

STRUCTURAL CONTROLS ON ROLL-FRONT MINERALIZATION AT THE
BUSS PIT DEPOSIT, GAS HILLS DISTRICT, WYOMING

by
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ABSTRACT

A significant portion of the world's uranium resources are hosted by sandstone-hosted roll-front deposits. This type of deposit is an attractive exploration target as it is amenable to *in situ* mining methods. Roll-front deposits form when oxidized, uranium-bearing groundwater encounters a redox boundary creating a crescent-shaped ore body. Reducing conditions downstream of the ore body are thought to be maintained by the presence of diagenetic pyrite or organic material within the host aquifer. However, some roll-front deposits occur within aquifers that contain only low amounts of *in situ* reductants. Under such circumstances it is possible that leakage of reduced fluids along faults creates the necessary chemical trap for deposit formation.

The Buss Pit is a roll-front deposit in the Gas Hills district of Wyoming hosted by sandstones of the Wind River Formation. The host rocks of this past producer contain low amounts of organic carbon and minor diagenetic pyrite, possibly not providing a sufficient amount of reductant to form a major uranium deposit. The Gas Hills district, however, is known for the surface discharge of hydrocarbons derived from deep in the Wind River Basin. A three-dimensional model of the deposit area has been developed to test whether there is a potential connection between the location of uranium ore at the Buss Pit and faults that may control upflow of mobile reductants.

Geophysical logs were used to reconstruct the deposit stratigraphy, shape of ore zones, and location of faults. The stratigraphy of the Wind River Formation was modeled by correlating resistance curves across the study area. The shape of the ore zones and the grade distribution were derived by digitizing gamma ray curves and calculating equivalent percent uranium oxide grades for each log. The interpreted geophysical dataset was combined to create a three-dimensional model that shows resistive and non-resistive lithologies, ore zones, and major faults. The host rock succession is composed primarily of fining-up units of dominantly arkosic conglomerate to sandstone with variably discontinuous siltstone to mudstone interbeds. This sedimentary package has six fining-up units that dip gently to the south. The steeply dipping, normal Buss fault strikes E-SE, bisecting the deposit area and historic open pit. The ore zones were modeled into three grade shells, which generally occur in resistive lithologies in the

southwest quadrant of the study area. Grade shells define an amalgamation of intricate planar and crescent-shaped ore bodies that collectively dip to the west. The three-dimensional model highlights the spatial relationship between the ore zones of the Buss Pit deposit and the faults. The complexity of the ore zone morphologies can only be explained by upflow of mobile reductants along the fault.

The results of the three-dimensional modeling reveal the importance of large scale structural controls on the formation of at least some roll-front uranium deposits. It is shown that three-dimensional modeling of geologically complex uranium deposits can provide important insights for exploration and *in situ* extraction.

TABLE OF CONTENTS

ABSTRACT.....	iii
LIST OF FIGURES	vii
LIST OF TABLES.....	ix
LIST OF ABBREVIATIONS.....	x
ACKNOWLEDGEMENTS.....	xi
CHAPTER 1 INTRODUCTION	1
CHAPTER 2 REGIONAL GEOLOGY.....	3
CHAPTER 3 MATERIALS AND METHODS	9
CHAPTER 4 STRATIGRAPHIC MODEL.....	13
4.1 Sedimentary Facies	13
4.2 Interpretation of Resistance Logs	14
4.3 Deposit Stratigraphy	18
CHAPTER 5 STRUCTURAL MODEL.....	23
5.1 Field Observations	23
5.2 Results of 3D Modeling.....	25
CHAPTER 6 GRADE DISTRIBUTION.....	27
6.1 Spatial Distribution of Ore Zones	27
6.2 Stratigraphic Controls on Ore Subzones.....	30
6.3 Ore Subzone Morphology.....	31
6.4 Structural Controls on Ore Subzones.....	33
CHAPTER 7 DISCUSSION.....	37
7.1 Roll-front Formation of the Buss Pit Deposit	37
7.1.1 Reducing Capacity of the Host Rocks	37
7.1.2 External Source of Reductants.....	37
7.1.3 Stratigraphic Controls	40
7.1.4 Structural Controls.....	40
7.1.5 Geometry of Ore Body.....	42
7.2 Comparison to Other Roll-front Deposits in Wyoming.....	44
7.3 Implication for the Deposit Model.....	46

7.4 Implications for Exploration and Mining	46
7.4.1 Exploration.....	47
7.4.2 Mining.....	48
CHAPTER 8 CONCLUSIONS	50
REFERENCES CITED.....	52
APPENDIX A: SUPPLEMENTAL ELECTRONIC FILE	59
APPENDIX B: FIELD DESCRIPTIONS AND GEOCHEMICAL DATA.....	60

LIST OF FIGURES

Figure 2.1	Geologic map of Wyoming showing the Wind River Basin	4
Figure 2.2	Geologic map of the Gas Hills district showing the Buss Pit	5
Figure 2.3	Schematic stratigraphic column of the Cenozoic basin fill	6
Figure 3.1	Plan view of bore hole collars used for lithology correlation and grade distribution	10
Figure 3.2	Leapfrog 3D model with bore hole distribution	12
Figure 4.1	Field photos showing important lithological	16
Figure 4.2	Resistance logs and lithology interpretation overlain on outcrop image	17
Figure 4.3	Leapfrog 3D model of stratigraphy.....	18
Figure 4.4	Measured sections, representative resistance curve and generalized stratigraphic section	21
Figure 4.5	North-facing pit wall with scour surfaces.....	22
Figure 5.1	Photo of the Buss fault in outcrop.....	23
Figure 5.2	Detailed photos of the Buss fault in outcrop.....	24
Figure 5.3	Leapfrog 3D model showing faults.....	26
Figure 5.4	Three-dimensional visualization of the SE and Buss faults.....	26
Figure 6.1	Leapfrog 3D model of faults and ore shells.....	28
Figure 6.2	North facing cross-section showing dip of ore body	28
Figure 6.3	Ore distribution in plan view with fault traces, logs used to calculate ore zones and cross-section locations	29
Figure 6.4	North-south ore subzone cross-sections.....	31
Figure 6.5	East-west ore subzone cross-sections	32
Figure 6.6	Northwest-southeast ore subzone cross-sections	33
Figure 6.7	Cross-sections showing ore subzone morphologies near the Buss fault.....	34
Figure 6.8	Location map showing cross-sections A – A', B – B', and C – C'	35
Figure 6.9	Cross-sections A – A', B – B', and C – C'	36
Figure 7.1	Organic carbon and iron sulfide contents of structurally associated roll- front deposits.....	39
Figure 7.2	Schematic diagram of fluid interaction at the Buss fault.....	45

Figure 7.3	Schematic diagram of the proposed basin scale processes	47
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LIST OF TABLES

Table B-1	Sample field descriptions.....	61
Table B-2	Major and trace element geochemistry of samples.....	63

LIST OF ABBREVIATIONS

Chemistry

U ₃ O ₈	uranium oxide
H ₂ S	hydrogen sulfide
U/Pb	uranium-lead
Ra	radium
Rn	radon
ICP-OES	inductively coupled plasma – optical emission spectrometry
ICM-MS	inductively coupled plasma – mass spectrometry
Eh	oxidation potential

Units

cm	centimeter
m	meter
km	kilometer
ft	foot

Other abbreviations

ISL	<i>in situ</i> leach
ppb	parts per billion
Ma	million years
%RSD	percent relative standard deviation
%	percent
wt. %	weight percent
e%	equivalent percent
ss	sandstone
congl	conglomerate

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CHAPTER 1

INTRODUCTION

The Gas Hills district in central Wyoming represents one of the most important uranium producing regions of the United States (Boberg, 2010). Mining in the district followed the initial discovery of uranium in 1953 and accounted for approximately twelve percent of the past uranium production of the country (Anderson, 1969). Although uranium recovery from roll-front deposits in the Gas Hills district came to an end in 1988, significant resources remain in the Eocene sandstones of the Wind River Formation (Nielsen et al., 2012).

Roll-front uranium deposits such as those of the Gas Hills district are epigenetic concentrations of uranium minerals that occur as impregnations and massive replacements in continental sandstone formations within sedimentary basins (Adler, 1964; Harshman and Adams, 1980; Boberg, 2010). They occur as crescent or roll-shaped deposits having average grades between 0.05 and 0.25 wt.% U_3O_8 (Anderson, 1969; Harshman and Adams, 1980; Burrows, 2010). The deposits form as uranium dissolved in oxidized groundwater precipitates as uraninite or coffinite when the groundwater encounters a redox boundary in the sandstone aquifer (Spirakis, 1996).

Over the past decades, the nature of the reductant in the host sandstone of roll-front deposits has been a matter of considerable debate. Traditionally, reducing conditions in the sandstone aquifer are thought to be related to the presence of organic matter and/or diagenetic pyrite (Adler, 1964; Cheney and Jensen, 1966; Granger and Warren, 1978; Spirakis, 1996). However, it has been suggested that deep-seated faults may control upflow of reductants such as hydrogen sulfide, hydrocarbons, or reducing brines from deep within the sedimentary basins (Grutt, 1957; Dickinson and Duval, 1977; Goldhaber et al., 1983; Spirakis, 1996; Jaireth et al., 2008; Burrows, 2010). Examples of this type of structural control include the deposits of the Ray Point uranium district in South Texas, where saline brines ascended along the Oakville fault (McKnight, 1972; Dickinson and Duval, 1977; Goldhaber et al., 1983). Similarly, uranium deposition in the Chu-Sarysu oil and gas basins of Kazakhstan has been interpreted to be related to hydrocarbon seepage along regional faults (Jaireth et al., 2008; Burrows, 2010). The host rocks in these structurally controlled roll-front uranium deposits are characteristically low in their organic carbon and pyrite contents (Jaireth et al., 2008).

The present paper evaluates to what extent the location of roll-front uranium deposits in the Gas Hills district of central Wyoming are structurally controlled. Based on interpretation and correlation of geophysical logs from exploration and delineation drill holes at the Buss Pit deposit, the stratigraphy, structural geology, and shape of roll-front ore zones at one of the major past producers of the Gas Hills district was reconstructed. Three dimensional modeling demonstrates that there is a spatial correlation between the location of the ore zones at the Buss Pit and the occurrence of a major steeply-dipping, normal fault, implying that upwelling of mobile reductants along the fault played a major role in uranium enrichment in the host sandstone. The findings of the research contribute to an improved understanding of the processes of roll-front formation in the intramontane basins of the western United States, which has significant implications for future exploration for this deposit type. The present contribution also demonstrates that three dimensional modeling represents a powerful tool that is currently underutilized in the exploration and development of roll-front uranium deposits.

CHAPTER 2

REGIONAL GEOLOGY

The Gas Hills district of central Wyoming forms part of the Wyoming uranium province, which encompasses the Laramide basins and uplifts of Wyoming as well as adjacent areas in Montana, North Dakota, South Dakota, and Colorado (Finch, 1996). The total past uranium production of the Wyoming uranium province is estimated to be approximately 91,000 metric tons of U_3O_8 (Boberg, 2010). Current operating uranium mines are exploited by *in situ* leaching and located in the Powder River and Great Divide Basins (Fig. 2.1).

The intramontane basins of Wyoming were formed by deformation initiated by the Laramide Orogeny from Late Cretaceous to Eocene times when Archean basement core complexes were uplifted and the overlying Paleozoic and Mesozoic sedimentary succession, formed in a stable shelf to shallow oceanic environment, was folded and faulted (Bell and Middleton, 1978; Boberg, 2010). Uplift ceased during the Eocene while the resulting basins began to fill with terrestrial sediments shed from the igneous and metamorphic highlands in alluvial and fluvial systems during the Cenozoic (Seeland, 1978). Oligocene volcanic eruptions in the Absaroka and Yellowstone volcanic fields deposited thick ash units followed by Miocene conglomerates and sandstones capping the Cenozoic succession (Houston, 1969). Uranium occurrences in Wyoming have been identified in all Eocene and younger sedimentary packages with deposits usually clustering near Archean core complexes (Boberg, 2010). The uranium is thought to have been sourced from the Oligocene volcanic ash and/or the Archean crystalline basement (Burrows, 2010).

The Wind River Basin is a 21,000 km² sedimentary basin that is bordered by the Beaver Rim escarpment and the Granite Mountains to the south, the Owl Creek Mountains to the north and the Wind River Range to the west (Fig. 2.1; Houston, 1969). The Gas Hills district is located on the southeastern edge of the Wind River Basin in Fremont and Natrona Counties (Fig. 2.2). Historically, the Gas Hills have been the second most productive uranium district in the United States (Anderson, 1969). Approximately 45,500 metric tons of uranium have been produced from the Gas Hills since 1953, primarily by open pit mining (Nielsen et al., 2012). The district comprises over 20 historic open pit mines, three former uranium mills, and a number of current exploration sites (Fig. 2.2; Nielsen et al., 2012).

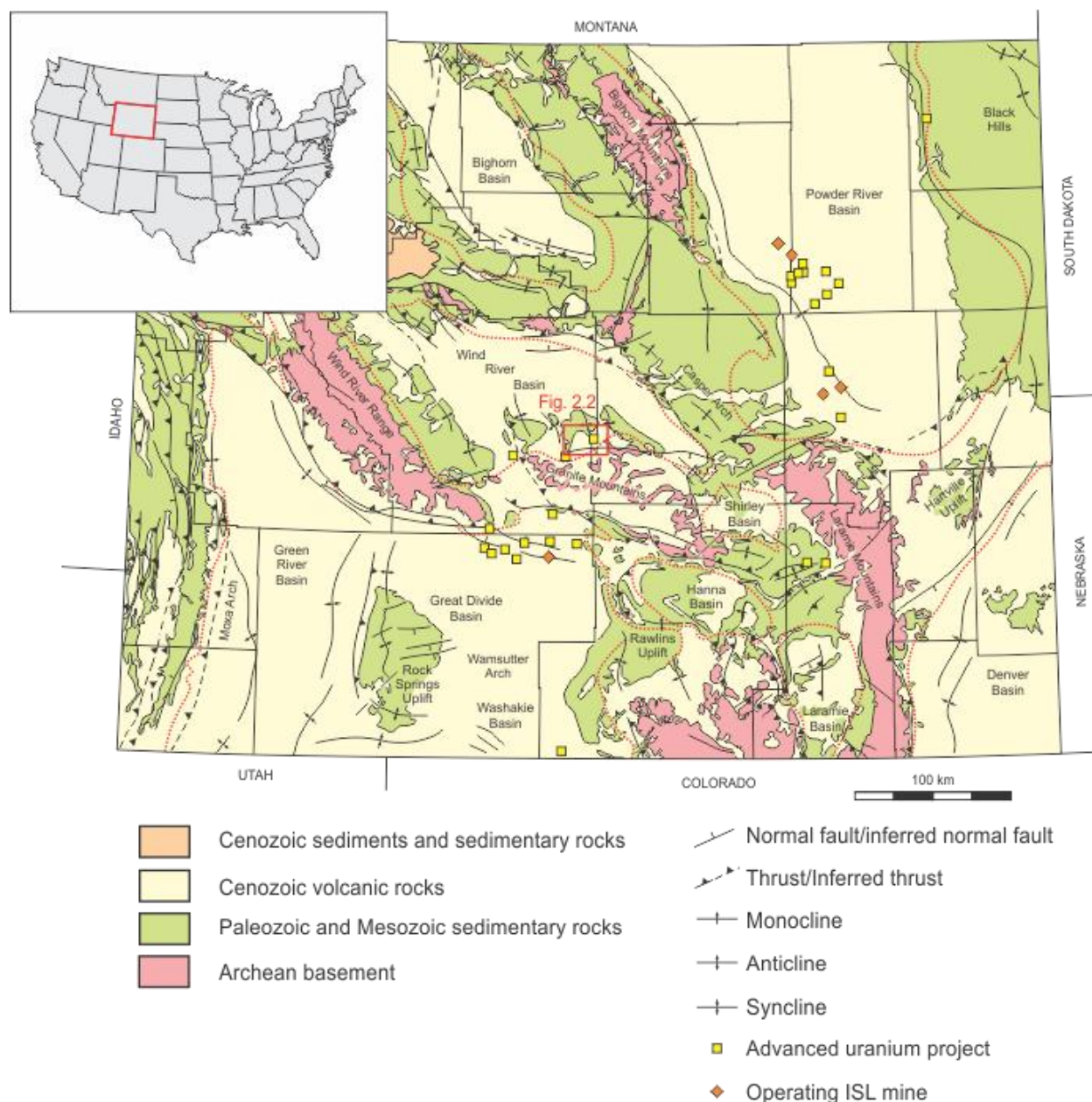


Figure 2.1: Geologic map of Wyoming showing the locations of advanced uranium projects and operating *in situ* leach (ISL) mines. The Gas Hills uranium district is located in the southeast of the Wind River Basin. The location of Figure 2.2 is highlighted.

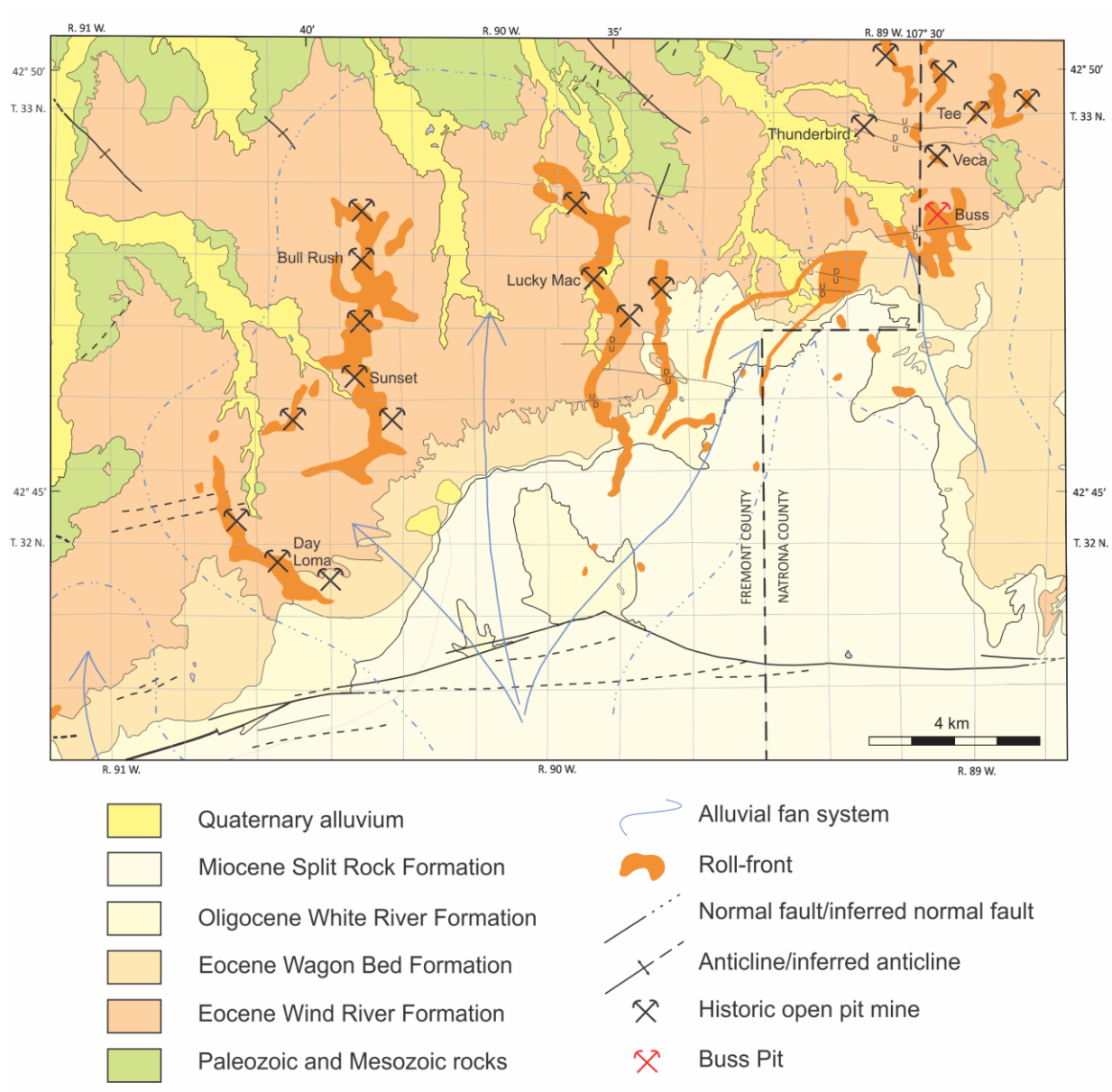


Figure 2.2: Geologic map of the Gas Hills uranium district showing the location of historic open pit mines, structures, roll-fronts, and the estimated extent of alluvial fan systems (modified from Van Houten, 1964 and Power Resources, Inc. Gas Hills Project WDEQ-LQD Permit to Mine Application, Appendix D5-Geology, 1998). The location of the Buss Pit deposit is highlighted.

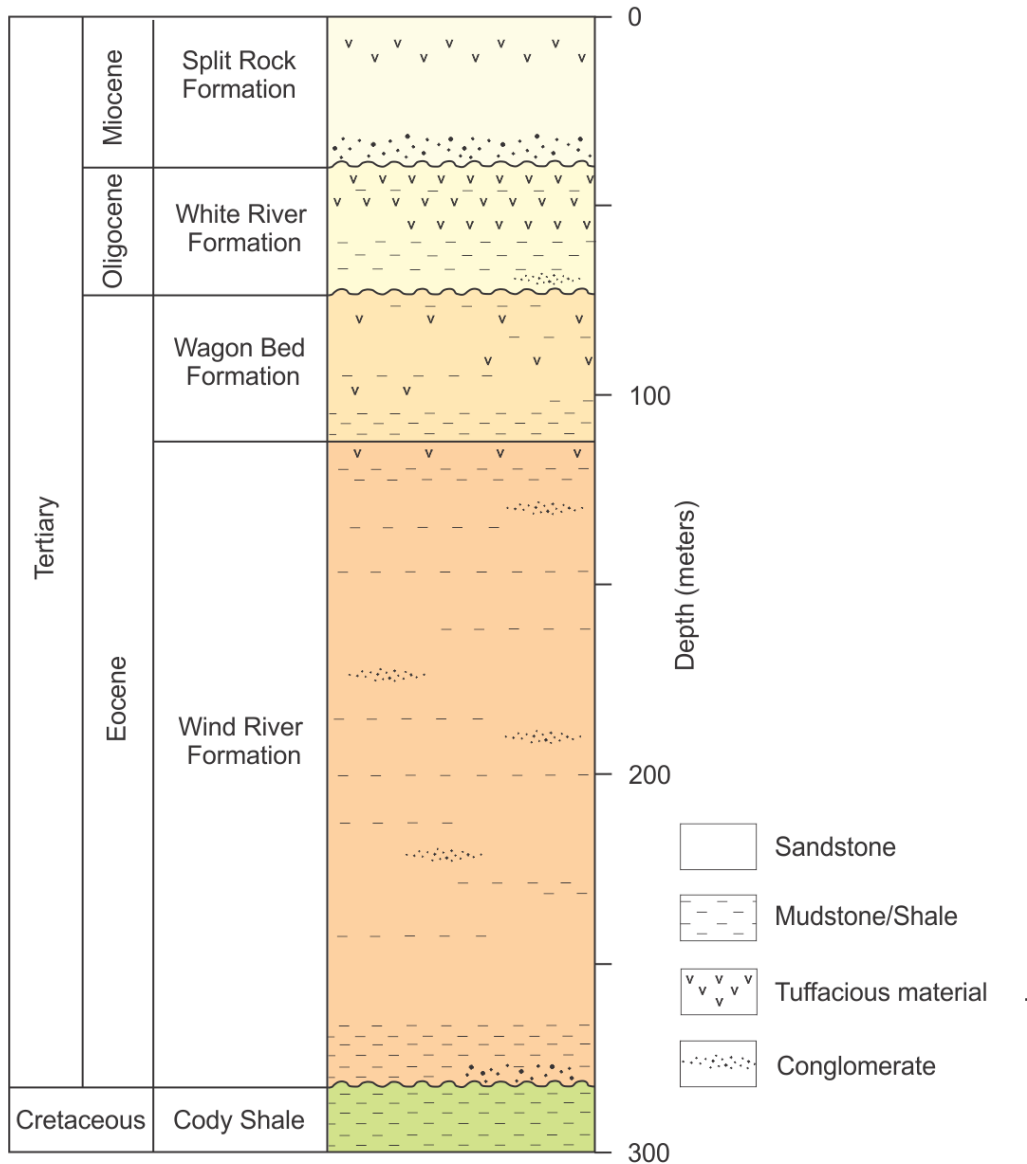


Figure 2.3: Schematic stratigraphic column of the Cenozoic sedimentary strata in the Wind River Basin (modified from Love, 1954; Armstrong, 1970; Nielsen et al., 2012).

Archean basement rocks are exposed in a Laramide core complex to the south of the Gas Hills district within the Granite Mountains (Soister, 1968; Boberg, 2010). Folded and faulted Paleozoic sandstone, limestone, and dolomite, as well as Mesozoic shale and sandstone are exposed as hogbacks within the basin (Figs. 2.1 and 2.2; Houston, 1969). High sulfur oil and sour gas have been produced throughout the Wind River Basin from the lower Eocene Wind River Formation to the Mississippian Madison Limestone (Fig. 2.3; Johnson and Keighin, 1998).

These units were deformed into multiple anticlinal traps and have been exploited for oil and gas by many companies. Inexco Oil Company produced oil and gas in the Madden anticline from the Mesaverde Formation, Cody Shale, and Madison Formation with a total of 1.4 trillion cubic feet gas, 1.1 million barrels of condensate, and 44 million barrels of water through 2005 (Hawkins and Baugh, 2006). The 1000 m thick Cody Shale underlies the majority of the basin and serves as a regional aquitard as well as a hydrocarbon trap (Fig. 2.3; Love, 1954).

Gently dipping Cenozoic sedimentary rocks unconformably overlie the deformed Paleozoic and Mesozoic successions (Fig. 2.3; Houston, 1969). The Cenozoic units are sourced from the metamorphic and igneous core complexes with pyroclastic input from the Absaroka and Yellowstone volcanic fields (Armstrong, 1970).

The Eocene Wind River Formation outcrops extensively within the basin and is thought to have formed in overlapping alluvial fan and channel environments (Houston, 1969; Boberg, 2010). The Wind River Formation is a 130-170 m thick succession of yellowish-gray, arkosic sandstone, conglomerate, and variegated mudstone lenses with increasing tuffaceous material up section (Seeland, 1978). It is divided into three members, namely, the lower, fine-grained member, the middle Puddle Springs Arkose member and the upper transitional, fine-grained member (Armstrong, 1970). The lower, fine-grained member (thickness of 0-40 m) is composed of partly variegated mudstone, siltstone, and shale with conglomerate near the base (Soister, 1968; Nielsen et al., 2012). The Puddle Springs Arkose member (thickness of 6-100 m) is the main ore host. It is composed of dominantly poorly-sorted, poorly calcite-cemented, feldspathic sandstone with interbedded sandy clay, shale, and conglomerate lenses (Soister, 1968; Anderson, 1969; Armstrong, 1970). Conglomerate lenses increase in abundance and clast size to the south towards the Granite Mountains (Van Houten, 1964). The upper transitional member (thickness of 15-30 m) consists of interbedded arkosic sandstone and shale with tuffaceous mudstone, this formation does not extend over the entire basin (Armstrong, 1970; Soister, 1968).

The Wind River Formation is conformably overlain by the Wagon Bed Formation (Fig. 2.3) that consists of 30-45 m of a thin basal mudstone layer overlain by sandstones and mudstones with increasing tuffaceous material up section (Nielsen et al., 2012). The Wagon Bed Formation is unconformably overlain by 40 m of Oligocene White River Formation (Fig. 2.3), which is dominantly composed of tuffaceous mudstones with arkosic sandstone and conglomerate lenses (Anderson, 1969; Nielsen et al., 2012). The 45 m, Miocene Split Rock

Formation unconformably overlies the White River Formation with a basal conglomerate and massive tuffaceous sandstone with pebble conglomerate lenses (Love, 1954; Nielsen et al., 2012).

The sedimentary succession filling the basin dips 1-3° to the southeast as the result of the post-Miocene to Pleistocene subsidence of the Granite Mountains (Armstrong, 1970). At the time of deposition and uranium mineralization, the succession dipped shallowly to the north in the Gas Hills district (Soister, 1968). The sedimentary package has been affected by two normal faulting events, likely in the early Eocene and between the post-Miocene and Pleistocene (Cheney and Jensen, 1966). Uplift in the late Pliocene and early Pleistocene initiated the current erosional cycle that included the drainages and 120-150 m Beaver Rim escarpment (Anderson, 1969; Armstrong, 1970).

The uranium mineralizing event in the Gas Hills district is constrained to be 22±3 Ma by U/Pb dating (Dooley et al., 1974). Uranium deposits in the Gas Hills district occur in four styles, however, over 90% of the total ore occurs as laterally extensive, crescent-shaped roll-front deposits consisting dominantly of uraninite and coffinite in the sandstones of the Puddle Springs Arkose member (Anderson, 1969).

CHAPTER 3

MATERIALS AND METHODS

The present study is based on resistance and gamma ray data logged from 754 bore holes drilled from 1964 to 1987. The geophysical data was gathered by multiple companies with “ore” probes; these probes most likely contained a thallium-activated sodium iodide detector, a spontaneous-potential electrode and a single-point resistance electrode. They were used in reverse circulation drill holes to produce paper logs with gamma ray, spontaneous potential, and resistance curves (Bailey and Childers, 1977). Collar coordinates, elevation, date, and probe parameters were documented on the historical logs. All bore holes used in the present study were located within the 1.2 km by 1 km Buss Pit study area (Fig. 3.1). The holes ranged from 50 m to 240 m in length and were collared at a spacing of approximately 15 m.

Initial work involved the digitalization of the resistance logs from 464 bore holes for the development of a stratigraphic model. For this, the paper logs were scanned into high-resolution image files. The bore holes selected for lithological correlation were located along 21 cross-sections with an average spacing of 95 m between the sections (Fig. 3.1). A more detailed area (280 m by 95 m) in the center of the Buss Pit area was correlated with a 15 m grid to study the small scale relationships between stratigraphy and grade distribution near the Buss fault, which transects the study area (Fig. 3.1).

Using the high-resolution image files, two categories of sedimentary facies were distinguished based on their resistance response. Resistive intervals in the logs were interpreted to represent sedimentary facies with a low clay content such as conglomerates and sandstones. The pore spaces in these resistive rocks are likely filled by fresh water or air (Jorgensen, 1989). Non-resistive intervals were interpreted to be clay-rich facies, including siltstone and mudstone (Jorgensen, 1989). During lithological interpretation, only continuous resistive and non-resistive intervals with a thickness exceeding 60 cm (2 feet) were recorded. For each drill hole, the observed down-hole distribution of interpreted sedimentary facies was recorded in an Excel spreadsheet.

In addition to the stratigraphic model, the gamma curves of the 754 paper logs were digitalized (Fig. 3.1). Digitalization was performed using NeuraLog, an advanced automated well log digitizing software. Based on log-specific probe parameters recorded on the paper logs,

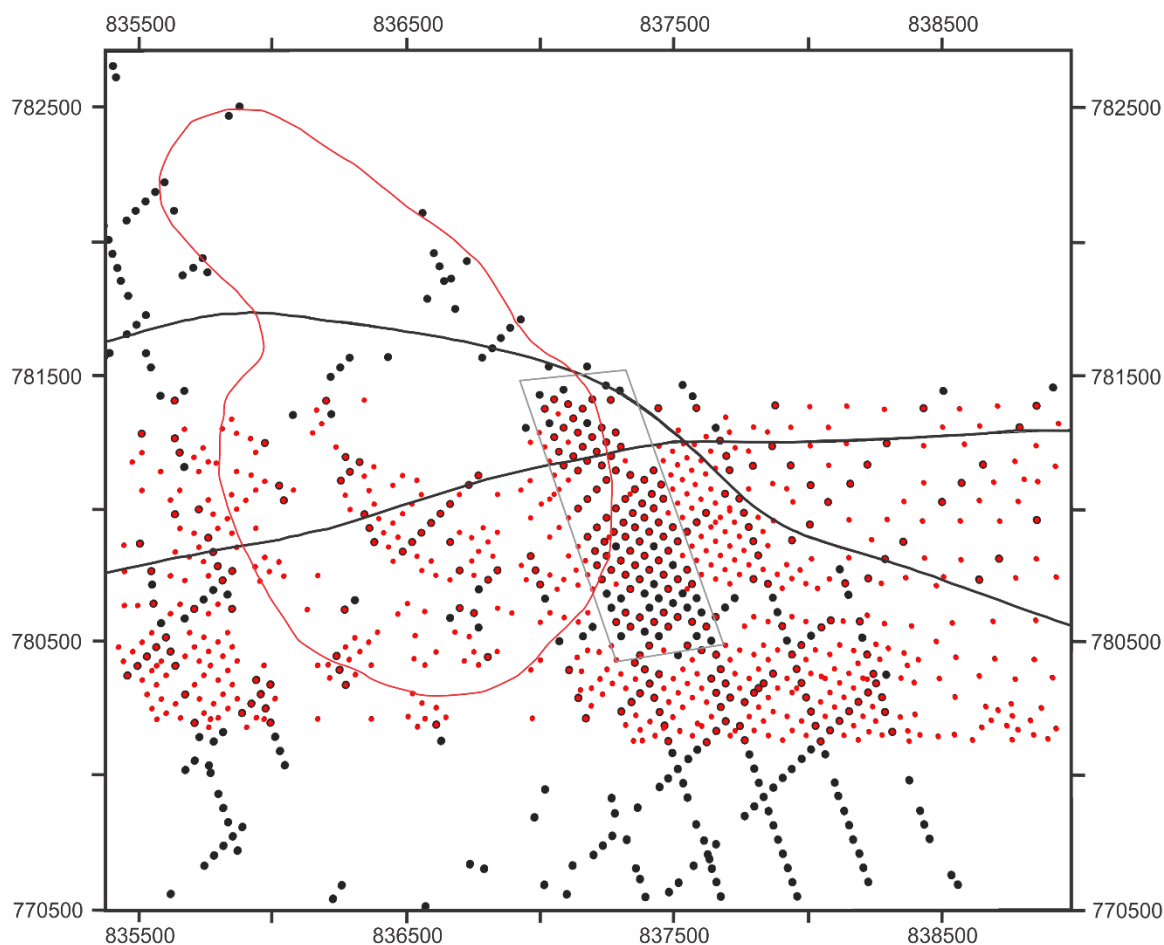


Figure 3.1: Bore hole location map of the Buss deposit area. The black bore hole collars were used to model stratigraphy and the red bore hole collars were used to model grade distribution. The gray box outlines the detailed model area and the red line outlines the open pit. The map also shows the surface trace of two faults dissecting the deposit area. Coordinates in Wyoming State Plane coordinate system with units of US feet.

the digitalized gamma curves obtained this way were recalculated into equivalent percent U_3O_8 (e% U_3O_8) concentrations at 15 cm (0.5 foot) intervals. Equivalent percentages are calculated under the assumption of radioactive equilibrium in the ^{238}U decay series (Brooks, 2008). Direct testing of this assumption was not possible as chemical assay values are not available for the historic bore holes. Although the gamma response may not be used for resource estimation, the shapes of the reconstructed ore zones resemble those reported for roll-fronts elsewhere,

suggesting that the gamma logs correctly map out the distribution of ore at Buss Pit. This approximated down-hole uranium distribution for each digitalized bore hole was archived as an Excel spreadsheet.

The Leapfrog Geo three-dimensional modeling software was used to build and visualize the stratigraphic model and the grade distribution model. For this, all data compiled into spreadsheets was imported into the 3D environment. The stratigraphic model was built separately for the four blocks separated by faults. The location of the faults in the deposit area was inferred from GPS measurements in the open pit and offsets in stratigraphy inferred from the constructed stratigraphic sections. The distribution of uranium grades was modeled as three grade shells of >0.02, >0.05 and >0.1 e% U_3O_8 . The ore shells were interpolated using a spheroidal interpolant with a 45 m range, a 1.5 m surface resolution, and a trend striking 087° and dipping 1.9° south to mimic stratigraphy. The 3D model was completed by establishing the pre-mine topography. The topographic information in the area of the pit was derived from the USGS Ervay Basin SW Quadrangle 7.5 minute series topographic map from 1952. Current topography was established from a recent aerial survey conducted by Cameco Corporation. Figure 3.2 shows the 3D model of the deposit area displaying the reconstructed pre-mine surface topography and the distribution of bore holes used in the present study.

In addition to the 3D modeling, the stratigraphic relationships in the open pit were documented during a field visit. Measured sections were constructed at the eastern reclaimed high wall of the open pit to allow direct correlation between the stratigraphy observed in outcrop and the stratigraphy inferred from the resistance logs.

During field work, a total of eight grab samples were collected to determine the relative amount of reductant present in the host rocks of the Buss Pit deposit. One sample of fault gouge was taken from the Buss fault. Two samples were collected near the fault and one from 6 m, 30 m, 39 m, 61 m, and 72 m to the north of the fault. In the laboratory, the samples were disaggregated, split, and milled to a grain size <63 μm using a tungsten carbide ring mill. The obtained sample powders were submitted to Actlabs in Ancaster, Ontario, for geochemical analysis. Initially, the samples were mixed with a flux of lithium metaborate and lithium tetraborate then fused in an induction furnace. The melt produced was poured into a solution of 5% nitric acid containing an internal standard, and mixed continuously until completely dissolved. The samples were then analyzed for their major and trace element contents by a

combination of inductively coupled plasma – optical emission spectrometry (ICP-OES) and inductively coupled plasma-mass spectrometry (ICP-MS). Selected elements were determined by ICP-OES following acid digestion. This included initial treatment with hydrofluoric acid, followed by a mixture of nitric and perchloric acids. The sample is then taken to incipient dryness. After incipient dryness is attained, the sample is brought back into solution using aqua regia. In addition to the major and trace element analyses, the total carbon contents of the samples were measured by automated combustion and coulometric detection at the Colorado School of Mines. The analyses were performed using a UIC CM5300 furnace module and a UIC CM5014 CO₂ coulometer.

The precision and accuracy of the geochemical investigations were monitored by repeated analysis of international georeference materials. Repeated analysis showed that the precision of the analytical method was typically better than 3 %RSD for element concentrations significantly above their respective detection limits. Comparison with the certified values shows that the geochemical analyses were also highly precise.

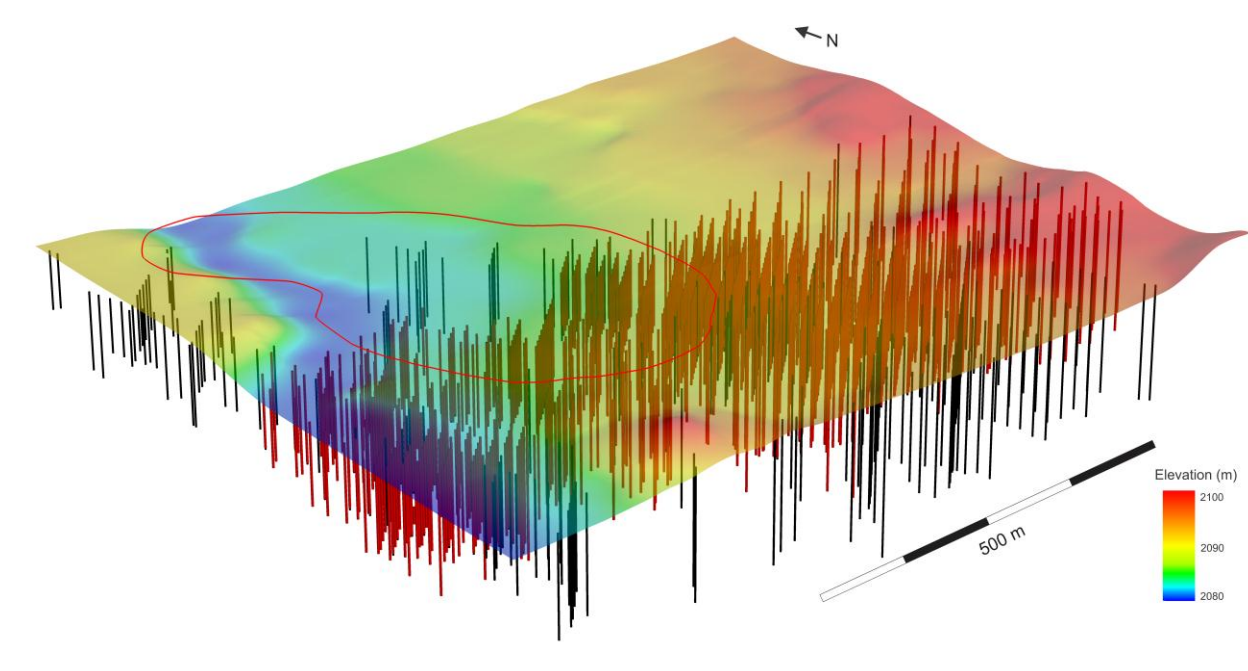


Figure 3.2: Leapfrog Geo 3D model of the deposit area displaying the pre-mine surface topography and the location of bore holes used for lithological correlation (red) and the modeling of the grade distribution (black). The red line gives the outline of the open pit.

CHAPTER 4

STRATIGRAPHIC MODEL

4.1 Sedimentary Facies

A ~48 m thick portion of the Puddle Springs Arkose member hosting the Buss Pit deposit is exposed in the eastern high wall of the open pit, allowing direct observation of parts of the deposit stratigraphy and the study of the sedimentological character of the host rocks.

Based on grain size, two main sedimentary facies can be distinguished in outcrop. A sandstone/conglomerate facies comprises gray to yellow-white, cobble conglomerates to fine sandstones (Fig. 4.1). The major clastic components recognized in the field include quartz, altered feldspars, smoky quartz, minor clay minerals, muscovite, and rounded to subrounded lithic clasts of granite and quartz vein material. The yellow-white, white to light gray sandstone/conglomerate facies display channel geometry on the meter scale. Channel fill fines upward from poorly-sorted, cobble or pebble conglomerates to moderately to well-sorted, fine sand with no sedimentary structures, weak laminar bedding or cross bedding. Channels fine upward, however each can contain multiple fining up beds.

Six unmineralized sandstone/conglomerate facies samples were analyzed and contain 77.6 – 80.0% SiO₂, 10.2 – 13.2% Al₂O₃, 0.51 – 1.59% Fe₂O₃, 0.05 – 0.11% total carbon and 0.026 – 0.178% pyrite. According to Herron's (1988) chemical classification of terrigenous sandstones, these samples would be classified as an arkose. The total carbon measurements from the host sandstones provide an estimate for the amount of organic material that could have served as an authigenic reductant, assuming no carbonate being present in the rocks. The iron sulfide content is calculated from the amount of sulfur contained in the host sandstones, assuming all sulfur was present as diagenetic iron sulfide minerals before mineralization.

Mudrock facies consist of medium to dark gray siltstones and fissile mudstones and are characterized by elevated clay mineral contents. Mudrock facies form the top of the major fining up channels and can have an erosional top contact with the overlying channel above (Fig. 4.1). Mudrock facies form lenticular beds between the more continuous sandstone/conglomerate channels. These fine-grained rocks are quite susceptible to erosion and commonly display orange Fe-oxide staining at the surface.

Geochemical analysis of a green clay-rich mudstone sampled at the Buss Pit fault showed that the material contained 64.5% SiO₂, 15.3% Al₂O₃, 4.05% Fe₂O₃, 0.09% total carbon and a pyrite content of 0.494%. The comparably high Al₂O₃ content corresponds to the elevated clay content of the rock. The mudstone sample has the highest pyrite content of all samples analyzed.

The eastern high wall of the open pit shows four major sandstone/conglomerate units that range from 4 to 15 m in thickness. Each unit consists of a discontinuous basal cobble conglomerate that fines upward to a fine sandstone (Fig. 4.2). At the outcrop scale, the cobble conglomerate forms lenses at scour surfaces while coarse to fine sandstones are laterally more continuous across the outcrop. In detail, each sandstone/conglomerate unit may be comprised of multiple fining-up beds that have thicknesses of up to several decimeters. The sandstone/conglomerate facies units are interbedded with mudrock facies units of variable thickness. The mudrock units are typically not as continuous as the coarser grained units in the eastern high wall of the deposit. Where observed, the mudrock units range from 30 cm to ~2 m in thickness. The units strike 087° and dip 04° south.

4.2 Interpretation of Resistance Logs

To test whether the stratigraphy of the sedimentary host rocks of the Buss Pit deposit can be modeled from the historic resistance logs, outcrop photos taken in the open pit were georeferenced and compared to resistance logs collected in nearby bore holes collared prior to mining. Visual comparison shows a good correlation between the observations in the field and the interpreted resistance logs. In general, resistive intervals in the logs correlate with intervals of sandstones or conglomerate in outcrop while non-resistive intervals correspond to the mudrock facies (Fig. 4.1). This suggests that breaks in the down-hole resistance data can indeed be used to identify contacts between the major sedimentary facies in the Buss Pit area. However, fine-scale sedimentological variations within those units cannot be easily resolve and are impossible to correlate between adjacent holes.

Figure 4.1: Field photos showing important lithological characteristics of the host rocks of the Buss Pit deposit. A. Sandstone/conglomerate channel fill sequence with a scoured base. B. Sandstone overlain by a mudstone. C. Mudstone overlain by a sandstone and granule conglomerate channel fill. D. Cobble conglomerate with an erosional basal contact with the underlying sandstone. E. Multiple beds fining up from pebble conglomerate to coarse sandstone. F. Bedding in conglomerate and sandstone beds visible at an inaccessible ~4 m buttress outcrop. G. Cobble conglomerate channel fill with an erosional contact with the underlying sandstone which contains large siltstone clasts. H. Thin cobble conglomerate beds that fine to cross-bedded, coarse sandstone. Geologic hammer (42 cm) for scale.



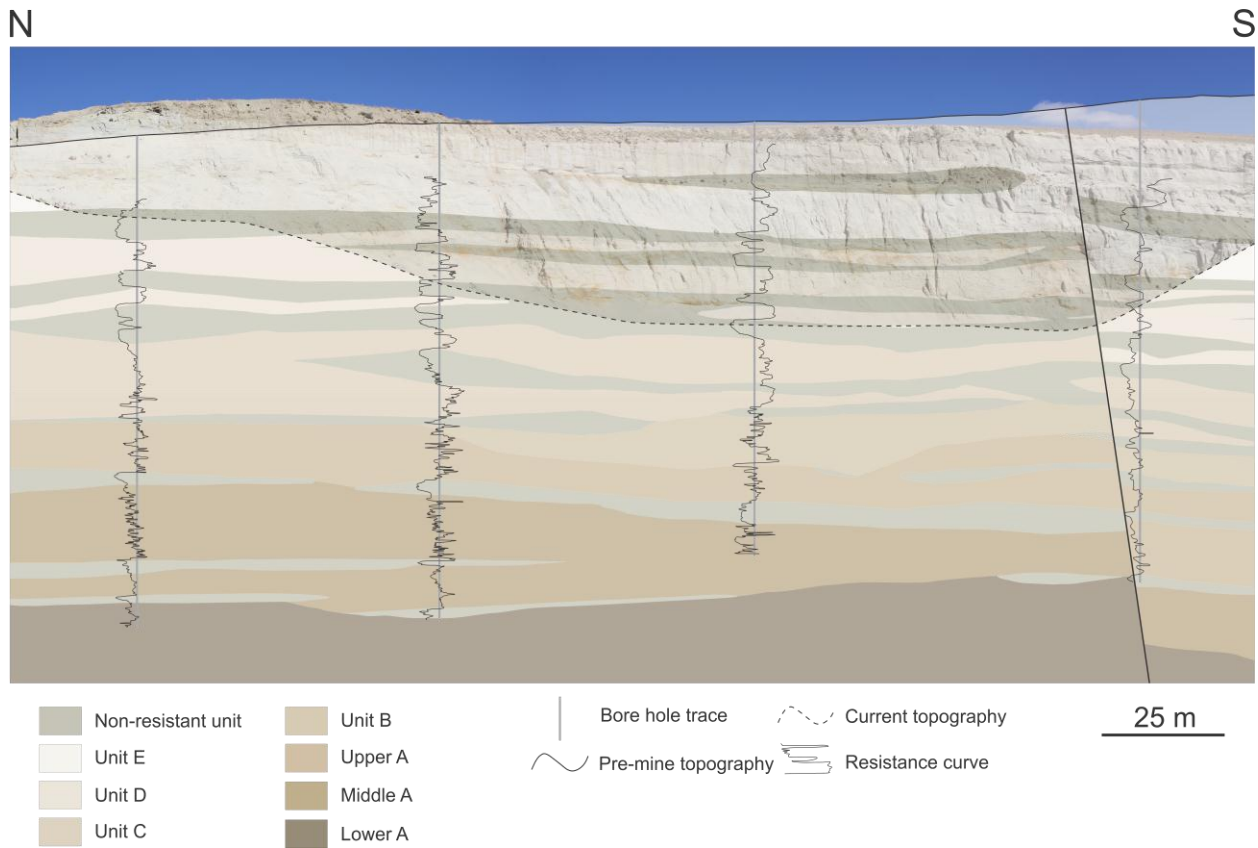


Figure 4.2: Panoramic photograph of the eastern high wall of the open pit. Geophysical resistance logs collected in bore holes collared prior to mining are overlain to illustrate the relationships between geophysical measurements and observed stratigraphy. Thin discontinuous conglomerate lenses were not distinguishable from the resistance data. Non-resistive units correlate to observed siltstones, mudstone, or areas of preferential erosion.

4.3 Deposit Stratigraphy

Based on the resistive logs, the stratigraphy of the Buss Pit area has been modeled in three dimensions (Fig. 4.3). Modeling shows that the stratigraphy strikes 087° and dips 1.9 to 3.0° to the south, which is consistent with the observations in the open pit.

Within the deposit area, six main resistive units occur that are from stratigraphic bottom to top referred to as the A, B, C, D, E, and F sandstone/conglomerate units (Fig. 4.4). Units B through E are exposed in the high wall of the open pit (Fig. 4.1). The six sandstone/conglomerate units are separated from one another by thinner non-resistive intervals that are interpreted to correlate to the mudrock units observed in the open pit (Fig. 4.1). The mudrock units are not

labeled in the present contribution as not all of them are laterally continuous across the study area.

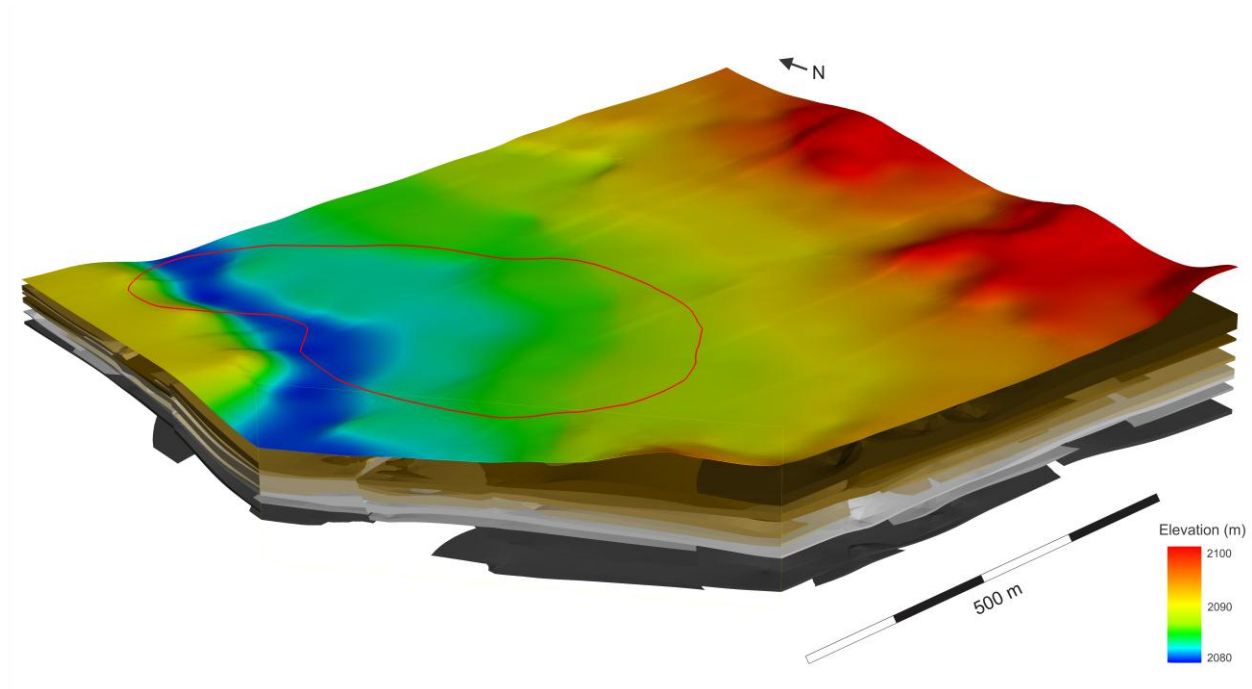


Figure 4.3: Leapfrog Geo 3D model of the deposit area displaying the pre-mine surface topography. The outline of the open pit is given in red. A total of six main sandstone/conglomerate stratigraphic units were observed

Most bore holes collared within the study area terminate within the A sandstone/conglomerate unit. For this reason, the true thickness of this unit is comparably poorly constrained. However, a total of four bore holes penetrated through this unit. Geophysical interpretation suggests that the A sandstone/conglomerate unit directly overlies Mesozoic sedimentary rocks. The basal contact of the A unit appears to be highly irregular due to paleotopography of the underlying sedimentary rocks.

The A sandstone/conglomerate unit can be subdivided into the Lower A, Middle A, and Upper A sandstone/conglomerate subunits. Where data is available, the Lower A subunit has a thickness of at least 90 m. The Middle A subunit ranges from 0 to over 45 m in thickness. It

contains one to four discontinuous, non-resistive, mudrock intercalations that are not necessarily parallel to the major mudrock units recognized in the deposit area. The Middle A subunit is thickest in the northwestern portion of the deposit area and thins towards the east. Locally, the Middle A sandstone/conglomerate subunit pinches out, resulting in the Lower A subunit to be in contact with the Upper A subunit. The Middle A sandstone/conglomerate subunit is in irregular contact with the overlying Upper A subunit as a result of the highly varying thickness of the Middle A subunit. The Upper A subunit varies from 0 to 24 m in thickness. In general this subunit thins towards the north-west. Where an overlying mudrock unit is missing, the Upper A subunit amalgamates with the B sandstone/conglomerate unit. The B sandstone/conglomerate unit has a thickness of 0 to 9 m. It thins to the eastern and western edges of the study area. The upper contact of the B unit is a thin lenticular, discontinuous mudrock layer that increases in thickness to the SE and is absent from a central, north-south trending, sinuous, ~150-200 m wide band.

The C sandstone/conglomerate unit has a thickness of 0 to 10 m. It pinches out towards the east and northwest of the study area and thins towards the southeast. The D sandstone/conglomerate unit has a thickness between 0 and 18 m. It pinches out to the northwest and in the center of the study area, creating two large packages that thin and join in the northwest of the model area.

The E sandstone/conglomerate unit can be divided into Lower and Upper E subunits. The Lower E subunit varies from 0 to 21 m in thickness. It is the thickest in the southeastern portion of the study area and pinches out to the northwest. The Upper E sandstone/conglomerate subunit is 0 to 9 m in thickness. It pinches out in the center of the study area. It thins and pinches out to the northwest together with the Lower E subunit. The F sandstone/conglomerate unit appears to thicken to the southeast. However, its total thickness is not known as the upper contact of this unit has been eroded in the deposit area.

The C and D sandstone/conglomerate units and associated mudrock facies show a lateral trend from sandstone/conglomerate dominated towards mudrock dominated facies from the south-southwest to the east and west. However, the D and E sandstone/conglomerate units and associated mudrock units trend laterally from sandstone/conglomerate facies in the southeast to dominantly mudrock facies in the northwest. These trends correspond to past studies (unpublished data by Power Resources Inc.) showing this area as an intersection of two alluvial

systems (Fig. 2.2) and suggest an older system from the southwest followed by a more recent system from the southeast. More lenticular sedimentary packages and large scale scour features were visible in the inaccessible southern high wall of the pit, suggesting the orientation of channels in units D and E are generally north-south (Fig. 4.5). Permeable, resistive, sandstone/conglomerate facies dominate the study area. This facies has a high level of connectivity between the permeable, stacked channel fill beds. The large resistive packages are separated by thin, non-resistive, mudrock facies. This geometry controls permeability and allows for lateral groundwater flow.

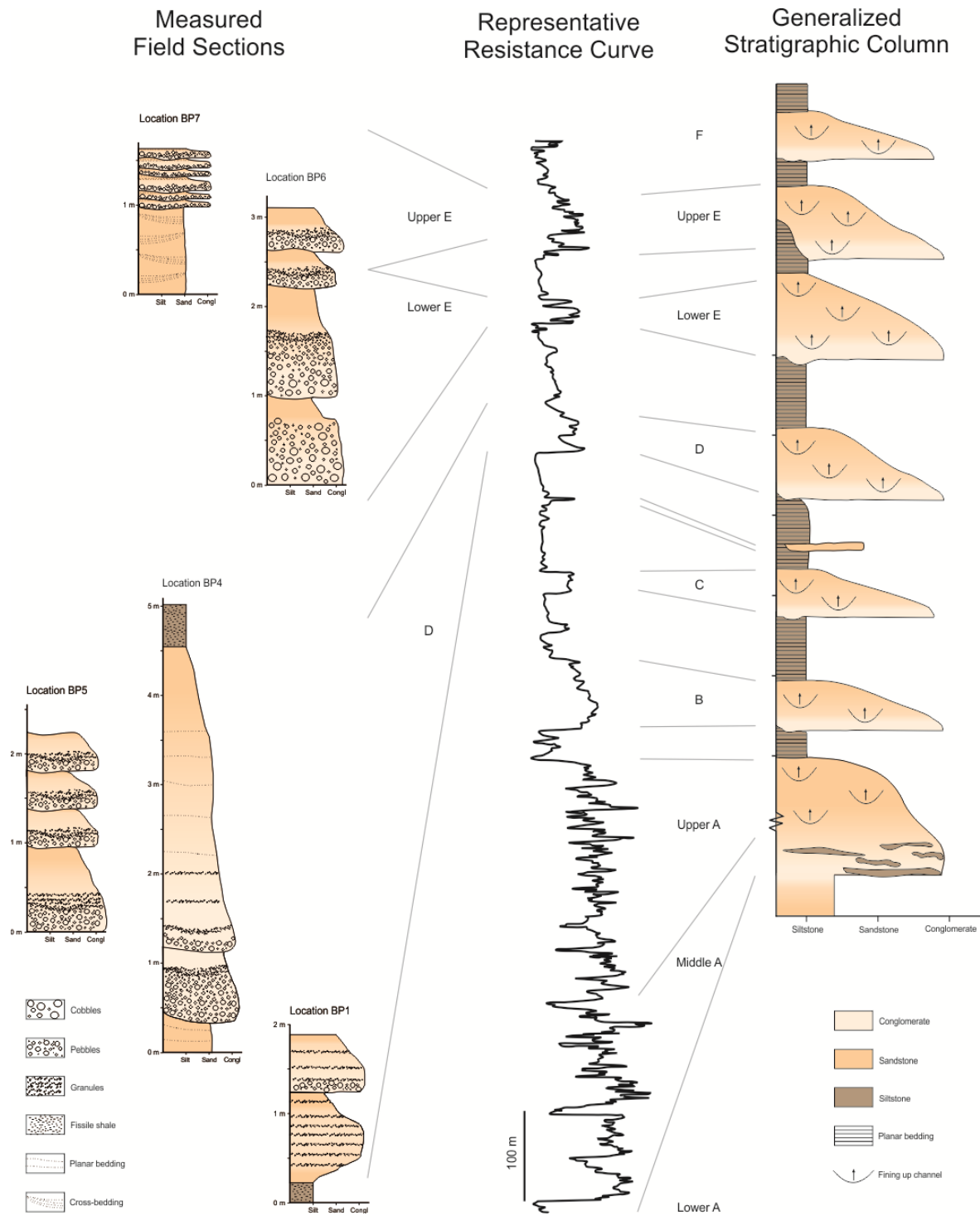


Figure 4.4: Measured sections in sandstones D and E are represented from five field locations. These observations can be compared to a representative resistance log that shows all the major units. The field, geophysical, and model observations are compiled into a generalized stratigraphic column for the deposit area. Field observations correlate with the major packages interpreted from the geophysical resistance dataset.



Figure 4.5: Photo of the north-facing, vertical wall of the open pit with visible scour surfaces between stratigraphic units highlighted to show north-south channel orientation.

CHAPTER 5

STRUCTURAL MODEL

5.1 Field Observations

The Buss Pit deposit area is crosscut by the E-W trending, steep, normal Buss fault. This fault can be seen on the eastern and western high walls of the open pit. The Buss Fault is a normal fault striking 060° and dipping 71° to the southeast. It has an estimated 5 m of offset in the open pit (Fig. 5.1). The fault is marked by approximately 35 cm of dark brown to green clay formed by incorporation of mudstone from the surrounding strata (Fig. 5.2). This addition of material to the structure effects permeability vertically along the fault as the nature of the strata incorporated into the fault zone varies. The visible damage zone is approximately 3 m wide with small visible splays extending towards the top of the pit. One major splay deviates 2 m from the



Figure 5.1: Photo of the eastern high wall of the open pit showing the Buss fault (stippled line). One conglomerate bed is highlighted to illustrate fault displacement. The amount of offset fully displaces the thin mudstone units, altering the connectivity of the permeable sandstone and conglomerate units.

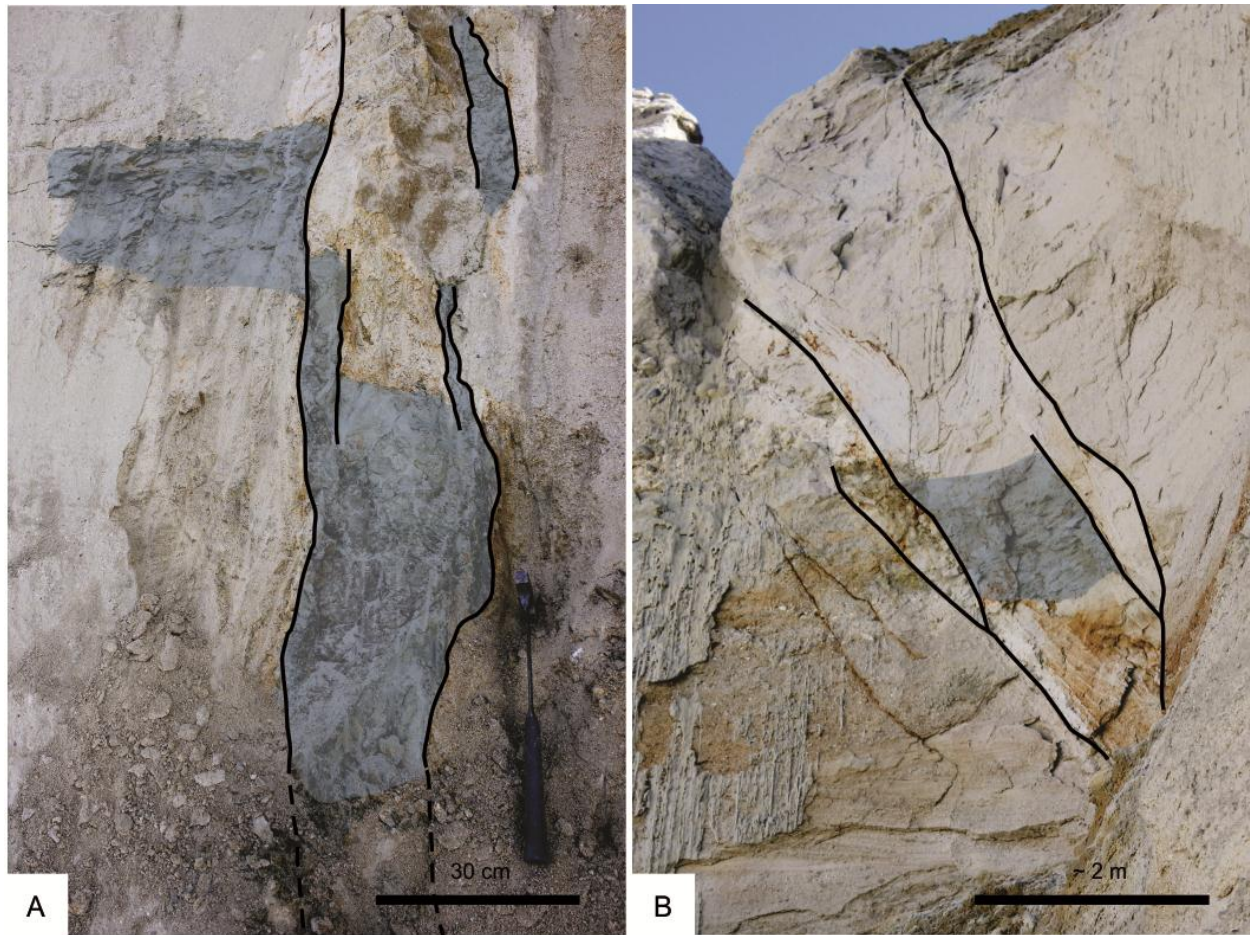


Figure 5.2: Photos of the Buss fault in outcrop. A. The fault shows complex offset and incorporation of a mudstone unit into the core of the structure. B. Near the top of the pit the fault splays into the hanging wall. The faulted block between the splay and the main structure contains a small, transported mudstone block. These observed structures display how the permeability of the Buss fault can be enhanced by increased fracture density and decreased by incorporation of impermeable lithologies.

main fault into the hanging wall (Fig. 5.2B). In contrast to the eastern high wall, the western high wall is inaccessible by foot. Although observable from a distance, the fault is less obvious due to partial collapse of the high wall.

5.2 Results of 3D Modeling

The location of the Buss fault was modeled in 3D based on lithological offsets observed in sections constructed across the deposit area. The offset observed along the fault is consistent throughout the model area, ranging from 5 to 9 m. The fault has an overall strike of 075° and a dip of 80° south-southeast (Fig. 5.3). Decreasing data density near the periphery of the model results in decreasing control on fault location and offset. The dip is modeled as slightly shallower in areas of lower data density. Due to the data spacing and model resolution, minor splays off the Buss fault could not be identified.

Offsets observed in the deposit stratigraphy required the presence of an additional fault, referred to as the SE fault in the present study. The SE fault is a SE-trending, SW-side down structure that intersects the Buss fault near the center of the study area, but outside the open pit (Fig. 5.3). The fault is steeply dipping, but the dip is not well defined. The offset along this fault varies from 1.5 to 12 m. The offset generally increases from the intersection of the two faults towards the west.

In the western portion of the deposit, the SE fault appears to be related to some additional structural complications. Three-dimensional modeling suggests that the stratigraphy in the western fault block, bounded by the Buss fault and the SE fault, dips approximately $5 - 8^{\circ}$ more steeply than in the other fault blocks. This apparent steeper dip may be an artifact of the low drill hole density in the area. However, it is also possible that multiple discrete, synthetic normal faults occur in the area that are characterized by small offsets that could not be mapped due to the resolution of the model (Fig. 5.4). Alternatively, the apparently steeper dip could be related to a more diffuse damage zone or an area of tilted stratigraphy caused by homogeneous extension. The first two possible explanations are consistent with the discrete nature of the fault in the eastern outcrop and the more diffuse manner of the offset in the western high wall, suggesting that faulting is less well-defined in the western high wall of the open pit.

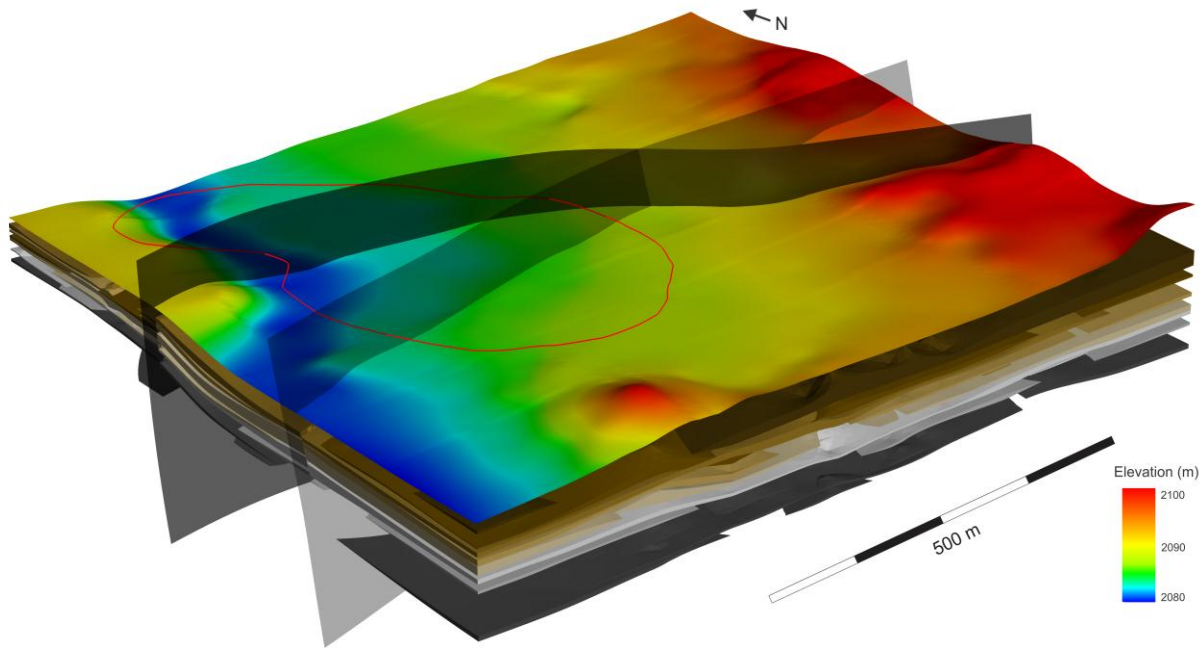


Figure 5.3: Leapfrog Geo 3D model of the deposit area displaying the pre-mine surface topography, the outline of the open pit in red, and the deposit stratigraphy. The locations of two faults, referred to as the Buss fault and the SE fault, are illustrated.

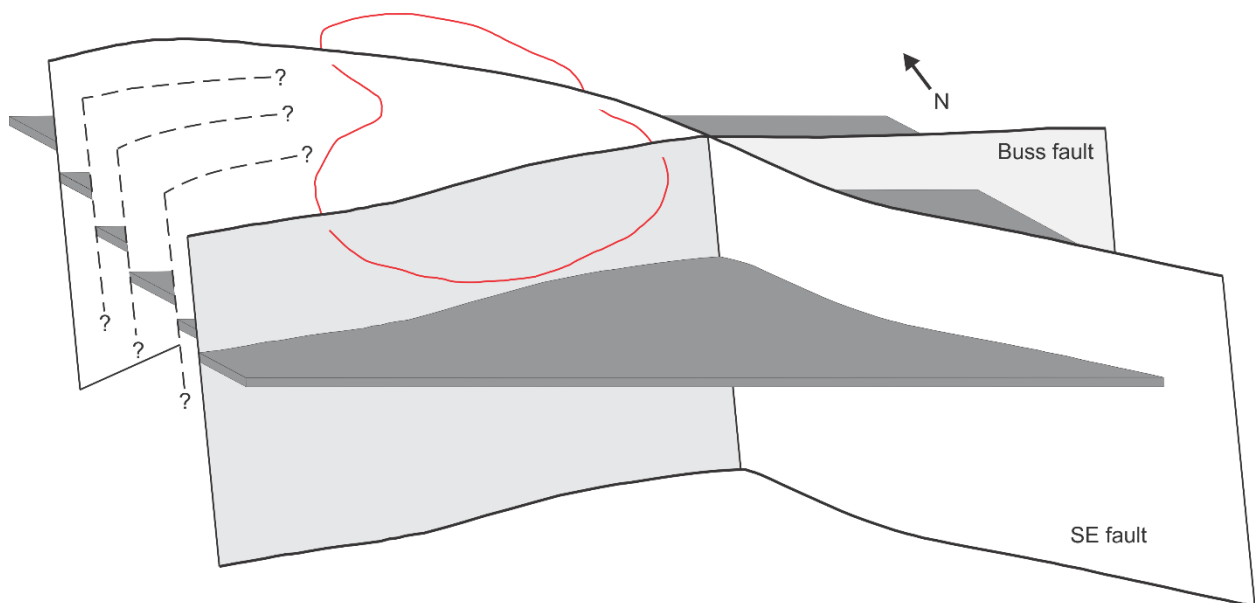


Figure 5.4: Schematic representation of the two faults intersecting the deposit area. The diagram shows the offsets along a hypothetical marker bed and the location of inferred discrete, synthetic faults in the western fault block. The diagram shows that the SE fault is a south-side down structure. The approximate location of the open pit is outlined in red.

CHAPTER 6

GRADE DISTRIBUTION

6.1 Spatial Distribution of Ore Zones

Roll-front uranium at the Buss Pit deposit was mined by Federal American Partners and Tennessee Valley Authority in the 1960s. Mining focused on the extraction of the uranium resource located above the water table. Only a portion of the uranium resource present in the Buss Pit area was extracted. A significant resource remains in the eastern and southeastern portion of the deposit area (Fig. 6.1).

To visualize the grade distribution in three dimensions, the > 0.02 , > 0.05 , and > 0.1 e% U_3O_8 grade shells have been modeled based on the digitalized gamma curves of the historic bore holes. The resulting model reveals that the ore body consist of elongate pods and crescents of asymmetric, concentric shells of decreasing grade (Fig. 6.1). As a whole, the ore body strikes 174° and dips 03° west, cutting across stratigraphy (Fig. 6.2).

In plan view, the ore body at the Buss Pit occurs as an asymmetrically concave band of elevated uranium grades that is oriented to the north-west. The apex of the curved ore body is located in the western fault block defined by the Buss and SE faults (Fig. 6.3). The ore body is comprised of three ore zones, each of which have numerous, individual subzones (Fig. 6.3). The eastern ore zone has a northwestern trend, essentially paralleling the strike of the SE fault, while the western ore zone shows a northwest to north-south trend. The number of stacked subzones increases in the southeast region of the ore body. Elevated uranium grades do not occur to the east of the SE fault (Fig. 6.3).

Each of the three ore zones contain a large subzone exceeding 0.1 e% U_3O_8 although many small subzones with a diameter less than 15 m are scattered through the deposit area. The smallest of the three high grade subzones ($27 \times 14 \times 3$ m) lies near the fault directly under the reclaimed Buss Pit in the center ore zone. The second largest subzone of high grade ore ($52 \times 27 \times 7$ m) is located on the east ore zone and has two nearby high-grade pods (15×15 m) to the southwest. The largest high grade subzone is composed of two large pods aligned and elongated north-south. The northern pod ($61 \times 30 \times 10$ m) is dipping north while the southern pod ($46 \times 16 \times 5$ m) is flat lying.

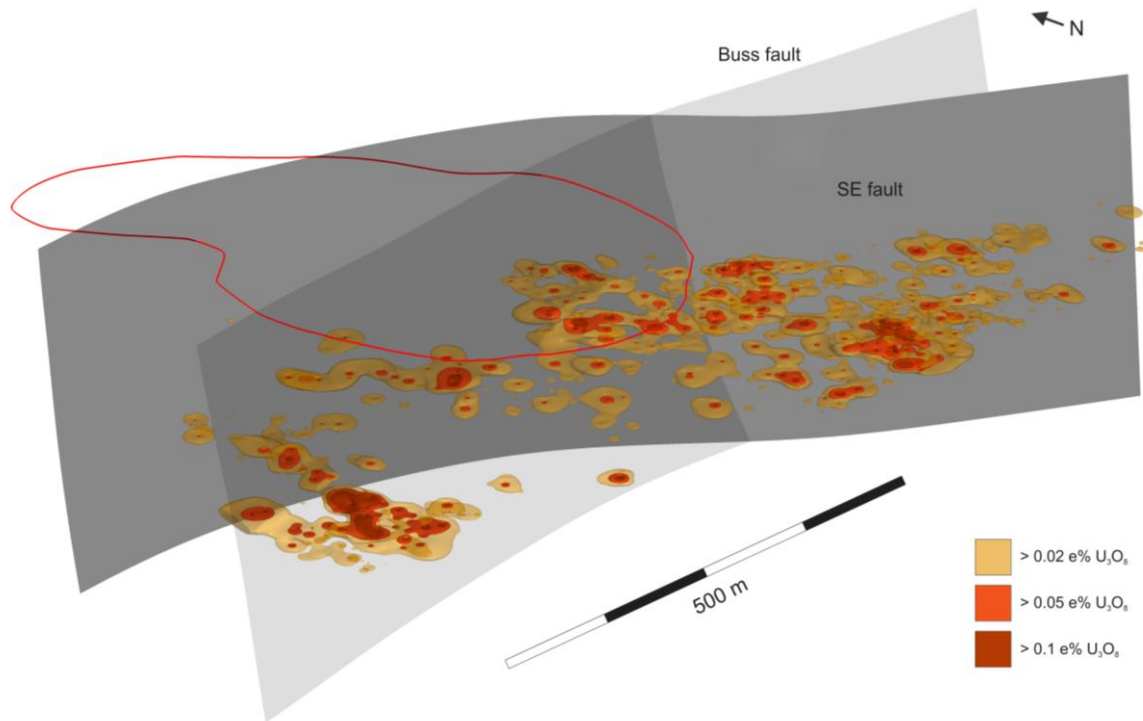


Figure 6.1: Leapfrog Geo 3D model of the three grade shells and the Buss and SE faults. The outline of the open pit is given in red.

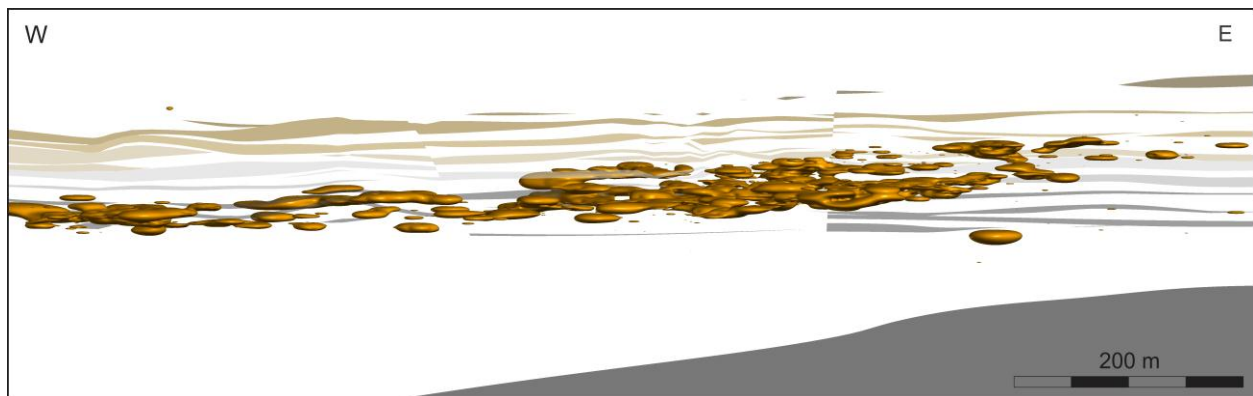


Figure 6.2: Three-dimensional view of the 0.02 e% U_3O_8 grade shell looking north. The image shows the modeled ore body in orange dipping W-SW across an east-west stratigraphic cross-section with non-resistant units colored at 780966 ft N along the strike of the Buss Fault. This discordant geometry is not consistent with the typical roll-front model of formation.

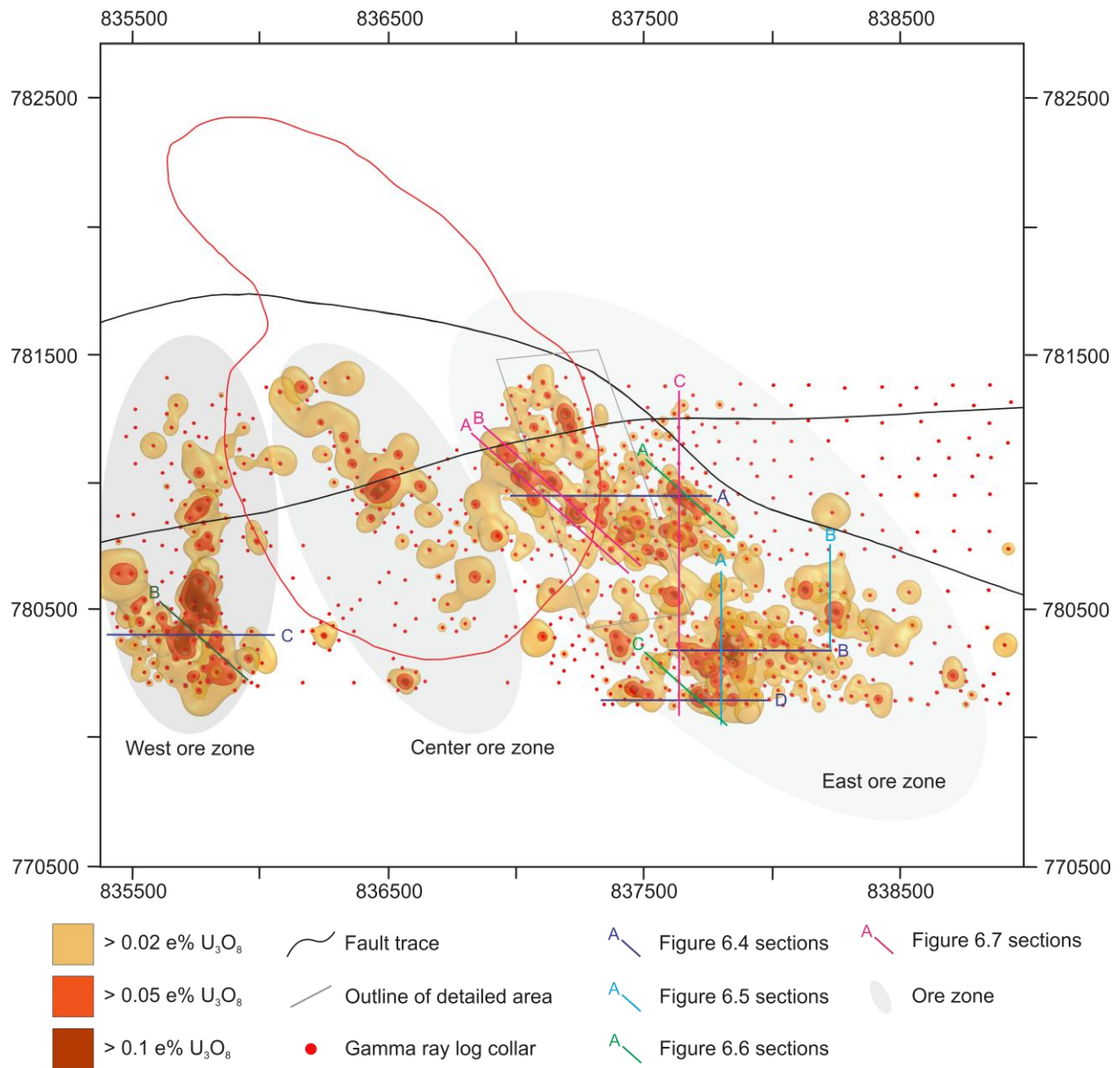


Figure 6.3: Plan view of the Buss Pit deposit area showing the distribution of three grade shells projected to surface and cross-section locations. The image illustrates the geometrical relationship between the three ore zones and the two faults along with locations of bore holes used to constrain the location of the ore. Overlapping subzones appear to be darker in color. Northwest-southeast and north-south subzone trends may reflect channel geometries in the host sandstones. Some trends, however, are an artifact of data distribution, such as the abrupt eastern edge of the west ore zone.

6.2 Stratigraphic Controls on Ore Subzones

Uranium occurs throughout the ~ 82 m thick stratigraphic interval from the Lower A sandstone/conglomerate subunit to the D sandstone/conglomerate unit. Ore dominantly occurs in and between mudrock lithologies in the Middle A and Upper A subunits. There is one small occurrence of high-grade uranium in the Lower A subunit, which is anomalously low in stratigraphic position in the east ore zone. Approximately 30% of the mineralized area lies above the Middle A subunit, with the ore body stepping up in stratigraphy to the east. The stratigraphically highest subzones occur in the D sandstone/conglomerate unit and extend into the overlying mudrock unit.

Within each sandstone/conglomerate unit, subzones of ore greater than 0.05 e% U_3O_8 exist predominantly in the middle to top of the units, with grades commonly extending into the overlying mudrock unit. Higher grades are usually contained within one sandstone/conglomerate unit and the adjacent mudrock units, but 0.02 e% U_3O_8 subzones can connect smaller subzones of higher grade. The small, northern most high-grade subzone lies towards the top of a mudrock unit in the Middle A subunit. The high-grade subzone in the east ore zone is located in the Upper A subunit at the top of a thick mudrock interval. The largest high-grade subzone in the west is hosted in the middle of a thick mudrock interval of the Middle A subunit. The stratiform morphology of the subzones within the highly connected sandstone/conglomerate units reveals the influence of these extensive, well-connected units on fluid flow.

During stratigraphic correlation, it was observed that some geophysical resistance lows correspond to high grade subzones in the Middle A subunit. This is anomalous as ore subzones are dominantly in resistive units. These low resistance signatures were not considered a mudrock unit as they were unable to be correlated outside of the ore zone. This geophysical response may be a product of alteration of the host rocks in areas of high ore grade as opposed to a characteristic of the host stratigraphy.

6.3 Ore Subzone Morphology

Most ore subzones are simple, small pods encompassing one or two bore hole intersections. However the larger subzones show much more complexity. The larger high-grade subzones appear as crescent-shaped areas of uranium enrichment in cross-section. The shapes resemble the “rolls” of the roll-front uranium deposit model which should point in the direction of fluid flow (Adler, 1964). Accordingly, the dominant orientation of the crescent-shaped ore subzones shows the direction of highest fluid flow at the time of mineralization. In north-south cross-sections, the crescent-shapes near the SE fault point north (Fig. 6.4). In east-west cross-sections across the deposit area, crescent-shaped subzones have a west pointing component (Fig. 6.5). The most complex subzone morphology is observed in northwest sections (Fig. 6.6). Over the field area the dominant orientation of crescent-shaped subzones is to the northwest. Subzones that showed a northward component were dominantly along the SE fault (Fig. 6.4). This implies the orientation of uranium-bearing fluid flow was to the northwest, except near the SE fault where the flow was north-northwest.

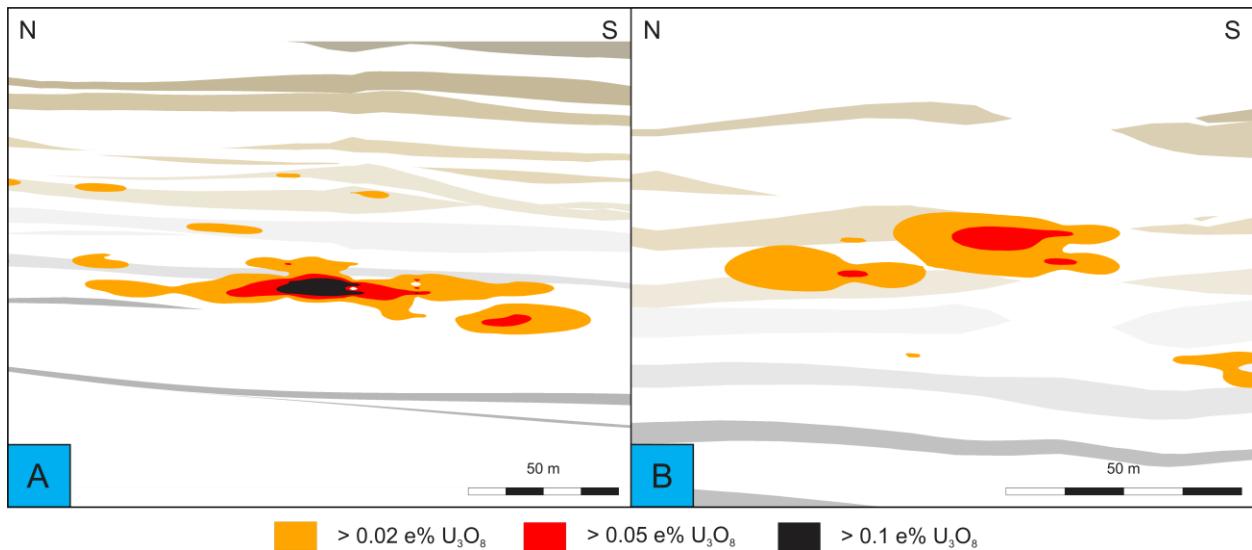


Figure 6.4: North-south sections of simple roll-front uranium subzones. The sections show examples of roll-front geometries pointing towards the north near the SE fault. The ore is dominantly hosted by sandstone/conglomerate lithologies. Mudrock units are colored for reference. A. Section through the eastern high grade subzone at 837860 ft E. B. Section through a far eastern subzone at 838262 ft E.

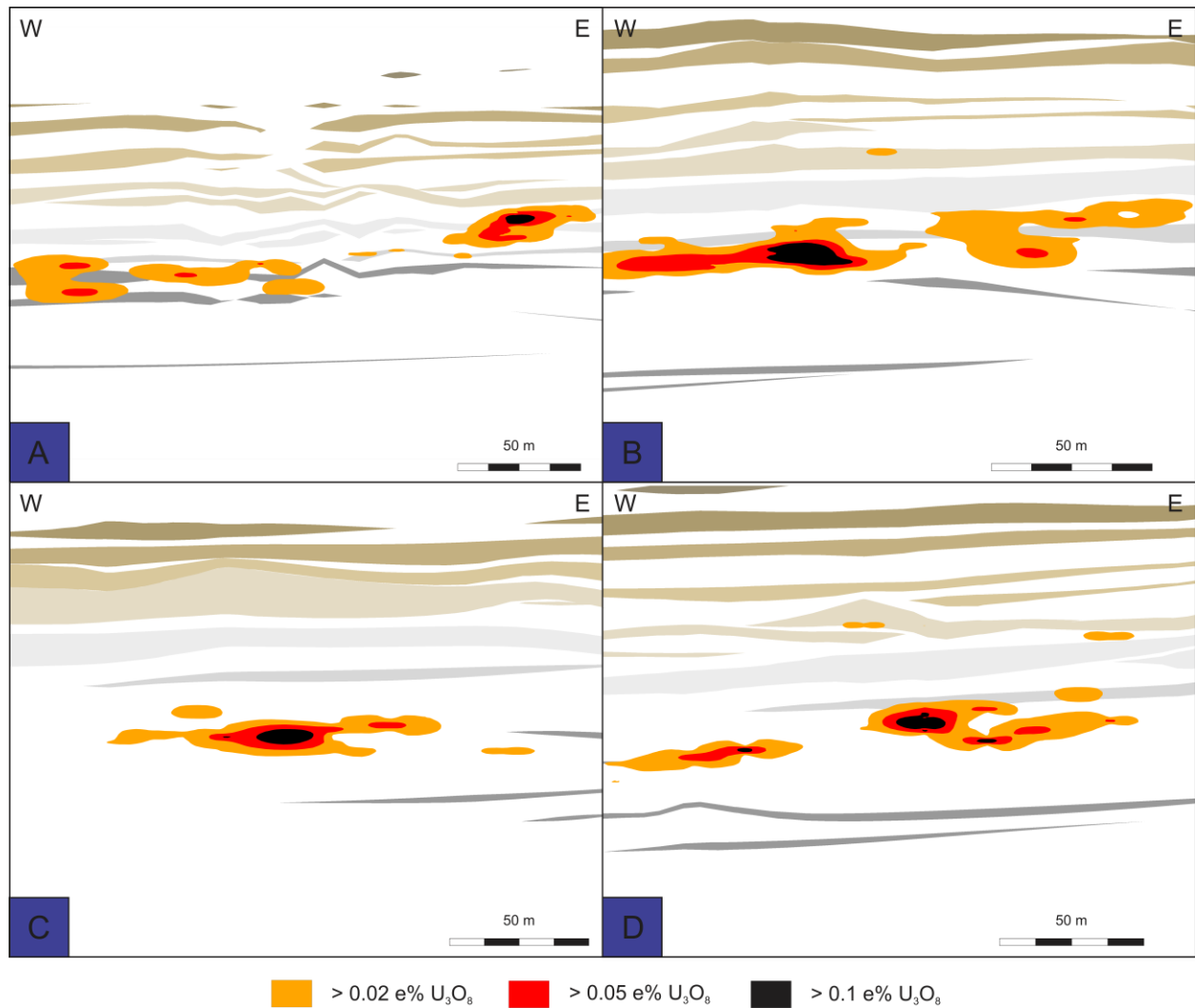


Figure 6.5: East-west sections illustrating roll orientations to the west. Mudrock units are colored for reference. A. Section through the central high-grade subzone to the south of the fault intersection at 780925 ft N. B. Section through high-grade subzone in the east of the study area at 780320 ft N. C. Section through western high-grade subzone at 780391 ft N. D. Section through the eastern high grade subzone at 780149 ft N.

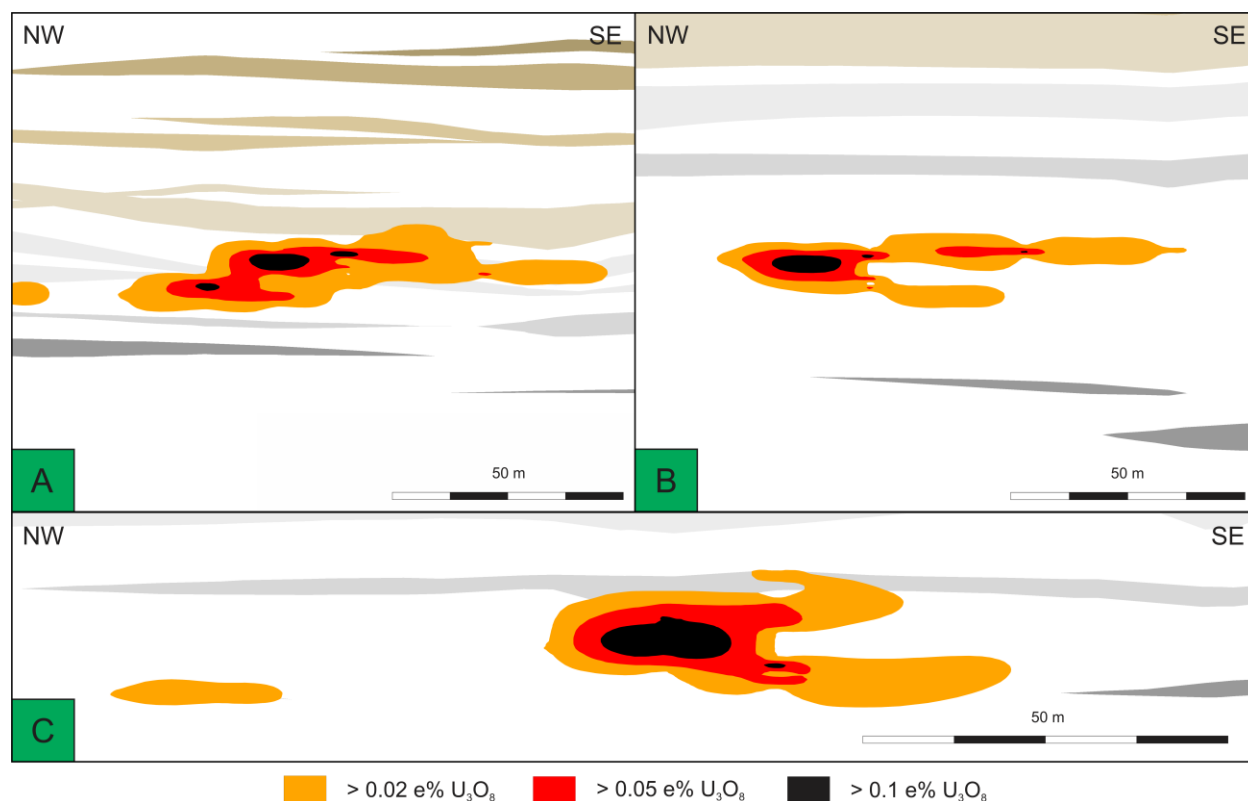


Figure 6.6: Northwest-southeast sections of highly complex uranium subzones, including double rolls. Mudrock units are given for reference. A. Section through the eastern high-grade subzone at 837689 ft E and 780913 ft N. B. Section through the western high-grade subzone at 835767 ft E and 780430 ft N. C. Section through one central high grade subzone at 837753 ft E and 780147 ft N. These morphologies and orientations are interpreted to express that the dominant direction of fluid flow during mineralization was to the northwest.

6.4 Structural Controls on Ore Subzones

Ore subzones have unique morphologies near the Buss fault. Some subzones show an apparent normal offset at the fault that may range from 7 to 15 m. However, in most cases the subzone partially continues across the fault and appears to flare up along the fault. The step-up to the north at the fault is marked by a complex amoeboid shape of the 0.02 e% U_3O_8 grade shell that connects high-grade pods on either side of the fault (Fig. 6.7). Crescent-shaped features occur with their apex pointing northeast on both sides of the fault, although most crescent-shapes occur to the south of the Buss fault (Fig. 6.7). Apparent offsets of the subzones across the fault

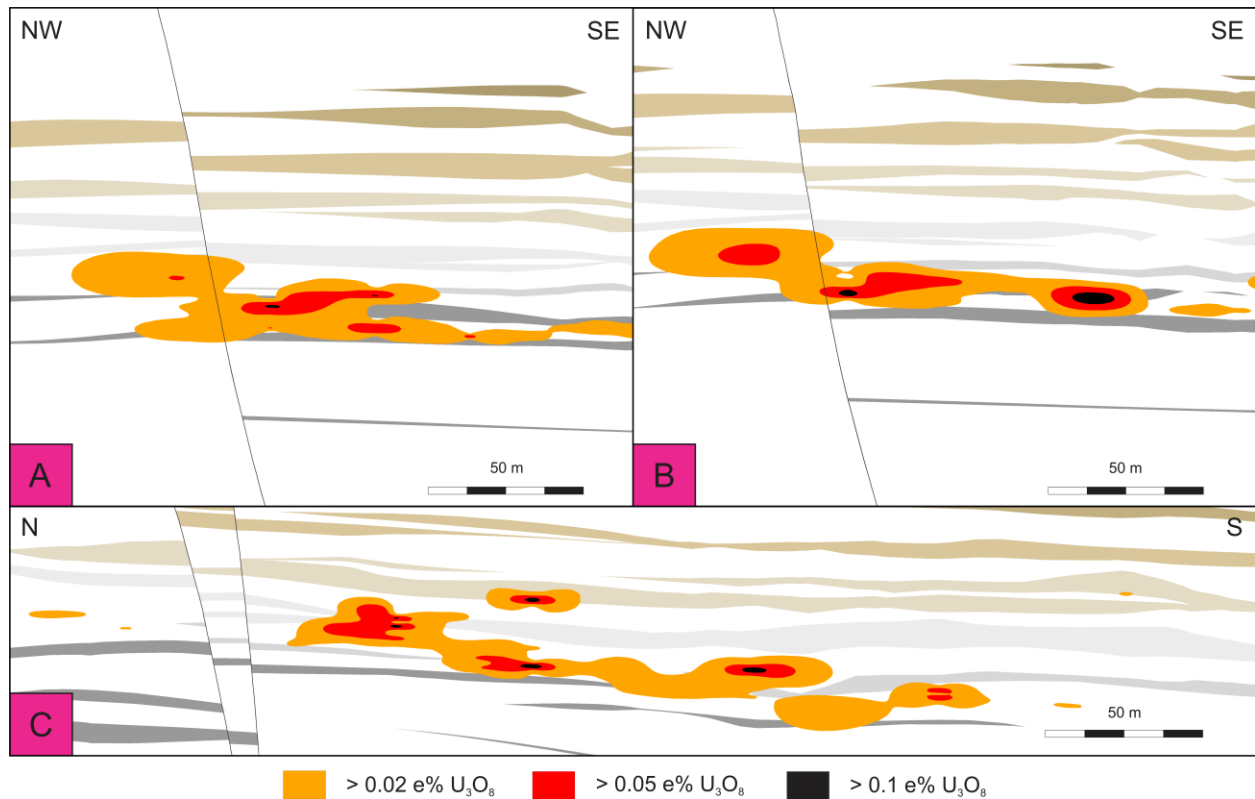


Figure 6.7: Cross-sections showing the shape of the ore subzones in proximity to the faults. Mudrock units are colored for reference. A. Northwest-southeast section illustrating that the apparent offset of the subzone by the Buss fault is larger than the stratigraphic offset. The subzone is located in the center of the model at 837035 ft E and 780997 ft N. B. Northwest-southeast section to the northeast of the section shown in the previous image. The apparent offset of the subzone does not match the displacement of the sandstone units. Note that the ore appears to be essentially continuous across the fault and then flares up into the overlying sandstone unit. C. North-south section at 837662 ft E at the intersection of the Buss fault and the SE fault displaying a high grade subzone located directly to the south of the faults.

do not match the offset in stratigraphy (Fig. 6.7). Subzones that cross the Buss fault in the western portion of the study area display both apparent offset and no offset. The geometrical relationships indicate that the fault does not simply dissect the subzone, implying that movement along the fault could not have entirely been post-mineralization.

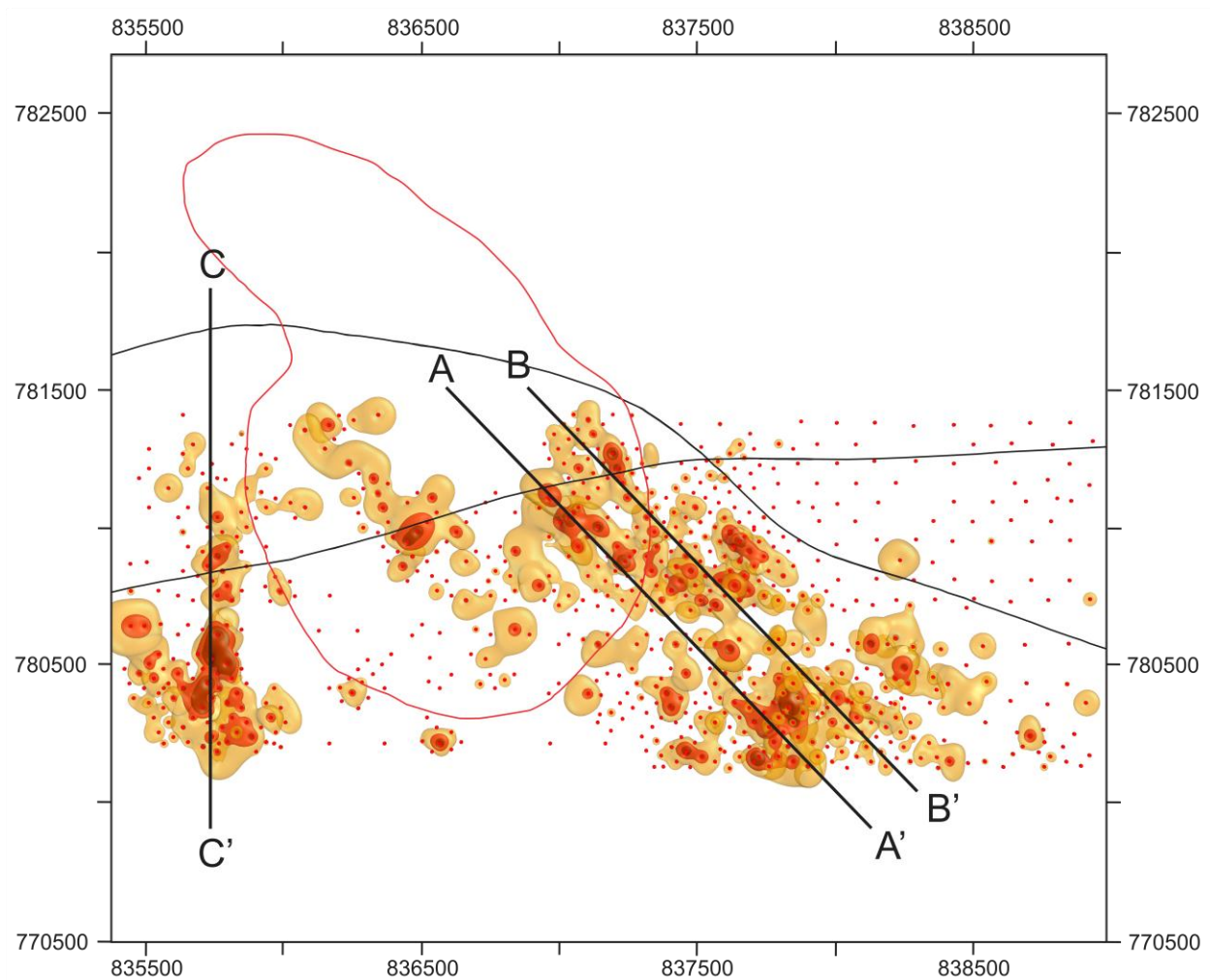


Figure 6.8: NW – SE cross-sections A – A' and B – B' intersect the east ore zone. Cross-section C – C' trends N – S and intersects the west ore zone.

Northwest to southeast cross-sections, parallel to the flow direction during mineralization, through the east ore zone show stratiform ore subzones (Figs. 6.8, 6.9). This differs significantly from the discordant orientation seen in east-west sections through the deposit (Fig. 6.2). Cross-section C – C' is at high angle to the Buss fault and intersects the largest high grade subzone. Cross-sections B – B' and C – C' show continuous ore across the Buss fault (Figs. 6.8, 6.9).

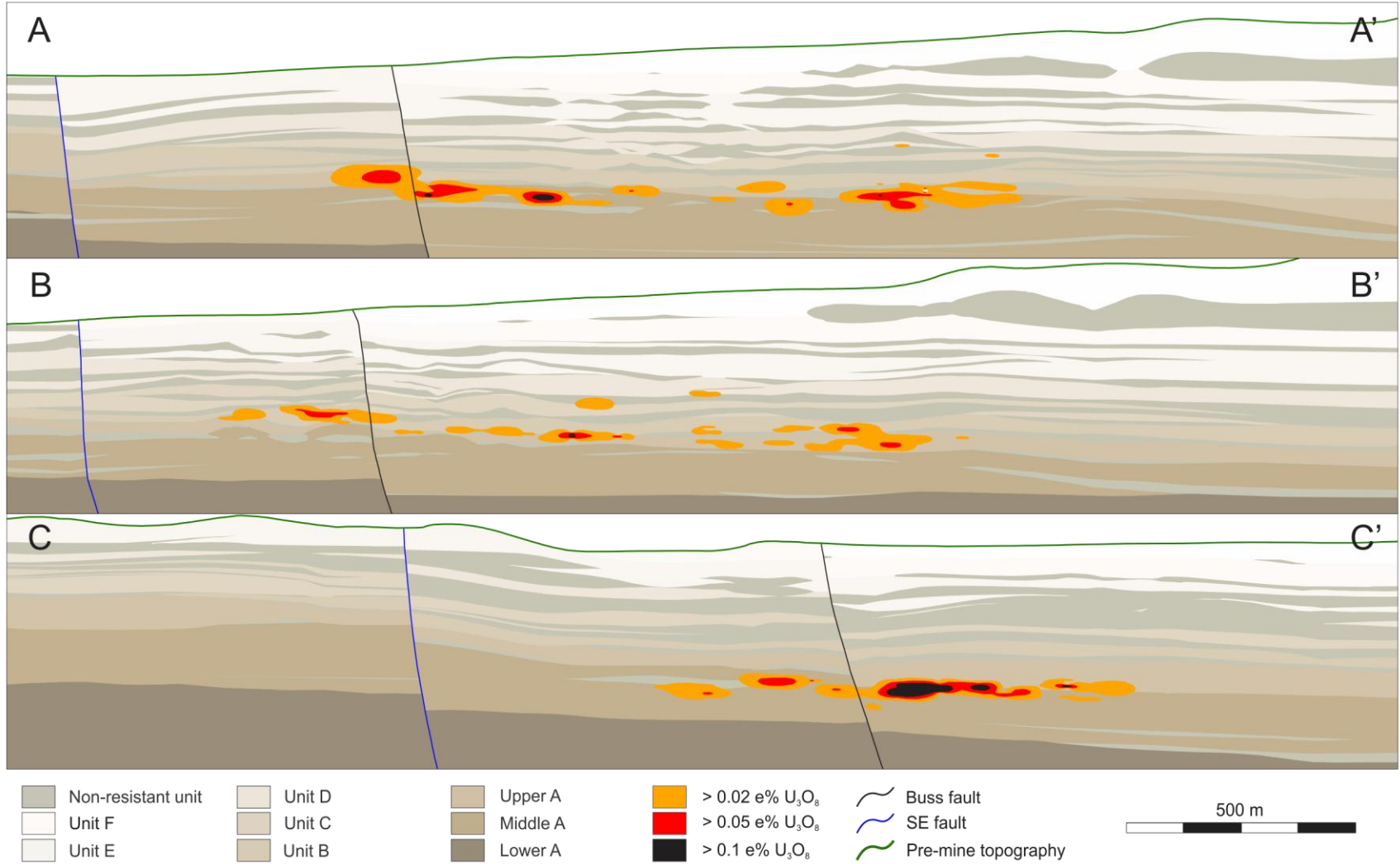


Figure 6.9: Cross-sections showing the spatial relationships of the stratigraphy, NE fault, Buss fault and ore zones in the Buss Pit study area. Cross-section A – A' shows a plume morphology of the subzone near the Buss fault. Cross-sections B – B' and C – C' show subzones with more continuous, lenticular morphology across the Buss fault. Cross-sections display both structural and stratigraphic controls.

CHAPTER 7

DISCUSSION

7.1 Roll-front Formation at the Buss Pit Deposit

A number of observations made as part of the present study are inconsistent with the widely accepted roll-front model (Anderson, 1969; Harshman and Adams, 1980; Burrows, 2010). In the following, the possible source of the reductant causing uranium mineralization in the Buss Pit area is discussed. The role of faults at Buss Pit and the relationships between the faults and the observed shape of the ore zones are examined.

7.1.1 Reducing Capacity of the Host Rocks

The roll-front uranium model assumes that uranium is transported in oxidizing groundwater and precipitates along a redox boundary within the aquifer. Walsh et al. (1984) demonstrated that the uranium content of oxidized water is typically low (25 ppb uranium). These waters are reduced through oxidation of a sandstone host that typically contains 1% iron sulfide or 0.2% organic carbon to create a deposit with average uranium concentration of 0.1-0.2% (Walsh et al., 1984).

The geochemical analyses performed as part of the present study demonstrate that the sandstone hosts of the Buss Pit deposit contain relatively low iron sulfides and organic material when compared to the amounts of reductant mentioned by Walsh et al. (1984). For comparison, the sandstones contain slightly more iron sulfides and slightly less organic carbon than the Lost Creek deposit in the Great Divide Basin, Wyoming which has been shown to have a mobile reductant source (Fig. 7.1; Hancock, 2012). The organic carbon and iron sulfide contents are comparable to the world-class deposits of the Chu-Syr-Darya region in Kazakhstan that are reduced by hydrocarbons dissolved in water (Fig. 7.1; Fyodorov, 1990). Roll-front deposits of South Texas, USA are found to have comparable organic carbon, but up to 4% iron sulfide (Fig. 4.3). These deposits, however, are known to be associated with basinal brines. The roll-fronts in these deposits are stationary and did not migrate through the sandstone host (Dickinson and Duval, 1977). In the Ray Point district of South Texas, isotopic and textural evidence suggests a

post-mineralization sulfidation event, accounting for the elevated iron sulfide contents in the deposits (Goldhaber et al., 1983). The Angela deposit in the hydrocarbon producing Amadeus basin, Northern Territories, Australia has been documented to have even lower iron sulfide and organic carbon contents than the Buss Pit deposit. The amount of authigenic reductants in this deposit are negligible (Fig. 7.1; Borshoff and Faris, 1990).

The low amounts of authigenic iron sulfides and organic carbon in the host rocks highlight the need for a mobile, allogenic reductant in the Buss Pit area (Granger and Warren, 1978; Spirakis, 1996). Such a mobile reductant could be hydrocarbons, hydrogen sulfide-rich gas or a reduced brine, examples of these fluids acting as reductants have been documented in the Great Divide Basin in Wyoming, South Texas, and Kazakhstan (Dickinson and Duval, 1977; Fyodorov, 1990; Hancock, 2012). An *in situ* reductant in contact with oxidized groundwater causes a migrating oxidation-reduction front as the groundwater pushes the boundary down the physical gradient leaving an oxidized environment behind (Reynolds and Goldhaber, 1983). Conversely, a mobile reductant is usually supplied to the aquifer along a fault, creating a more static redox boundary (Dickinson and Duval, 1977). A static conduit for a mobile reductant is hypothesized to be key in producing large uranium accumulations in host rocks with little *in situ* reducing capacity (Jaireth et al., 2008).

7.1.2 External Source of Reductants

The Gas Hills district in the Wind River Basin is typified by surface gas discharge (Grutt, 1957). Petroleum production in the basin reported high sulfur oil and hydrogen sulfide-rich natural gas as the dominant hydrocarbon forms sourced from the Cody Shale and trapped in anticlines in the underlying Mesozoic succession (Grutt, 1957; Johnson and Keighin, 1998). Historic uranium exploration drilling in the Gas Hills has intercepted pockets of hydrogen sulfide gas in the permeable stratigraphy (Grutt, 1957).

During field observations in the Buss Pit area, a nearby well was inspected that intersected an aquifer containing warm and saline water. The water from this well was historically used to wash trucks from the open pit, suggesting that water flux must have been substantial and stable over decades. Although no temperature measurements were conducted, the

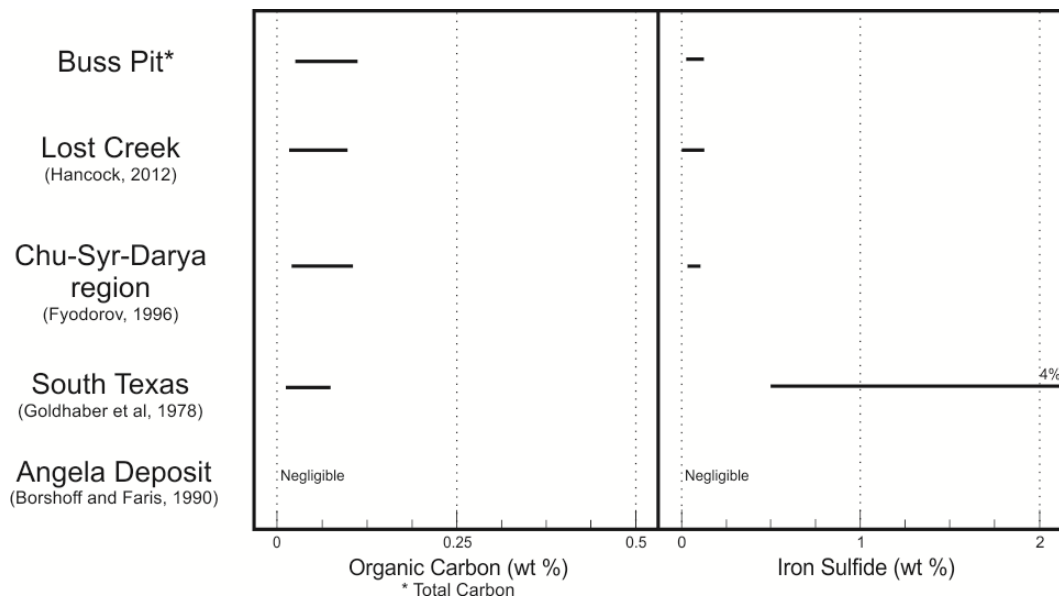


Figure 7.1: Organic carbon and iron sulfide contents of five areas that are proven or possibly structurally controlled roll-front deposits in hydrocarbon producing basins. The Buss Pit sedimentary rocks are within the range of organic carbon and iron sulfide contents in these deposits.

water from the well was clearly above ambient temperature, suggesting the existence of saline warm water flow in the Wind River Basin.

In the light of these observations, the reductant responsible for the formation of the Buss Pit roll-front uranium deposit could have been easily derived from an external source, with the observed faults being instrumental in controlling the location of uranium mineralization.

The entire sedimentary basin fill succession in the Gas Hills district is currently under reduced conditions, apart from the very near surface (Harshman and Adams, 1980). This occurred after mineralization as the oxidized groundwater and the gaseous reductant reached a dynamic equilibrium in the system (McKnight, 1972; Dickinson and Duval, 1977; Goldhaber et al., 1983). If this occurred soon after the deposition of the uranium it would have immobilized the roll-front. In this case, the shape of the ore body as observed today would reflect the morphology of the redox boundary at the time of uranium deposition.

7.1.3 Stratigraphic Controls

The two host rock facies, sandstone/conglomerate and mudrock, are interpreted to be channel fill deposits and overbank deposits, respectively. During the time of deposition, the deposit areas is thought to have been located in a braided fluvial environment, possibly near the distal alluvial fan environment, as it is dominated by coarse grained channel fill but does not appear to have debris flow deposits (Miall, 1978).

Large permeability contrasts between the sandstone/conglomerate facies and the mudrock facies serve to direct lateral fluid flow through the sedimentary rocks and hence control the location of uranium mineralization. In general, sandstone and conglomerate lithologies allow for a greater fluid flux than siltstones or mudstones. These properties are reflected in the elongate ore subzones modeled in the Buss Pit deposit (Fig. 6.9). In the host rocks of the Buss Pit deposit sandstone/conglomerate facies have a high level of connectivity between the various channel fill successions. Most mudrock beds in the deposit area pinch out laterally, allowing for additional vertical connectivity of the coarser grained facies. These areas of increased sandstone/conglomerate connectivity and decreased impermeable mudrock continuity increase the potential for vertical migration of fluids.

7.1.4 Structural Controls

Although the structural history of the Wind River Basin after the Laramide Orogeny is not fully understood (Thompson, 2010), some important observations relevant to the formation of the Buss Pit deposit can be made. The ENE-striking structures in the Paleozoic and Mesozoic succession are consistent with Laramide compression (Thompson, 2010). These Laramide faults probably underwent extensional reactivation during the post-early Eocene collapse of the Granite Mountain core complex (Keefer, 1970; Erslev and Koenig, 2009; Thompson, 2010). Younger E-W striking faults through the Eocene basin fill show a compressional history that corresponds to post-Laramide conditions, but have not been convincingly correlated to a specific deformational event (Thompson, 2010).

The ENE-striking Buss fault is parallel to the Laramide structures, but offsets the Eocene Wind River Formation. The original fault was formed prior to uranium mineralization, but the

fault underwent steepening and possibly reactivation during the collapse of the Granite Mountains (cf. Love, 1978). The post-mineralization collapse of the Granite Mountains also inverted the northward stratigraphic dip of the study area to the current dip to the south (cf. Love, 1978).

NW-SE trending normal faults in the Wind River Basin, such as the SE fault, formed under post-Laramide stresses and are consistent with the current NE-SW extensional stress-field of the basin (Thompson, 2010). Post-Laramide, continental extension is documented by the emplacement of mid-Miocene mafic dikes in northwestern Colorado (Thompson et al., 1989; Thompson, 2010). This allows for the initiation of extension, and thus the NW-SE structures in the Wind River Basin, to have occurred before the documented dikes which would possibly be before the estimated time of mineralization at 21 – 25 Ma (Dooley et al., 1974).

The nature of intersection of the crossing faults depends on their relative timing of formation. If the two faults in the deposit area formed independently, a simple offset would result where one structure offset the other. However, if the faults formed contemporaneously a wide damage zone could be formed between the two structures (Fossen et al., 2005). The exact relationship between the two faults cannot be defined by this study, however the influence of a wide fracture network on upflow of reductants during mineralization would result in increased ore formation in or near the damage zone. The locations of the ore zones near the Buss fault seem to support the existence of a highly fractured system that resulted from a synchronous faulting event (Figs. 6.7, 6.9). This is thought to have occurred by the reactivation of an ENE-striking, Laramide structure during the post-Laramide NE-SW extension. This inherited zone of weakness accommodated some of the extensional stress to form the Buss fault observed today. The post-Laramide NE-SW extensional stress formed the SE fault synchronously with the Buss fault.

Faults can play various roles in this environment depending on the nature of the structure and the character of the fluids. If the fault is impermeable it may have directed or slowed water flow, in some cases increasing the likelihood of uranium accumulation (Grutt, 1957; McKnight, 1972; Dickinson and Duval, 1977). Impermeable structures may also act as physical traps for reduced gases in these environments (Grutt, 1957; McKnight, 1972). Permeable faults, fractures and potential damage zones surrounding structures can channel groundwater flow and gas movement (Grutt, 1957). Small offset faults and joints create higher permeability at the

Rosenbrock mine in South Texas (Dickinson and Duval, 1977). However, small faults and joints are difficult to identify with the correlation techniques used in the present study. Outcrop observations show both permeable and impermeable portions of the Buss fault (Fig. 5.2). It is reasonable to assume that the Buss and SE faults pose a variety of characteristics, increasing the complexity of the fluid flow system.

For example, the Duval area in South Texas shows dominantly permeable fault characteristics where reduced gases are thought to permeate up the fault, with the roll-front deposit occurring at the intersection of an aquifer and the fault (Dickinson and Duval, 1977). The South Texas Mineral Belt also contains deposits with faults that have acted as impermeable barriers (McKnight, 1972). The Ray Point district of South Texas shows mineralized zones parallel and perpendicular to a major fault (Goldhaber et al., 1983). The Lost Creek deposit in the Great Divide Basin of Wyoming is an example where a possible reduced saline water was controlled by a fault to create a uranium deposit dominantly in the footwall of a normal fault zone (Hancock, 2012).

In the Buss Pit area, the Buss fault zone appears to pose a complex blend of characteristics influencing oxidized groundwater flow and reductant movement (Fig. 5.2). The potential additional faults, splays, and fractures that are not well constrained from this study may play important roles in focusing the fluids to interact at this location. On the east side of the study area, the SE fault seems to be directing oxidized groundwater towards the intersection with the Buss fault as shown by the abrupt edge of the uranium accumulation (Fig. 6.3). The Buss fault seems to have acted as a conduit for the rising reductants and a partial barrier to groundwater flow. The fractured area between the two structures allows for increased reductant and groundwater flow.

7.1.5 Geometry of Ore Body

Roll-front uranium deposits are generally thought to be curved or tabular in cross-section, thin and sinuous in plan view and generally within a favorable horizon (Penney, 2012). Deposit morphology is controlled by permeability of the host rocks, with mudstone or clay layers confining a permeable sandstone (Goldhaber et al., 1983). Variations on the generalized, ideal model have been observed. One such example in the Gas Hills shows stacked subzones in

proximity to faults (Grutt, 1957). The Kellner deposit in South Texas is comprised of tabular ore bodies up dip from crescent-shaped bodies which are up dip from a fault (Dickinson and Duval, 1977). This is thought to have occurred by partial precipitation of the uranium up stream of the main redox boundary near the fault.

In the Buss Pit study area, the paleowater flow direction is from the S-SE, which corresponds with the crescent-shaped rolls modeled, but stratigraphic dip is now to the S-SE (Fig. 6.6; Love, 1978). The ore distribution at the deposit scale is wide in plan view, dips through stratigraphy and ranges vertically over 82 m of stratigraphy (Figs. 6.2, 6.3). However, at a smaller scale, ore is distributed mainly in sandstone and conglomerate units confined by mudrock intervals. Permeability and connectivity of the sandstone/conglomerate dominated facies acts as a secondary control on the position of ore formation (Fig. 6.9). Reductant flow up the fault resulted in rolls and tabular zones dominantly up paleo-dip from the fault. The buoyancy of a possible gas reductant may have resulted in the subzones being dominantly in the middle to upper portion of a fining-up, sandstone/conglomerate unit, when highest permeability host rocks are thought to have highest grades. Fine-grained, mudrock host rocks may have higher uranium grades as a result of gas reductants being trapped in the less permeable lithology or increased precipitation due to retarded oxidized fluid flow (Weeks and Eargle, 1963; Dickinson and Duval, 1977). This study confirmed the discontinuous, fine-grained lithologies observed by Grutt (1957) in the Gas Hills district, which may have lead to uranium precipitation over more stratigraphic height in the system as the fluids were poorly confined (Fig. 6.9).

The entire fault system was slightly more shallowly dipping prior to post-mineralization deformation, based on the orientation of the stratigraphy. Ore distribution near the Buss and SE faults is dominantly controlled by the additional permeability and/or impermeability caused by the structures themselves (Fig. 6.7). Uranium is concentrated in the hanging wall of the SE fault (Fig. 6.3). This is believed to have resulted from the impermeable properties of this structure. The water flow from the S-SE would have been directed along the NW-SE structure towards the intersection with the Buss fault. This is supported by the subzone morphology that shows a dominantly northward paleowater flow. The Buss fault seems to have alternating permeability characteristics over the vertical extent, which is believed to be the result of the stratigraphy that is being offset and incorporated into the fault (Fig. 7.2). Permeable characteristics are observed at the fault interface where fluid flow seems to cross the fault in some areas resulting in ore

zones that step across the structure. The step morphology may be the result of groundwater pressure along a portion of the fault where the flow could more easily move upward as opposed to down into a water saturated environment (Fig. 7.2). Step features have been enhanced by the post-mineralization fault movement. Impermeable characteristics were observed in outcrop and are inferred from the stepped shapes at the fault and crescent-shaped morphologies up dip from the fault (Fig. 5.2). This fractured intersection of two structures has created a physical trap for ground water flow as well as a conduit system for rising reductants, creating an ore zone that dips away from these structures to the S-SW. This complex redox boundary is thought to be dynamic based on variations in fluid flow rates. It is possible that the redox boundary migrated away from the faults as the area was flushed by reductants, creating a layered ore zone with the youngest uranium minerals furthest from the fault. The entire system was eventually overwhelmed by reductant preserving the redox boundary morphologies. The approximate vector of highest oxidized fluid flow corresponds to the area we see the greatest bend in deposit scale ore distribution (Fig. 6.3). This is thought to have occurred as the high flow of fluid pushed back the plume of reduced gas.

Ore subzone morphology supports the gas reductant and the structural control hypotheses. Subzones near the fault show a billowing shape, are dominantly in the upper portions of the aquifer and crescent-shaped morphologies are dominantly up dip from the structure (Fig. 6.7). The orientation of the faults and the corresponding orientation of the deposit show a structural dimension to the formation of this deposit (Figs. 6.2, 6.7).

7.2 Comparison to Other Roll-front Deposits in Wyoming

The study has implications to better understanding roll-front deposits in the Gas Hills district and the greater Wyoming Uranium Province. The Gas Hills contains a vast array of faults that have been associated with deposits in the past (Grutt, 1957) yet are ignored in current deposit models. Some faults are known to be clearly post-mineralization. However, little research has been carried out to establish the age relationships between mineralization and faulting in most cases. Correlation between steeply dipping, normal faults and “most of the mines” in the Gas Hills including the Buss Pit, P-C and RanRex deposits was documented in the Gas Hills during the height of mining activity (Grutt, 1957; Zeller, 1957). The great number of

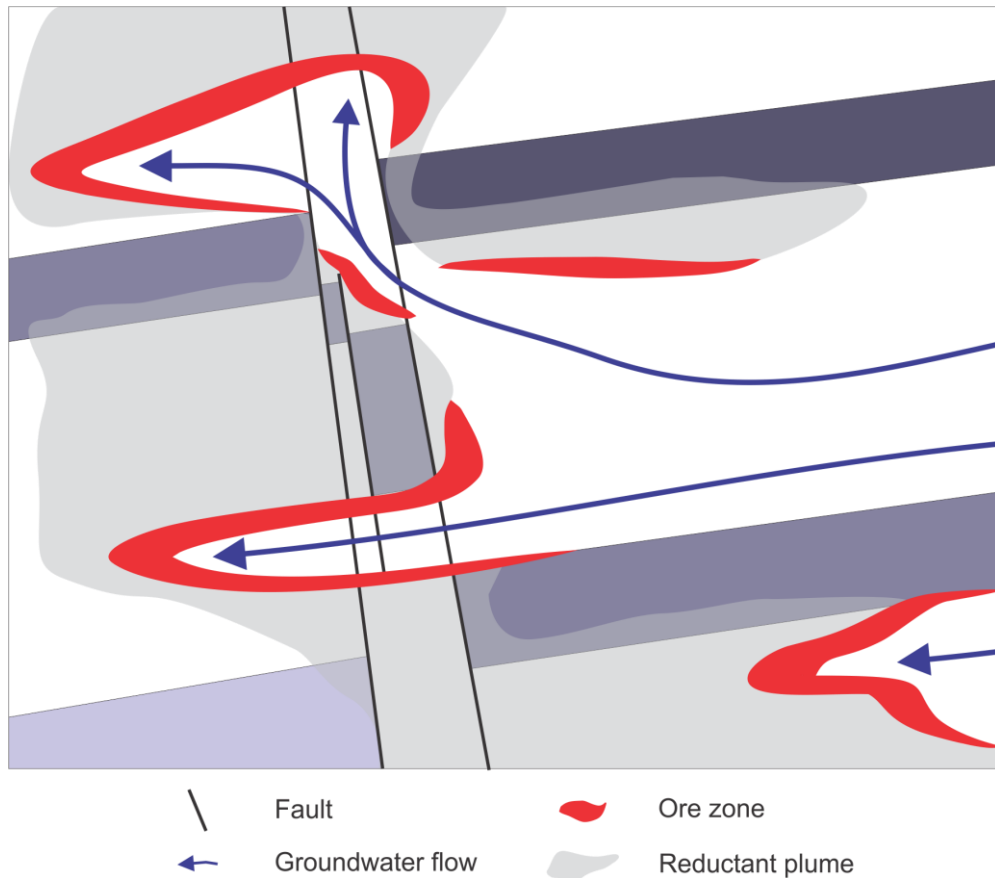


Figure 7.2: Schematic diagram showing the potential interaction of the oxidized groundwater flow with the reductant plume at a fault with the geometry of the Buss fault observed in outcrop (see Fig. 5.2). This fluid interaction would result in the ore geometries modeled at the Buss fault in the deposit area.

steep faults in the Gas Hills area and the numerous uranium deposits may be evidence that the processes discussed above are at work.

Other basins in the Wyoming Uranium Province are characterized by similar geological relationships. At the Lost Creek deposit in the Great Divide Basin, for example, the roll-front formed along a steeply-dipping normal fault that has been documented to have conspicuously saline groundwater, suggesting a reduced basinal brine acted as the reductant (Hancock, 2012). In the Maybell district of Colorado, high-angle normal faults cut host rocks with low carbonaceous material; the ore zones form tabular to lenticular bodies and vein-like bodies along faults (Chenoweth, 1986). The Baggs and Poison Basin areas have low organic carbon contents, wide-spread faulting and uranium deposits associated with faults (Vine and Prichard, 1954;

Grutt, 1957). The Crooks Gap district, between Lost Creek and the Gas Hills, hosted uranium associated with normal faults, high fracture density, and thrust faults (Stephens, 1964). The Crooks Gap, Maybell, Baggs, and Poison Basin areas are in hydrocarbon producing basins. These deposit areas may exemplify how the above discussed processes can vary in geologic systems in the region.

7.3 Implications for the Deposit Model

The present study provides a modified formation model for roll-front type deposits in faulted hydrocarbon producing basins with low *in situ* reductants. This revision is not necessarily applicable in every system and does not replace the original roll-front formation model. As Burrows (2010) stated, studies based on the processes of formation benefit the uranium industry and should encourage an updated deposit classification based on process rather than host rock type. Sandstone-hosted uranium deposit classification includes roll-front, tectonic-lithologic, tabular and basal channel types (Kyser and Cuney, 2008). This study shows a possible link between roll-front and tectonic-lithologic types.

At the basin scale this model can be simplified into a system of dipping aquifers with oxidized groundwater being directed by a physical fluid trap into a chemical uranium trap (Fig. 7.3). The physical trap is a combination of impermeable faults and stratigraphy that provides direction for both groundwater and reductant. Conditions in the reductant plume form a chemical trap for uranium. These processes result in an ore zone geometry that can be more complex than predicted by the conventional roll-front deposit model.

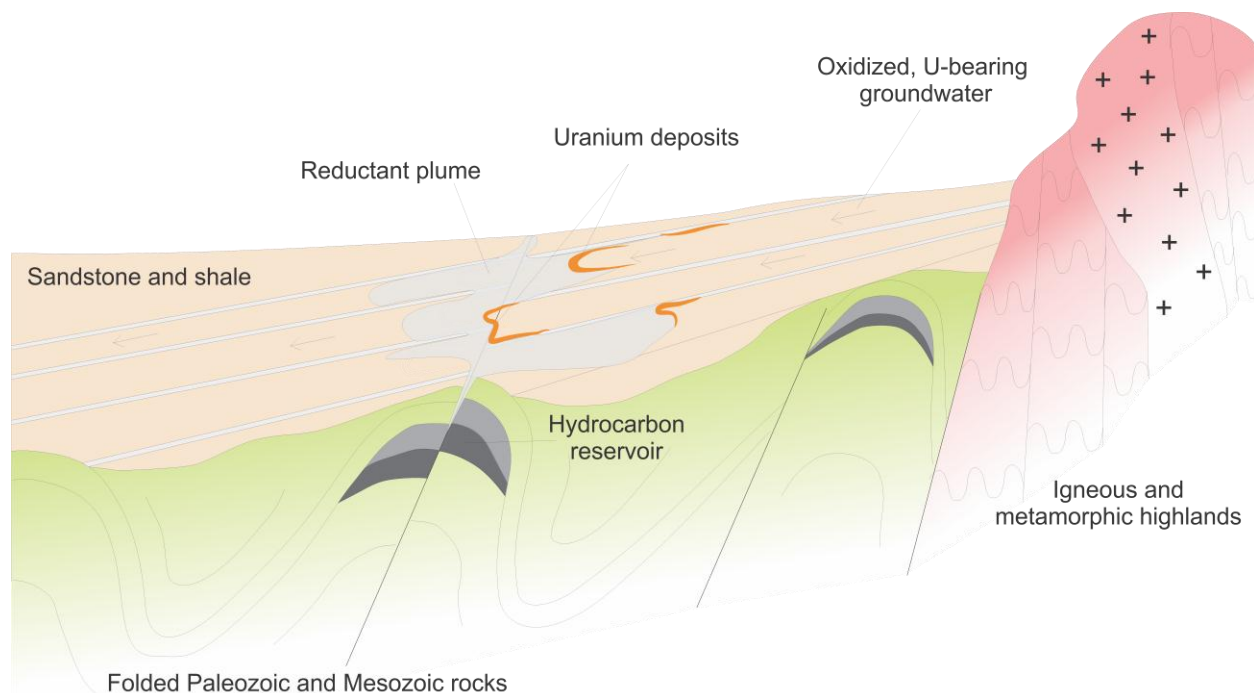


Figure 7.3: Schematic diagram of the simplified basin scale processes proposed to have formed the uranium deposit at the Buss Pit and may form other complex, fault-influenced roll-front deposits in similar environments (Jaireth et al., 2008). This model proposes a system of dipping aquifers transporting oxidized groundwater being directed by stratigraphy and structures to a chemical trap which resulted from the rising of reductants along a deep structure.

7.4 Implications for Exploration and Mining

The findings of this study have important implications to both mineral exploration for roll-front deposits and extraction of economic zones of uranium enrichment. Exploration for these deposits could be enhanced with the application of the proposed formation processes and 3D modeling. At the same time, uranium mine planning could benefit from the use of 3D modeling, especially in deposits that have complex shapes or are associated with faults.

7.4.1 Exploration

The classic uranium roll-front formation model has been used with ample success in exploration for this type of energy resources in basins around the world (Penney, 2012). In areas

without allogenic, *in situ* reductants, however, success could be increased by acknowledging the proposed processes of formation. Successful exploration under deeper cover is benefited by the increased knowledge of deposit formation. These insights will allow targets to be formed near the intersection of structures and favorable stratigraphy in prospective basins. An updated set of exploration techniques can be developed to better target the characteristics of this possibly structurally controlled type of deposit.

Identification of faults in potentially productive basins could represent a first important step in targeting exploration efforts. This could potentially be done through an array of geophysical methods or remote sensing techniques that could identify subtle changes in topography caused by the presence of faults. Ideally, areas should be targeted where potential faults intersect paleochannels in the host rocks, providing the necessary permeability for ground water flow. It will be necessary to understand sedimentological variation and paleofluid flow to predict the zones of favorable permeability. Exploration for deposits similar to the Buss Pit deposit should not use the reducing capacity of the host rocks as a criterion as this would rule out deposit formation by an externally sourced reductant. If reductant upflow is still active, as in the Gas Hills, it is possible that soil geochemical surveys could be used to identify deep-seated faults from surface.

The results of the present study also imply that building a 3D model at an early stage of exploration may be highly useful. Routine implementation of 3D visualization tools could increase the accuracy of geologic interpretation and extrapolation, thus decreasing exploration costs for a deposit type that is notoriously difficult to delineate such as a roll-front. As demonstrated in the Buss Pit area, fault offsets can be comparably small, but important to identify during early phases of exploration to better target drilling.

7.4.2 Mining

The least invasive and most advanced method of mining sandstone-hosted uranium deposits is by *in situ* leach (ISL) extraction. ISL mines are comprised of injection wells that insert an oxidizing fluid into the host rock, extraction wells to withdraw the uranium-rich fluid and monitoring wells on the periphery for testing groundwater quality around the mine (Stover, 2004). Injection and extraction wells are placed in patterns engineered to enhance production

from individual ore bodies (Stover, 2004). Uranium roll-front deposits have an immense amount of variation on a small scale, these variations are important to address for optimum mine productivity. Not only are permeability and grade important, but porosity, lithology, hydrology and the precise locations and combinations of these characteristics are crucial.

It is proposed here that 3D modeling should form an integral part of the design phase of the well patterns. The results of the 3D modeling could be used to design a well pattern configuration allowing maximum recovery of a specific ore body. Not unlike software packages optimizing open pit design based on grade distribution, algorithms determining optimal well pattern configuration could be developed that would make use of the geological information gathered in the 3D environment.

Another important point is that structural complications such as those at the Buss Pit deposit make ISL mining complicated to permit and execute. The Lost Creek deposit Environmental Assessment included extensive testing to show that the faults in the mine area act as impermeable barriers (Cooper and Bull, 2012). Permeable faults in the proposed mine area may result in decreased permitted area or multiple well fields that exclude a perimeter around problematic faults (William R. Wilson, personal communication, 11 March, 2014). This type of deposit will necessitate increased testing and could involve complicated permitting. 3D modeling of the deposit geology would be crucial in such cases.

CHAPTER 8

CONCLUSIONS

The present study on the Buss Pit deposit represents one of the first three-dimensional reconstructions of a structurally controlled roll-front uranium deposit. The main findings of this study are as follows:

(1) The case study at Buss Pit demonstrates that gamma ray and resistance geophysical data from historic, analog logs can be compiled and translated into a more useful format through digitization and correlative interpretation. Paper logs represent a large amount of useful information that can be utilized to reinterpret the geology of a deposit or deposit area. Integration of data into a 3D knowledge cube for subsequent data mining and interpretation is a more efficient and holistic means of analysis than conventional methods.

(2) The study at Buss Pit shows that this particular uranium deposit did not form prior to faulting, which contradicts the generally accepted deposit model. The two faults in the deposit area are interpreted to have formed before mineralization and had an intimate effect on fluid flow through the sedimentary package.

(3) The observed spatial relationships between the deposit and the faults, as well as the interpreted effects of those faults on ore formation, required the development of a new deposit model for at least a subgroup of roll-front uranium deposits. This model assumes the presence of a deep structure that provides a conduit for reduced fluids, creating a stationary zone of interaction between reduced and meteoric oxidized fluids, therefore having the potential to produce large uranium accumulations at the resulting oxidation-reduction boundary. This can include the complex interactions of sedimentological permeability variation, fault permeability and orientation, variability based on type of reductant, amount of reductant, variation of fluid flow rates and paleogradients.

(4) The research shows that three-dimensional modeling can be a useful tool to visualize the complex ore zone morphologies of roll-front deposits for research, exploration, and mining

applications. Three-dimensional modeling could be implemented into early stage exploration to assist in the identification of major faults and for improved targeting. It is feasible that such models built during the exploration phase could be directly used during mine planning and design of the well fields use in *in situ* mining.

Based on the results of the present study, the following recommendations for future work on structurally controlled roll-front deposits are made:

(1) More three-dimensional deposit models made of potential and historic mines in the Gas Hills district to better understand interactions between the stratigraphy, structure, and ore zone components in the Wind River Basin system, particularly the Gas Hills. Specific work correlating the locations of past-producing hydrocarbon wells with uranium accumulations may lead to a potential exploration tool.

(2) Detailed structural mapping utilizing geophysical methods, log correlation, and the limited outcrop in the Wind River Basin could be carried out to understand the complex faulting that intersects multiple historic mines in the Gas Hills area. This should include dating of faulting events, possibly by the $^{40}\text{Ar}/^{39}\text{Ar}$ dating of fault clays.

(3) Analysis of carbon and sulfur isotopes in fault gauge may be used to identify the reductant source and thus clarify the source as a hydrocarbon from depth, potentially expounding upon specific characteristics as well.

(4) Further study of similar deposits around the world with associated structures in hydrocarbon producing basins will further illuminate the proposed deposit forming processes and refine the complex interactions.

(5) Additional geochemical, geophysical, and mining engineering research is essential to determine the reality of specific exploration and *in situ* mining for complex, mobile reductant related, near-fault uranium deposits.

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APPENDIX A
SUPPLEMENTAL ELECTRONIC FILE

The Leapfrog Geo Buss Pit model (BussPit.lfview) is attached as a supplemental electronic file. This file includes bore hole data, fault surfaces, a geologic model with enclosed non-resistive lithology shapes, and three grade shells showing > 0.02 , > 0.05 , and > 0.1 e% U_3O_8 . The file can be viewed in the Leapfrog Viewer software which can be downloaded from the Leapfrog website at no cost (<http://www.leapfrog3d.com/products/Leapfrog-Viewer/downloads>) and used in Mac and Windows operating systems. In Leapfrog Viewer, the user can hide components of the model, vary transparency, rotate, slice, and measure in 3D space.

File Name	Description
BussPit.lfview	Leapfrog Geo model containing bore hole data, fault surfaces, a geologic model with enclosed non-resistive lithology shapes and three grade shell shapes

APPENDIX B

FIELD DESCRIPTIONS AND GEOCHEMICAL DATA

Sample Location Descriptions

At the location where sample BP-S1 was taken (Fig. 4.1A), a dark gray fissile mudstone is overlain by a 1.5 m thick yellow-white, poorly-sorted, coarse sandstone unit. The sandstone contains angular to subangular clasts up to pebble size. It shows weak, decimeter-scale bedding and reverse followed by normal grading up section. The sandstone is overlain by a fining-up, poorly-sorted, pebble to cobble conglomerate. Sample BP-S3 (Fig. 4.1B) was taken on the north side of the Buss fault, 1.5 m north along the outcrop from BP-S1. This location shows a 50 cm, light gray, poorly-sorted, medium grained sandstone overlain by a 23 cm, medium gray mudstone. This mudstone was incorporated into the dark gray to green, clay, fault gouge where sample BP-S2 was taken. At the location BP-S4 was taken (Fig. 4.1C), the top 20 cm of a dark gray, fissile mudstone was overlain by sandstone and conglomerate. The sandstone was exposed for approximately 1 m and showed a moderately-sorted, coarse grained sandstone to granule conglomerate with weak, decimeter-scale bedding. Sample BP-S4 is from a location slightly lower in the stratigraphy than sample BP-S2. The locations shows the coarser grained base of the larger sandstone bed. At the location where sample BP-S5 was collected (Fig. 4.1D), a 1 m thick, light gray, moderately-sorted, medium-grained, very weakly bedded sandstone truncates at a scour surface with a > 1 m, cobble conglomerate that fines upward to weakly bedded, fining-up sandstone. The location of sample BP-S6 (Fig. 4.1E) shows multiple fining-up sandstone beds ranging in thickness from 40 cm to 4.5 m. These beds are composed of pebble conglomerate to coarse sand. At the location where sample BP-S7 was collected (Fig. 4.1G), a cobble conglomerate fills a scour surface while in the same stratigraphic position, 3 m south, a light gray, granule to coarse grained sandstone contains 10-40 cm, gray to green, siltstone rip-up clasts. The location sample BP-S8 was taken (Fig. 4.1H) near the top of the pit shows 1 m of cross-bedded, coarse, pale yellow sandstone overlain by multiple 10 cm cobble conglomerate beds rapidly transitioning to pale yellow, weakly cross-bedded, coarse sand.

Geochemical Analyses

Samples BP-S1, BP-S2, BP-S4, BP-S5, BP-S6, BP-S7 are sandstones to pebble conglomerates. These unmineralized samples from the open pit contain 77.6 – 80.0% SiO₂, 10.2 – 13.2% Al₂O₃, 0.51 – 1.59% Fe₂O₃, 0.05 – 0.11% total carbon, and 0.026 – 0.178% pyrite. Sample BP-S2 is a mudstone from the Buss fault. It contains 64.5% SiO₂, 15.3% Al₂O₃, 4.05% Fe₂O₃, 0.09% total carbon, and the highest pyrite content of 0.494% (Table B-1).

Table B-1 : Description of grab samples from Buss Pit

Sample	Location	Color	Description
BP-S1	x: 837287 y: 781117	Yellow/white	Poorly-sorted, dominantly 1-4 mm, arkosic coarse sandstone containing muscovite grains up to 6 mm and granule sized clasts of quartz, granite rock fragments and highly altered clay amalgamations
BP-S2	x: 837286 y: 781118	Dark gray/green	Mudstone with ~10% arkosic coarse grained sand and minor visible muscovite grains from fault
BP-S3	x: 837286 y: 781118	Light gray	Poorly-sorted, arkosic medium grained sandstone with 10-15% clay size fraction in matrix and minor highly altered, soft clasts (1-3 mm)
BP-S4	x: 837255 y: 781168	Gray	Moderately-sorted, dominantly granule sized (1-9 mm) altered, arkosic clasts with 3-5% green mica and medium sand matrix
BP-S5	x: 837175 y: 781424	Gray/light green	Well-sorted, medium to fine, arkosic sandstone with 5-7% dark (green to black) grains
BP-S6	x: 837119 y: 781497	Gray/green	Well-sorted, very fine grained, lithified, arkosic sandstone
BP-S7	x: 836986 y: 781695	Gray/white	Poorly-sorted, conglomerate with granite and quartz clasts (0.5-5 cm) in an arkosic, coarse sand matrix
BP-S8	x: 836916 y: 781780	White/light yellow	Poorly-sorted, medium to coarse, arkosic sandstone with 10-15% clay size fraction in matrix

Table B-2: Major and trace element concentrations of grab samples from Buss Pit

Sample		Detection	BP-S1	BP-S2	BP-S3	BP-S4	BP-S5	BP-S6	BP-S7	BP-S8
Rock type		limit	ss	clay	ss	ss	ss	fine ss	congl	ss
SiO ₂	%	0.01	79.09	64.48	78.43	79.7	78.84	70.98	79.95	77.58
Al ₂ O ₃	%	0.01	11.3	15.26	11.2	10.23	11	13.24	10.78	11.67
Fe ₂ O ₃	%	0.01	1.15	4.05	1.16	0.61	0.78	1.59	0.51	0.93
MnO	%	0.001	0.007	0.013	0.008	0.005	0.007	0.032	0.005	0.005
MgO	%	0.01	0.3	0.81	0.39	0.16	0.42	0.5	0.19	0.31
CaO	%	0.01	0.41	0.56	0.38	0.28	0.36	1.67	0.39	0.53
Na ₂ O	%	0.01	2.04	0.97	1.6	1.57	1.55	1.74	2.27	2.07
K ₂ O	%	0.01	3.71	3.39	3.87	3.91	3.68	4.02	3.69	3.82
TiO ₂	%	0.001	0.14	0.49	0.122	0.101	0.157	0.349	0.111	0.124
P ₂ O ₅	%	0.01	0.03	0.03	0.03	0.04	0.02	0.03	0.02	0.04
LOI	%		2.73	8.71	2.46	1.96	2.98	4.25	1.68	2.7
Total		0.01	100.9	98.76	99.63	98.56	99.79	98.41	99.61	99.77
C	%	0.00004	0.049	0.092	0.080	0.109	0.051	0.101	0.092	0.075
S	%	0.001	0.194	0.924	0.051	0.148	0.332	0.236	0.117	0.143
Sc	ppm	1	5	9	4	3	5	7	3	5
Be	ppm	1	3	7	4	2	4	5	2	2
V	ppm	5	58	119	241	51	50	115	41	42
Cr	ppm	20	30	80	60	20	40	80	< 20	20
Co	ppm	1	109	40	96	124	126	52	101	114
Ni	ppm	1	12	48	14	7	9	20	6	14
Cu	ppm	1	15	23	7	6	5	11	3	10
Zn	ppm	1	25	66	32	12	16	31	15	26
Cd	ppm	0.5	< 0.5	0.7	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Ga	ppm	1	13	20	13	11	13	18	11	13
Ge	ppm	0.5	2.1	2.9	2.1	2	3.3	3.4	2.9	2.2
As	ppm	5	< 5	90	6	9	5	7	< 5	< 5
Rb	ppm	1	117	164	130	119	110	168	113	118
Sr	ppm	2	74	64	88	81	94	78	88	131
Y	ppm	0.5	23.9	24.7	12.7	9.6	13.2	20.8	11	15.2
Zr	ppm	1	143	297	115	81	154	269	94	115
Nb	ppm	0.2	6.8	13.8	3.7	3.2	5.3	9.8	4.3	4.9
Mo	ppm	2	< 2	2	< 2	< 2	< 2	< 2	< 2	< 2
Ag	ppm	0.3	0.4	0.8	0.4	0.4	0.4	0.7	0.3	0.4
In	ppm	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Sn	ppm	1	< 1	2	< 1	< 1	< 1	2	< 1	< 1
Sb	ppm	0.2	0.3	1.1	0.2	0.6	0.5	0.3	0.2	< 0.2
Cs	ppm	0.1	11.1	59.4	15	6.6	8.2	48.3	19	12.6

Table B-2: continued

Sample		Detection	BP-S1	BP-S2	BP-S3	BP-S4	BP-S5	BP-S6	BP-S7	BP-S8
Rock type		limit	ss	clay	ss	ss	ss	fine ss	congl	ss
Ce	ppm	0.05	52	51	25.3	20.4	32.4	43.7	28.2	38
Pr	ppm	0.01	5.86	5.85	2.81	2.23	3.61	4.83	3.16	4.15
Nd	ppm	0.05	19.7	20.3	9.17	7.23	12	15.2	10.4	14.1
Sm	ppm	0.01	3.83	3.88	1.8	1.36	2.13	2.77	2.11	2.68
Eu	ppm	0.005	0.515	0.65	0.339	0.2	0.372	0.481	0.275	0.485
Gd	ppm	0.01	3.35	3.38	1.71	1.15	1.87	2.51	1.87	2.37
Tb	ppm	0.01	0.58	0.6	0.31	0.2	0.32	0.45	0.3	0.4
Dy	ppm	0.01	3.67	3.85	1.89	1.24	1.97	2.91	1.73	2.44
Ho	ppm	0.01	0.79	0.82	0.38	0.28	0.41	0.66	0.35	0.5
Er	ppm	0.01	2.39	2.45	1.17	0.92	1.28	2.17	1.07	1.5
Tm	ppm	0.005	0.374	0.384	0.185	0.149	0.216	0.362	0.177	0.242
Yb	ppm	0.01	2.53	2.49	1.16	1.1	1.41	2.48	1.2	1.54
Lu	ppm	0.002	0.386	0.41	0.181	0.163	0.216	0.374	0.179	0.215
Hf	ppm	0.1	4.7	7.3	3.7	2.6	4.3	7.6	3.1	4.4
Ta	ppm	0.01	4.46	2.29	3.24	4.09	4.47	2.69	3.98	4.22
Tl	ppm	0.05	0.59	1.91	0.77	0.7	0.56	0.9	0.51	0.47
Pb	ppm	3	20	25	27	25	27	20	18	23
Bi	ppm	0.1	0.2	0.4	0.2	0.1	0.1	0.2	< 0.1	< 0.1
Th	ppm	0.05	16.1	17.4	6.84	5.56	14.1	17.3	9.45	11
U	ppm	0.01	4.93	21.4	3.16	2.83	4.97	6.59	3.61	8.92