4A). The U concentration was not significantly different between regions where TDS ranges from 0 – 1 k mg/L (median $[U]_{0\text{-}1}$ = 2.19 μg/L) and 1 – 3 k mg/L (median $[U]_{1\text{-}3}$ = 4.37 μg/L), but was higher in regions where TDS ranges from 3 – 25 k mg/L (median $[U]_{3\text{-}25}$ = 22.4 μg/L) (Tukey's HSD: 0 – 1 k vs. 1 – 3 k TDS: p = 0.09; 0 – 1 k vs. 3 – 25 TDS: p = $7*10^{-6}$; 1– 3 k vs. 3–25 TDS: p = $6*10^{-4}$).

U concentration was also related to the elevation (z) of a groundwater sampling site across the southern Colorado Plateau. Locations at higher elevations exhibited decreased U concentrations compared to those at lower elevations ($[U] = 10\text{\^{}}(-0.0013*z + 2.59)$, r^2 = 0.11, p = $5*10^{-7}$) (Figure 4B).

Rock formations in the region also showed relationships with U concentrations in groundwater. Sampling locations that were present in areas where the Chinle Fm. outcropps exhibited higher U concentrations (median $[U]_{Chinle}$ = 6.54 μg/L) than locations where the Chinle Fm. is not present (median $[U]_{no\ Chinle}$ = 2.26 μg/L) (Wilcoxon Rank Sum Test: W = 2521, p = 0.002) (Figure 4C). In contrast, U concentrations in areas where the Morrison Fm. outcropps were not statistically different (median $[U]_{Morrison}$ = 1.23 μg/L) from U concentrations in other regions (median $[U]_{no\ Morrison}$ = 2.26 μg/L) (Wilcoxon Rank Sum Test: W = 1032, p = 0.69) (Figure 4D).

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Average U concentrations at a site were related to the presence of mines upstream. The number of sites downstream from a mine, and the maximum number of mines upstream from a sampling site increased as the window of analysis expanded from 1 to 5 km. In all cases, water from sites with the presence of a mine upstream exhibited higher U concentrations than sites without a mine upstream (Figure 5, Table 1). Additionally, U concentrations in waters increased with the number of mines upstream from a sampling location (Table 1).

Samples obtained from water sources within the Chinle Fm. showed different patterns compared to those that were obtained from waters outside of the Chinle Fm. Within the Chinle Fm., the elevation of a site was an important predictor of the U concentration in the water source ($[U] = 10^{(-0.0014*z + 3.04}$, $r^2 = 0.32$; $p = 2*10^{-5}$) (Figure 6A), and the presence of a mine within 2 km of a water source did not significantly influence the U concentration of the water source (median $[U]_{mine < 2\ km}$ = 16.5 μg/L, median $[U]_{no\ mine}$ = 2.87 μg/L, Wilcoxon Rank Sum Test: W = 253, p = 0.06) (Figure 6B). Opposite trends were observed for water sources outside of the Chinle Fm. Elevation did a poor job of predicting the U concentration in a water source in locations outside of the Chinle Fm. ($[U] = 10^{(-0.0009*z + 1.92}$, $r^2 = 0.03$; $p = 0.008$) (Figure 6C), and the presence of a mine within 2 km of a water source resulted in statistically greater U concentrations in waters in those locations (median $[U]_{mine < 2\ km}$ = 9.39 μg/L, median $[U]_{no\ mine}$ = 1.61 μg/L, Wilcoxon Rank Sum Test: W = 2143, p = 0.001) (Figure 6D).

5. Discussion

5.1. A regional context for U in groundwater of the southern Colorado Plateau

Our results show that U concentrations in waters of the southern Colorado Plateau are related to elevation, the presence of U-rich rocks in the region, the presence of mines upstream from a water source, and the salinity of the Coconino-De Chelly aquifer. These patterns are consistent with a model whereby U increases in groundwater as groundwater spends more time in contact with a U-rich source and additional inputs of U to regional waters from mining. Similar models have been used to predict the contaminant load of waters in other systems (Jasechko et al., 2017; Frei et al., 2020; Vautier et al., 2021).

Ultimately, the driver of the flow of water in the southern Colorado Plateau is the elevation of the ground surface. The Colorado Plateau is bounded on its south, southeast, and southwest by the uplifted Mogollon Rim and in its east by the Southern Rockies (Elston and Young, 1991; Blakey, 2019). One internal region of uplift in the plateau occurs in the Chuska Mountains. The major drainages in the basin are the San Juan River, the Colorado River, and the Little Colorado River (Cooley et al., 1969). Rain falling on the western side of the Chuska Mountains either flows north and into the San Juan River or flows south where it eventually enters the Little Colorado River.

Groundwater flow in the region follows a similar pattern. The De Chelly Sandstone—a major unit of the Coconino-De Chelly aquifer—outcrops in the Chuska Mountains and serves as a place for water to infiltrate and recharge the aquifer. As water flows northwards, it interacts little with the Chinle Fm. since it is more isolated from the aquifer (Robson and Banta, 1995). However, in the southern portion of the aquifer, the Chinle Fm., which directly overlies the De Chelly Sandstone, is exposed at the surface. As a result, water may directly enter in to the Coconino-De Chelly aquifer as it infiltrates and percolates through pores and fractures in the Chinle Fm. Therefore, U has a much greater chance to enter groundwater in the southern portion of the Coconino-De Chelly aquifer.

 doi:10.20944/preprints202208.0077.v1

5.2. U concentrations in waters and U-rich rocks

Our results show that U tends to be elevated in water sources that are located in regions where the Chinle Fm. outcrops (Figure 4C). Additionally, elevation is a predictor of U concentration in water sources that are in regions where the Chinle Fm. outcrops (Figure 6A). Furthermore, the water sources located within the Chinle Fm. appear to drive the overall relationship between U concentrations and elevation since elevation is a poor predictor of U concentration if a water source is not located in the Chinle formation (Figure 4B, Figure 6C).

These patterns are consistent with a model whereby U enters groundwater as a result of interactions with a U-rich rock body. In the upstream portions of the Chinle Fm and Coconino-De Chelly aquifer, water has had little time to dissolve U, but downstream portions tend to contain more U. As water flows in an aquifer, including the Coconino-De Chelly aquifer, it accumulates more solids the longer the water has spent in the aquifer (Robson and Banta, 1995; Gaillardet et al., 1999; Raymond, 2017). This also helps explain the relationship between TDS and U concentration observed in the data (Figure 4A). Our results are also similar to work showing that U in the Chinle Fm. is mobile and that radiation in areas where the Chinle Fm. outcrops is higher than in the surrounding regions (Johnson and Writ, 2009). Recent work has shown that U concentrations increased in soil effluent from the Chinle region when the longer the soils were exposed to water—again demonstrating the mobility of U in areas where the Chinle Fm. outcrops (Webber et al., 2021).

In contrast to water sources in the Chinle Fm., water sources within the Morrison Fm. did not show increases in U concentration (Figure 4D). Our observation that groundwaters associated with the Morrison Fm. are not enriched in U agrees with other work yielding similar observations

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from outcrops of the Morrison Fm. in Colorado where the Salt Wash Member of the Morrison Fm. is in contact with groundwater (Phoenix, 1959). Low U concentrations in the waters of the Morrison Fm. were attributed to the Eh and pH of groundwater that inhibited the dissolution of U. Additionally, outcrops of the Morrison Fm. are limited in the extent in the study region and this may limit the amount of time ground water spends in these units.

It is important to note that the depth to the groundwater table in the water sources used in this study is not known. However, water sources in the region are thought to be sourced by shallow groundwater (Charley, personal communication, 2021). This agrees with our observations that U concentrations tend to be higher in water sources that are located where the Chinle Fm. outcrops. The depth to the water table of each well in the study area is potentially a factor that contributes to the variation in U concentration in the sampled waters.

Another source of variation in the data is the velocity of groundwater flow. The velocity of groundwater—especially shallow groundwater—may vary with the inputs to the system over time. Potentially illustrating this variation is that the U concentrations from two springs located near each other show yearly differences (Ingram et al., 2020). This suggests the total amount of water moving through the system in a given year may influence U concentrations. Work in other systems shows that the velocity of the flow of groundwater influences the concentration of dissolved material in groundwater (Lakey and Krother, 1996). Samples used in our study were collected over a period of years, and flow variability represents a source of variation that we did not control for in our analysis.

5.3. U concentrations in waters and mines

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U concentrations in the water sources were higher when a mine was present upstream (Figure 5). This result agrees with a study that found elevated U concentrations within 6 km from an abandoned mine (Hoover et al., 2017). When the analyzed water sources were restricted to those that were present within the Chinle Fm. the presence of a mine upstream did not appear to influence the U concentration in the groundwater (Figure 6B). However, if the sampled water source was located outside of the Chinle Fm., the waters tended to show elevated U concentrations if a mine was present upstream (Figure 6D).

The increased U concentration in water sources downstream from a mine in locations where the Chinle Fm. does not outcrop suggest that tailings or material from a mine may enter water from these locations. It is known that such materials influence U concentrations in water sources (Winde, 2010; Hoover et al., 2017). In areas where the Chinle Fm. outcrops, U concentrations from water sources from locations with a mining feature present upstream were statistically indistinguishable from those locations without a mining feature upstream. There are two likely explanations for this. The first could be that U concentrations in these water sources are already high because of interactions with U-rich material and that interactions with material from mines may not sufficiently increase U concentrations. A second possible explanation is that our result is a false negative. It is possible that more data from such locations may show that U tends to be elevated in these waters. Future work on the ratio of $^{234}U/^{238}U$ of waters in the region where the Chinle Fm. outcrops may help determine the influence of a mine by assessing how long water from a water source has been in the aquifer (Johnson and Writ, 2009; Campbell and Ingram, 2014). An analysis of the stable isotopes of U in a location where the Chinle Fm. did not outcrop revealed that high U concentrations downstream from mine tailings were associated with a short groundwater residence time (Johnson and Writ, 2009).

5.4. Implications for well placement and remediation

The preliminary framework identified in this article has implications for remediation and mitigation of U in groundwater in the region. If possible, new water sources should not be installed in areas that are downstream from mines or located within the Chinle Fm. Further, residents should be taught to recognize the locations where the Chinle Fm. outcrops and to avoid using water from such locations, if possible. Additionally, remediation and or mitigation efforts should first be targeted to water sources in downstream regions where the Chinle Fm. outcrops since dissolved elements of concern—including U—are likely to be found at greater concentrations.

6. Conclusions

U concentrations in waters of the southern Colorado Plateau show statistical relationships with elevation, locations where the Chinle Fm. outcrops, the presence of mines upstream from water sources, and the salinity of the Coconino-De Chelly aquifer. These relationships can be explained by the regional flow paths of groundwater, and additional interactions with U-rich material from mines. This work provides insight into elevated U concentrations in groundwater of the southwestern Colorado Plateau and begins the work of parsing natural contributions to increased U concentrations in the region and anthropogenic inputs. Results from this work can provide a basis for helping people understand if an unregulated water source is at risk for elevated U concentrations and public education programs. Future studies may assess the depth to the water table in water

 doi:10.20944/preprints202208.0077.v1

sources and more closely monitor the U concentrations in water sources over the presence of a year to better understand possible temporal fluctuations in elements of concern. Additionally, numerical modeling of groundwater flow may yield greater insight into variations in U across the region. Future regional assessments of U may analyze the stable isotopic concentration of U in water sources to better understand the flow paths and how much time water has spent in the aquifer.

Competing Interests

The authors declare no competing interests.

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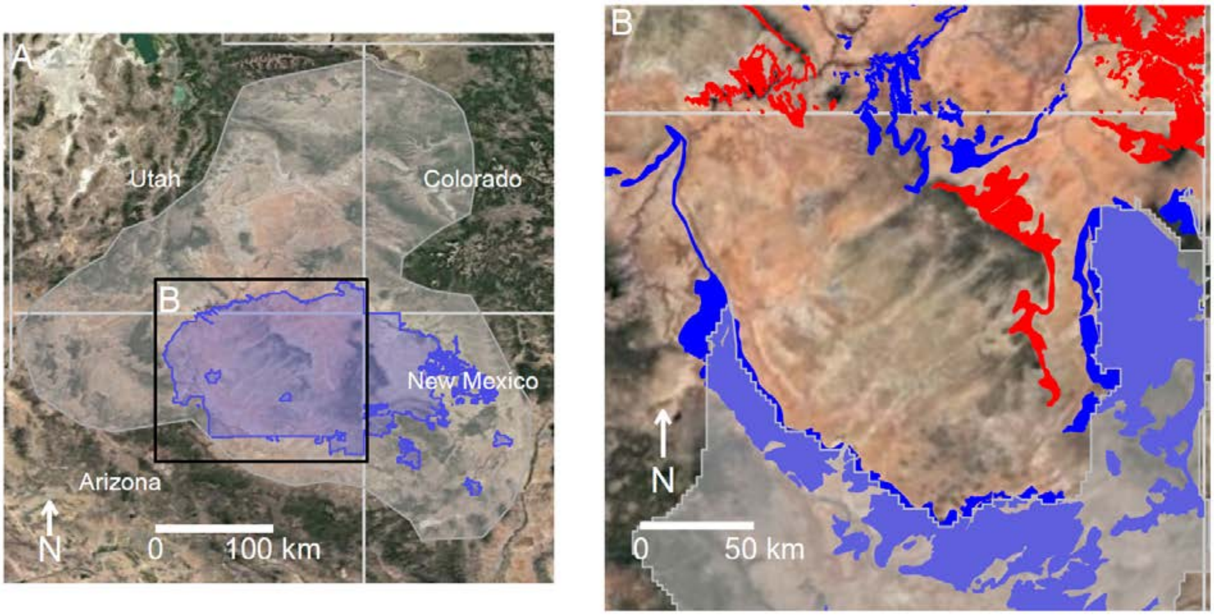

Figure 1: A) The location of the Colorado Plateau shaded in gray within the mountain-west region of the United States. Note the presence of the Navajo Nation and Hopi Reservation (blue) within the Colorado Plateau. B) The location of the study area showing the presence of the Chinle Formation (blue), Morrison Formation (red), and the area where the Coconino-De Chelly aquifer is the surface-most aquifer (gray). Satellite imagery from Google Earth.

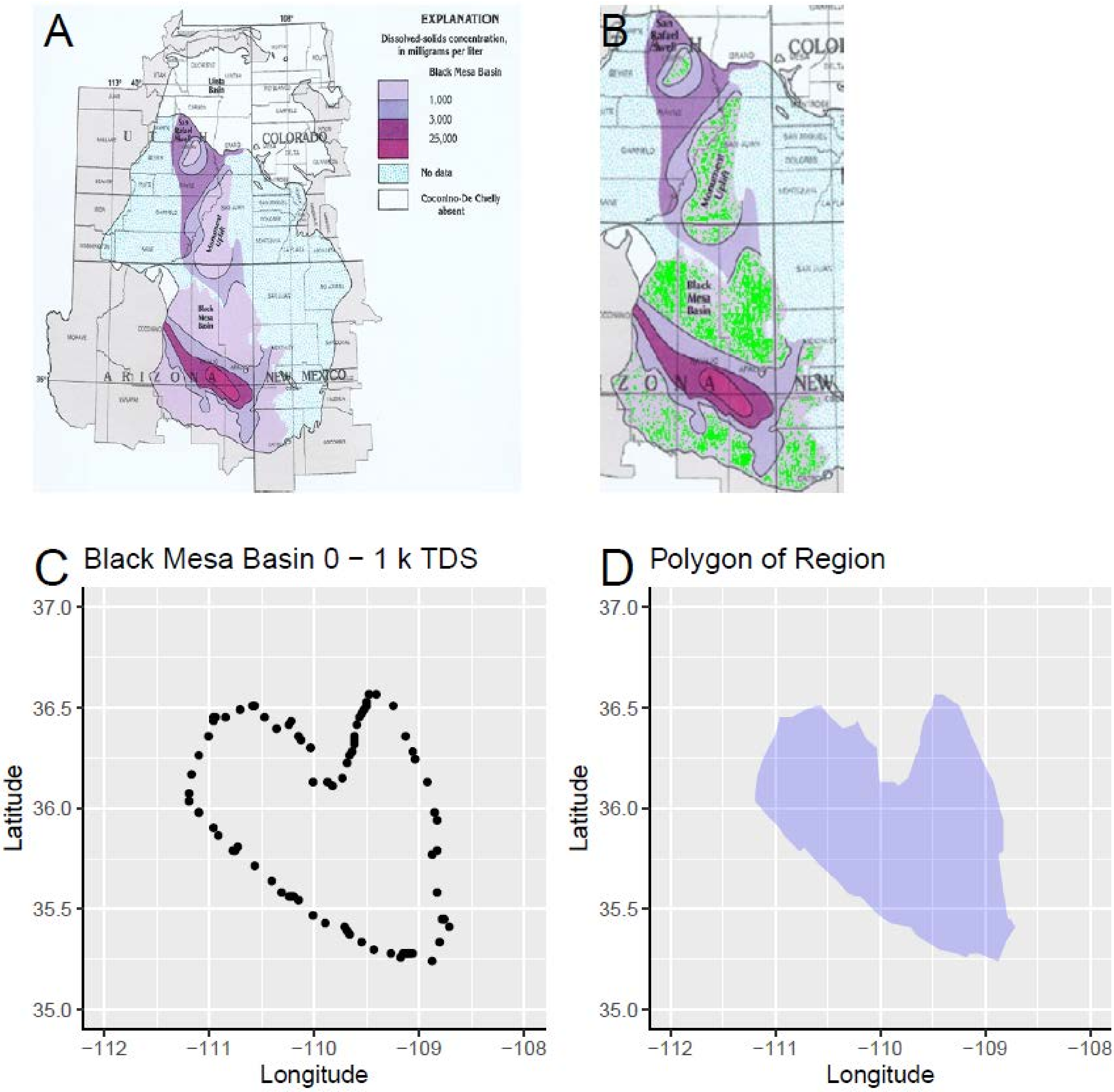

Figure 2: A) The regions of total dissolved solids in the Coconino-De Chelly aquifer from Robson and Banta (1995). B) A particular region with the aquifer was converted into a digital format depending on the color in the figure. C) Outlines of the identified regions were then obtained, and finally converted into polygons (D) for later analysis.

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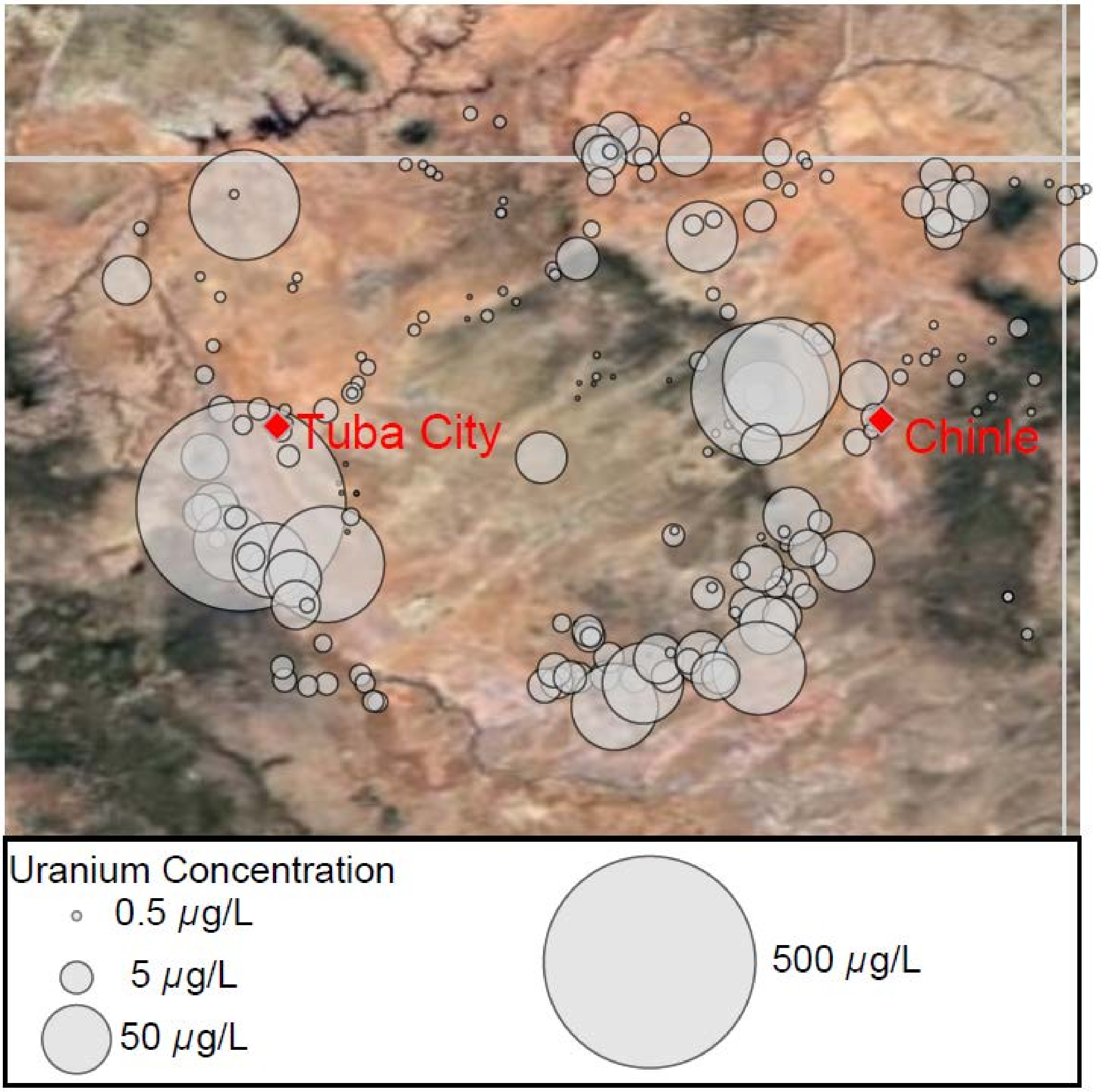

Figure 3: A visual representation of the concentration of uranium (U) concentration in unregulated water sources across the study region. Note the range of U concentration in the samples is from 0.047 µg/L to 490 µg/L. The towns of Chinle and Tuba City are shown for reference. Satellite imagery from Google Earth.

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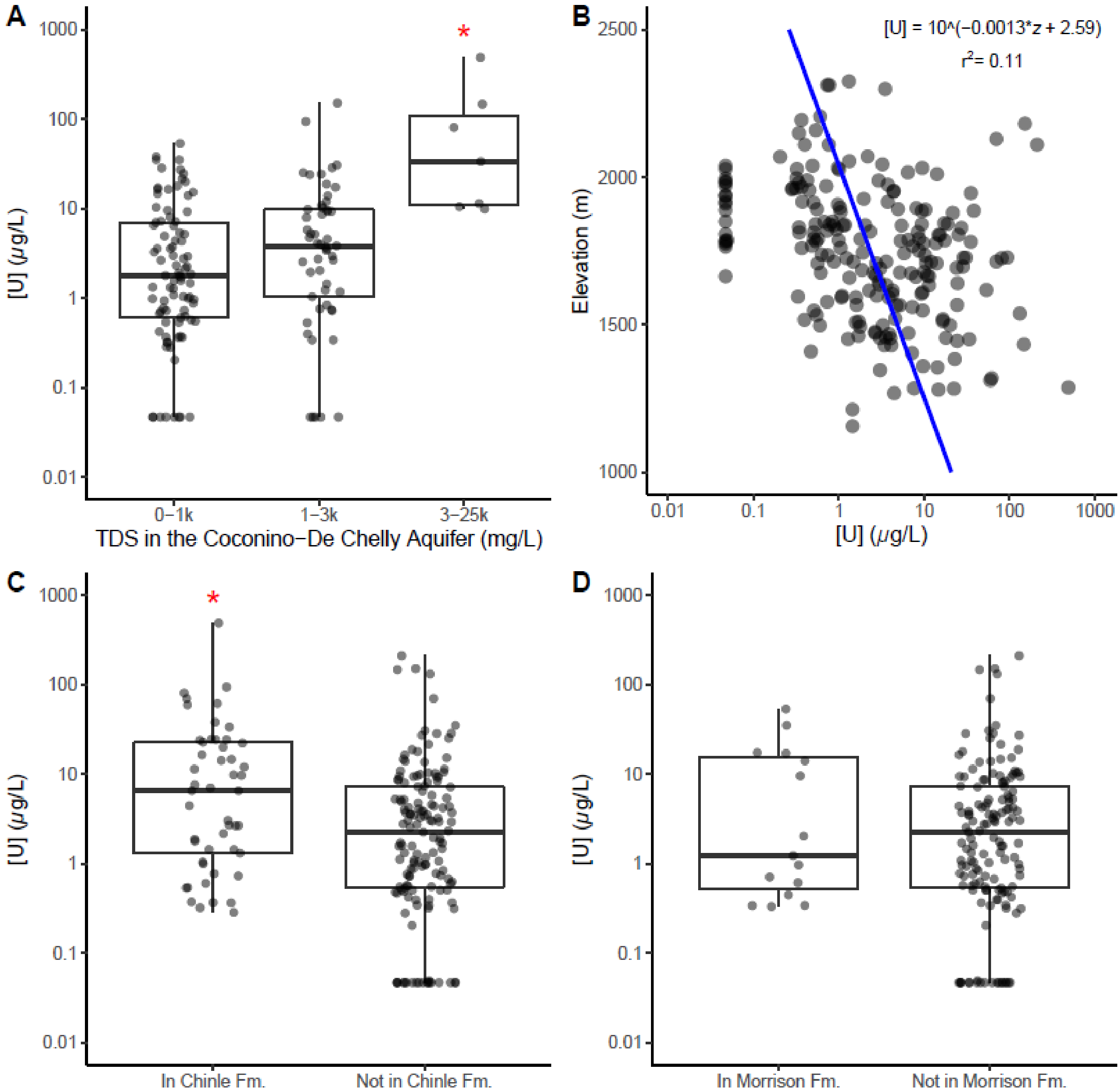

Figure 4: A) A boxplot showing the relationship between U concentrations in groundwater and Total Dissolved Solids region in the Coconino-De Chelly aquifer. The asterisk indicates that significantly higher U concentrations were observed in regions of the Coconino-De Chelly aquifer where TDS ranges from 3 – 25k mg/L. B) U concentrations in groundwater plotted against elevation. C) A boxplot showing the relationship between U concentrations in groundwater and whether a water source is located in a location where the Chinle Formation outcrops. The asterisk indicates that significantly higher U concentrations were observed in regions where the Chinle Formation

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outcrops. D) A boxplot showing the relationship between U concentrations in groundwater and whether a water source is located in a location where the Morrison Formation outcrops. Note that U concentrations are always expressed on a $\log_{10}$ axis.

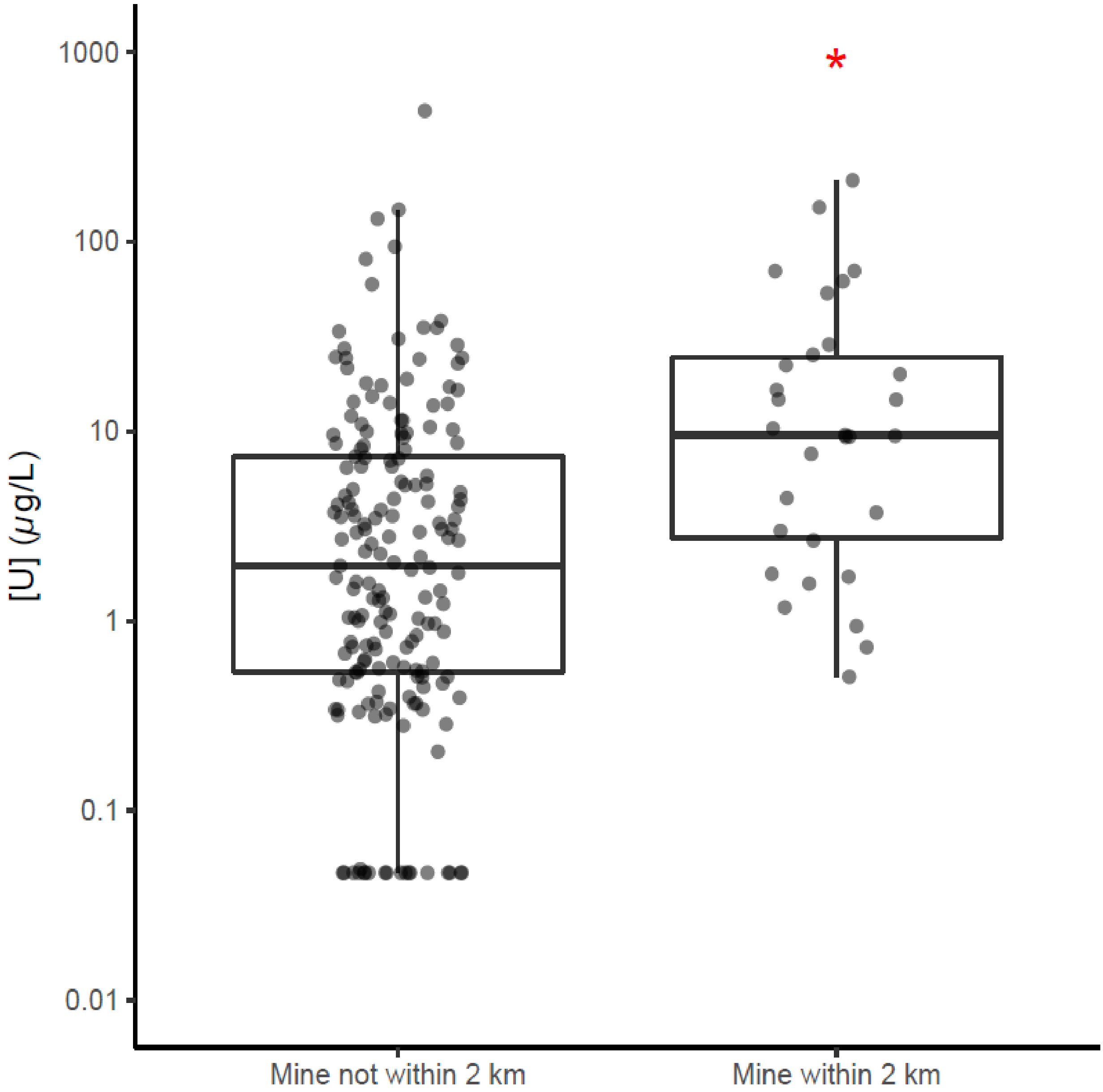

Figure 5: A boxplot showing the relationship between U concentrations in groundwater and whether a mine is located upstream and within 2 km of the water source. The asterisk indicates that

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significantly higher U concentrations were observed in sources that were within 2 km and downstream from a mine. Note that U concentrations are expressed on a $\log_{10}$ axis.

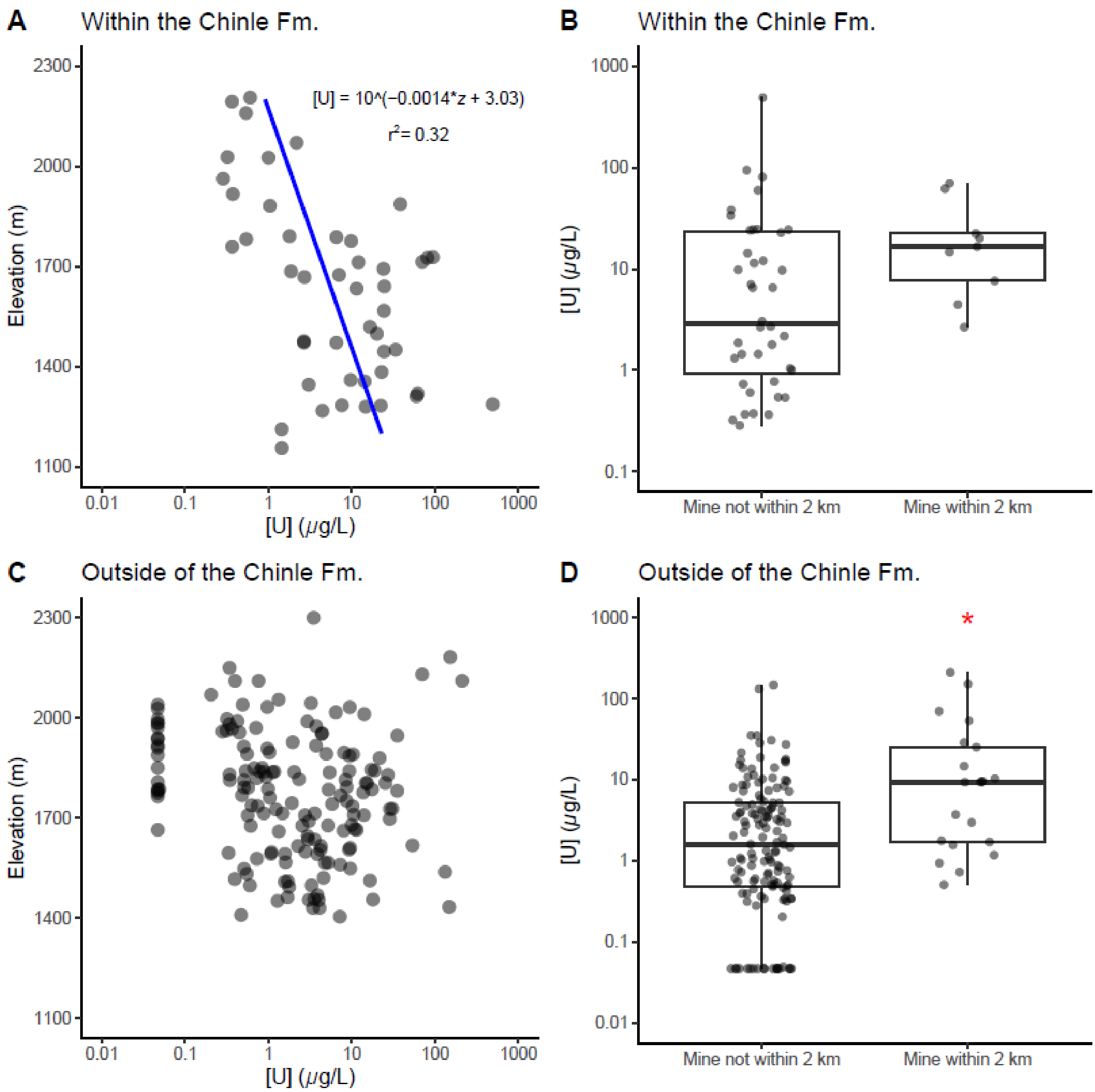

Figure 6: A) Within the Chinle Fm., the elevation of sample locations is an important predictor of the U concentration in a water source. B) Samples obtained from locations that were within 2 km of a mine within the Chinle Formation were statistically indistinguishable from those that were not in the vicinity of a mine. C) The elevation of sample locations is not an important predictor of the U concentration in a water source in locations outside of the Chinle Fm. D) Samples obtained from

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locations that were within 2 km of a mine outside of the Chinle Formation exhibited statistically greater U concentrations compared to those that were not in the vicinity of a mine. Note that U concentrations are always expressed on a $\log_{10}$ axis.

Table 1: Statistical relationships between average U concentrations and upstream mines

Distance to a mine	Number of sites with a mine upstream	Maximum number of mines upstream from a sample site	Wilcoxon $[U]_{mine}$ vs $[U]_{no\ mine}$ (W, p)	Regression [U] vs. $N_{mines\ upstream}$ (r^2, p)
1 km	13	2	(3978, $4*10^{-5}$)	(0.04, 0.003)
2 km	30	6	(1920, 0.003)	(0.05, 0.0004)
3 km	41	10	(5180, $1*10^{-6}$)	(0.06, 0.0002)
4 km	50	20	(5799, $3*10^{-6}$)	(0.06, 0.0003)
5 km	56	22	(6221, $2*10^{-6}$)	(0.07, 0.0001)