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D5 GEOLOGY

D5.1 Regional Geology

The Great Divide Basin (Basin) is an oval-shaped structural depression, encompassing some 3,500 square miles in south-central Wyoming. The Basin is bounded on the north by the Wind River Range and Granite Mountains, on the east by the Rawlins Uplift, on the south by the Wamsutter Arch and on the west by the Rock Springs Uplift. The regional geologic map is shown in **Figure D5-1**. Geologic development of the Basin began in the Late Cretaceous and continued through much of the Early Eocene.

D5.1.1 Stratigraphy

The earliest sedimentation in the Basin was the Paleocene (Early Tertiary) Fort Union Formation, which was unconformably deposited on the Lance Formation of Late Cretaceous age. The Fort Union Formation consists mostly of lacustrine shales, siltstones, and thin sandstones, which locally contain lignite beds. The thickness of the Fort Union Formation varies from place to place in the Basin, and it is approximately 4,650 feet thick in the Permit Area.

The Fort Union Formation is unconformably overlain by sediments of Eocene age, making up about 6,200 feet of basin fill. The western and southern portions of the Basin are covered by the Wasatch Group, which consists of sandstone, siltstone, limestone, conglomerate and lignite beds. The rocks in the Wasatch Group are believed to be of fluvial-lacustrine origin. Towards the north and northeast, the Wasatch Group rapidly grades into and inter-tongues with the equally thick, fine- to coarse-grained arkosic sandstones and conglomerates of the Battle Spring Formation, a typical alluvial fan complex. The source of the Battle Spring sediments is believed to be the ancestral Granite Mountains to the north. Pliocene pediment deposits and recent alluvium cover large areas of the surface in the Basin. **Table D5-1** and **Figure D5-2a** show the general stratigraphy of the Basin.

The upper portion of the Battle Spring Formation is the host to the uranium mineralization in the Permit Area. In the Permit Area, the top 700 feet of the Battle Spring Formation is divided into at least five horizons marked from top to bottom as BC, DE, FG, HJ, and KM. These horizons are separated from one another by various thicknesses of shale, mudstone and siltstone (**Figure D5-2b**).

D5.1.2 Structure

The present physiographic feature of the Basin was generated by the Laramide Orogeny. During the Late Cretaceous and Early Tertiary, the structures surrounding the Basin were either rejuvenated or were formed, transforming the area into a bowl-shaped geological structure, the Basin. During this upheaval, the Wind River Mountains and Granite Mountains were uplifted on the north side of the Basin. The Rawlins Uplift formed to the east; the Wamsutter Arch formed to the south; and the Rock Spring Uplift formed to the west. All of these highs formed a ring around the Basin, turning the Basin into a bowl-like structure with drainage being inward. The Continental Divide, extending from the south, splits into two and forms half circles on the east and west sides of the Basin, joining again as one topographic high on the north side of the Basin.

The Basin is asymmetrical with its major axis trending west-northwest. Several anticlines and synclines have been mapped within the Basin, and some of these features are oil-bearing (at much deeper levels than the uranium-bearing formations). Noteworthy among these structures is the Lost Soldier anticline in the northeastern part of the Basin, approximately 15 miles northeast of the Permit Area. The Battle Spring and Fort Union formations, as well as older rocks crop out in the anticline; and the formations on the southwestern flank of the anticline dip 20 to 25 degrees to the southwest. The dip gradually becomes gentler, and, at the Permit Area, it is merely three degrees to the west.

Contemporaneous with the uplift of the mountains surrounding the Basin, there were episodes of normal and thrust faulting within and around the Basin. Most of the major faults are located in the northern part of the Basin, with displacement ranging from a few feet to over 3,000 feet. But, toward the center of the Basin near the Permit Area, faulting seems to be only on a minor scale. For example, the displacement at the Lost Creek Fault which traverses the mineralized area from west-southwest to east-northeast is zero to about 80 feet. More details about the Lost Creek Fault are given in **Section D5.2.2**.

D5.2 Site Geology

The Permit Area is located near the north-central part of the Basin, where the Basin fills are predominantly the Eocene Battle Spring Formation and the Paleocene Fort Union Formation. Geological cross sections throughout the Permit Area are presented in **Plates D5-1a**, **b**, **c**, **d**, **e**, **f**, and **g**, and thickness (isopach) maps of the major sands and shales are presented in **Plates 5-2a**, **b**, **c**, and **d**. The locations of the cross sections are illustrated in **Plate D5-3** (General Location Map-Geology) and also on insets within each cross section. These cross sections display stratigraphic and structural relationships interpreted from drill hole log data and projected onto true north-south or east-west planes. The true distance between drill holes are annotated near the top of each section. Endpoints of each cross-section are projected to the permit boundaries. Extrapolation of the stratigraphy to the permit boundary is based on data from historic exploration drill holes located just outside of the permit boundary. These hole locations have not been identified on drill hole maps or cross-sections as they are outside of the permit boundary. The following information presents the historic drill holes used for the extrapolations:

Cross-Section F-F' (**Plate D5-1e**) - The northern extrapolation of the stratigraphy is based on exploration Drill Hole #85-1, which is about 180 feet north of the property boundary. This drill hole is located at the following coordinates: Easting 2,204,464; Northing 598,174 (NAD 83, State Plane).
Cross-Section G-G' (**Plate D5-1f**) - The northern extrapolation is based on exploration Drill Hole #TT-10, about 120 feet north of the property boundary. This drill hole is located at: Easting 2,209,068; Northing 599,245 (NAD 83, State Plane).
Cross-Section H-H' (**Plate D5-1g**) - The northern extrapolation is based on exploration Drill Hole #A-530, about 940 feet north of the property boundary. This drill hole is located at: Easting 2,213,017; Northing 601,164 (NAD 83, State Plane). The southern extrapolation is based on exploration Drill Hole #RD-187, about 174 feet south of the property boundary. This drill hole is located: Easting 2,213,202; Northing 594,142 (NAD 83, State Plane).

The cross sections also illustrate the piezometric surfaces for the DE, LFG, HJ and UKM horizons. Depiction of these surfaces on the cross sections were generated by tracking the intersection of the plane of the cross section profile with potentiometric contours plotted for the given horizons (**Plates D6-11a to D6-11d**). **Attachment D5-1** contains copies of typical geophysical logs from the Permit Area, and **Attachment D6-3** contains copies of the geophysical logs from the baseline monitoring wells.

Section 16 of T25N, R92W was not included on the cross-sections because of the limited subsurface data in this section and because no mining of this section is planned. Twenty holes have been drilled in Section 16, five of which are regional baseline monitor wells installed by LC ISR, LLC. Two of the exploration holes, OH1 and RD393, were shallow and did not penetrate to a depth sufficient to fully measure any of the stratigraphic units. Similarly, two of the existing monitor wells, MB-07 and MB-08, were only drilled to monitor shallow units. The stratigraphy and structure in Section 16 are discussed in the following sections. If LC ISR, LLC's plans change for Section 16, additional subsurface information will be collected and the permit revised to include that information.

D5.2.1 Stratigraphy

The entire Permit Area is covered by the upper part of the Battle Spring Formation, which is the host to uranium mineralization. Generally, in the Basin, Battle Spring and Wasatch formations, which are time equivalent, interfinger with one another. In the Permit Area, the upper half of the lithologic units consists of Battle Spring Formation and the lower half is made up of Wasatch Formation. The total thickness of the Battle Spring and Wasatch formations under the Permit Area is about 6,200 feet. The Fort Union Formation is 4,650 feet thick beneath the Permit Area and unconformably underlies the Battle Spring/Wasatch formations. Deeper in the Basin and lying unconformably are various Cretaceous, Jurassic, Triassic, Paleozoic, and Precambrian basement lithologic units (**Table D5-1**). A schematic geologic cross section across the Permit Area is shown in **Figure D5-2a**, depicting all lithologic units present under the Permit Area.

The Battle Spring Formation in the Permit Area is part of a major alluvial system, consisting of thick beds of very fine- to coarse-grained arkosic sandstones separated by various layers of mudstones and siltstones. Conglomerate beds may exist locally. Economic uranium mineralization is generally associated with medium to coarse-grained sandstone, which may contain minor organic matter locally. At least five horizons with various amounts of mineralization have been identified in and near the Permit Area.

Aquifers in the Battle Spring Formation typically consist of thick sequences of multiple, medium to coarse-grained, fluvial channel-fill sands. *Mapable sand units* (for example: the UHJ Sand) may range from five to 50 feet in composite thickness, and typically consist of multiple stacked channel-fill sands. *Aquifers*, in turn, typically consist of multiple stacked sand units. Sand units are commonly separated vertically by locally thick beds of mudstone, claystone, siltstone or fine-grained sands. These interbeds represent local aquitards and aquicludes which can be considered internal to the regional aquifer. Total composite thickness of an aquifer (for example: the HJ Horizon) is commonly in excess of 100 feet.

Aquiclides and aquitards (for example: the Lost Creek Shale or Sage Brush Shale) represent quiescent floodplain and overbank sedimentary environments between channel fill sequences. Generally referred to as 'shales' they are, in essence, sedimentary sequences dominated by mudstone and claystone lithology; but also may include substantial amounts of siltsone and fine-grained sands. These lithologies can exhibit considerable lateral facies changes and interfingering, and are often transitional to the aquifers above or below. As a result, dramatic thickening and thinning of the aquicludes can occur locally. Thicknesses of the Lost Creek and Sagebrush Shales are commonly in excess of 25 feet. The thinnest observed occurrences of these units are five feet thick, within the accuracy of the interpretation of down-hole geophysical logs which is plus or minus six inches.

Aquicludes may locally include occurrences of mineralization in the vicinity of lithologic interfingering and facies changes with mineralized sands. Mineralization in this setting will not be targeted for mining and thus will experience minimal, if any, contact with production lixiviant. Given the very low concentrations of uranium within the shales (0.05% or less), the structural integrity and confinement characteristics of the shales will remain unchanged, even if uranium in the shales were incidentally contacted and removed through mining.

Figure D5-2c provides a detailed illustration of the lithologic changes over a 400-foot section in the central portion of the ore-body in the Permit Area. The five mineralized horizons in the Permit Area are designated, from the surface down: the BC, DE, FG, HJ, and KM Horizons. The two horizons with the most mineralization are HJ and KM, which have been further divided into upper, middle and lower sub-units of sandstones (UHJ Sand, MHJ Sand, and LHJ Sand; and UKM Sand, MKM Sand, and LKM Sand). Geological cross sections through the mineralized zones in the Permit Area are presented in **Plates D5-1a**, **b**, **c**, **d**, **e**, **f**, and **g**. Thickness (isopach) maps of the HJ Horizon and UKM Sand, as well as the shales above the HJ Horizon (Lost Creek Shale) and below the HJ Horizon (Sage Brush Shale), are presented in **Plates D5-2a**, **b**, **c**, and **d**.

The HJ Horizon is 110 to 130 feet thick, averaging about 120 feet. The thinner part of HJ is generally south of the Lost Creek Fault. A thicker part of the HJ Horizon runs parallel to the Lost Creek Fault, trending in a west-southwest to east-northeasterly direction. The mineralization is mostly concentrated in the middle part of the HJ Horizon and occurs as both roll front and tabular deposits. The subdivided sand units within the HJ Horizon are separated by discontinuous shale, siltstone and mudstones. The shales overlying and underlying the HJ Horizon are the Lost Creek and Sage Brush Shales, which range from five to over 25 feet thick. The UKM Sand lies under the Sage Brush Shale and is 20 to more than 60 feet thick, averaging about 40 feet. In the eastern part of the Permit Area, the unit is 20 to 50 feet thick; whereas the sand unit in the western portion of the permit area is 40 to more than 60 feet thick, indicating the development of a major paleo-channel. The mineralization occurs as both roll front and tabular deposits.

The stratigraphic layering extends east into Section 16. The layers of interest (DE, EF, FG, LCS, HJ, SBS, KM and KSH) have very similar thicknesses to MU1, although the uppermost BC layer is absent and the underlying layers are slightly shallower in Section 16 because of dip. (The strike at Lost Creek is approximately NE/SW with a dip of roughly 2° NW.) Gamma log signatures for holes drilled in the southeastern portion of Section 16 indicate the existence of mineralized roll front trends. Based on the trends in the HJ and KM Horizons in the rest of the Permit Area, LC ISR, LLC expects these fronts to extend into this portion of Section 16. The top of the HJ Horizon is on the order of 320 feet below surface. The thicknesses of the HJ and KM Horizons range from about 100 to 140 feet and 90 to 135 feet, respectively, somewhat thicker than in the rest of the Permit Area. (The HJ Horizon was not subdivided in Section 16 because of the limited data.) The Lost Creek and Sage Brush Shales are about the same thickness as in the rest of the Permit Area. The LCS ranges from about 5 to 25 feet thick, and the SBS ranges from about 5 to 40 feet thick.

D5.2.2 Structure

Geologic structural features in the Permit Area are illustrated on: the cross sections (**Plates D5-1a** to **D5-1g**); the isopach maps (**Plates D5-2a** to **D5-2d**; and on **Plate D5-3** (General Location Map). In the Permit Area, the Battle Spring Formation is nearly flat-lying, dipping gently to the northwest at roughly three degrees. This pattern is slightly modified locally due to displacement by normal faulting which is post-mineralization in relative time. The genesis of these faults is not certain, however, they may be the product of regional basin unloading. They are not considered to be currently active.

Three faults have been identified. The primary fault is referred to as the Lost Creek Fault. It is centrally located sub-parallel with the mineral trend. It was initially interpreted to be a scissor fault, with reversal of displacement direction in the western third of the Permit Area. Recent interpretation has revealed that it is, instead, a sequence of sub-parallel faults with opposite displacement occurring in an en-echelon configuration.

The 'main' Lost Creek Fault trends east to west and dissects the eastern two-thirds of the Permit Area. Downward displacement occurs on the south block. Throw is approximately 70 to 80 feet in the eastern portion of the Permit Area, decreasing to the west, and eventually losing identity in the western one-third of the Permit Area. In addition, a minor 'splinter' fault has been identified close to the 'main' fault in the west-central portion of the mineral trend. Maximum displacement on this fault is roughly 20 feet. A subsidiary, sub-parallel fault becomes apparent south of the 'main' Lost Creek Fault in the general vicinity where the 'main' fault loses identity. This portion of the Lost Creek Fault sequence continues west to the western edge of the Permit Area. Direction of throw on this fault is opposite to the 'main' fault; i.e., downthrown to the north. Displacement ranges from approximately 40 to 50 feet in the east, decreasing to 20 to 30 feet to the west.

Recent activity has identified the presence of additional faulting. A second fault (the North Fault) occurs in the northwestern portions of the Permit Area. Limited data indicates that the maximum displacement is approximately 70 feet, with the downthrown block to the north. Likewise, a third fault (the South Fault) is found in the south-central portion of the Permit Area. Maximum displacement is roughly 40 feet, with the downthrown block to the north. Both of these faults are oriented sub-parallel to the Lost Creek Fault sequence. Also, both are located outside of anticipated production areas.

No faulting has not been identified in Section 16. The Lost Creek Fault, however, is known to extend east-northeast out of the central portion of the Permit Area and is suspected to extend into the southeastern portion of Section 16. The current drill hole spacing is insufficient to confidently identify faulting because topographic relief could mask the occurrence of any fault with offset on the order of 20 to 40 feet. However, it is possible that further drilling will identify normal faulting in the southern part of Section 16.

D5.2.3 Ore Mineralogy and Geochemistry

The age of mineralization in the Battle Spring Formation is considered to be between 35 and 26 million years before present. Uranium mineralization in the Basin generally occurs either as tabular or C-shaped roll-front deposits. Oxygen-rich surface water, carrying dissolved uranium, entered various sandstones in the Basin. The water percolated down dip, oxidizing the sandstones on its way down dip. Upon reaching sites rich in organic matter, the water lost its oxidizing potential and deposited the uranium, forming the two types of mineralization mentioned above.

Tabular deposits may form at the interface between oxidizing and reducing conditions (the redox front), where oxidation, for all practical purposes, stops. Localized tabular deposits may also form up-dip from the redox front in an entirely oxidized zone, where carbonaceous materials have gathered and formed locally reducing conditions.

The C-shaped roll-front deposits normally form just at the redox front, where the water loses its oxidizing potential. The uranium precipitates and accumulates in a "C"-shaped deposit, with the concave side facing up-dip toward the oxidized sand. Uranium usually accumulates in finer-grained sandstones that carry various amounts of organic matter, which provides a reducing condition.

The alteration process not only changes the color, but also alters the mineralogy of the host sandstones. The color of unaltered, reduced sandstone is light to dark grey, with carbon trash, dark accessories, and traces of pyrite. Altered, oxidized, sandstone contains iron oxide staining (where former carbonaceous matter and pyrite were present), kaolinized feldspar, and has a pink to tan-buff, greenish-grey to bleached appearance. The presence of pyrite and carbonaceous material appear to be the major controlling factors for the precipitation of uranium mineralization. Thinning of sandstones and diminishing grain size probably slowed the advance of the uranium-bearing solutions and further enhanced the chances of precipitation.

The main uranium minerals are uraninite, a uranium oxide, and coffinite, a uranium silicate. Russell Honea (1979) and John V. Heyse (1979) studied several core samples by scanning electron microprobe (SEM), polished section and thin section. Their conclusions were that the host sands are fine- to coarse-grained, poorly sorted arkose. The uranium mineralization is of sub-microscopic size and can be seen only in SEM magnification. They are associated and at times intergrown with round pyrite particles. The uranium minerals identified are mostly uraninite and, possibly, coffinite. The uranium, besides occurring with pyrite, also occurs as a coating around sand grains and as filling of voids between grains. It also occurs as minute particles within larger clay particles.

The most recent study of the lithology and mineralogy was conducted by Hazen Research under the guidance of Dr. Nick Ferris, Ur-E geologist (Ferris, 2007, company report). He concluded that the rocks, represented by a core sample from a depth of 506 to 507 feet of Hole Number LC-64C, are composed of medium- to coarse-grained sand with interstitial clay and silt. Uranium occurrences are very fine-grained and micron-sized, and are mainly dispersed throughout some of the interstitial clays, and occur similarly in some of the interstitial pyrite as well. Because of the size of uranium mineral particles, it was not certain whether the uranium mineral was coffinite or uraninite. The sample tested, comes from the Upper KM Sand unit and may or may not be representative of the majority of the mineralization in the overlying HJ Horizon within the Permit Area.

Known mineralized intervals are found at depths ranging from near surface down to 1,150 feet below the surface in the Permit Area. It is possible that deeper mineralization may exist as well. The main mineralization horizons trend in an east-northeast direction for at least three miles, and are up to 2,000 feet wide. The thickness of individual mineralized beds at the Permit Area ranges from five to 28 feet and averages about 16 feet. The mineralization grade ranges from 0.03 percent to more than 0.20 percent equivalent uranium oxide (eU_3O_8). Four main mineralized horizons, from depths of 300 to 700 feet, have been identified. The richest mineralized zone occurs in the middle part of the HJ Horizon (MHJ Sand) and it is about 30 feet thick, 400 to 450 feet deep, and is believed to contain more than 50 percent of the total resource under the Permit Area.

Leach amenability studies, using the bottle roll method, were performed on core samples collected from the Permit Area in 2007. The analytical results of the bottle roll tests indicate leach efficiencies of 84 percent to 93 percent where bicarbonate was added to the leach solution (a standard in situ recovery practice). The testing demonstrated leach amenability to varying levels of bicarbonate and oxidant addition and accomplished the goal of defining the chemical factors for leaching the ore body and determining the maximum economic leach efficiencies.

The bottle roll tests were conducted using standard industry practice and rigorous modern laboratory controls. The tests were performed on seven uniform splits of a composite core recovered from hole LC66C. Oxidation of uranium in core that has been exposed to the atmosphere can increase the leachability of the uranium, yielding results which are not representative of the in situ deposit. Therefore, the drill core was vacuum sealed in airtight plastic sleeves immediately after recovery to protect the uranium bearing minerals from exposure to the air.

Upon completion of the coring program, the sealed core was characterized by geologists and transferred to the laboratory. A single core composite of eight feet of core was selected for leach amenability, bicarbonate and oxidant studies. The selected core composite was chosen to represent a typical production zone for the Project. The composite splits were then subjected to "bottle roll" amenability testing in which each individual sample was placed in a plastic container with a hydrogen peroxide lixiviant in a measured volume estimated to be five pore volumes of the tested interval, and then rolled mechanically for 16 hours. The lixiviant was extracted and tested for uranium content in the solution and new lixiviant was added and the process was repeated. Each sample was subjected to five additional periods of leaching, to represent the total volume of fluid that would leach uranium from the host over the life of an in situ recovery operation. These six roll sets, each being leached with five pore volumes of lixiviant, replicates a total of 30 pore volumes of lixiviant passing through the deposit, thus closely simulating an actual in situ leach operation. Once the six sets of rotation were completed, the core was analyzed to determine the amount of uranium remaining, in order to establish the efficiency of the leaching system. This allows a determination of the potential in situ leachability of the uranium-bearing sandstone and the potential rate of recovery.

A total of seven tests were conducted. The first test, LC-2001-01, showed low recovery without a bicarbonate addition, which demonstrated the requirement for bicarbonate addition to the lixiviant and the effectiveness of the sample preparation for the test. The other six samples (LC-2001-02 through -07) successfully demonstrated the ore's wide range of amenability to varying chemical conditions. The results of these tests demonstrate that uranium is easily mobilized for production and that the chemical conditions utilized in the tests will be equally effective under both low and high oxidant injection rates. The results of this testing are summarized in **Table D5-2**.

D5.2.4 Exploration and Production Activities

D5.2.4.1 Uranium

Historic and current uranium explorations exist in several areas of the Basin; however, uranium mining has been limited. The closest production was at the Kennecott Uranium Project, located about five miles south-southwest of the center of the Project, with about two miles separating the permit boundaries. (NRC License No. SUA-1350; WDEQ-LQD Permit No. 481). The project includes the Sweetwater Mill, a conventional mill which is currently on stand-by, a mill tailings disposal area, and reclaimed surface mining areas.

There has been no uranium production within the Permit Area. Historic exploration activities in the Permit Area can be summarized as follows:

- Pre-1976: Numerous companies held the property; uranium mineralization was discovered by Climax Uranium and Conoco.
- 1976: Texasgulf optioned property from Valley Development Inc.1977 through 1979: Texasgulf optioned property from Valley Development Inc., delineated the main trend of the mineralization, obtained a 50-percent interest in the Conoco claims on the trend to the east, and exercised its option with Valley Development Inc.
- 1986: Power Nuclear Corporation acquired the properties.
- 2000: Power Nuclear Corporation sold its Lost Creek properties to New Frontiers Uranium, LLC.
- 2005: New Frontiers Uranium, LLC transferred its Wyoming properties and data including its Lost Creek property to NFU.
- 2005: Ur-Energy USA Inc. purchased NFU from New Frontiers Uranium, LLC on terms.
- 2007: Ur-Energy USA Inc. completes the acquisition of NFU from New Frontiers Uranium, LLC, and maintains NFU as a wholly owned subsidiary.
- 2007: Ur-Energy USA Inc. forms Lost Creek ISR, LLC (LC ISR, LLC) to develop the Lost Creek property into an ISR facility and transfers the Lost Creek property from NFU to LC ISR, LLC.

At least 560 uranium exploration holes had been drilled in Permit Area prior to 2000. The plates and table in **Attachment D5-2** present the locations and total depths of all the known historic drill holes drilled in the Permit Area. The information that LC ISR LLC has pertaining to historic drill hole abandonment and re-plugging is provided in **Table D5-3**, including total depths of holes.

There have been continuing efforts over the years to ensure that drill holes are properly abandoned. In the early 1980s, the Conoco/Texasgulf Joint Venture worked to correct a WDEQ LQD violation resulting from incorrect surface capping and hole abandonment. Copies of the memos to WDEQ LQD explaining the work are included as **Attachment D5-3**. WDEQ-LQD subsequently approved the hole abandonment and released the bond.

In 2006, LC ISR, LLC re-located and re-abandoned twelve historic holes (**Table D5-3**). A drill rig was placed on each hole, and the hole was reamed/washed to 650 fbs A mixture of BH Thermal Grout, exceeding WDEQ-LQD Rules and Regulations Chapter 8 requirements, was pumped into the hole as the drill stem was retrieved. No effort was made to determine the depth of historic drill mud but the rig did have to ream/wash out mud from each hole. The upper 25 feet of each hole was plugged with cement. An attempt to relocate three additional holes was unsuccessful. LC ISR, LLC supplied this information to WDEQ-LQD in a letter dated January 15, 2007 (**Attachment D5-3**). In 2008, geologists discovered four historic holes with failed surface caps (Holes TT31, TT80, TT96, and TT141). Drill rigs were put on each of the four holes so they could be re-plugged. In each case, the drill stem was lowered between 180 and 220 fbs before hitting significant resistance. The holes were washed out and re-plugged to surface using grout. Each hole was also re-capped. **Table D5-3** contains information pertaining to the re-abandonment of these four holes.

Some pumping tests have shown very minor communication between the overlying and underlying aquifers and the HJ horizon (**Section 6.2.2.3**). There are several possible reasons for this communication, one of which is leakage through an improperly abandoned drill hole(s). However, the consistent nature of the response, regardless of distance from the pumping well, suggests that leakage through an improperly abandoned hole(s) is not the most likely cause of communication. Other more likely causes are: pumping from other wells in the area; regional communication between aquifers; background trends; or leakage through the juxtaposed aquifers across the Lost Creek Fault.

If additional, improperly abandoned drill holes are found in the future, LC ISR, LLC will plug the holes as described above. In particular, before operations begin in a mine unit, a field inspection will be performed to locate any historic holes with surface capping issues. If the inspection identifies any capping problems, the hole will be re-entered with a drill rig or tremie pipe and re-plugged with grout. A new cement surface cap will also be installed. Aquifer testing of the mine unit prior to operation will also help identify any improperly abandoned holes that could interfere with mine unit operation.

Upon receipt of a permit to mine and prior to injecting mining solutions in Mine Unit 1, LC ISR, LLC will attempt to locate and properly abandon all historic drill holes within the monitor well ring boundary of Mine Unit 1. In the event that the majority of the identified holes are located and abandoned such that there is an expectation that a definitive conclusion can be obtained from additional testing, a pump test will be performed to determine the effect of the hole abandonment effort. This pump test will be designed to mimic the 2008 mine unit pump tests (length of test, wells monitored, and pump rate).

The results of the test may show that the proper abandonment had a positive impact on reducing communication between the aquifers and therefore future mine units will need to go through the same effort. However if the pump test results indicate no change in the drawdown observed in the overlying and underlying aquifer, then it will be determined that the communication comes from lack of geological controls. The results of the test will be added to the permit document.

D5.2.4.2 Other Minerals

Historic and current oil and gas exploration drilling are also in the region. There are no current oil and gas activities within the Basin that are completed in the same horizons as those discussed for ISR production in this application. The nearest significant gas fields are approximately ten miles to the southwest; therefore, no interference is anticipated between oil and gas production activities and ISR activities. There is no exploration of coal bed methane or other mineral resources within the Permit Area and the nearby region.

D5.3 Seismology

The discussion of the seismology of the Permit Area and surrounding areas includes: an analysis of historic seismicity; an analysis of the Uniform Building Code (UBC); a deterministic analysis of nearby faults; an analysis of the maximum credible “floating earthquake;” and a discussion of the existing short- and long-term probabilistic seismic hazard analysis. The materials presented here are mainly based on the seismologic characterization of Sweetwater, Carbon, Fremont, and Natrona Counties by James C.

Case and others from the Wyoming State Geological Survey (Case et al., 2002a, 2002b, 2002c and 2003).

D5.3.1 Historic Seismicity

The Permit Area is located in the north-eastern portion of the Basin, in south-central Wyoming. Historically, south-central Wyoming has had a low to moderate level of seismicity compared to the rest of the State of Wyoming. As shown in **Figure D5-3**, most of the historical earthquakes occurred in the west-northwest portion of Wyoming. Significant historical earthquakes adjacent to the Permit Area are described below, and are organized by areas in which they occurred.

D5.3.1.1 Town of Bairoil Area

Bairoil is located about 15 miles northeast of the Permit Area. Historically, there have been only a few earthquakes that have occurred within 20 miles of Bairoil. On August 11, 1916, a non-damaging intensity III earthquake occurred approximately 17 miles northwest of Bairoil. On June 1, 1993, a non-damaging magnitude 3.8, intensity III earthquake occurred four miles north of Bairoil, and was felt by some residents. On December 10, 1996, a non-damaging magnitude 2.6 earthquake occurred approximately ten miles northwest of Bairoil. A few residents also felt that event.

Two recent earthquakes were recorded near Bairoil in 2000. On May 26, 2000, a magnitude 4.0 earthquake occurred, followed by another (magnitude 2.8) four days later, on May 30, 2000. Both earthquakes were located about 3.5 miles southwest of Bairoil. Most residents in Bairoil felt the first earthquake. No significant damage was associated with either seismic event (Cook, 2000).

D5.3.1.2 City of Rawlins Area

Rawlins is approximately 38 miles southeast of the Permit Area. The first recorded earthquake that was felt and reported immediately southwest of Rawlins occurred on March 28, 1896. The intensity IV earthquake shook for about two seconds. On March 10, 1917, an earthquake (intensity IV) was recorded approximately one mile northeast of Rawlins. The earthquake was felt as a distinct shock that caused wooden buildings to noticeably vibrate. Stone buildings were not affected by the event (*Rawlins Republican*, 1917).

On September 10, 1964, a magnitude 4.1 earthquake occurred approximately 30 miles west of Rawlins. One Rawlins resident reported that the earthquake caused a crack in the basement of his home in Happy Hollow. No other damage was reported (*Daily Times*, 1964).

Small earthquakes were detected, on April 13, 1973, May 30, 1973, and June 1, 1973, approximately six miles west of Hanna. No one reported feeling these events. On July 11, 1975, Rawlins residents felt an earthquake (intensity II) event. On January 27, 1976, an earthquake (magnitude 2.3, intensity V) occurred approximately 12 miles north of Rawlins. Several people reported that they were thrown out of bed (*Daily Times*, 1976). On March 3, 1977, an earthquake (intensity V) was reported approximately 18.5 miles west-northwest of Encampment. Doors and dishes were rattled in southern Carbon County homes; but no significant damage was reported (*Laramie Daily Boomerang*, 1977).

On April 13, 1991 and April 19, 1991, magnitude 3.2 and magnitude 2.9 earthquakes, respectively, occurred near the center of the Seminoe Reservoir. A magnitude 3.1 earthquake occurred on December 18, 1991, southwest of the Seminoe Reservoir, approximately 15 miles northeast of Sinclair. No one reported feeling these Seminoe-Reservoir-area earthquakes. On August 6, 1998, a magnitude 3.6 earthquake occurred approximately 13 miles north of Rawlins. Residents in Rawlins reported hearing a sound and then feeling a jolt. On April, 1999, a magnitude 4.3 earthquake occurred approximately 29 miles north-northwest of Baggs. It was felt in Rawlins; and residents reported that pictures fell off the walls.

D5.3.1.3 City of Rock Springs Area

Rock Springs is located approximately 80 miles southwest of the Permit Area. The first recorded earthquake that was felt in Sweetwater County occurred on April 28, 1888. This intensity IV earthquake, which originated near Rock Springs, did not cause any appreciable damage. On July 25, 1910, an intensity V earthquake occurred at the same time that the Union Pacific Number One Mine in Rock Springs partially collapsed. On July 28, 1930, an intensity IV earthquake, with an epicenter near Rock Springs, was felt in Rock Springs and Reliance (*Casper Daily Tribune*, 1930). The earthquake awakened many residents; and some merchandise fell off of store shelves.

On March 21, 1942, a non-damaging, intensity III earthquake was felt in the Rock Springs area. This event was followed, on September 14, 1946, by an intensity IV earthquake. On October 25, 1947, a small earthquake with no assigned intensity or magnitude occurred southeast of Rock Springs. Two intensity IV earthquakes occurred in the Rock Springs area on September 24, 1948. The events rattled dishes in parts of Rock Springs.

A magnitude 3.9 event was recorded on January 5, 1964, approximately 23 miles south of Rock Springs. The University of Utah Seismograph Stations detected a non-damaging, magnitude 2.4 earthquake on March 19, 1968. This event was centered approximately 17 miles southeast of Rock Springs. A magnitude 3.2 event occurred on May 29, 1975, approximately 13 miles northeast of Superior. A week later, on June 6, 1975, a magnitude 3.7 earthquake was recorded in the same area. No damage was associated with any of the 1975 events.

The University of Utah Seismograph Stations recorded a non-damaging magnitude 2.7 earthquake on June 5, 1986. This event was located approximately 14 miles southwest of Green River, Wyoming.

On February 1, 1992, the University of Utah Seismograph Stations recorded a non-damaging magnitude 2.3 earthquake, approximately seven miles north of Rock Springs.

D5.3.1.4 City of Lander Area

Lander is about 70 miles northwest of the Permit Area. A number of earthquakes have occurred in the Lander area. The first reported earthquake occurred on January 22, 1889, and had an intensity of III to IV. This was followed by an intensity IV event on November 21, 1895, during which houses were jarred and dishes rattled. On November 23, 1934, an intensity V earthquake was centered approximately 20 miles northwest of Lander. For a radius of ten miles around Lander, residents reported that dishes were thrown from cupboards, and that pictures fell down from the walls. Cracks were found in buildings along two business blocks; and the brick chimney of the Fremont County Courthouse was separated by two inches from the building. The earthquake was felt at Rock Springs and Green River, Wyoming (*Casper Tribune-Herald*, 1934).

There were a series of earthquakes in the Lander area in the 1950s that caused little damage. On August 17, 1950, there was an intensity IV earthquake that caused loose objects to rattle and buildings to creak. On January 12, 1954, there was an intensity II event; and on December 13, 1955, there was an intensity IV event near Lander, with no damage reported.

On June 14, 1973, a small earthquake was reported about eight miles east-northeast of Lander. The earthquake has been recently interpreted as a probable explosion. On January 31, 1992, a non-damaging magnitude 2.8 earthquake occurred approximately 20 miles northwest of Lander. This event was followed, on October 10, 1992, by a magnitude 4.0, intensity III earthquake centered approximately 22 miles east of Lander.

D5.3.1.5 City of Casper Area

Casper is located about 90 miles northeast of the Permit Area. Two of the earliest recorded earthquakes in Wyoming occurred near Casper. The first was on June 25, 1894, and had an estimated intensity of V. In residences on Casper Mountain, dishes rattled and fell on the floor and people were thrown from their beds. Water in the Platte River changed from fairly clear to reddish, and became thick with mud, due to the river banks slumping into the river during the earthquake. On November 14, 1897, an even larger event was felt. An intensity VI to VII earthquake, one of the largest recorded in central and eastern Wyoming, caused considerable damage to a few buildings. As a result of the earthquake, a portion of the Grand Central Hotel was cracked from the first to the third story. Some of the ceilings in the Grand Central Hotel were also severely damaged.

On October 25, 1922, an intensity IV earthquake was reported in the Casper area. The event was felt in Casper; at Salt Creek, 50 miles north of Casper; and at Bucknum, 22 miles west of Casper. Dishes were rattled and hanging pictures were tilted near Salt Creek. No significant damage was reported in Casper (*Casper Daily Tribune*, 1922). On December 11, 1942, an intensity IV earthquake was recorded north of Casper. Although no damage was reported, the event was felt in Casper, Salt Creek, and Glenrock (*Casper Tribune-Herald*, 1941). On August 2, 1948, another intensity IV earthquake was reported in the Casper area. No damage was reported (*Casper Tribune-Herald*, 1948). In the 1950s, two earthquakes caused some concern among Casper residents. On January 24, 1954, an intensity IV earthquake near Alcova did not result in any reported damage (*Casper Tribune-Herald*, 1954). On August 19, 1959, an intensity IV earthquake was felt in Casper. Most recently, on October 19, 1996, a magnitude 4.2 earthquake was recorded approximately 15 miles north-northeast of Casper. No damage was reported.

D5.3.2 Uniform Building Code

With safety in mind, the UBC provides Seismic Zone Maps to help identify which building design factors are critical to specific areas of the country. Five UBC seismic zones are recognized, ranging from Zone 0 to Zone 4. These seismic zones are, in part, defined by the probability of having a certain level of ground shaking (horizontal acceleration) in 50 years. The criteria used for defining boundaries on the Seismic Zone Map were established by the Seismology Committee of the Structural Engineers Association of California (SEAOC, 1986). The criteria they developed are as follows:

- Zone 4: ≥ 30 percent gravity (g) effective peak acceleration;
- Zone 3: 20 to ≤ 30 percent g effective peak acceleration;
- Zone 2: 10 to ≤ 20 percent g effective peak acceleration;
- Zone 1: 5 to ≤ 10 percent g effective peak acceleration; and
- Zone 0: ≤ 5 percent g effective peak acceleration.

The Seismology Committee of the Structural Engineers Association of California assumed that there was a 90 percent probability that the above values would not be exceeded in 50 years, or a 100 percent probability that the values would be exceeded in 475 years.

Figure D5-4 shows the delineation of UBC seismic zones in Wyoming. The Permit Area is located in Seismic Zone 1. Since effective peak accelerations (90 percent chance of non-exceedance in 50 years) can range from five to ten percent g in Zone 1, it may be reasonable to assume that an average peak acceleration of 7.5 percent g could be applied to the design of a non-critical facility located near the center of Zone 1.

D5.3.3 Deterministic Analysis of Active Fault Systems

There are two active fault systems in the vicinity of the Permit Area, the Chicken Springs Fault System and the South Granite Mountain Fault System (**Figure D5-5**).

The Chicken Springs Fault System, located six miles east of the Permit Area, is composed of a series of east-west trending segments. In 1996, the Wyoming State Geological Survey investigated this fault system, and determined that the most recent activity on the system appears to be Holocene in age. Reconnaissance-level studies indicated that the fault system is capable of generating a magnitude 6.5 earthquake (Case et al., 2002a). A magnitude 6.5 earthquake on the Chicken Springs Fault System would generate peak horizontal accelerations of approximately 4.8 percent g at Rawlins (Case et al., 2002a). These accelerations would be roughly equivalent to an intensity V earthquake, which may cause some light damage. Bairoil, however, would be subjected to a peak horizontal acceleration of approximately 23 percent g, or an intensity VII earthquake (Case et al., 2002a). Intensity VII events have the potential to cause moderate damage.

The South Granite Mountain Fault System is located about 14 miles northeast of the Permit Area. This fault system is composed of several northwest-southeast trending normal and thrust faults in southeastern Fremont County and northwestern Carbon County. The active segments of the system have been assigned a maximum magnitude of 6.75, which could generate peak horizontal accelerations of approximately 20 percent g at Bairoil and 6.1 percent g at the Rawlins (Case et al., 2002a). These accelerations would be roughly equivalent to an intensity VII earthquake at the Bairoil and an intensity V earthquake at Rawlins. Bairoil could sustain moderate damage; whereas minor or no damage could occur at Rawlins.

D5.3.4 Maximum Tectonic Province Earthquake "Floating Earthquake" Seismogenic Source

Tectonic provinces are regions with a uniform potential for the occurrence of earthquakes that are tied to buried faults with no surface expression. Within a tectonic province, earthquakes associated with buried faults are assumed to occur randomly, and, as a result, can theoretically occur anywhere within that area of uniform earthquake potential. In reality, that random distribution may not be the case, as most earthquakes are associated with specific faults. If all buried faults have not been identified, however, the distribution has to be considered random. "Floating earthquakes" are earthquakes that are considered to occur randomly in a tectonic province.

The US Geological Survey (USGS) identified tectonic provinces in a report titled "Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States" (Algermissen et al., 1982). In that report, Sweetwater County was classified as being in a tectonic province with a "floating earthquake" maximum magnitude of 6.1. Geomatrix (1988) suggested using a more extensive regional tectonic province, called the "Wyoming Foreland Structural Province," which is approximately defined by the Idaho-Wyoming Thrust Belt on the west, 104 degrees West longitude on the east, 40 degrees North latitude on the south, and 45 degrees North latitude on the north. Geomatrix (1988) estimated that the largest "floating earthquake" in the "Wyoming Foreland Structural Province" would have a magnitude in the 6.0 to 6.5 range, with an average value of magnitude 6.25.

D5.3.5 Short-Term Probabilistic Seismic Hazard Analysis

The USGS publishes probabilistic acceleration maps for 500-; 1,000-; and 2,500-year time frames. The maps show what accelerations may be met or exceeded in those time frames by expressing the probability that the accelerations will be met or exceeded in a shorter time frame. For example, a ten percent probability that acceleration may be met or exceeded in 50 years is roughly equivalent to a 100 percent probability of exceedance in 500 years.

The 500-year map provides accelerations that are comparable to those derived from the UBC and from the deterministic analysis on the Green Mountain Segment of the South Granite Mountain Fault System. It was often used for planning purposes for average structures. Based on the 500-year map (ten percent probability of exceedance in 50 years), the estimated peak horizontal acceleration in the Permit Area is approximately 6.5 percent g, which is comparable to the acceleration expected in Seismic Zone 1 of the UBC (**Figure D5-6**). These accelerations (3.9 – 9.2 percent g) are roughly comparable to intensity V earthquakes which can result in cracked plaster and broken dishes, but minor or no construction damages (Case, 2002). All facilities, including the processing plant, pipelines and well structures, at Lost Creek will be designed and constructed to sustain an intensity V earthquake. In addition, the observations of injection, production, and pipeline pressures and associated monitor well measurements, necessary for the in situ operation, will provide short-term information about any unanticipated seismic impacts. The estimated acceleration in the Permit Area is 20 percent g on the 2,500 year map.