Paleotopographic influences of the Cretaceous/Tertiary angular unconformity on uranium mineralization in the Shirley Basin, Wyoming

James H. Covington* and Patrick Kennelly

*College of Earth and Mineral Sciences, The Pennsylvania State University, University Park, PA, USA; †Department of Earth and Environmental Science, LIU Post, Brookville, NY, USA

ABSTRACT
The Shirley Basin is a small asymmetric synclinal structure located in northern Carbon County, Wyoming approximately 65 km (40 miles) south of Casper, Wyoming, USA. The basin formed during the Laramide orogeny of the Late Cretaceous to Early Tertiary (78–49 Ma) and contains economically significant uranium deposits. The underlying Cretaceous units form an angular unconformity with the overlying Tertiary units that represents a paleotopographic erosional surface characterized by stream channels and overbank deposits of interbedded sand and clay with some organic detritus. Furthermore, the Cretaceous shales function as the lower confining unit/aquitard for in-situ recovery (ISR) uranium mining, and the overlying Tertiary sandstones host the uranium mineralization.

This study maps the K/T boundary in greater detail than previous studies and identifies paleotopographic features that influence sedimentary environments and structures that favor uranium mineralization. Using a larger study region and thousands of historical wells and associated electric logs not available to previous studies, this research identifies unit boundaries and enters them into Golden Software’s Surfer and Esri’s ArcGIS to construct a detailed structure contour map on the K/T surface. The map delineates paleotopography such as hills and river channels, with the latter showing a strong spatial association with uranium mineralization. Geologists can use these maps to identify thicker host sands and fluvial features which enhance uranium mineralization. Mining companies can reduce operational and exploration costs by drilling in these more favorable areas to efficiently delineate the ore body geometry and develop more accurate mine unit designs that will maximize uranium recovery.

1. Introduction
Wyoming is a state in the western United States with many geological structural basins containing natural gas, oil, coal, and uranium deposits. During the 1950’s, many of these basins were prospected for uranium and resulted in many significant discoveries, including Shirley Basin. Early attempts to map the K/T boundary (Harshman, 1972) resulted in rudimentary topographic maps that revealed large-scale features, such as ridges and knobs, but were limited to a smaller sample size of e-logs covering a smaller study area and used a 30.48 m (100 feet) contour interval. This study improves the detail of the paleotopographic map using a larger sample size of e-logs (nearly 6000 e-logs from 1956 to 2014) encompassing a larger study area and a smaller 5 m (16.4 ft) contour interval.

The Shirley Basin is one of many isolated basins formed in the northern Rocky Mountains during the Laramide orogeny, subdividing the preceding late Cretaceous foreland basin. It is classified as a small axial basin due to its relatively north-south trend aligned along what would later become the Rio Grande rift system (Dickinson et al., 1988). Such basins have unique, localized stratigraphic packages deposited upon the regional Cretaceous/Tertiary (K/T) unconformity. The Shirley Basin is an asymmetric synclinal structure with an approximate area of 1327 km² (512 mi²) and with ground surface elevations varying between 2100 and 2225 m (6900–7300 ft). The basin is located in northern Carbon County in the western state of Wyoming, USA and is approximately 64 km (40 mi) south of Casper, Wyoming (Figure 1). The basin formed between the Late Cretaceous to Early Tertiary (78–49 Ma) geological time frame with the synclinal axis plunging northwest. The underlying Cretaceous deep marine shale units of the Steele (Ks) and Niobrara (Kn) formations form the basin structure with beds gently dipping between 5° and 10°.

The Cretaceous units are unconformably covered by near horizontal terrestrial Tertiary units composed of poorly consolidated sands interbedded with silt/clays units that filled the basin during the Eocene epoch of the Tertiary period (Seeland, 1978). These units include the Wind River formation (Twdr) and the upper and lower members of the White River formation (Twru...
and Twrl, respectively) (Figure 2). The angular unconformity between the Cretaceous and Tertiary beds indicate a period of erosion by high energy streams depositing cobble (64–256 mm) to boulder (> 256 mm) sized clasts (Williams et al., 2007) which are thought to be derived from three sets of mountain ranges surrounding the basin: Shirley Mountains to the southwest, Granite Mountains to the northwest, and the Laramie Mountains to the east and southeast. (Bailey & Gregory, 2011).

The resulting angular unconformity between the Cretaceous and Tertiary units is known as the K/T boundary and is important to uranium exploration companies for two reasons. First, the boundary represents a paleotopographic surface of a fluvial system characterized by streams, overbank deposits, and alluvial fan deposits of the Wind River formation that are capped by Cenozoic era volcaniclastic rocks and ash of the White River formation (Bullock & Parnell, 2017; Dahlkamp, 1993). Outcrops within the basin (Figure 3) provide evidence of high energy streams eroding and scouring the underlying Cretaceous beds and depositing cobble to boulder sized sediment, as well as incorporating clay rip-up clasts from the underlying Cretaceous units (Harshman & Adams, 1980; Bullock & Parnell, 2017; Dahlkamp, 1993). Second, the coarse basal Tertiary sediments overlying Cretaceous marine shales form ideal sandstone hosts that are characterized by high porosity and permeability that function as a groundwater conduits which enhances mineralization by the process discussed below. The underlying Cretaceous shales also prevent mining solutions from percolating into the aquifers below the mining zone during recovery (Ur-Énergy, 2015).

Previous subsurface investigations mapped the K/T surface and identified gross paleotopographic features, such as a long north-south ridge with an adjacent main channel west of the ridge (Harshman, 1961, 1972). However, a limited sample of drill holes and a large contour interval prevented the discovery of smaller scale features and did not include existing uranium mineralization (Figure 4). Detailed maps of the Wind River sands documented two main sand sequences and included many cross sections but did not include information regarding the paleotopography of the K/T boundary (Bailey & Gregory, 2011).

The uranium mineralization within Shirley Basin is classified as a sandstone hosted ‘roll front’ or chemical cell deposit (Childers, 1978; Dahlkamp, 1993; Harshman, 1962). Roll fronts develop over time from oxygenated meteoric water percolating through the surrounding source rocks of the overlying White River volcanic tuffs and the adjacent granitic rocks of the Shirley, Granite and Laramie Mountains and dissolving uranium and other elements, such as selenium (Se), molybdenum (Mo), and vanadium (V). Tertiary sources of uranium and associated elements may also be derived from organic marine shales which underlies a majority of the basin (Bailey & Gregory, 2011; Harshman, 1961; Jones, 1978; Zielinski, 1983). The dissolved uranium and other elements are carried in the groundwater down-gradient through the sandstone host units chemically altering clays and minerals such as pyrite
until sufficient reductants, such as organic material or biogenic activity producing hydrogen sulphide ($H_2S$) gas, changes the water chemistry to a reducing or oxygen-poor environment and results in precipitation of uranium and other dissolved elements (Harshman, 1972). The boundary where this chemical change occurs is called a reduction-oxidation (redox) boundary. (Rubin, 1970) (Figure 5).

Uranium and the other dissolved elements precipitate along the roll front in different zones with other minerals such as pyrite ($FeS_2$) and form a C-shaped structure that is parallel to groundwater flow and concave toward the reduced zone (Rubin, 1970). Further, roll fronts vary in size and thickness and average 1.5–3 m (5–10 feet) in thickness with uranium mineralization grades between 0.1% and 0.7% (Harshman, 1972). The largest roll fronts can extend vertically and laterally for great distances and make marginal mineralization grades economic to recover. Mo, Se, and V elemental concentrations vary spatially relative to the redox boundary within the roll front. For example, Se maximum concentrations vary from 136 ppm at the redox front and 18.2 ppm at the nose with averages of 52.1 ppm at the redox front and 63 ppm at the nose. Mo maximum concentrations vary from 19 ppm at the redox front, 9 ppm at the nose, 35.6 ppm in the seepage zone, and 15 ppm in barren-reduced zones. The average Mo concentrations range from 7.8 ppm at the redox front, 6.2 ppm at the nose, and 16.7 ppm in seepage zones (Bullock & Parnell, 2017). Ur-Energy analysed 33 samples from different drill cores from the nose zone and obtained average concentrations of 10.4 ppm Mo, 2.9 ppm Se, and 71 ppm V (Ur-Energy, 2015).

The Shirley Basin was once the second largest uranium district within Wyoming (Melin, 1969). Historical uranium mining operations began in 1954 by Teton Exploration and ended with the closure of the last open-pit mine in 1992 (Boberg, 1981). A 2015 preliminary economic assessment by Ur-Energy reported that the average measured uranium grade is 0.275% at a 0.25 grade thickness (GT) cut-off and translates

![Figure 2. Stratigraphic column of the Shirley Basin study area, modified from Ur-Energy (2015).](image-url)
into 3.4 million kilograms (7.5 million lbs.) measured resources with an additional 0.6 million kilograms (1.3 million lbs.) of indicated resources for a total of 4 million kilograms (8.8 million lbs.) of measured and indicated resources remain (Ur-Energy, 2015). Experts estimate that 23.3 million kilograms (51.3 million pounds) of uranium were produced between 1960 and 1992 using traditional underground mining and open pit mining methods. From 1959 to 1963, underground mining methods produced 0.7 million kilograms (1.5 million pounds) and from 1969 to 1992 open pit mining methods produced a total of 11.8 million kilograms (25 million lbs.) (Schiffer, 2014; Ur-Energy, 2015). Between 1963 and 1970, a then-experimental mining method called In-Situ Recovery (ISR) was introduced at Shirley Basin to investigate a more cost effective and environmentally friendly mining method (Chenoweth, 1991). ISR mining uses a series of water wells to inject oxygenated water into the host sandstone to dissolve the uranium minerals, usually uraninite and coffinite (Harshman & Adams, 1980; Dahlkamp, 1993). Recovery water wells pump the uranium rich water to the surface, and then to a central processing facility where the uranium bearing water is treated to precipitate the uranium onto specialized polymer resin beads. The recovered water is returned to the well field for re-use and the uranium precipitate is removed from the polymer beads. The precipitate is filtered and dried into a yellow powder called yellow cake.
During 1957–1990, Wyoming uranium mills and solution mining operations produced 85.3 million kilograms (188 million lbs.) of uranium yellow cake and represents 22% of the total uranium production since 1947. (Chenoweth, 1991). As of June 2017, Wyoming represented 22% of the total uranium production since 1947. (Chenoweth, 1991). As of June 2017, Wyoming listed six operating uranium mine sites statewide: Lost Creek Mine (Ur-Energy), Ross Mine (Strata Energy), Smith Ranch Mine ( Cameco), North Butte Mine (Cameco), Nichols Ranch (Energy Fuels), and Willow Creek Mine (Uranium One) (WyomingMining Association, 2017).

2. Methodologies

The study area extents were determined by the availability of public domain and proprietary drill hole data. Several uranium mining companies were contacted and asked to contribute data. All but Ur-Energy declined citing privacy concerns. Ur-Energy provided access to historical drill hole location maps, mineralization data, and drill logs for a majority of the study area and the Wyoming Geological Survey provided public domain digital copies of logs for the western section of the study area.

The methodology used in constructing this map is summarized in Figure 6. There were 14159 electric logs (e-logs) that were initially examined for this study. Paper copies of e-logs were provided by Ur-Energy and 1012 digital logs were downloaded from the Wyoming Geological Survey ftp site. The e-logs were examined for X, Y location, surface elevation, and stratigraphic picks for the K/T depth from surface and the data recorded into a spreadsheet. Many of the drill hole X, Y locations were in various coordinate systems and were standardized to NAD83 East Central Wyoming FIPS 4902 (feet) State Plane coordinates. Any drill holes with incomplete X, Y locations, incomplete or missing geophysical information or inconclusive K/T contact data were removed from the data set.

Surface elevations required addition data processing, due to inconsistent survey methods or missing survey data. All elevations were standardized using a Digital Elevation Models (DEM) downloaded from the United States Geological Survey’s National Map.

Using the standardized surface drill hole elevation, the K/T subsurface elevation is calculated by subtracting the K/T depth from the surface elevation value. The remaining 5969 drill holes in the data set were imported in Surfer software and the K/T surface was interpolated with kriging. The resulting surface was examined for any bull’s eye anomalies, which can highlight an inaccurate elevation value that varies significantly when compared to surrounding data points. These drill holes were identified, and the elevation and depth of the K/T boundary on the e-logs were rechecked. If a location was inconclusive, the e-log was no longer available, or there were other issues with properly identifying the surface elevation or K/T depth, the drill hole was removed from the data set and the interpolation surface regenerated. The resulting surface was contoured at a 5 m (16.4 ft) contour

Figure 5. Typical roll-front model showing gamma ray log characterics signatures with their relative position to redox boundary and some mineral and elemental distributions along the roll-front deposit. Modified from (Rubin, 1970) and (Ur-Energy, 2015).
interval, exported from Surfer, and imported into ArcGIS.

The cross-section A-A’ transects one of the fluvial channel features to confirm the presence of a stream channel/valley and determine the width and shape of the channel. The location of potential cross sections was limited due to confidentiality concerns from Ur-Energy regarding their data, so a location using the public domain data was selected. Next, lithology breaks between clay and sand were added to the cross-section along with uranium mineralization locations to determine if there were additional factors influencing uranium deposition.

3. Results and discussion

The resulting paleotopographic map and three-dimension view (Figure 7) shows the presence of several north to northwest trending bed-load stream channels (Harshman & Adams, 1980; Dahlkamp, 1993), tributaries, and a possible meander bend around a central topographic hill. These results confirm the earlier work of Harshman (1961, 1972) and Bailey and Gregory (2011) whom identified the large paleotopographic hill and north-west trending main channel in the central portion of the study area. However, this study reveals a more refined map with finer topo-graphic detail due to the greater availability of drill hole log data, wider geographical coverage within the study area and a smaller contour interval.

With the addition of uranium mineralization data, more correlations with the paleotopographic features are evident. Uranium mineralization is measured as Grade Thickness or GT and is a product of the assay percent and the thickness of the mineralization zone. For example, an e-log with an assay of 0.21% and a...
thickness of 1.5 feet (0.46 m) would calculate as 0.31 GT and be considered ‘ore’ or economic to mine. The ore cut-off for economic drill holes varies from company to company, with the lowest ore GT cut-off at 0.25 GT or as high as 0.50 GT, depending on how conservative a company chooses for ore reserve calculations (Ur-Energy, 2015). This study uses a 0.30 GT cut-off to represent economic levels of mineralization and are represented by red symbols on the map. GT values less than 0.30 GT but greater than 0.10 GT are considered sub economic and may be selectively included in mining operations and are represented by orange symbols on the map. GT values less than 0.10 GT are considered uneconomic to mine or have no mineralization data and are represented by gray symbols on the map.

The red and orange regions of economic mineralization appear to coincide with two primary features in the map. The first feature is the outer edge of the central topographic knob with the associated low area indicating water flow from the north, around the knob, and then toward the northwest as indicated by the arrows on the map. This pattern of drainage and mineralization appears to be consistent with a meander feature where organic material accumulates on the inside of the meander loop as the stream flows around the knob and enhances uranium mineralization. Over time, the stream would meander toward the south and result in the u-shaped mineralization distribution as seen in the map.

The second area is the erosional scour within the north to northeast trending channel features, including the channel bisected by cross section A-A’ on the west side of the project area. This feature appears to concentrate organic material in a paleotopographic depression and coincides with higher uranium mineralization. Decreasing mineral deposition and GT values are observed as one moves east or west away from the channel axis.

Occasionally there are decreased GT values within a greater mineralized area. These can be attributed to compartmentalization occurring in the channel and overbank areas. This variation could be due to lack of organic debris, lack of pyrite or biogenic activity to produce H2S gas or represent compartmentalization of permeable zones in a channel or overbank deposit (Rackley, Shockey, & Dahill, 1968). Complexities associated with the pattern of meandering channels apparent in the map and variations in highly localized Tertiary clay units illustrated in the cross-section A-A’ are likely the sources of detailed variations in mineralization. Regardless, geologic patterns are apparent, such as the uranium being found throughout and in overbank areas of smaller scoured channels, and uranium being found on the northern point bar of the main meander loop. Such depositional environments would tend to contain organic material and enhance the redox process required for the roll-front model. Finally, uranium is absent for the most apparent paleotopographic highs in the study area, including the high area to the east and the central topographic knob first identified by Harshman (1972) and delineated in greater detail with this study.

4. Conclusions

The map of the K/T erosional unconformity in the Shirley Basin indicates paleotopographic features influenced the pattern of uranium deposits in a manner consistent with a roll-front mineralization model. The morphology and composition of the paleochannels is consistent with the characteristics of bed-load channel type that form interconnected multilateral sand bodies that serve as conduits for uranium-rich groundwater, moving through an aquifer of coarse sands and gravels directly above a regional aquitard (Harshman & Adams, 1980).

Mining companies will benefit economically by including paleotopographic maps into their exploration program. Paleotopographic maps facilitate a greater understanding of the depositional environment, geometry and mineralization mechanism of the roll-front ore body and provide target areas for favorable host sand deposition and sedimentary traps where organic material is most likely to accumulate and enhance uranium mineralization. These target areas reduce the amount of time and number of unnecessary drill holes required to delineate existing ore bodies or locate new deposits.

Software

The data were compiled, and basic calculations were performed using Microsoft Excel 2016. The kriging surface interpolation and contouring was produced using Golden Software Surfer 15. The cross section was constructed in Autodesk AutoCAD 2017 and the map and other map elements were added and the layout was customized using Esri ArcGIS 10.4.

Data

Digital e-logs were downloaded from the Wyoming State Geological Survey website http://www.wsgs.wyo.gov/uranium-logs/carbon/ and non-digitized logs were obtained from Ur-Energy data storage in Casper, Wyoming. The Digital Elevation Model for the Shirley Basin was downloaded from the USGS website ftp://rockyftp.cr.usgs.gov/vdelivery/Datasets/Staged/NED/13/ArcGrid/n43w107.zip and has a 1/3 arc-sec resolution raster using a NAD88 vertical datum.

Uranium mineralization GT values were obtained from historic drill hole maps and some of the historic drill hole logs.
Acknowledgements

The authors are very grateful to Jim Bonner, Vice President of Geology, John Cash, Vice President of Regulatory Affairs, and John Cooper, Senior Geologist from Ur-Energy for providing insight, assistance, and access to historic drill hole records and logs for the Shirley Basin. The authors also thank the three reviewers of the original manuscript. Finally, the authors thank the Wyoming Geological Survey for providing online access to digital historic drill hole logs and maps for Shirley Basin area.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Patrick Kennelly http://orcid.org/0000-0003-1687-7547

References

Bailey, R. A., & Gregory, R. B. (2011). The Shirley Basin Mine and the development of the roll-front model of uranium ore deposits: A historical perspective. Wyoming Geological Survey Memoir 6.

Boberg, W. (1981). Some speculations on the development of central Wyoming as a uranium province. 32nd Annual Field Conference Guidebook (pp. 161–180). Wyoming Geological Association.

Bullock, L. A., & Parnell, J. (2017). Selenium and molybdenum enrichment in uranium roll-front deposits of Wyoming and Colorado, USA. Journal of Geochemical Exploration, 180, 101–112.

Chenoweth, W. (1991). A summary of uranium production in Wyoming. Mineral Resources of Wyoming 42nd Annual Field Conference Guidebook (pp. 169–179). Wyoming Geological Association.

Childers, M. (1978). Classification of uranium deposits. In W. D. David & R. Lageson (Eds.), Occurrences of uranium in precambrian and younger rocks of Wyoming and adjacent areas (pp. 7–8). Laramie, WY: Wyoming Geological Survey.

Dahlkamp, F. J. (1993). Typology of uranium deposits. In Uranium ore deposits (pp. 92–93). Berlin: Springer-Verlag.

Dickinson, W. R., Klute, M. A., Hayes, M. J., Janecke, S. U., Lundin, E. R., McKittrick, M. A., & Olivares, M. D. (1988). Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region. Geological Society of America Bulletin, 100(7), 1023–1039.

Harshman, E. (1961). Paleotopographic control of a uranium mineral belt, Shirley Basin, Wyoming. Short Papers in the Geologic and Hydrologic Science, Articles 120–179, USGS Professional Paper 424-C (pp. 4–6).

Harshman, E. N. (1962). Article 122 – alteration as a guide to uranium ore, Shirley Basin, Wyoming. Short Papers in the Geologic and Hydrologic Science, Articles 120–179, USGS Professional Paper 450-D.

Harshman, E. N. (1972). Geology and uranium deposits, Shirley Basin Area, Wyoming. United States Geological Professional Paper 745.

Harshman, E. N., & Adams, S. (1980). Geology and recognition criteria for roll-type uranium deposits in continental sandstones. United States Department of Energy Report GJBX-1 (81).

Jones, C. A. (1978, May). A preliminary classification of uranium deposits (D. G. Mickle, ed.). United States Department of Energy Report GJBX-63. Grand Junction, CO: Bendix Field Engineering Corporation (pp. 78).

Melin, R. E. (1969). Uranium deposits in Shirley Basin, Wyoming. Contributions to Geology: Wyoming Uranium Issue, 8(2), 143–149.

Rackley, R., Shockey, P., & Dahill, M. (1968). Concepts and methods of uranium exploration. 20th Annual Field Conference Guidebook (pp. 115–124). Wyoming Geological Association.

Rubin, B. (1970). Uranium roll front zonation in the southern powder river Basin, Wyoming. WGA Earth Science Bulletin, 3, 5–12.

Schiffer, B. J. (2014). Technical report on resources Shirley Basin uranium project carbon county, Wyoming, USA. Sheridan, WY: WWC Engineering.

Seeland, D. (1978). Sedimentology and stratigraphy of the lower Eocene wind river formation, central Wyoming. 30th Annual Field Conference Guidebook (pp. 181–198). Wyoming Geological Association.

Ur-Energy, Inc. (2015, January 27). Preliminary economic assessment Shirley Basin uranium project carbon county, Wyoming, USA. Report for NI 43-101. Prepared under the supervision of: Benjamin, J., Schi, P. G., & Ray Moores, P. E., WWC Engineering, Sheridan, WY. Retrieved from http://www.ur-energy.com/technical-reports/

Williams, J., Arsenault, M., Buczkowski, B., Reid, J., Flocks, J., Kulp, M., … Jenkins, C. (2007). Wentworth grain size chart. United States geological survey open-file report 2006–1195. Surficial sediment character of the Louisiana offshore continental shelf region: A GIS Compilation. Retrieved from https://pubs.usgs.gov/of/2006/1195/html/docs/images/chart.pdf

Wyoming Mining Association. (2017, June 29). Wyoming uranium: An overview for Wyoming legislature joint minerals committee. Retrieved from http://www. wyomingmining.org/wp-content/uploads/2018/01/ 170626-Wyoming-Uranium-Overview.pdf

Zielinski, R. A. (1983). Tuffaceous sediments as source rocks for uranium: A case study of the white river formation, Wyoming. Journal of Geochemical Exploration, 18, 285–306.