2.6 Geology and Seismology

This section describes the regional and local geology and seismology of the MEA area. The geology of the CPF, NTEA, and TCEA has been discussed in previous license applications submitted to the NRC. Detailed information contained in those reports (e.g., laboratory results and field data that describe formation characteristics [lithology, mineralology, permeability] for the Pierre Shale, Chadron Formation, and the Brule Formation at the CPF), also applies in a general sense to the MEA. These data, in addition to new information from exploratory drilling/logging activities within the MEA, are used to describe the geology and seismology in this section.

2.6.1 Geology and Seismology

2.6.1.1 Regional Setting

As shown on **Figure 4.2-1**, the northwest corner of the proposed MEA license boundary is approximately 11 miles (17.7 km) south-southeast of the southeast corner of the city limits of the City of Crawford, Nebraska in sections 26 and 35 Township 30 North, Range 51 West; sections 1, 2, 11, 12, and 13 Township 29 North, Range 51 West; and sections 7, 18, 19, 20, 29, and 30 Township 29 North, Range 50 West. The City of Crawford is 25 miles (40.2 km) west of Chadron, Nebraska and 70 miles (112.6 km) north of Scottsbluff, Nebraska. The City of Crawford is 21 miles (33.8 km) south of the South Dakota state line and 33 miles (53.1 km) east of the Wyoming state line. The Marsland area is located near the northern limits of the High Plains section of the Great Plains physiographic province. Topography of the Marsland area includes gently sloping, rolling hills with outlying, broad ridges dissected by intermittent and perennial streams. The most prominent physiographic feature in the region is the Pine Ridge Escarpment, which rises roughly 300 to 900 feet above the basal plain and bounds three sides of the Crawford Basin. Colluvial and alluvial deposits originating from this escarpment cover the license area. The elevation of the MEA ranges from 3,880 to 4,400 feet above mean sea level (amsl).

Regional Stratigraphy

Table 2.6-1 summarizes the regional stratigraphic section for northwest Nebraska that include the White River Group (Brule Formation through basal sandstone of the Chadron Formation). A geologic map of bedrock in northwestern Nebraska is shown on **Figure 2.6-1**. The bedrock map depicts the occurrence of the Miocene Ogallala Group, Miocene Arikaree Group, the Eocene-Oligocene White River Group, and Upper Cretaceous strata belonging to the Montana Group and Colorado Group. The Upper Cretaceous Pierre Shale, the unconformably overlying White River Group (Brule Formation, Chadron Formation, and Chamberlain Pass Formation), and the Arikaree Group outcrop in the vicinity of the City of Crawford and MEA (**Figure 2.6-1**, see inset).

MEA Stratigraphy

The local stratigraphy at the MEA consists of the following geological units in descending order: alluvial sediments, upper Harrison Beds, Monroe Creek - Harrison Formation, Gering Formation, Brule Formation, upper Chadron Formation, upper/middle Chadron Formation, middle Chadron Formation, basal sandstone of the Chadron Formation, and Pierre Shale. The channel sandstone

facies of the basal sandstone of the Chadron Formation represents the production zone and target of solution mining in the MEA. The general stratigraphic section for the MEA is summarized in **Table 2.6-2**. **Figure 2.6-2** is a cross-section index map depicting the locations of 14 north-south and east-west cross-sections through the MEA depicted on **Figures 2.6-3a** through **2.6-3n**.

Though a thick (approximately 1,200 to 1,500 feet), regionally extensive stratigraphic section of sedimentary units underlies the Pierre Shale, those units are not relevant to this proposal. The absence of sandstone units for more than 1,000 feet below the top of the Pierre Shale precludes the need for monitoring zones below the surface of the Pierre Shale. Discussion in this report is limited to the Arikaree Group, White River Group, and Pierre Shale (Petrotek 2004; Wyoming Fuel Company 1983).

This section provides a detailed description of the stratigraphy of the MEA based on an extensive review of existing site-specific drilling logs and published literature. Geological units are described from stratigraphically youngest to stratigraphically oldest. Revised nomenclature for these stratigraphic units is discussed, where applicable, and referred to throughout this application. To be consistent with historical permitting, the majority of stratigraphic nomenclature used in previous submittals to the NRC and the NDEQ has been preserved.

Alluvium

Quaternary alluvium as much as 30 feet thick overlies the Arikaree Group along drainages in the study area. In general, the alluvium consists of fragments of locally outcropping Oligocene-Miocene sedimentary rocks, sand, gravel, sandy soil horizons, and may include weathered portions of the Arikaree Formation. Because alluvium is unconsolidated and may incorporate one or both of the vadose and phreatic (shallow groundwater) zones, log signatures within this unit vary in comparison with those of geologic units in the underlying units. On most MEA logs, resistivity values for alluvium are very high, beyond the log scale, indicating the presence of either soil vapor or fresh water (**Figure 2.6-4**). In general, shallow zones with elevated resistivity are also distinguished by a negatively deflected spontaneous potential (SP) curve, suggesting the presence of a permeable zone and formation fluid with lower resistivity than the fluid within the borehole. Although these log signatures suggest that the base of the alluvium can be readily identified in geophysical logs, this relationship has not been verified at MEA. Therefore, the alluvium-Arikaree Group contact illustrated on cross-section **Figure 2.6-3a** through **Figure 2.6-3n** is an inferred contact.

Arikaree Group (Oligocene-Miocene)

The Oligocene–Miocene Arikaree Group is a water-bearing unit overlain by alluvium. The thickness varies from 50 to 210 feet depending upon the degree of erosion. The Arikaree lies unconformably above the Brule Formation and is composed of the upper Harrison Beds, Harrison-Monroe Creek and Gering Formations, aged youngest to oldest, respectively (**Table 2.6-2**) (Collings and Knode 1984; Swinehart et al. 1985; LaGarry 1998; McFadden and Hunt, Jr. 1998).

Literature has named the upper Harrison Beds the Marsland Formation or split into the Harrison and Monroe Creek Formations. This application uses nomenclature presented in Swinehart et al. (1985), which uses the upper Harrison Beds, Harrison-Monroe Creek, and Gering Formations.

The Arikaree Group contains numerous channel and flood plain deposits. In some locations, cross bedding is observed. Grain size increases from very fine to fine to medium. The coarsest materials are epiclasts from the White River Group and the Rocky Mountains (Bradley and Rainwater 1956; Tedford et al. 1985; Hoganson et al. 1998).

An isopach map of the undifferentiated Arikaree Group is shown on **Figure 2.6-5**. Within the license boundary, the thickness of the Arikaree Group ranges from approximately 50 to 210 feet and averages about 106 feet. The unit is thickest throughout the central portion of the license boundary but thins on both the northwest and southeast ends of the project. The unit is stratigraphically continuous across the MEA.

On geophysical logs, the Arikaree Group is characterized by an off-scale resistivity signature (**Figure 2.6-4**). The neutron-neutron (N-N) or spontaneous potential (SP) curve exhibits small fluctuations and is relatively straight. The SP or neutron curve can also be off the scale. The gamma curve indicates no anomalous radioactivity. No distinguishing features are seen within the geophysical logs to ascertain contacts within the Arikaree Group. The contact between the Arikaree Group and the overlying alluvium is difficult to ascertain. Often, the SP or neutron curve will begin at the base of the alluvium and the resistivity will move sharply to the right. The contact between the Arikaree and Brule Formations is indicated where the resistivity begins to move left (becomes lower). Little change is seen within the gamma or SP curves.

Upper Harrison Beds

The upper Harrison Beds are composed of buff to gray fine sand without abundant silt and clay, white sand with abundant silt and clay, and a siliceous pedogenic horizon. Thickness of this unit can be up to 150 feet. Convolute laminae occur within the fine sand and contain very little silt or clay. The massive unlaminated white sand was deposited by sheet flow following rains and/or flooding after a heavy ash fall. The lower part of the upper Harrison Beds contains large blocks of sandstone formed from underlying strata; this indicates fluvial channel deposition. Cross stratified beds are also found (Cook 1915; Witzel 1974; Hunt 1981; Vicars and Breyer 1981).

The upper Harrison Beds contain preserved paleosurfaces which were overlain by silica cement. The paleosurfaces are valleys, which were infilled by ephemeral stream deposits and overlain by aeolian volacnoclasitc sands. Freshwater ostracods, animal burrow, and root casts are abundant (Hunt 1981).

Harrison - Monroe Creek Formation

The Harrison-Monroe Creek Formation can be divided into upper, middle, and lower portions. All of the portions are similar, and the middle and lower portions are sometimes undistinguished.

The upper portion of the Harrison-Monroe Creek Formation is fine grey sand. This sand is generally 200 feet thick and is massively bedded. The sands were deposited from channel fills. Concretions can be found within the unit (Witzel 1974; McFadden and Hunt Jr., 1998).

The middle portion of the Harrison-Monroe Creek Formation is composed of fine, unconsolidated grey sediments. The lower portion is composed of compact fine sandy silt and clay, pinkish to buff in color, and a fine to medium grained gray sand. In the vicinity of Harrison and Crawford, the middle portion of the Harrison-Monroe Creek Formation is 285 to more than 360 feet thick,

and the lower portion ranges in thickness from 185 to 220 feet (Witzel 1974; McFadden and Hunt, Jr. 1998).

Grey concretions composed of long, irregular, fine grained cylindrical masses are found in the middle and lower portions of the Harrison-Monroe Creek Formation (Lugn 1939; Witzel 1974; Collings and Knode 1984). According to Schultz (1941) and Svoboda (1950), the concretions were formed when groundwater enriched with calcium carbonate flowed through deposited sediments and calcite was precipitated "...in a situation similar to stalactite formation only in a horizontal direction" (Svoboda 1950). Schultz (1941) mapped the orientations of the concretions and found that, within northwest Nebraska, the trend orientation was to the southeast and away from uplift. This finding agrees with groundwater flow at the time of formation (Witzel 1974).

Gering Formation

The Gering Formation is mainly composed of gray, grayish-brown volcaniclastic fine to medium grained sandstones; silty sandstones; silt and local beds of ash; coarse sand; and fine gravel. Most of the sand is laminated and contains local cross beds. Beds of greenish-white bentonitic diatomaceous earth, which weathers into hard white layers, are found throughout most of the Gering. Wellman (1964) divided the Gering into upper and lower units. The two portions of the Gering Formation are separated by a volcanic ash which is up to 6 feet thick. At some localities outside of the MEA, the Gering Formation is up to 200 feet thick. Towards Chadron, the Formation thins to about 70 feet (Cady and Scherer 1946; Witzel 1974; Collings and Knode 1984; McFadden and Hunt, Jr. 1998).

The upper portion of the Gering is finer grained than the lower portion. It is composed of sandy siltstones and silty fine grained sandstones which were deposited by floodplains. There are some clay pebble conglomerates and clay lenses. It is distinguished from the overlying Harrison-Monroe Creek Formation by having pipy concretions which are less elongated in form (Witzel 1974).

The lower portion of the Gering contains coarse to fine grained sandstone, silty fine grained sandstone, sandy siltstone, and silty claystone. Channel deposits formed the coarse to fine grained sandstones. Distal and proximal floodplains formed the sandy siltstone and silty claystone, respectively. The unconformable contact between the Brule and Gering Formations is readily observed when coarse sediments of the Gering Formation are in contact with the finer grained Brule Formation. When the sediments of the Gering are fine grained, the contact is more difficult to discern (Witzel 1974; Collings and Knode 1984; McFadden and Hunt Jr., 1998). The contact can also be determined by a change in slope or color. The Gering Formation is white in color and forms steeper slopes than the underlying Whitney Member of the Brule Formation (Witzel 1974).

White River Group (Eocene-Oligocene)

The White River Group consists of the Chamberlain Pass Formation overlain by the Chadron Formation, which is, in turn, overlain by the Brule Formation (**Table 2.6-2**). Strata assigned to this group were deposited within fluvial, lacustrine, and eolian environments (Terry and LaGarry 1998). In northwest Nebraska, it rests unconformably on weathered Pierre Shale. The bulk of the White River Group consists of air fall and reworked volcaniclastics derived from sources in Nevada and Utah (Larson and Evanoff 1998; Terry and LaGarry 1998).

There have been various interpretations of the history of stratigraphic nomenclature for the White River Group of Nebraska and South Dakota as described by Harksen and Macdonald (1969). The following stratigraphic nomenclature retains the formal and informal members based on nomenclature by Schultz and Stout (1955), but also includes more recent nomenclature (Terry and LaGarry 1998; Terry 1998; LaGarry 1998; Hoganson et al. 1998).

Brule Formation

The Oligocene Brule Formation represents the youngest unit within the White River Group, which outcrops throughout most of the Crow Butte area. The unit conformably overlies the Chadron Formation and is unconformably overlain by sandstones of the Arikaree Group (**Figure 2.6-1**). The Brule Formation was originally subdivided by Swinehart, et al. (1985) and later revised by LaGarry (1998) into three members, from youngest to oldest: the "brown siltstone" member, the Whitney Member, and underlying Orella Member (**Table 2.6-2**). The "brown siltstone" member consists of pale brown and brown, nodular, cross bedded eolian volcaniclastic siltstones and sandy siltstones.

The contact with the underlying Whitney Member varies from a gradational contact to a sharp disconformity where the "brown siltstone" fills valleys incised into the older strata of the Whitney Member. The Whitney Member consists mostly of pale brown, massive, typically nodular eolian siltstones with rare thin interbeds of brown and bluish-green sandstone, and volcanic ash. The basal 10 meters of the Whitney Member consist of white or green laminated fluvial siltstones, sheet sandstones, and channel sandstones. The contact between the Whitney Member and the underlying Orella Member is intertonguing. The Orella Member consists of pale brown, brown, and brownish-orange volcaniclastic overbank clayey siltstones and silty claystones, brown and bluish-green overbank sheet sandstones, and thin volcanic ashes. Rare thick, fine to medium grained, channelized sandstones appear throughout the Orella Member. These sandstones appear to have very limited lateral extent. The overall thickness of the Brule Formation within the MEA is generally less than 400 feet and ranges from approximately 50 to 350 feet.

An isopach map of the undifferentiated Brule Formation is shown on **Figure 2.6-6**. The thickness ranges from approximately 50 to 350 feet and averages about 170 feet. The unit steadily increases in thickness from the southeast to the northwest end of the project, and the unit is stratigraphically continuous.

The contact between the Brule Formation and underlying Chadron Formation is difficult to identify in some places, as the contact between the two formations is intertonguing (LaGarry 1998). Regionally, the contact is recognized as the lithologic change from thinly interbedded and less pedogenically modified brown, orange, and tan volcaniclastic clayey siltstones and sheet sandstones of the Orella Member to pedogenically modified green, red, and pink volcaniclastic silty claystones of Big Cottonwood Creek Member in the upper Chadron Formation (Terry and LaGarry 1998). The Brule Formation is characterized by rapidly fluctuating geophysical log curves, or "log chatter" (**Figure 2.6-4**). This response is recognized in resistivity curves, and to a lesser extent in SP curves, throughout the MEA. Such fluctuations result from resistivity contrasts between the thinly interbedded siltstones and sandstones of the Orella Member. Because the sandstones are porous and constitute a part of the regional aquifer, the contacts with the interbedded, dry siltstones are sharp and easily recognized on logs (Gutentag et al. 1984). Lateral correlation of beds within the Brule Formation is very difficult due to generally thin bed thicknesses and limited lateral extent.

The contact between the interbedded siltstones and sandstone of the Brule Formation and the silty claystones of the upper Chadron Formation is distinguished by a dropoff of "log chatter' and establishment of relatively flat or straight curves (i.e., the shale baseline) on both resistivity and SP logs (**Figure 2.6-4**). Because of the intertonguing nature of the lower Brule and upper Chadron Formations, thin, isolated sandstones and siltstones may be present in the upper Chadron, making it appear that the formation contact is deeper in some wells. **Figures 2.6-3a** through **2.6-3n** depict the subsurface geology of the Brule Formation within the MEA.

Chadron Formation

The Eocene-Oligocene Chadron Formation is in the lower part of the White River Group (**Table 2.6-2**). The Chadron Formation conformably overlies the basal sandstone and is conformably overlain by the Brule Formation. From top to bottom, the Chadron Formation historically consists of the following stratigraphic units: Big Cottonwood Creek Member (herein referred to as the informal upper Chadron and upper/middle Chadron to be consistent with historical permitting), Peanut Peak Member (herein referred to as the informal middle Chadron to also be consistent with historical permitting), and basal sandstone of the Chadron Formation (also known formally as the Chamberlain Pass Formation). The basal sandstone of the Chadron Formation represents the production zone and target of ISR mining within the MEA. **Figures 2.6-3a** through **2.6-3n** depict the subsurface geology of the Chadron Formation within the MEA.

Upper Chadron Formation

The upper Chadron Formation and upper/middle Chadron Formation are composed primarily of volcaniclastic overbank silty claystones interbedded with tabular and lenticular channel sandstones, lacustrine limestones, pedogenic calcretes, marls, volcanic ashes, and gypsum (Terry and LaGarry 1998). Tuffs in the Toadstool Park area that occur in the upper Chadron were dated by $^{40}Ar/^{39}Ar$ methods as late Eocene (~34,000,000 years ago) in age (Terry and LaGarry 1998). The lower boundary of this member is an intertonguing contact with the underlying middle Chadron, or is a local unconformity where the upper/middle Chadron fills valleys and depressions (Terry and LaGarry 1998; **Table 2.6-2**). The upper boundary is recognized by a lithologic change from pedogenically modified green, red, and pink volcaniclastic silty claystones of the upper Chadron to thinly interbedded and less pedogenically modified brown, orange, and tan volcaniclastic clayey siltstones and sheet sandstones of the Orella Member of the Brule Formation (Terry and LaGarry 1998; **Table 2.6-2**).

The upper Chadron is the youngest member of the Chadron Formation (**Table 2.6-2**). The upper part of the upper Chadron is light green-gray bentonitic clay grading downward to green and frequently red clay, though interbedded sandstones also occur. An isopach map of the upper Chadron is shown on **Figure 2.6-7**. The available data suggest that the upper Chadron ranges in stratigraphic thickness from approximately 410 to 650 feet and averages about 507 feet across the MEA (**Figure 2.6-3a** through **2.6-3n**). Two core samples (M-1454c, Run 1 and M-1624c, Run 1) were collected from the upper Chadron by CBR at boreholes M-1454c and M1624c, sections 1 and 12, T29N, R51W of the MEA (**Figure 2.6-2**). X-ray diffraction (XRD) analyses of M-1454c Run 1 and M-1624 Run 1 samples indicate varied compositions. M-1454c Run 1 was primarily composed of calcite, montmorillonite, and quartz. Minor amounts of plagioclase, potassium feldspar, and illite/mica were recorded. M-1624c was primarily composed of mixed layered illite/smectite, calcite, and quartz. Minor amounts of plagioclase, potassium feldspar, magnetite, and illite/mica were recorded. Particle size distribution analyses of M-1454c Run 1 and M-1624c

Run 1 give median grain sizes of 0.056 mm (silt) and 0.049 mm (silt), respectively. Both samples are dominated by silt-sized grains; however, M-1454c Run 1 contained more medium sand than M-1624c, which increased the median grain size. M-1454c Run 1 contained 47.25 percent silt and 9.64 percent clay. M-1624c Run 1 contained 54.65 percent silt and 8.73 percent clay. As M-1454c Run 1 and M-1624c Run 1 both contain more than 50 percent combined silt and clay-sized particles, and because more than 67 percent of the silt+clay component is silt, they are classified as siltstones (Brown and Harrell 1991).

Typical gamma ray (GR), SP, and resistivity log signatures for the upper Chadron exhibit curves representative of the relatively flat shale baseline (**Figure 2.6-4**). Fluctuations are present among upper Chadron log curves, representing interbedded siltstones, sandstones, limestones, and volcanic ash deposits that occur less commonly than in the overlying Brule Formation. Logging tools/procedures and other tests are described in Section 3.1.2.4.

Upper/Middle Chadron Formation

The upper/middle Chadron is directly overlain by the upper Chadron (**Table 2.6-2**). At some locations, the upper/middle Chadron is similar in appearance to the channel sandstone facies of the upper portion of the basal sandstone of the Chadron Formation (described later in this section) and is typically very fine to fine grained, well-sorted, poorly cemented sandstone. However, within the MEA license boundary, the water-bearing sandstones of the upper/middle Chadron Formation that are recognized in other locations such as NTEA are not present within the MEA. Geophysical logs (discussed below) and core samples indicate the presence of a finer grained facies than is present at NTEA. Therefore, because the sandstones of the upper/middle Chadron are absent, the upper Chadron and middle Chadron Formation comprise a thick continuous mudstone and siltstone sequence within the MEA. **Figures 2.6-3a** through **Figure 2.6-3n** show an inferred stratigraphic position for the upper/middle Chadron at the contact between the upper Chadron and middle Chadron units across the license area.

Review of geophysical logs from within the license boundary indicates that the upper/middle Chadron has poor reservoir characteristics and minimal water saturation. When compared to aquifers of the Brule Formation and basal sandstone of the Chadron Formation (discussed below), inflections in resistivity, neutron, and SP curves are almost wholly unseen within the upper/middle Chadron (**Figures 2.6-3a** through **2.6-3n** and **2.6-4**). At TCEA, the upper/middle Chadron was recognized and correlated primarily on the basis of decreased neutron counts (indicating increased porosity), increased resistivity (indicating the possible presence of relatively fresh water), and other log signature combinations. Correlation of the upper/middle Chadron at MEA using GR log signatures is problematic due to the presence of bentonitic deposits throughout the upper and middle Chadron Formation. Occasional, very minor increases in resistivity are present at the stratigraphic level likely to represent the upper/middle Chadron, but are not consistent across the MEA. These comparatively muted log signatures indicate that water may be intermittently present within the upper/middle Chadron. However, water saturations are not significant enough to create strong log responses as recognized in other known aquifers within the MEA. Therefore, a continuous sandstone aquifer within the upper/middle Chadron is interpreted to be absent within the MEA.

Middle Chadron Formation

The middle Chadron is a clay-rich interval that grades from brick red to grey in color with interbedded bentonitic clay and sands. A light green-gray "sticky" clay within this unit serves as

an excellent marker bed in drill cuttings and has been observed in virtually all regional test holes both within the MEA, TCEA, NTEA, and the CPF. The middle Chadron unconformably overlies the basal sandstone of the Chadron Formation (Chamberlain Pass Formation) in South Dakota and Nebraska (Terry 1998; **Table 2.6-2**). As described above, the upper boundary is variable and is overlain either by the upper/middle Chadron, where present, or by the upper Chadron (**Table 2.6-2**). The middle Chadron differs from the overlying upper/middle and upper Chadron in that the middle Chadron is composed of bluish-green, smectite-rich mudstone and claystone; weathers into hummocky, "haystack-shaped" hills and slopes with a popcorn-like surface; is less variegated in color; and contains less silt (Terry 1998). The predominantly clay lithology of the middle Chadron represents a distinct and rapid facies change from the underlying basal sandstone of the Chadron Formation. An isopach map of the middle Chadron is shown on **Figure 2.6-8**. The available data suggest that the middle Chadron typically ranges in thickness from approximately 20 to 290 feet and averages about 180 feet across the MEA.

Two core samples (M-1454c, Run 2 and M-1624c, Run 2) were collected from the middle Chadron by CBR at boreholes M-1454c and M1624c, sections 1 and 12, T29N, R51W of the MEA (**Figure 2.6-2**). XRD analyses of M-1454c Run 2 and M-1624 Run 2 samples indicate varied compositions. Samples M-1454c Run 2 and M-1624c Run 2 are primarily composed of mixed layered illite/smectite; however, M-1454c Run 2 also contains a high amount of calcite. Other minor minerals found within the samples include quartz, plagioclase, potassium feldspar, chlorite, and illite/mica. Particle size distribution analyses of M-1454c Run 2 and M-1624c Run 2 give median grain sizes of 0.027 mm (silt) and 0.065 (very fine sand) mm, respectively. Both were mainly composed of silt-sized particles; however, M-1624c Run 2 contained more medium sand than M-1454c Run 2, which increased the median grain size. M-1454c Run 2 contained 46.36 percent silt and 20.65 percent clay. M1624c Run 2 contained 34.6 percent silt and 16.54 percent clay. Both are classified as siltstones (Brown and Harrell 1991).

Typical GR, SP, and resistivity log signatures for the middle Chadron exhibit curves representative of the shale baseline (**Figure 2.6-4**). The contact between the top of the middle Chadron and the overlying upper Chadron is difficult to ascertain due to similarities in grain size. At MEA, due to like lithology and geophysical log responses between the upper/middle and middle Chadron Formation, it is difficult to define the contact between these units. Therefore, **Figures 2.6-3a** through **Figure 2.6-3n** show an inferred stratigraphic location for the upper/middle Chadron and middle Chadron contact across the license area.

The upper and middle Chadron units represent the upper confining zone for the basal sandstone of the Chadron Formation within the MEA (see detailed discussion in Section 2.7.2.3). Isopach maps created for the formations that comprise the upper confining zone are presented as **Figures 2.6-7** (upper Chadron) and **2.6-8** (middle Chadron). Because the upper/middle Chadron is not recognizable on geophysical logs or in cores, its thickness is considered to be zero across the MEA and it is not included as part of either upper confining zone isopach map. The total thickness of the upper confining zone ranges from approximately 430 to 940 feet, averages about 690 feet, and generally appears to thicken toward the south and southwest across the MEA.

<u>Basal Sandstone of the Chadron Formation – Mining Unit</u>

The basal sandstone of the Chadron Formation is the oldest unit in the White River Group. The lower part is a coarse grained, arkosic sandstone with common, discontinuous interbedded thin silt and clay lenses of varying thickness. The basal sandstone of the Chadron Formation overlies

a distinct regional unconformity with the underlying Yellow Mounds Paleosol (Terry 1998). The lower contact is easily recognized as a change from the underlying black or bright yellow, pedogenically modified surface of the Pierre Shale (i.e., the Yellow Mounds Paleosol) to white channel sandstone. In places, the basal sandstone of the Chadron Formation grades upward to fine sandstone containing varying amounts of interstitial clay and persistent clay interbeds. Vertebrate fossils from the basal sandstone of the Chadron Formation in northwestern Nebraska and South Dakota indicate a late Eocene age (Chadronian; Clark et al. 1967; LaGarry et al. 1996; Lillegraven 1970; Vondra 1958). The Upper Interior Paleosol, occurring as a persistent clay horizon, typically brick red in color, developed on top of the basal sandstone of the Chadron Formation and generally marks the upper limit of the basal sandstone of the Chadron Formation (**Table 2.6-2**). The Upper Interior Paleosol represents pedogenically modified distal overbank deposits of a distinct fluvial system developed on the surface of the basal sandstone of the Chadron Formation which predates deposition of the Chadron Formation.

The basal sandstone of the Chadron Formation occurs at depths ranging from about 817 to 1,130 feet bgs and was encountered in all exploration holes. An isopach map of the basal sandstone of the Chadron Formation across the MEA is presented on **Figure 2.6-9**. Stratigraphic thickness of the unit within the MEA ranges from approximately 20 to 110 feet and averages about 55 feet. The thickest sections of the unit occur in the western portions of the MEA (**Figure 2.6-9**). Up to four distinct sandstone packages are present in the thickest portions of this unit and are separated by variable amounts of interbedded clay. A structure contour map was generated of the contact of the basal sandstone of the Chadron Formation and the Pierre Shale (**Figure 2.6-10**). The structure map indicates that the base of the Chadron Formation dips slightly to the north-northwest across the MEA and ranges in elevation from 3,101 to 3,252 feet amsl (**Figure 2.6-10**).

The greenish-white channel sandstones of the basal sandstone of the Chadron Formation that overlie the Yellow Mounds Paleosol are the target of ISR mining activities in the MEA. Regionally, deposition of the basal sandstone of the Chadron Formation has been attributed to large, high-energy braided streams (Collings and Knode 1984; Hansley et al. 1989; Hansley and Dickenson 1990). This depositional environment produced lenticular sandstone deposits with numerous facies changes occurring within short distances. Interbedded thin silt and clay lenses most likely represent flood plain or low velocity deposits normally associated with fluvial sedimentation.

Core samples (M-1454C, Runs 3 and 4, and M-1624C, Runs 3 and 4) were collected from the basal sandstone of the Chadron Formation by CBR at boreholes M-1454c and M-1624c in sections 1 and 7, T29N, R51W (**Figure 2.6-2**). XRD analysis of the M1454c sample indicates a varied composition. Run 3 is mainly composed of quartz, whereas Run 4 is mainly composed of mixed-layered smectitie. Minor amounts of plagioclase feldspar, potassium feldspar, kaolinite, and illite/mica were found in both samples. Run 3 also had trace amounts of calcite, siderite, pyrite, magnetite, and magnesium vanadium oxide, while run 4 had minor amounts of dolomite and chlorite. Particle size distribution analyses of M-1454c Run 3 and M-1624c Run 4 give median grain sizes of 0.075 mm (very fine sand) and 0.711 (coarse sand) mm, respectively. M-1454c Run 3 contained 29.85 percent silt and 19.92 percent clay. M1624c Run 4 contained 11.56 percent silt and 4.5 percent clay. Both are classified as sandstones (Brown and Harrell 1991).

The sandstones of the basal sandstone of the Chadron Formation within the CPF are dominated by quartz (50 percent monocrystalline) and feldspar (30 to 40 percent undifferentiated feldspar)

with the remainder made up of chert, pyrite, various heavy metals, and polycrystalline and chalcedonic quartz (Collings and Knode 1984). XRD analyses indicate that the basal sandstone of the Chadron Formation within the area of the CPF is 75 percent quartz, with the remaining 25 percent consisting of a combination of potassium feldspar, plagioclase, illite, smectite, expandable mixed layer illite-smectite, and kaolinite (Collings and Knode 1984).

Geophysical logs record a unique signature for the basal sandstone of the Chadron Formation (**Figure 2.6-4**). A distinct GR spike is present at the base of the unit in most of the MEA exploration boreholes, indicating an abundance of radioactive material. Increased resistivity (i.e., log curve shift to the right), decreased N-N count (i.e., log curve shift to the left), and decreased SP (i.e., log curve shift to the left) are typically associated with GR spikes. These log signatures support interpretations of a uranium-bearing, fluid-filled sandstone interval. Overlying channel sandstone intervals that are present in the middle and upper portions of the unit typically have lower GR readings, indicative of both lower amounts of radioactive materials and potentially non-uranium-bearing intervals. Such intervals are typically marked by increased resistivity (i.e., higher porosity and fluid-filled) and lower N-N counts and, in contrast to the uranium-bearing units, typically have positive SP curve deviations. This log response indicates that, within the higher uranium-bearing units, mud filtrate resistivity is higher than formation water resistivity, which may be the result of the presence of higher salinity waters in uranium-bearing units. Pervasive interbedded clay intervals are indicated by high GR responses accompanied by lower resistivity (i.e., reduced porosity and decrease in water content), an interpretation that is further supported by driller or geologist's notes. The high radioactivity of these clay-rich units suggests the presence of rhyolitic ash (Hansley and Dickenson 1990). The top of the formation is marked by a gradual return of SP and resistivity curves to the shale baseline.

Montana Group

Interior Paleosol (Yellow Mounds Paleosol)

The Interior Paleosol of Schultz and Stout (1955) was subsequently divided into the younger Eocene Upper Interior Paleosol and the older Cretaceous Yellow Mounds Paleosol (Pierre Shale) (Terry 1991; Evans and Terry 1994; Terry and Evans 1994; Terry 1998) (**Table 2.6-2**). As noted above, the Upper Interior Paleosol represents pedogenically modified distal overbank deposits of a distinct fluvial system developed on the surface of the basal sandstone of the Chadron Formation which predates deposition of the Chadron Formation. The Yellow Mounds Paleosol developed on the Cretaceous Pierre Shale and altered the normally black marine shale to bright yellow, purple, light bluish-grey, and orange.

Review of available data for the MEA indicates that neither of the two paleosol units could be consistently interpreted based solely on geophysical logs. For simplicity, these units are not represented on the type log or cross-sections.

Pierre Shale

Offshore deposition in the Cretaceous Interior Seaway produced the late Cretaceous Pierre Shale (**Table 2.6-2**). The Pierre Shale is a thick, homogenous black marine shale with low permeability that represents one of the most laterally extensive formations of northwest Nebraska. Regional geologic data indicate that this formation can be up to 1,500 feet thick in the Dawes County area (Wyoming Fuel Company 1983; Petrotek 2004). The southward retreat of the Cretaceous Interior Seaway resulted in the subaerial exposure and weathering of rock units from Early Cretaceous to

Eocene age across the northern Great Plains (Lisenbee 1988). This event resulted in the erosion and pedogenic modification of the surface of the Pierre Shale and formation of the brightly colored Yellow Mounds Paleosol (Terry and LaGarry 1998) (**Table 2.6-2**). Consequently, the pedogenically modified surface of the Pierre Shale marks a major unconformity with the overlying White River Group and exhibits a paleotopography with considerable relief (DeGraw 1969). The Pierre Shale is underlain by organic-rich shale and marl with minor amounts of sandstone, siltstone, limestone, and chalk of the Niobrara Formation (**Table 2.6-1**).

Core samples (M-1454C, Run 4, and M-1624C, Run 5) were collected from the Pierre Shale by CBR at boreholes M-1454c and M-1624c in sections 1 and 7, T29N, R51W (**Figure 2.6-2**). XRD analysis of the samples indicated a primary composition of mixed layered illite/smectite and quartz, with minor amounts of plagioclase, potassium feldspar, dolomite, pyrite, kaolinite, chlorite, and illite/mica. Particle size distribution analyses of M-1454c Run 4 and M-1624c Run 5 give median grain sizes of 0.007 mm (silt) and 0.005 mm (silt), respectively. M-1454c Run 3 contained 60.15 percent silt and 39.4 percent clay. M1624c Run 4 contained 50.88 percent silt and 47.85 percent clay. Both are classified as claystones (Brown and Harrell 1991).

Typical geophysical log responses for the Pierre Shale exhibit shale baseline curves that are relatively flat or straight (**Figure 2.6-4**; **Appendix C**). On resistance logs, the top of the Pierre Shale is noted where the curves break either sharply to the left or to the right and represent the occurrence of the basal sandstone of the Chadron Formation. Spontaneous potential and resistivity curves qualitatively indicate a lack of permeable water-bearing zones within the Pierre Shale.

Six deep oil and gas exploration wells were drilled in the vicinity of the MEA (Chicoine 1, Chiocoine 1A, Hollibaugh No. 1, Porter, Roscoe Royal #1, and #1-A Smith) (**Appendix C**). Oil and gas exploration wells have typically been drilled to depths much greater than on-lease uranium exploration wells. The character of the entire Pierre Shale in the vicinity of the MEA can best be observed in geophysical logs from three of the six nearby abandoned oil and gas wells (Hollibaugh No. 1, Roscoe Royal #1, and #1-A Smith), and the CBR DDW (CBR UIC #1), which were completed through the entire thickness of the unit. Based on observations from logging, the thickness of the Pierre Shale in the vicinity of the MEA ranges from approximately 750 to more than 1,000 feet. The top of the Pierre Shale was encountered in all wells at depths ranging from approximately 600 to 1,300 feet bgs. The Hollibaugh No. 1 well is located within the license boundary (T29N, R51W, section 12) and has a total depth of 3,283 feet bgs. The Pierre Shale was encountered at 1,025 to 1,915 feet bgs. The Roscoe Royal #1 is located about 0.5 mile (0.8 km) north of the license boundary (T30N, R51W, section 23) and has a total depth of 3,956 feet bgs. The Pierre Shale was encountered at 1,200 to 2,287 feet bgs. The #1-A Smith well is located about 0.25 mile (0.4 km) east of the license boundary (T29N, R50W, section 29) and has a total depth of 2,902 feet bgs. The Pierre Shale was encountered at 947 to 1,716 feet bgs. DDW CBR UIC #1 (T31N, R52W, section 19) is located approximately 10.7 miles (17.2 km) southeast of the MEA license boundary and has a total depth of 3,910 feet bgs. At UIC #1, the Pierre Shale was encountered from 925 to 1,560 feet bgs, where the base of the Pierre Shale is indicated by an increase in resistivity at the contact with the underlying Niobrara Formation (**Appendix C**). Plugging records for these wells are shown in **Appendix D-1.**

Stratigraphy of Units Below the Pierre Shale

Underlying the Pierre Shale is a thick sequence of Mississippian through Cretaceous age strata that unconformably overlie Precambrian granite (**Table 2.6-1**). Together with the Pierre Shale, the underlying Niobrara Formation, Carlile Shale, Greenhorn Limestone, and Graneros Shale compose a composite lower confining interval approximately 2,500 feet thick which immediately underlies the basal sandstone of the Chadron Formation. With exception of the hydrocarbon-bearing "D", "G", and "J" sands of the Dakota Group (occasionally interbedded with the Graneros and Huntsman Shales; **Table 2.6-1**), there do not appear to be significant sandstone units within this thick sequence of low-permeability strata.

All geologic units encountered during the drilling of oil and gas exploration wells in the vicinity of the MEA appear to be consistent with known regional stratigraphy. Geologic units that are consistently identified in all wells include the Niobrara Formation, Carlile Shale, Greenhorn Limestone, "D" and "J" sands of the Dakota Group, and the Skull Creek Formation (**Table 2.6-1**).

2.6.1.2 Geochemical Description of the Mineralized Zone

The depth to the ore body within the basal sandstone of the Chadron Formation in the MEA ranges from approximately 800 to 1,250 feet bgs (**Table 2.6-2**). The ore grade as U_3O_8 ranges from 0.11 to 0.33 percent with an average ore grade of 0.17 percent.

Hansley et al. (1989) conducted detailed geochemical analysis of the Crow Butte uranium ore to assess both ore genesis and composition. The Crow Butte deposits, including Marsland, are roll-type deposits with coffinite being the predominant uranium mineral species present. The origin of the uranium is rhyolitic ash, which is abundant within the matrix of the basal sandstone of the Chadron Formation (Hansley et al. 1989). Coffinite is associated with pyrite, and high silica activity due to dissolution of the rhyolitic ash which favored formation of coffinite over uraninite in most parts of this sandstone. In addition, smectite is present in the samples examined, with the most common minerals in the sandstone being quartz, plagioclase, K-feldspar, coffinite, pyrite, marcasite, calcite, illite/smectite, and tyuyamunite. The heavy mineral portion of the samples contained several minerals including those above as well as garnet, magnetite, marcasite, and illmenite. Vanadium was detected in the samples primarily as an amorphous species presumed to have originated from the *in-situ* ash. Hansley et al. state that at least some uranium and vanadium remain bound to amorphous volcanic material and/or smectite rather than as discrete mineral phases.

Petrographic data obtained and examined by Hansley et al. (1989) suggest that uranium mineralization occurred before lithification of the basal sandstone of the Chadron formation. Hansley states: *"Dissolution of abundant rhyolitic volcanic ash produced uranium (U) and silicon (Si) rich ground waters that were channeled through permeable sandstone at the base of the Chadron by relatively impermeable overlying and underlying beds. The precipitation of early authigenic pyrite created a reducing environment favorable for precipitation and accumulation of U in the basal sandstone. The U has remained in a reduced state, as evidenced by the fact that the unoxidized minerals, coffinite and uraninite, comprise the bulk of the ore."*

Based on similar regional deposition, the MEA ore body is expected to be similar mineralogically and geochemically to that of the ore body at the CPF. The ore bodies in the two areas are within

the same geologic unit (the basal sandstone of the Chadron Formation) and have the same mineralization source. The sites are separated by only a few miles, and the cause of mineral deposition in the two areas appears to be similar. Neither site is anticipated to be significantly affected by recharge or other processes.

2.6.1.3 Structural Geology

Regional uplift during the Laramide Orogeny forced the southward retreat of the Cretaceous Interior Seaway, resulting in the subaerial exposure and weathering of rock units from Early Cretaceous to Eocene age across the northern Great Plains (including the Pierre Shale). The depositional basin associated with deformation of the Wyoming thrust belt and initial Laramide uplifts to the west of Nebraska, represented a structural foredeep. The greatest uplift occurred in the Black Hills, which lie north of Sioux and Dawes Counties in southwestern South Dakota. Lisenbee (1988) provides a comprehensive summary of the tectonic history of the Black Hills uplift. The pre-Oligocene Black Hills uplift (<37 Ma) occurred prior to the deposition of the Eocene-Oligocene strata of the White River Group. Strata of the White River Group cover most of the eroded roots of the Black Hills uplift as well as the syntectonic sedimentary rocks in the Powder River and Williston basins. The Hartville, Laramie, and Black Hills uplifts supplied sediment for rivers that flowed east-southeast across the study area (Clark 1975; Stanley and Benson 1979; Swinehart et al. 1985).

The most prominent structural expression in northwest Nebraska is the Chadron Arch (**Figures 2.6-11** and **2.6-12**). Together with the Chadron Arch, the Black Hills Uplift produced many of the prominent structural features presently observed in the region. The Chadron Arch is an anticlinal feature that strikes roughly northwest-southeast along the northeastern boundary of Dawes County. Swinehart et al. (1985) suggested multiple phases of probable uplift in northwestern Nebraska near the Chadron Arch between about 28 Ma and <5 Ma. The only known surficial expressions of the Chadron Arch are outcroppings of Cretaceous rocks that predate deposition of the Pierre Shale in the northeastern corner of Dawes County, as well as in small portions of Sheridan County, Nebraska and Shannon County, South Dakota. The general locations of faults in northwest Nebraska are depicted on the State Geologic Map shown on **Figure 2.6-1**.

The 230-mile (370-km) long Pine Ridge escarpment exhibits an average of 1,200 feet of relief (Nixon 1995). The Pine Ridge is an arc roughly concentric to the Black Hills Dome, which suggests an apparent structural relationship. Nixon (1995) interpreted the escarpment as representing the southern outermost cuesta of the Black Hills Dome. The escarpment is capped by sandstone of the Arikaree Group with exposed deposits of the White River Group mapped along the topographically lower, northern side of the escarpment.

The Crow Butte area, including the CPF, NTEA, and TCEA, is within the Crawford Basin (DeGraw 1969). The proposed MEA lies just outside of the southern boundary of the basin along the Cochran Arch. DeGraw (1969) substantiated known structural features and proposed several previously unrecognized structures in western Nebraska based on detailed studies of primarily deep, oil test hole data collected from pre-Tertiary subsurface geology. The Crawford Basin was defined by DeGraw (1969) as a triangular asymmetrical basin about 50 miles (80 km) long in an east-west direction and 25 miles (40.2 km) to 30 miles (48.3 km) wide. The basin is bounded by the Toadstool Park Fault on the northwest, the Chadron Arch and Bordeaux Fault to the east, and the Cochran Arch and Pine Ridge Fault to the south (**Figures 2.6-11** and **2.6-12**). The Crawford

Basin is structurally folded into a westward-plunging syncline that trends roughly east-west. Note that the Bordeaux Fault, Pine Ridge Fault, and Toadstool Park Fault proposed by DeGraw (1969) are not presented on the State Geologic Map (**Figure 2.6-1**). The Toadstool Park Fault has been mapped at one location (T33N, R53W) and is estimated to have had approximately 60 feet of displacement (Singler and Picard 1980). The City of Crawford is located near the axis of the Crawford Basin. More recent fault interpretations by Hunt (1990) for northwest Nebraska are also shown on **Figure 2.6-12**, which include the Whetstone Fault, Eagle Crag Fault, Niobrara Canyon Fault, and Ranch 33 Fault in the vicinity of the Town of Harrison in Sioux County. The faults identified by Hunt (1990) all trend to the northeast-southwest, sub-parallel to the Pine Ridge Fault (**Figure 2.6-12**).

Diffendal (1994) performed lineament analyses on a mosaic of early Miocene synthetic-aperture radar images and largely confirmed known faults in the vicinity of Chadron. Lineaments in the radar image along Pine Ridge, located to the south of Chadron, are attributed to jointing or faulting and trend N40E and N50W (Diffendal 1982). Similar features were also noted west of Fort Robinson. Swinehart et al. (1985) report that these features are likely an extension of the Wheatland-Whalen trend in Wyoming (Hunt 1981; Wheeler and Crone 2001).

Former drilling activities at the Crow Butte Project identified a structural feature, referred to as the White River Fault, located between the CPF Class III permit area and the NTEA (**Figure 2.6-12**). Evidence of a fault was identified during the exploration drilling phase of the Crow Butte Project (Collings and Knode 1984). The fault is manifested in the vicinity of the NTEA as a significant northeast-trending subsurface fold. The detailed kinematics of the White River Fault were investigated during preparation of the NTEA Petition for Aquifer Exemption. An extensive review of drilling and logging data determined that, while the White River Fault may cut the Pierre Shale at depth along with stratigraphically lower units, there is no evidence that a fault offsets the geologic contact between the Pierre Shale and overlying White River Group or individual members of the White River Group. This fault does not appear to be present in the vicinity of the MEA.

2.6.1.4 Seismology

National Seismic Hazard Maps and Risks

The USGS updated the National Seismic Hazard Maps in 2008, which includes changes in the methodology used to model potential seismicity in any given region (Petersen et al. 2008). Wheeler and Crone (2001) described Quaternary fault zones and their potential seismic activity. Their findings were used to develop the prior National Seismic Hazard Map. The revised maps incorporate new seismic, geologic, and geodetic information on earthquake rates and associated ground shaking. The maps supersede versions released in 1996 and 2002. The next update to the National Seismic Hazard Maps is scheduled for 2014.

The National Hazard Maps show the distribution of earthquake shaking levels that have a certain probability of occurring in the U.S. (**Figure 2.6-13**). The hazard rating ranges from the lowest hazard (0.4 %g) to the highest (64+ %g), with the City of Crawford area and the majority of Nebraska being located in a low hazard ranking level of 4 to 8 %g. The term "%g" is a unit of acceleration (movement of earth) measured in terms of gravity (g) (i.e., acceleration due to gravity). Peak acceleration refers to the maximum acceleration (movement) experienced during a non-uniform earthquake event (i.e., starts off small, achieves a maximum, and then decreases).