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# Regional Geologic Evaluations for Disposal of HLW and SNF: The Pierre Shale of the Northern Great Plains

## Spent Fuel and Waste Disposition

*Prepared for*
*U.S. Department of Energy*
*Spent Fuel and Waste Technology*
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# ACRONYMS

| | |
|---|---|
| DOE | Department of Energy |
| EPRI | Electrical Power Research Institute. |
| g | gravity |
| GIS | Geographic Information System |
| HLW | High-Level Waste |
| LANL | Los Alamos National Laboratory |
| Ma | Mega-annum (units of millions of years before the present) |
| R&D | Research and Development |
| SFWT | Spent Fuel and Waste Technology |
| SMU | Southern Methodist University |
| SNF | Spent Nuclear Fuel |
| US | United States |
| USGS | United States Geological Survey |

# Regional Geologic Evaluations for Disposal of HLW and SNF: The Pierre Shale of the Northern Great Plains

## 1. Introduction

The DOE Spent Fuel and Waste Technology (SWFT) R&D Campaign is supporting research on crystalline rock, shale (argillite) and salt as potential host rocks for disposal of HLW and SNF in a mined geologic repository. The distribution of these three potential repository host rocks is limited to specific regions of the US and to different geologic and hydrologic environments (Perry et al., 2014), many of which may be technically suitable as a site for mined geologic disposal. This report documents a regional geologic evaluation of the Pierre Shale, as an example of evaluating a potentially suitable shale for siting a geologic HLW repository. This report follows a similar report competed in 2016 on a regional evaluation of crystalline rock that focused on the Superior Province of the north-central US (Perry et al., 2016).

This research was performed as part of the Defense Waste Repository (DWR) project. Based on revised DOE priorities in mid-2017, the development of a DWR has been discontinued; current work unique to the development of a DWR is being closed out and documentation will be completed by the end of fiscal year (FY) 2017. Implementation of any recommendations made in this report for further research regarding a DWR would require resumption of the DWR project at some future time.

Fine-grained, clay-rich sedimentary rocks have historically been of interest for disposal of HLW in several countries. The properties of these rocks include low permeability, self-sealing behavior (when clay content is high), a reducing chemical environment and high sorption capacity, all of which make shale a potentially suitable media for disposal of HLW (Hansen et al., 2010).

In this report, we present a regional geologic evaluation of the Pierre Shale, which has a large geographic extent in the northern Great Plains of the US. In fact, the Pierre Shale has the largest geographic extent of any shale formation in the U.S. (Figure 2-1). Because of its regional extent, thickness and stable tectonic setting, the Pierre Shale was studied by the USGS as a potential repository host rock beginning in the 1970s (Merewether et al., 1973; Shurr, 1977; Schultz et al., 1980; Gonzales and Johnson, 1985). This report has two main focuses. The first is to update the siting evaluations of Shurr (1977) and Gonzales and Johnson (1985) by documenting the application of siting guidelines using modern GIS tools and methods (e.g., Perry et al., 2014; Perry et al., 2016). The second is to provide an updated discussion of the natural barrier system and geologic environment of the Pierre using the most current information available from the scientific and technical literature. We do not address the potential challenges of repository construction and maintenance of repository openings in a low-strength shale. These issues are discussed in Nopola (2013) and Hardin (2014). Hardin et al. (2012) and Nopola (2013) address the thermal issues inherent in the design of a HLW repository in clay rock with low thermal conductivity.

While this report does not discuss every aspect of the Pierre Shale as it relates to HLW disposal, we believe it provides a useful resource that presents several aspects of the geologic and hydrologic environment of the Pierre Shale within the context of a single reference. All of the maps in this report (except Figure 4-1) were produced at LANL using GIS software (ArcGIS 10) and GIS data listed in Table 1-1, following methods developed by Perry et al. (2014).

### 1.1 Rock Terminology applied to the Pierre Shale

Crandell (1958) and Schultz et al. (1980) define *shale* as a fissile or laminated sedimentary rock containing predominantly clay- and silt-sized material that is sufficiently indurated to remain coherent after wetting, and *claystone* as indurated clay and silt that lacks fissility or lamination. Both shale and claystone typically have greater than 66% clay. S*iltstone* has a higher percentage of silt-sized particles and less clay (about half the proportion as found in shale and claystone, with greater amounts of quartz).

In this report, we use the terminology used in previous studies of the Pierre Shale to describe fine-grained, clay-bearing sedimentary rocks (Crandell, 1958; Tourtelot, 1962; Schultz et al., 1980; Gonzales and Johnson, 1985). The fine-grained rocks that make up the Pierre Shale are primarily claystone, shale and siltstone (in decreasing order of abundance). Sandstone and marl make up a smaller proportion of units within the Pierre Shale, with sandstones to the west in near-shore detrital environments and marls to the east in offshore depositional environments (Schultz et al., 1980). Although the Pierre Shale includes several rock types, we use the term "shale" in this report to describe the formation as a whole, both for purposes of simplicity and for consistency with previous usage.

# 2. Distribution, Age and Depth of Shale Formations in the US

Shale formations are common and widely distributed throughout the conterminous US (Figure 2-1). They are found in structural basins, basin margins and stable platform areas between basins (Gonzales and Johnson, 1985). Paleozoic shales occur widely in the eastern and southern interior of the US and commonly occur at depths of greater than 1000 meters in the center of basins (Figure 2-1). Paleozoic shales in the in Appalachian, Anadarko and Permian Basins occur at depths of 3000 meters or greater (Figure 2-1). Paleozoic shales are the most important source rock of oil and gas in the US.

Mesozoic shales occur widely throughout the middle and western interior of the US and in some basins overlie Paleozoic shales. In the Williston Basin, the Pierre Shale overlies the Paleozoic Bakken Formation and other Paleozoic shales that are source rocks for oil and gas (Figure 2-1).

Cenozoic shales are present in the Gulf Coast Basin where they lie above Mesozoic shales. Other notable Cenozoic shales are the Monterrey Formation in California and the Green River Formation of Wyoming, Utah and Colorado (Figure 2-1).

The Mesozoic (Upper Cretaceous) Pierre Shale, the subject of this report, lies relatively close to the surface (< 200 meters) over much of its extent. At its deepest, in the Denver, Williston and Powder River Basins, the Pierre shale lies at depths of between ~600 and 2200 meters. Other Cenozoic shales, such as the Mancos and Bear Paw (equivalent to the Pierre Shale) also lie at relatively shallow depths throughout much of their extent (Figure 2-1).The Pierre Shale in the Powder River Basin is not considered further in this report, primarily because much of it lies at a depth of greater than 1000 meters.

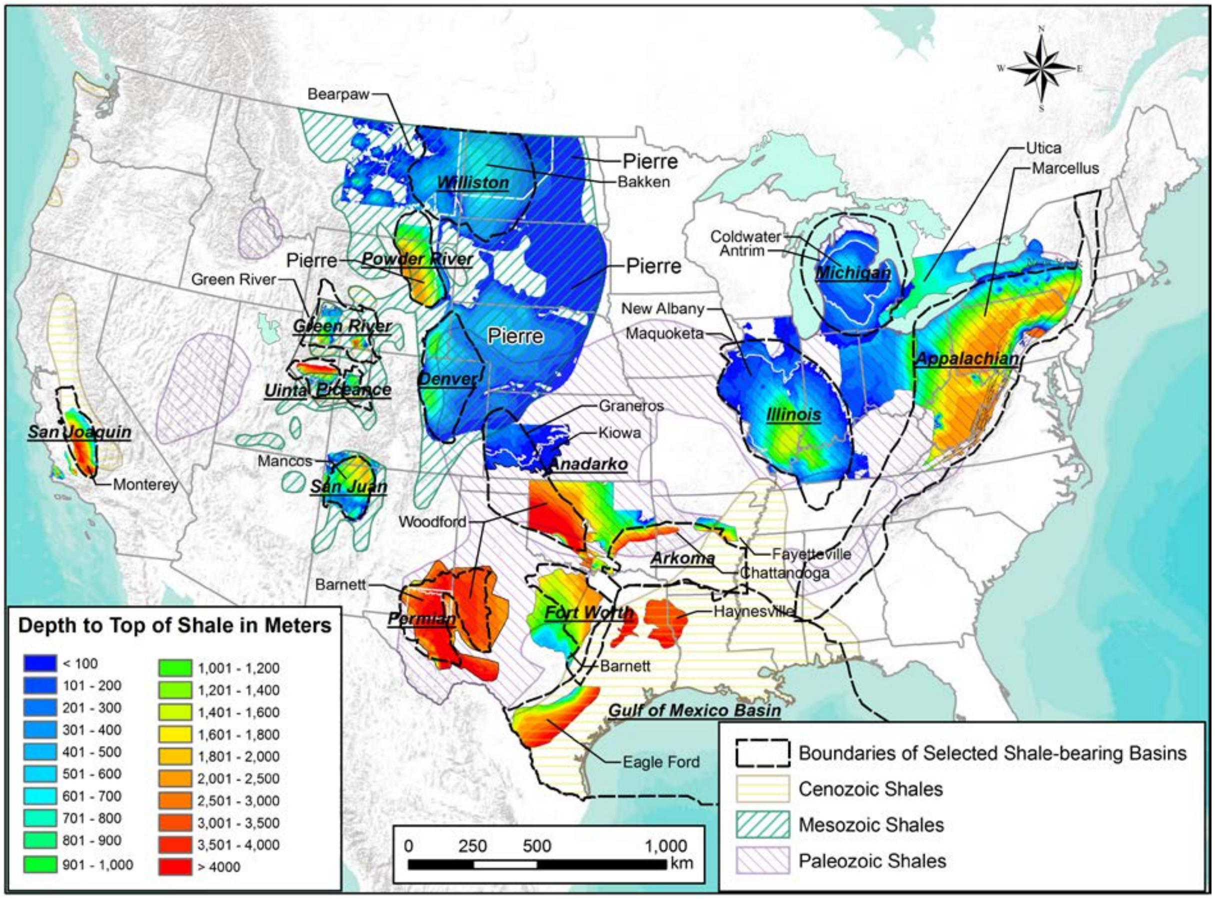


**Figure 2-1.** Distribution of shale formations in the conterminous US (modified from Perry et al., 2014).

# 3. Approach and Limitations of the Regional Geologic Evaluation

This report is a regional geologic evaluation of the Pierre Shale of the northern Great Plains Province. The goal is to evaluate the geologic and hydrologic environment of the region in relation to the Pierre Shale and provide a framework that supports modeling of a shale repository reference case. This evaluation focused on understanding the geologic and hydrologic characteristics of the sedimentary sequence that surrounds and includes the Pierre Shale as well as siting guidelines that would affect the long-term safety of HLW waste disposal in this region.

We chose the Pierre for this evaluation because of its large geographic extent, its thickness and because it lies relatively close to the surface throughout much of its extent. It was considered as one of the primary shale host rocks during studies by the USGS that began in the early 1970s. In this report, we update the evaluation of the Pierre Shales using modern GIS tools and current published information and data that is applicable to the natural barrier system, which includes the Pierre Shale and adjacent geologic formations. We discuss how this information might potentially bear on the long-term performance of a HLW repository located within the Pierre Shale host rock.

# 4. Regional Evaluation of the Pierre Shale in the Northern Great Plains

## 4.1 Overview of the Pierre Shale

The Pierre Shale consists primarily of fine-grained marine sediments deposited within the Western Interior Seaway during the Late Cretaceous Period. The seaway was formed during the Sevier Orogeny as the Farallon Plate was subducted under North America resulting in formation of a foreland basin (Bertog, 2010). The basin became a seaway through a combination of crustal flexure and changes in sea level (Figure 4-1).

The orogenic highlands to the west were the major source of clastic sedimentation in the basin, with coarser sediments being deposited in the west (nearshore environment) and increasingly finer sediments in the offshore environments to the east (Schultz et al., 1980; Bertog, 2010). Volcanism to the west was a source of volcanic ash deposited within the seaway and interbedded within the Pierre Shale as bentonite-rich layers (Bertog, 2010).

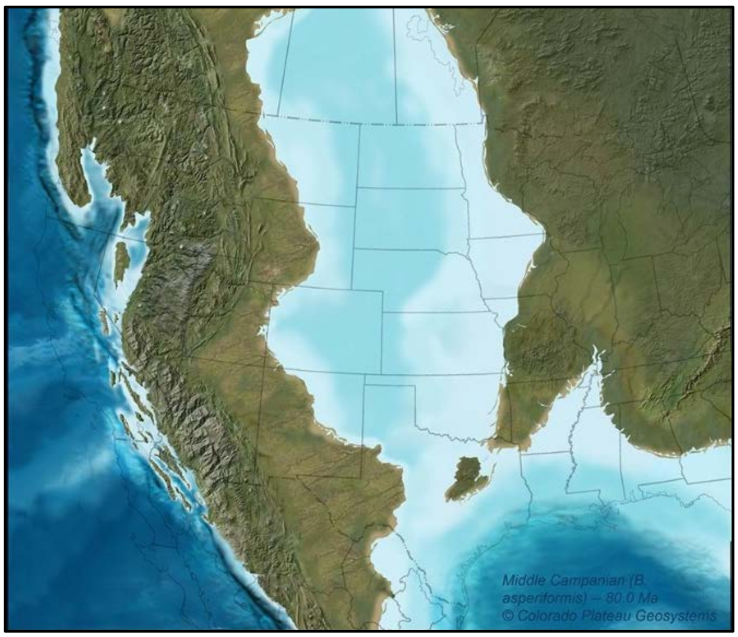


**Figure 4-1.** Geography of the Western Interior Seaway at the beginning of deposition of the Pierre Shale Group at about 80 m.y. ago (From Blakey, 2014).

The current thickness and surface relief of the Pierre Shale reflects the geometry of the Western Interior Seaway basin with as general thickening of the Pierre shale to the west (Figure 4-2).The thickest portions of the Pierre Shale are in the Denver and Williston Basins, with thickness of >1600 meters and >800 meters, respectively (Figure 4-2) . The shale becomes gradually thinner towards its eastern extent.

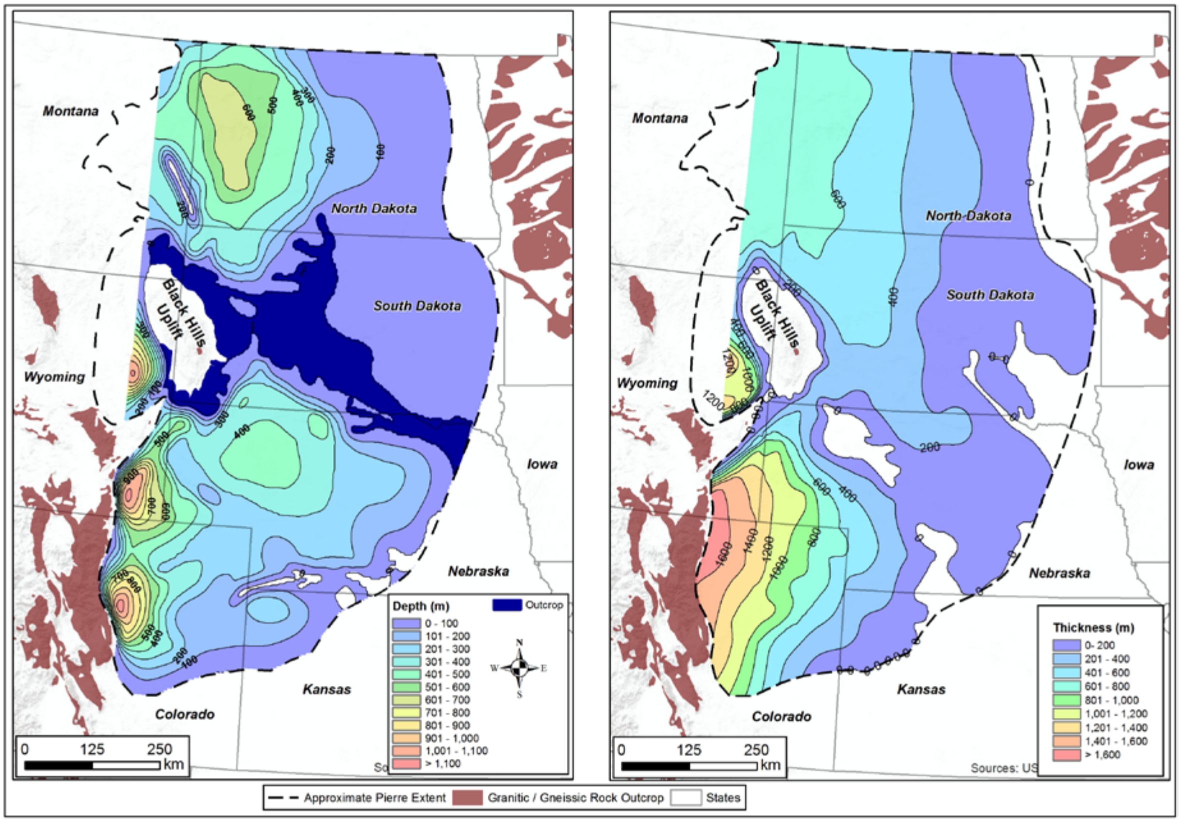


**Figure 4-2.** Depth (left panel) and thickness (right panel) maps for the Pierre Shale (modified from Perry et al., 2014).

The lithologic subdivisions and facies changes of the Pierre Shale have been recognized and described for more than 100 years. The stratigraphic nomenclature has evolved over the years depending on location within the Pierre Shale and has been reviewed in numerous papers over the years. Detailed descriptions of the stratigraphy of the Pierre Shale are included in Crandell (1958) and Martin et al. (2007).

Representative stratigraphy of the Pierre Shale from two areas is presented in Figure 4-3, based on Martin et al. (2007) and Fahrenbach et al. (2007). The first column represents stratigraphy near the Black Hills in the western extent of the Pierre Shale. The second column represents stratigraphy farther to the east in central South Dakota, near the type section of the Pierre Shale. Figure 4-3 reflects the proposal by Martin et al. (2007) to elevate the Pierre Shale from formation to group status with former members of the formation elevated to formation status.

The different formations of the Pierre Shale in the western extent compared to the central/eastern areas reflect the transgressive–regressive cycles of the Western Interior Seaway with siltier shales (Red Bird and Mitten) in the west and more clay-rich shales in the east (Schultz et al., 1980; Bertog, 2010). The stratigraphic sequence in the western Pierre extent also has a higher prevalence of bentonite layers from volcanic sources to the west (Bertog, 2010).

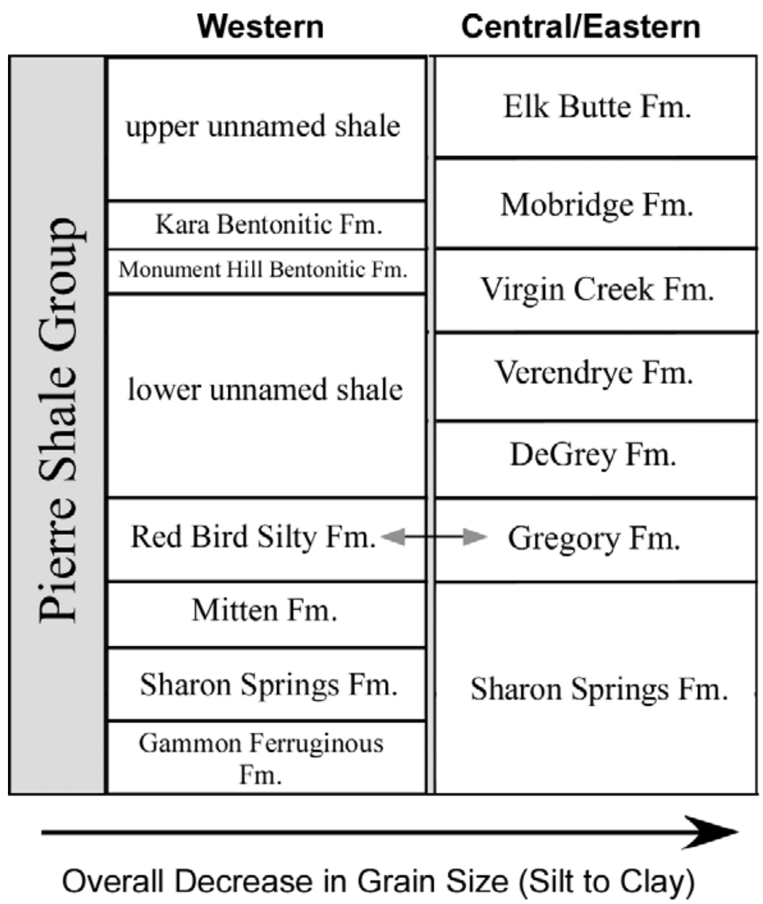


**Figure 4-3.** Subdivisions of the Pierre Shale Group. Western (left) column refers to subdivisions (formations) recognized in western South Dakota/North Dakota and Eastern Wyoming; Central/Eastern (right) column refers to subdivisions (formations) recognized in the central South Dakota region and to a lesser extent in eastern South Dakota/North Dakota (Martin et al., 2007; Fahrenbach et al., 2007). The relative vertical positions of formations above the Red Bird Silty Formation and the Gregory Formation (which are considered temporally equivalent) in the two columns does not imply strict temporal equivalency. Figure modified from Korn and Pagnac (2017).

With the exception of marine sandstone in the western equivalents of the Pierre Shale and siltstone (Red Bird Silty Formation) in Wyoming, Montana, and western North and South Dakota, nearly all of the formations within the Pierre Shale are fine-grained marine shales with silt content generally decreasing to the east away from the western sources of clastic deposition. Offshore marine shales of the Pierre are typically clay-rich with between 65-85% clay content (Schultz et al., 1980). Neuzil (2000) notes that the clay content of the Pierre Shale is at the 90$^{th}$ percentile of all shales.

The clay content of shales and siltstones influences several of their physical and hydrologic properties including compressive strength, deformation behavior and permeability (Bourg, 2015). The percentage of clay in the Pierre Shale is shown at an average value of 70% in Figure 4-4 (Schultz et al., 1980). Bourg (2015) discuss a sharp decrease in compressive strength and ability to maintain fractures at a clay fraction of > 1/3 (Figure 4-4). Because of its high clay content, the marine formations within the Pierre Shale would be expected to deform ductilely and be unable to support fractures. This sealing behavior is common to other shales being considered as host rocks in other countries (Figure 4-4)

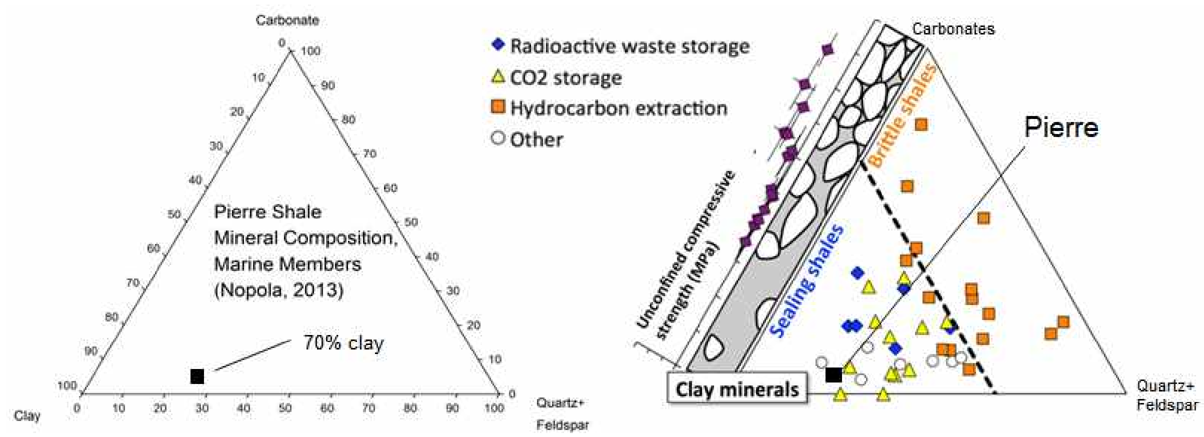


**Figure 4-4.** Mineralogy of the Pierre and other shales in the ternary system Clay-Carbonate-Quartz+Feldspar. The representative value of percent clay (70%) is from Nopolo (2013) base on data in Schultz et al. (1980).

## 4.2 Natural Barrier System/Geologic Environment

The natural barrier system of the Pierre Shale includes the physical, mineralogical and hydrologic properties of the shale and the properties of the stratigraphic sequence that lies above and below the Pierre shale. The natural barrier system, along with the engineered barrier system, are the components of the repository system that are relied upon to ensure the safety and long-term performance of the repository system.

### 4.2.1 Hydrologic Properties

#### *4.2.1.1 Permeability*

A key attribute of shale formations that make them desirable for disposal of HLW is their low permeabilities (e.g., Neuzil, 2013). Permeability values reported in the literature for shales worldwide range from about $10^{-16}$ $m^2$ to $10^{-22}$ $m^2$ (Brace, 1980; Neuzil, 1994; Hansen et al., 2010). Permeability values usually refer to vertical permeability normal to bedding planes and in most cases represent data collected in the laboratory from core samples (e.g., Neuzil, 1994; 2000). For indurated claystones and shales, there a positive correlation between increased permeability and increased porosity (Neuzil, 1994, Figure 1).

Neuzil (1986) determined hydraulic conductivity of core samples at different values of effective stress. Plotted as hydraulic conductivity versus equivalent depth in meters, the data show decreasing hydraulic conductivity with calculated equivalent depth, with permeability ranging from ~$10^{-19}$ to $10^{-20}$ $m^2$ at a depth of 100 meters and $10^{-19}$ to $10^{-21}$ $m^2$ at a depth of 1000 meters (Neuzil, 1986, Figure 1). In a subsequent paper, Neuzil (1993) reported on a series of borehole tests conducted in central South Dakota and concluded that the permeability values determined from borehole tests (~$10^{-20}$ to $10^{-21}$) were more reliable than his previously reported laboratory measurements (Neuzil, 1986). Neuzil concluded that core deterioration before testing resulted in increased porosity and possibly microfracturing. Many of the measured permeabilities were therefore larger (at ~$10^{-19}$ $m^2$) than the in-situ borehole measurements.

Bourg (2015) presented a relationship between clay content and permeability using data from 23 shales and siltstones (not including the Pierre Shale). A linear fit to these data yields the formula $\log k_v = -17.5 – 0.042 (X_{clay})$, where $X_{clay}$ is the estimated percent clay in the formation. Using this relationship, the offshore marine units of the Pierre Shale, with clay contents of between 65 and 85% (Schultz et al., 1980), have a calculated permeability of between $10^{-20}$ and $10^{-21}$ $m^2$. Based on analysis of his previous work, Neuzil (2000) states that the permeability of the Pierre Shale in central South Dakota is between $10^{-20}$ and $10^{-21}$ $m^2$ (based on his borehole measurements) and has a clay content of 70-80%, consistent with the analysis of Bourg (2015).

A debate that has not been completely resolved centers on the possibility that the permeability of shale is scale-dependent (Bredehoeft et al., 1983; Neuzil, 1986, 1993, 1994). From numerical simulations of the regional flow system in South Dakota, Bredehoeft et al. (1983) concluded that vertical leakage from the Dakota Sandstone into the overlying Cretaceous shale units constituted the dominant flow in the overall groundwater system. The hydraulic conductivity of the shales (i.e., the Pierre Shale) estimated from the simulations indicate a regional-scale permeability on the order of $10^{-16}$ $m^2$, which is several orders of magnitude higher than permeabilities estimated from laboratory and borehole tests reported in the same report. The higher permeability estimated at the regional scale suggested to Bredehoeft et al. (1983) that flow in the shale was primarily through vertical fractures, while permeabilities measured at smaller scales represented intact shale.

#### *4.2.1.2 Anomalous (Low or High) Fluid Pressures*

Neuzil (1993, 1994) pursued the question of the scale-dependent permeability in shales, and in particular, for the case of the Pierre Shale, the relationship between low permeability, fractures, and the ability of the shale to preserve anomalously low fluid pressures. Neuzil (1993) measured low fluid pressures within the formation interior that he concluded were created by erosion and rebound of the Pierre Shale. The geologic forcing was rapid relative to the time required for fluid pressures to re-equilibrate (i.e., return to steady state flow) within the low-permeability shale, allowing preservation of low fluid pressures. With this model, Neuzil (1993; 1994) was able to reconcile the apparent discrepancy in permeabilities estimated at the large (regional) and small scale. He concluded that a system of sparse transmissive fractures (spacing of greater than a few kilometers) could account for higher ($10^{-16}$) regional permeabilities (scale > 100 km) while allowing lower permeabilities to be preserved in intervening and unfractured large blocks. This conclusion has implications for repository siting in shale, as it would be desirable to site a repository within a large block that has preserved low fluid pressure (i.e., inward flow) over long time periods (Neuzil, 1994). On this same topic, Neuzil (2015) observed that formations with pressure anomalies (either low or high) have smaller ratios of permeability to formation thickness compared to formations with no pressure anomalies. In other words, formations with low permeability are able to maintain pressure anomalies over length scales (formation thickness) that a formation with higher permeability could not. From this relationship, Neuzil (2015) concluded that the presence of pressure anomalies within shale indicate a sizeable volume of low permeability rock where transport is dominated by diffusion rather than fracture flow. This has obvious implications for repository siting within a shale, and would depend on the scale of diffusion-dominated, unfractured blocks, which would need to be assessed on a site-specific basis.

#### *4.2.1.3 Porosity*

Schultz et al. (1980) reported a porosity range of 9-30% for all rock units in the Pierre Shale (shale, siltstone, marl) with an average of 20% for the “ordinary” marine shales. Siltstone is reported to have an average porosity of 17%. Neuzil (1994) plots porosity data for the Pierre Shale from unpublished data (borehole samples from central South Dakota) with values ranging from ~25-40%. Neuzil (1993) states that the in-situ porosity of core samples from central South Dakota is 32% (presumably a mean value) for samples with low permeabilities of $10^{-20}$ to $10^{-21}$ $m^2$.

### 4.2.2 Hydrogeochemistry

As in other geologic settings, the increase of salinity with depth in shales a well-established phenomenon (Kharaka and Hanor, 2003; Figure 4-5). Once present in the deep rock environment (several hundred meters or more), saline waters will tend to remain saline and immobile because their higher density makes them resistant to mixing with more dilute waters from meteoric sources (Phillips and Castro, 2003). This

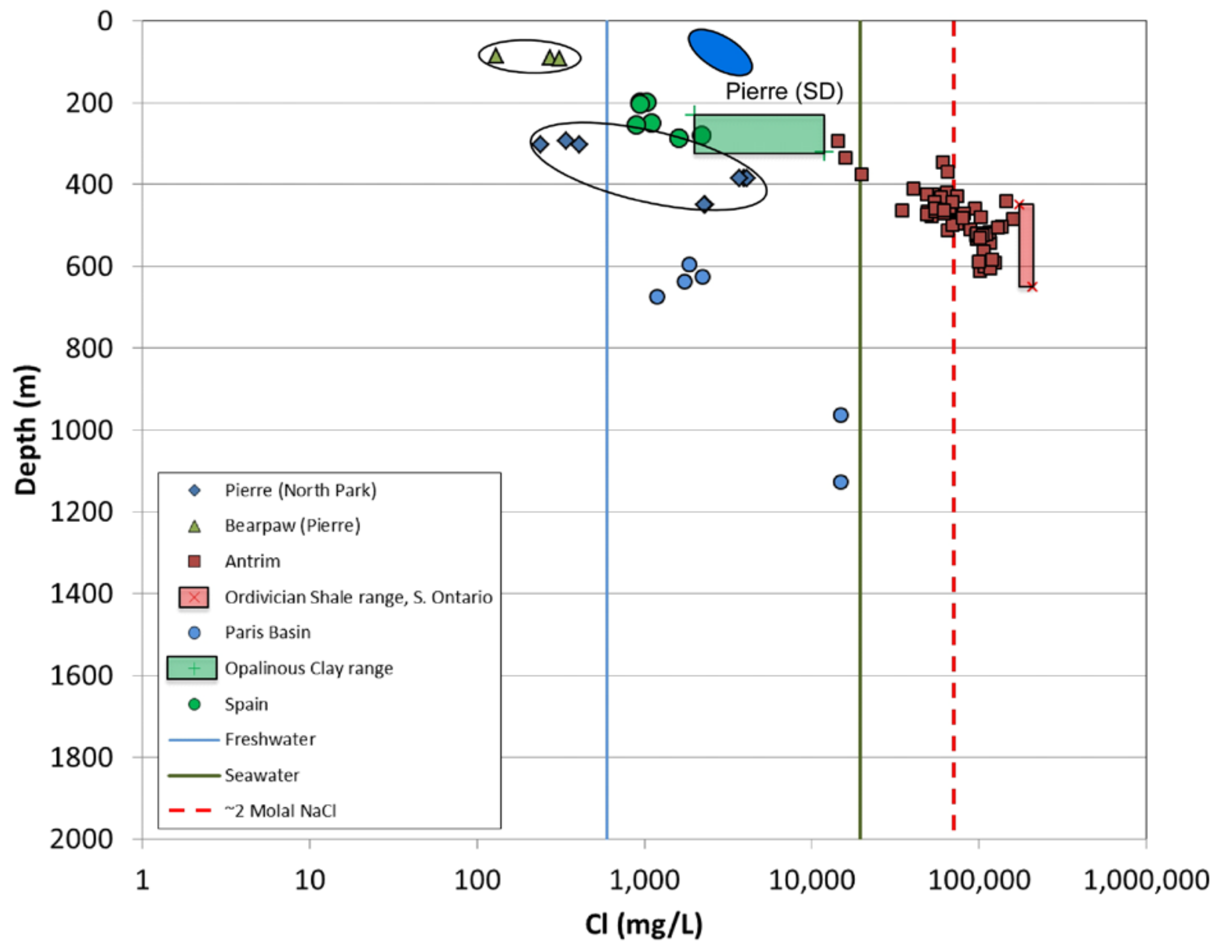


**Figure 4-5.** Depth versus Cl concentrations versus depth for selected shale formations in North America and Europe. Data for the Pierre and equivalent shales (Bearpaw) are indicated by the three oval fields at relatively low Cl concentration. The oval field filled with blue and labeled "Pierre (SD)" represents the range of values measured in central South Dakota by Neuzil (1993). Other data sources: 1. Pierre Shale in North Park Basin, Colorado (Blondes et al., 2014); 2. Bearpaw Shale in southern Saskatchewan (Hendry et al., 2000), 3. Antrim Shale in Michigan Basin (Blondes et al. 2014), 4. Ordovician shales in southern Ontario (Clark et al., 2013), 5. Paris Basin, France (Bensenouci et al., 2013), 6, 7. Opalinous Clay, Mont Terri, Switzerland and Jurassic mudrock, Spain (Terrero et al., 2006). Reference lines are the upper limit for freshwater Cl concentration, average seawater Cl concentration and the Cl concentration for 2 molal NaCl.

is particularly true for shale because of its low permeability, which limits communication with meteoric water and makes pore waters nearly immobile except for slow diffusion of ionic species across concentration gradients (Clark et al. 2013; Rebeix et al., 2013).

Pore water chemistry has been measured in a few studies of the Pierre Shale and shows salinity that is typically between that of freshwater and seawater and trends of increasing salinity with depth (Figure 4-5). The measurements are taken at depths of 400 meters or less where salinity is not expected to be extremely high. Water in the Pierre Shale is expected to be reducing throughout most of its geographic extent, as indicated by the presence of organic material and pyrite in unweathered (unoxidized) samples (Schultz et al., 1980). Pyrite is most commonly found in shale units representing offshore marine facies.

### 4.2.3 Stratigraphy and Groundwater Hydrology of Adjacent Formations

The Pierre Shale was deposited within the broad transgressive-regressive basin of the Western Interior Seaway as part of a succession of shales, sandstones, siltstones and limestones of Jurassic to Cretaceous age. The stratigraphic sequence that includes the Pierre Shale is therefore characterized by an alternating sequence of permeable and less permeable formations. In this report, we consider a stratigraphic sequence that is relevant to repository siting and the geologic environment of the Pierre Shale. The sequence extends from the surface to a depth of a kilometer or more, and includes the major regional aquifers that lie above and below the Pierre Shale. These aquifers are the Late Cretaceous Fox Hills Sandstone that occupies much of the western extent of the Pierre Shale and a group of Lower Cretaceous Sandstones that include the Inyan Kara Group in the west and the Dakota Sandstone in the east. The formations and lithologies within the stratigraphic sequence differ depending on location within the regional extent of the Pierre Shale. In this report, we consider the stratigraphy, lithology and subsurface hydrology of South Dakota and closely adjacent portions of other states as being representative of the geologic environment of the Pierre Shale. South Dakota occupies the entire central portion of the regional extent of the Pierre Shale and most of the Pierre shale within this region is at or near the surface (Figure 4-2).

A stratigraphic column representative of Cretaceous rocks in western South Dakota and North Dakota is shown in Figure 4-6. In its eastern extent, the Pierre Shale is generally the uppermost Cretaceous unit, present as outcrop or overlain by glacial till deposits of Quaternary age. Through much of its western extent (western South and North Dakota, eastern Montana, Wyoming, Colorado), the Pierre Shale is overlain by the Fox Hills Sandstone, representing a marginal marine facies. The contact between the Fox Hills and the Pierre is gradational, transitioning from shales of the upper Pierre to fine and medium grained sandstones of the lower Fox Hills (Cvancara, 1976).

The total overburden above the Pierre Shale is variable within its geographic extent but is equivalent to the depth to the top of the Pierre Shale (Figure 4-2). Overburden thickness varies from zero in areas where the Pierre outcrops (a large swath through South Dakota) to more than 1000 meters in parts of the Denver Basin (Figure 4-2). In eastern North and South Dakota, the Pierre Shale is overlain by Pleistocene glacial deposits. In western North and South Dakota (including the Williston Basin), the Pierre is overlain in most areas by Cretaceous sandstones (Fox Hills and Hell Creek Formations) and Tertiary gravels and sands (Figure 4-6). In areas to the south of the Dakotas, the Pierre Shale is overlain by Tertiary sediments, except for the Denver Basin, where it is overlain by the sequence of Cretaceous Sandstones (Fox Hills and Laramie Formations) and Tertiary gravels and sand (Shurr, 1977).

The nature and thickness of overburden may be less of a consideration for a repository in the Pierre Shale compared to other types of geologic media. Assuming that a sufficient thickness of shale lies above the repository horizon, the Pierre Shale itself would provide an effective isolation medium in the form of "overburden".

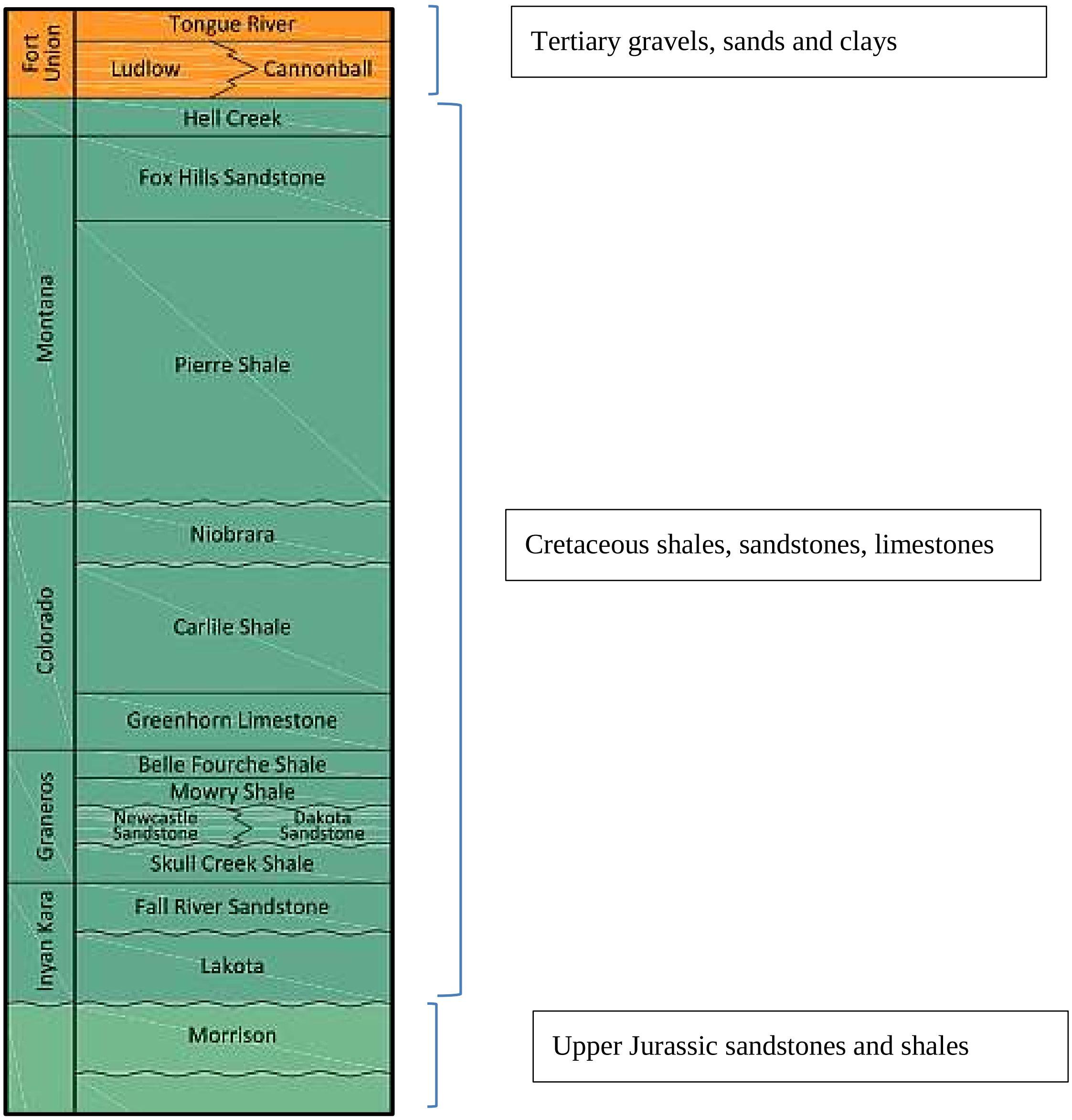


**Figure 4-6.** Stratigraphic column representative of western South and North Dakota showing Lower Cenozoic, Cretacous and Upper Jurrasic sedimentary rocks (from Fahrenbach, 2007, Black Hills column).

Below the Pierre Shale lies the Niobrara Formation, which consists of interbedded calcareous shales and limestones. The contact between the Pierre Shale and the Niobrara Formation is conformable in western areas but is marked by a widespread erosional uncomformity through much of its eastern extent (Gill and Cobban, 1966; Bertog, 2010). The Niobrara is characterized by an upper member that is primarily calcareous shale and chalk with interbeds of limestone, while the thinner, lower unit is primarily limestone (Scott and Cobban, 1964).

Below the Niobrara Formation lie the Carlile Shale, the Greenhorn Limestone, and the Belle Fourche and Mowry Shales. The Dakota/Inyan Kara sandstone formations lie beneath the shales and constitute a major regional aquifer for primarily agricultural use (Downey, 1986).

Permeability values have been measured for several of the non-shale formations within the stratigraphic sequence. Permeability of the Fox Hills Formation in the Powder River Basin is reported as $5{\times}10^{-14}$ $m^2$ in the Gulf Coast Carbon Center database, Texas Bureau of Economic Geology, accessed at http://www.beg.utexas.edu/gccc/CO2_data/FoxHills_002.php. Chalk at shallow depth in the Niobrara Formation has a reported permeability of $10^{-15}$ $m^2$ (Maldonado, 2011). Lockridge and Scholle (1978) report permeabilities as high as $10^{-14}$ $m^2$ at a porosity of ~40% in the uppermost Niobrara Formation. Bredehoeft et al. (1983) estimated a regional permeability value for the Dakota Sandstone aquifer of $2\times10^{-12}$ $m^2$ based on drilling records. We could find no data for siltstone intervals within the Pierre Shale, such as the Red Bird Silty Formation, but assume values intermediate between shale and sandstone. Brace (1980, Figure 1) reports the permeability of siltstone as falling in the range of $10^{-16}$ to $10^{-17}$ $m^2$.

The two major aquifers of interest in the context of this evaluation are the Dakota Sandstone aquifer and the Fox Hills aquifer. The Dakota (and the Inyan Kara) aquifer lies beneath the sequence of Cretaceous shales and typically lies 200 meters beneath the Pierre Shale (Figure 4-6). The Dakota aquifer is a major regional aquifer used mainly for agricultural purposes due of its salinity. It is recharged in the Black Hills and other uplifts to the west and the regional flow is to the east and northeast (Downey and Dinwiddie, 1980). The aquifer is artesian through much of its eastern extent and regional flow modeling indicates that groundwater from the aquifer leaks into the overlying Cretaceous shales through a system of sparse fractures as previously discussed in Section 4.2.1 (Bredehoeft et al., 1983; Neuzil, 1993). The Fox Hills aquifer lies immediately above the Pierre Shale through much of its western extent, including parts of North Dakota, South Dakota, Montana, Wyoming, Nebraska and Colorado. The Fox Hills is a major fresh water aquifer providing water for both municipal and agricultural use (e.g., Honeyman, 2007).

Another regionally significant aquifer lying above the Pierre Shale is the High Plains (Ogallala) aquifer that lies at shallow depth and is comprised of late Tertiary gravels, sands and silt (Gutentag et al., 1984). This aquifer extends from southern South Dakota through Nebraska, eastern Colorado and Kansas. It could potentially affect siting within the southern half of the geographic extent of the Pierre Shale (Figure 4-2).

To support a generic shale repository reference case, we developed a representative stratigraphic sequence based on the stratigraphic sequence that includes the Pierre Shale (Figure 4-7). For this generic stratigraphic sequence, we define the thickness and depth for each formation as well as representative values for permeability. For the shale host rock, we assign a permeability of $10^{-19}$ $m^2$, a value that is at the high end of estimates based on small-scale experiments. This is to make an allowance for the possibility of higher regional permeability due to sparse fractures (Neuzil, 1993). We include a siltstone interval within the shale host rock with a permeability of $10^{-17}$ $m^2$ based on the Red Bird Silty Formation, because we do not believe that the host rock would be completely homogeneous. We assign a permeability of $10^{-13}$ $m^2$ for an overlying sandstone aquifer, based on the properties of the Fox Hills Formation. For rocks below the host rock, we assign a value of $10^{-14}$ $m^2$ for a limestone/chalky shale interval, a value of $10^{-20}$ $m^2$ for lower shales, and a value of $10^{-13}$ $m^2$ for a lower aquifer that is based on the properties of the Dakota sandstone aquifer.

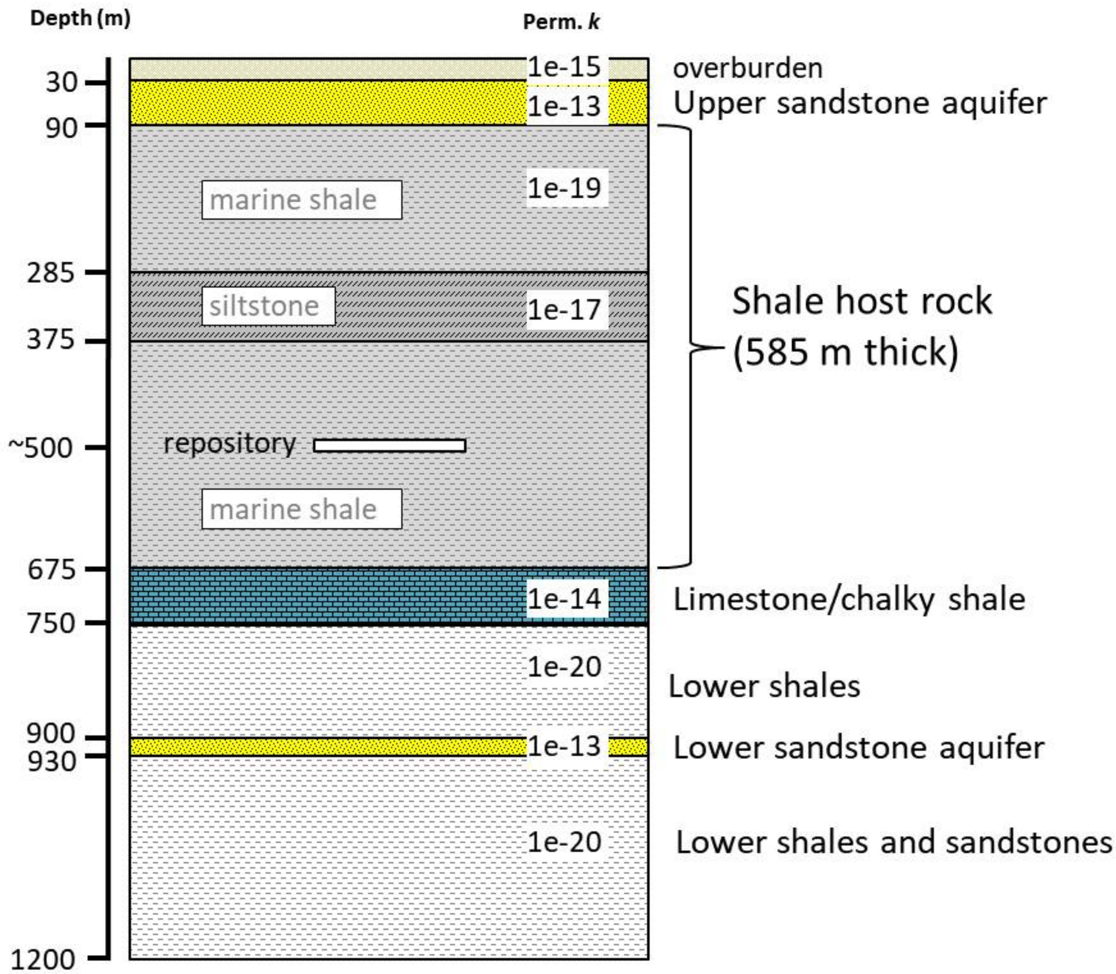


**Figure 4-7.** Generalized representative stratigraphic sequence for a repository sited within a shale host rock.

## 4.3 Siting Guidelines and the Pierre Shale

Siting of a HLW repository requires evaluation of the geologic environment of the potential host rock. For shales, factors to be evaluated include the geographic extent, thickness and depth of the formation, and the Pierre Shale, factors that could influence long-term repository performance and impacts on the biosphere including topography, regional seismicity, faulting, prevalence of drilling for natural resources, and cultural factors such as population density.

Merewether et al. (1973) presented one of the first set of siting guidelines for emplacement of radioactive waste in shale and included factors such as depth to the emplacement zone, formation thickness, uniformity of the rock mass, faulting, seismicity and borehole penetrations. In his study of the Pierre Shale, Shurr (1977) defined specific guidelines for siting of a radioactive waste repository. These guidelines (“criteria” in Shurr, 1977) were as follows:

- Depth: a repository horizon of between 300 and 900 meters.
- Shale thickness: minimum shale thickness of 150 meters, with maximum available thickness preferred.

- Overburden thickness: minimal thickness preferred, with a maximum of ~750 meters in order to have at least a 150 meter shale thickness and a depth of no more than 900 meters.
- Lithology and mineralogy: reasonably uniform shale with few or no beds of sandstone or other more permeable rock. Isolation horizons must be at least 15 meters thick and expandable clays are considered undesirable within the isolation horizon.
- Penetrations (boreholes): boreholes of any kind are undesirable, particularly if they penetrate to rocks below the shale.
- Structure: Bedding should be nearly horizontal with maximum dips of 5 degrees with no known faulting or folds within several miles of the site.
- Seismicity: future seismic activity is highly undesirable and regions of recorded earthquakes should be avoided.
- Topography: minimal topographic relief is desirable.
- Mineral and water resources: undesirable to consider a potential site near mineral or water resources.

In his analysis, Shurr (1977) identified one area (study area "B") that satisfied most of his criteria, including thickness and depth of the shale, borehole density, lithologic uniformity and topography. In this evaluation, we examine these guidelines and others using current data and GIS tools. Application of siting guidelines rely on data related to host-rock extent, thickness and depth, natural hazards such as seismic activity, cultural features and extraction of natural resources, including oil and gas production and geothermal energy (Table 4-1).

**Table 4-1**. Sources of data for used to evaluate siting guidelines.

| Technical Siting Guideline | Source |
|---|---|
| Extent, Thickness and Depth of Geologic Formations (Pierre Shale) | Shurr (1977); Gonzales and Johnson (1985) |
| Heat Flow | Blackwell et al. (2011) |
| Natural Resources (Oil and Natural Gas) | Biewick (2008) |
| Quaternary Faults; Class A Seismic Hazard Features in the Central and Eastern US | USGS (2006); Crone and Wheeler (2000); GIS data for central and eastern US from CEUS-SSC (2012) |
| Seismic Ground Motion Hazard | Petersen et al. (2014) |
| Quaternary Volcanism | Garrity and Soller (2009) |
| Topography and Smoothed Slope | NOAA (2006); Slope calculated at LANL |
| Population Distribution and Density | LandScan (2010), McKee et al. (2014) and courtesy of Femi Omitaomu and Randy Belles (ORNL) |

### 4.3.1 Depth and Thickness of the Pierre Shale

The depth and thickness of the Pierre Shale within its extent are a key constraint in siting a repository. Using Shurr (1977) as a guide, we consider a shale thickness of 200 meters as a minimum and assume that a repository would be located at a depth of between 300 and 600 meters. This depth range is considered flexible for potential siting purposes, but the maximum depth may be reasonable for the low-strength Pierre Shale considering increased construction costs and stability issues in a deeper repository (Nopola, 2013; Hardin, 2014). It is unlikely that a repository would be constructed in shale at a depth of less than 200 meters or greater than 1000 meters. A range of 300-600 meters thus represents a reasonable range of likely depths for repository construction. For comparison, repositories in clay or shale media in other countries are currently planned at depths of 230 meters in Belgium, 500 meters in France, and 400-700 meters in Switzerland (EPRI, 2010; ANDRA, 2005; Amann et al., 2015).

While specifying a repository depth and host-rock thickness could be considered somewhat arbitrary in the context of a regional evaluation, we believe that the depth and thickness values we have chosen are reasonable for any repository sited in shale. Specifying a set of values allows us to provide constraints on the areas of the Pierre Shale that might be considered for a potential repository site in terms of formation thickness and depth (Figure 4-8).

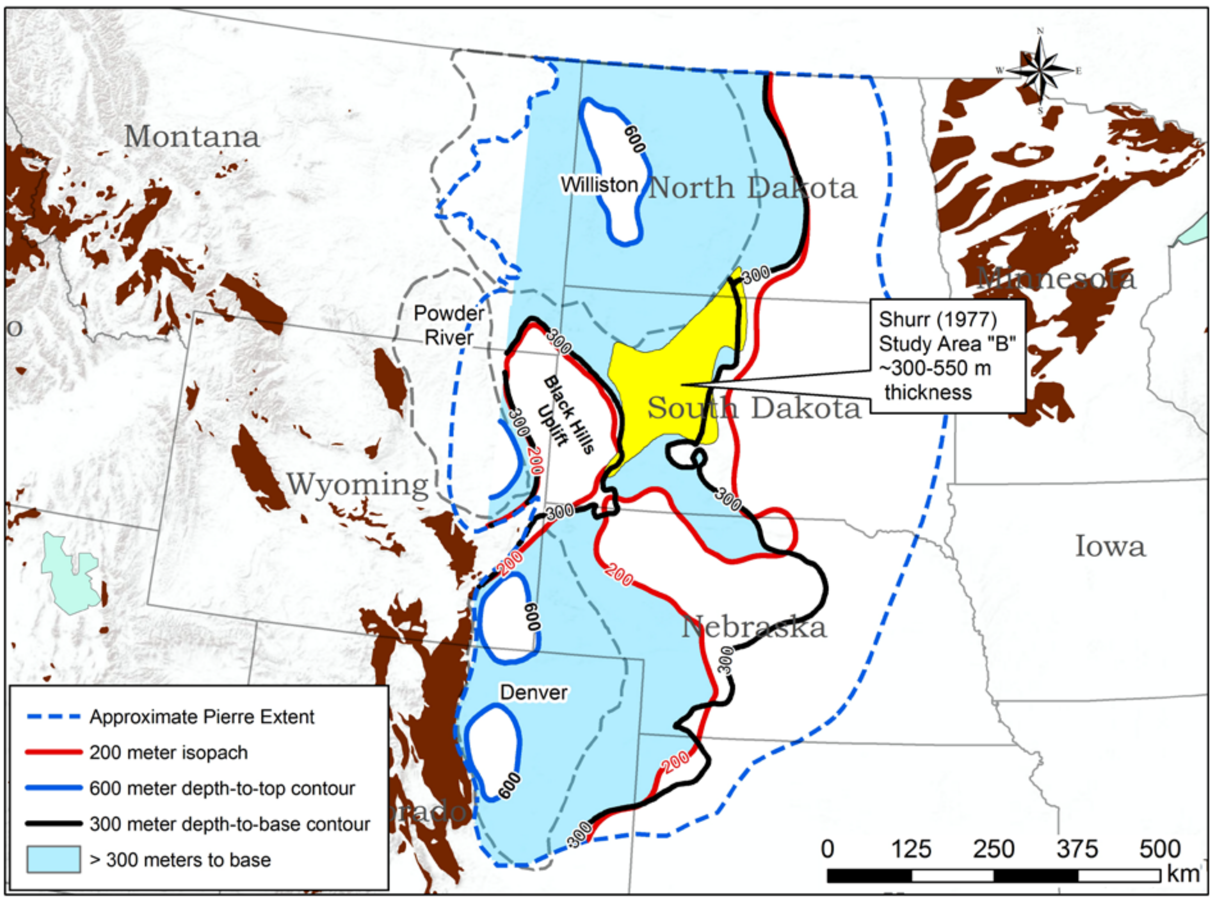


**Figure 4-8.** Map of the Pierre Shale with areas shown in blue meeting criteria for repository depth and formation thickness as discussed in text. Dark brown areas indicate location of granitic rocks. Light turquoise areas are lakes.

Specifying a repository depth range and minimum formation thickness places the following constraints on siting a potential repository within the extent of the Pierre Shale:

1. The thickness of the Pierre Shale cannot be less than 200 meters.
2. The base of the Pierre Shale must lie at a minimum depth of 300 meters to accommodate a repository in the 300-600 meter depth range. The base can lie at a depth > 300 meters.
3. The top of the Pierre Shale must lie at a maximum depth of 600 meters to accommodate a repository in the 300-600 meter depth range. The top can lie at a depth of < 600 meters.

In applying these constraints, we do not account for the likelihood that an undefined additional thickness of the formation would be required to accommodate the repository at these depth ranges. In other words, a repository at 300 meters depth might require a location where the top of the shale lies at a depth of 250 meters, so that 50 meters of host rock would still lie above the repository.

The results of applying these depth/thickness constraints to the Pierre Shale are shown in Figure 4-8, based on the depth/thickness data displayed in Figure 4-2. The area shown in blue on the figure meets the three constraints listed above. The first two constraints, formation thickness and minimum depth to base, limit roughly 1/3 of the area in the eastern extent of the Pierre Shale. The 200-meter isopach and the 300-meter contour for depth to base are nearly coincident, with the exception of a large area in central Nebraska. Applying these constraints allows consideration of a large area of the Pierre Shale based strictly on thickness and depth constraints. The eastern half of the area shown in blue in Figure 4-8 is where the Pierre Shale is most likely to be composed of uniform, offshore marine-facies shale, with little or no intervals of sandstone or siltstone (see Figure 4-3).

Of the three depth/thickness constraints, the most limiting is the minimum thickness of the host rock. Consideration of host rock less than 200 meters thick would allow consideration of more area to the east of the 200-meter isopach (Figure 4-8). The next most limiting constraint is the maximum depth of the repository of 600 meters. Allowing for a repository deeper than 600 meters would expand the area available within the Denver and Williston Basins, but only by a small amount.

The constraints applied in this report are consistent with the area of the preferred geologic study area “B” of Shurr (1977), which was based on thickness and depth criteria as well as other criteria including the number of boreholes, overburden thickness (equivalent to depth of formation top) and uniformity of the shale (Figure 4-8). The lithology of the Pierre Shale in the eastern half of the blue area in Figure 4-8 is more likely to be comprised of fine-grained claystone (“offshore marine shale”) compared to areas farther west (Shurr, 1977; Schultz et al., 1980; Figure 4-3).

### 4.3.2 Human Intrusion – Oil and Gas Drilling

Deep drilling is considered the most common mechanism of inadvertent human intrusion of a mined geologic repository. Oil and gas drilling has been the major consideration for human intrusion in siting studies for the Pierre Shale (Shurr, 1977). Drilling for water resources is another potential issue for siting within the Pierre Shale, as the underlying Dakota sandstone is a major aquifer (Bredehoeft et al., 1983). Evaluation of potential water wells is beyond the scope of this report, and could be more effectively carried out during a specific site evaluation. Geothermal exploration should also be considered as a potential intrusion event in areas of high heat flow (discussed in Section 4.3.4).

Oil and gas drilling in the region of the Pierre Shale has been concentrated primarily in the Williston Basin, the Denver Basin and adjacent areas to the east and southeast, and the Powder River Basin region to the west of the Black Hills (Figure 4-9). Areas within 100-200 kilometers to the west of the 200-meter isopach have a relatively low density of drilling, including the area encompassed by study area “B” of Shurr (1977).

Within the basins, formations that lie below the Pierre Shale are the typical targets for oil and gas drilling. These formations include the Devonian-Mississippian Bakken Formation in the Williston Basin, and

Lower Cretaceous sandstones in the Denver Basin (Higley and Cox, 2007). Sandstones members within

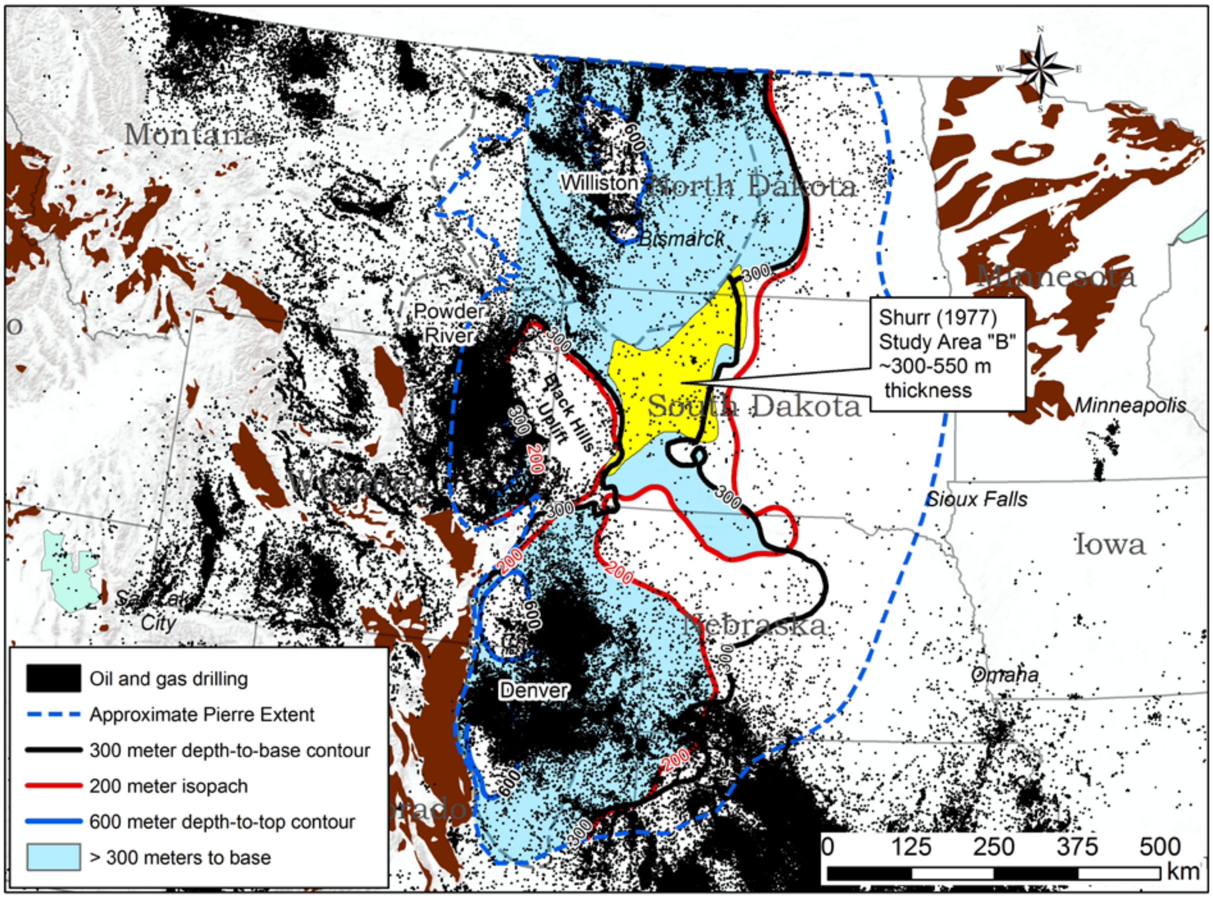


**Figure 4-9.** Map of areas of oil and gas drilling and the geographic extent of the Pierre Shale. Areas in black indicate quarter-mile parcels where oil or gas drilling has occurred (Biewick, 2008).

the Pierre Shale have produced oil and gas in parts of the Denver Basin north of the City of Denver, Colorado (Higley and Cox, 2007). Fractured marine shales of the Sharon Springs Formation (Pierre Shale) near the Front Range on the southern margin of the Denver Basin have also produced oil and gas (Higley and Cox, 2007). The oldest commercial natural gas production in the Williston Basin was from sandstone members in the Pierre Shale on the southwest margin of the basin in the early 1900s (Anna et al.,2013).

### 4.3.3 Topography

Topography and topographic relief is a siting consideration for the Pierre Shale because it exerts a primary control on regional groundwater flow, particularly in the Dakotas (Figure 4-10). Here, recharge occurs in uplifted areas to the west (Black Hills and uplifts in Wyoming and Montana) and regional flow is to the east though lower Cretaceous aquifers of the Inyan Kara and Dakota sandstones (Bredehoeft et al., 1983; Downey and Dinwiddie, 1988).

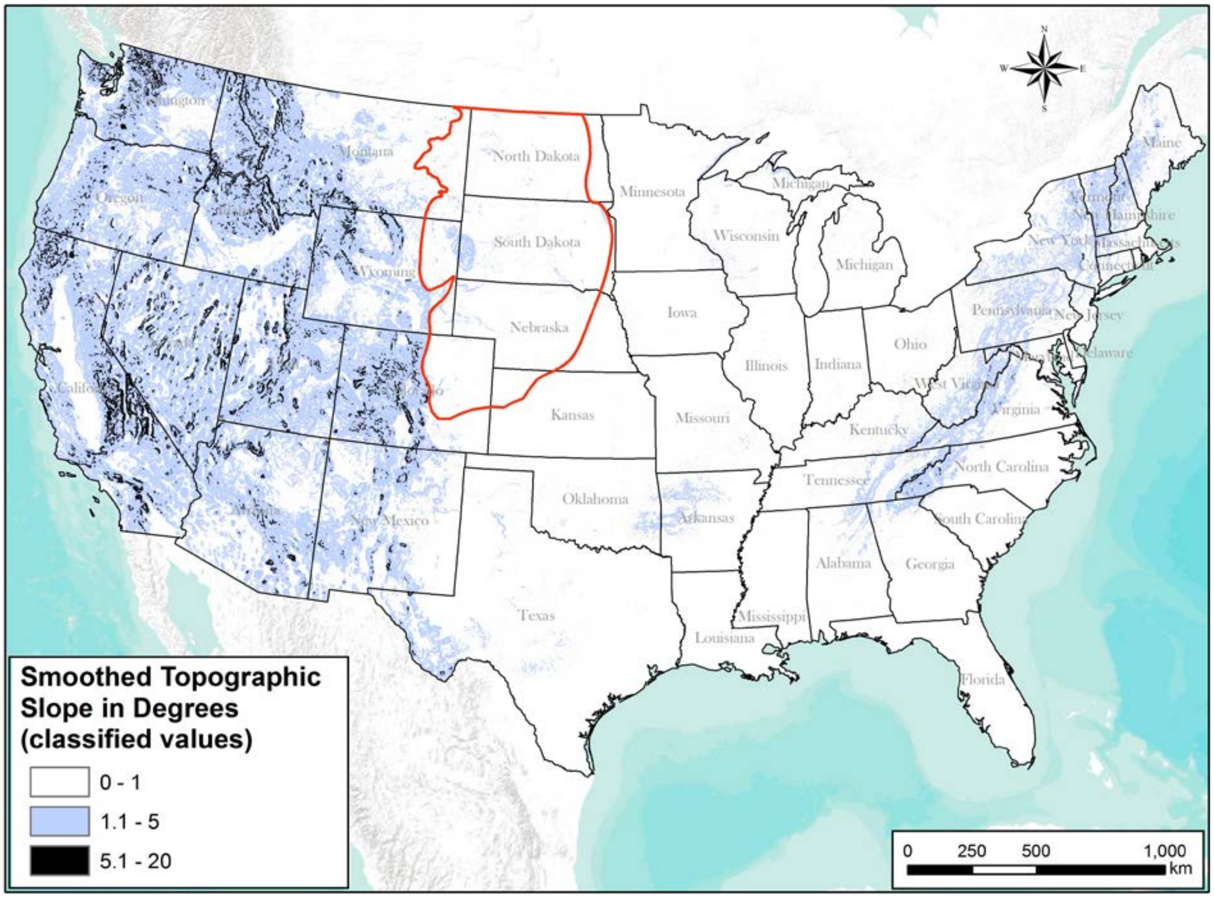


**Figure 4-10.** Map of topography and topographic slope for the US and the extent of the Pierre Shale (red line).

Within the extent of the Pierre Shale, the topography is fairly flat, with regional slopes of < 1 degree (Figure 4-10). The exception, and the most prominent topographic feature within the Pierre Shale region, is the Black Hills of western South Dakota. An area of higher heat flow in the Kennedy Basin of south-central South Dakota is thought to be caused by advection of heat through deep aquifers that have recharge areas in the Black Hills (see discussion in next section of this report).

### 4.3.4 Heat Flow

The geographic extent of the Pierre Shale lies to the east of the high heat flow areas that characterize much of the western US (Figure 4-11). For the most part, heat flow values in the northern Great Plains lie between 40 and 70 $mW/m^2$ (Figure 4-11). An anomalous area of high heat flow in the Kennedy Basin region in southern South Dakota and northernmost Nebraska has heat flow values that exceed 100 $mW/m^2$ (Gosnold, 1990; Figure 4-11). A model by Gosnold (1990) attributes the high heat flow to advective eastward flow through the Dakota aquifer from recharge areas to the west (Black Hills, Rocky Mountains) and upwards leakage from the Dakota through the Cretaceous shale section. The model indicates that vertical water flow with a velocity of 5 mm/yr can account for the thermal anomaly in the Kennedy Basin.

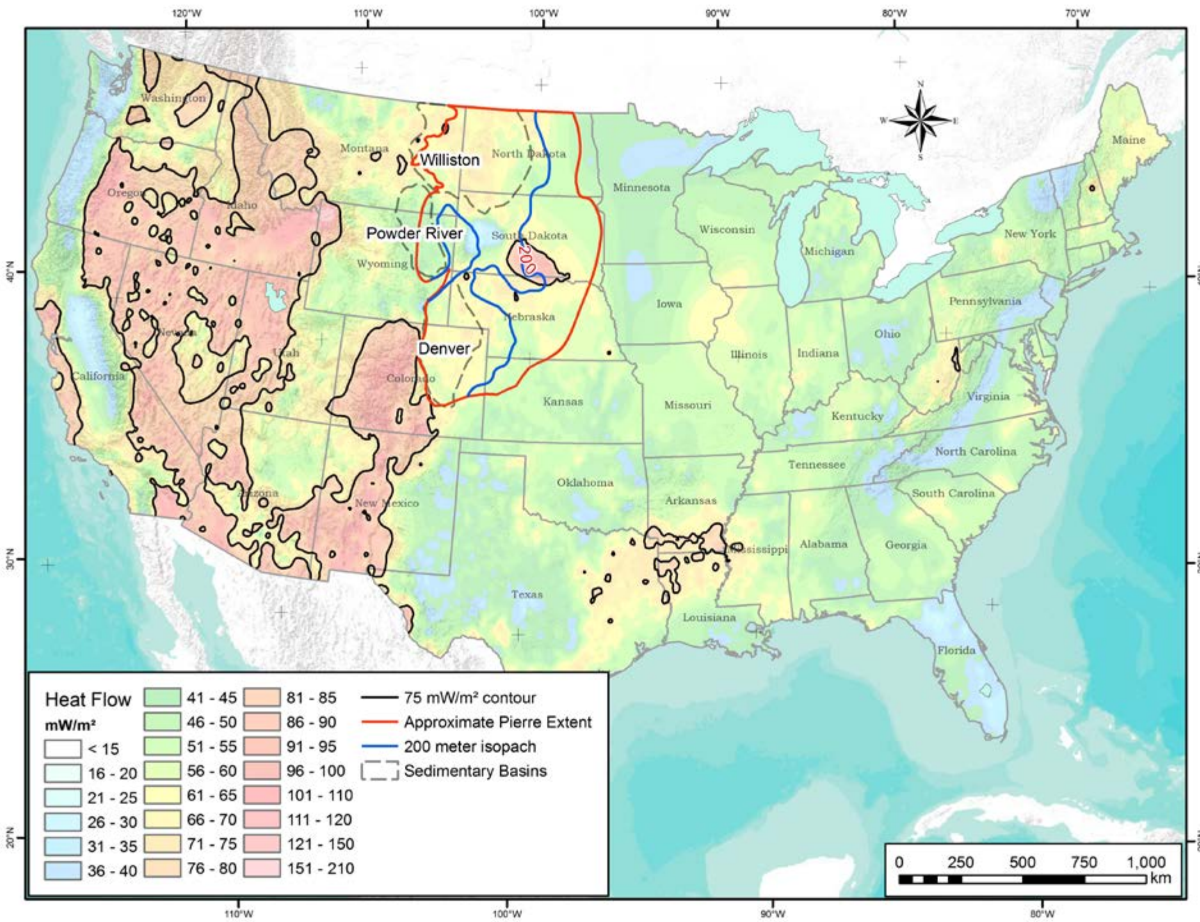


**Figure 4-11.** Heat flow map of the US and the extent of the Pierre Shale (red line).The blue line is the 200 meter isopach for the Pierre Shale.

Thermal conductivity values for the Pierre Shale of about 1.2 W/m·K are consistent with models of heat flow in the region (Gosnold, 1990). Gosnold also showed that thermal conductivities are not uniform in the Pierre Shale but depend on the lithologic characteristics of the formation members. For facies farther to the west that are siltier on average, Gosnold estimates a thermal conductivity of about 1.1 W/m·K. For more clay-rich facies to the east, his estimate is about 1.2 W/m·K.

Roughly half of the Kennedy Basin heat-flow anomaly lies to the west of the 200-meter isopach of the Pierre Shale (Figure 4-11). The high heat flow in this area could influence potential siting decisions either because of the geothermal potential of the area or because the high heat flow indicates vertical advection of heat through groundwater flow, consistent with a groundwater flow model that indicates leakage of deeper groundwater into the Pierre Shale through fractures (Bredehoeft et al., 1983; Neuzil, 1993).

## 4.3.5 Active Tectonics and Crustal Stability

The distribution of Quaternary faults, volcanism and strong seismic ground motion hazard delineate the "tectonically active" regions of the US, which is dominated by tectonic activity in the western US (Figure 3-10). The western US also encompasses large areas of high topographic relief and high heat flow, which are also indicators of active tectonism (see Figures 4-10 and 4-11). The northern Great Plains, which

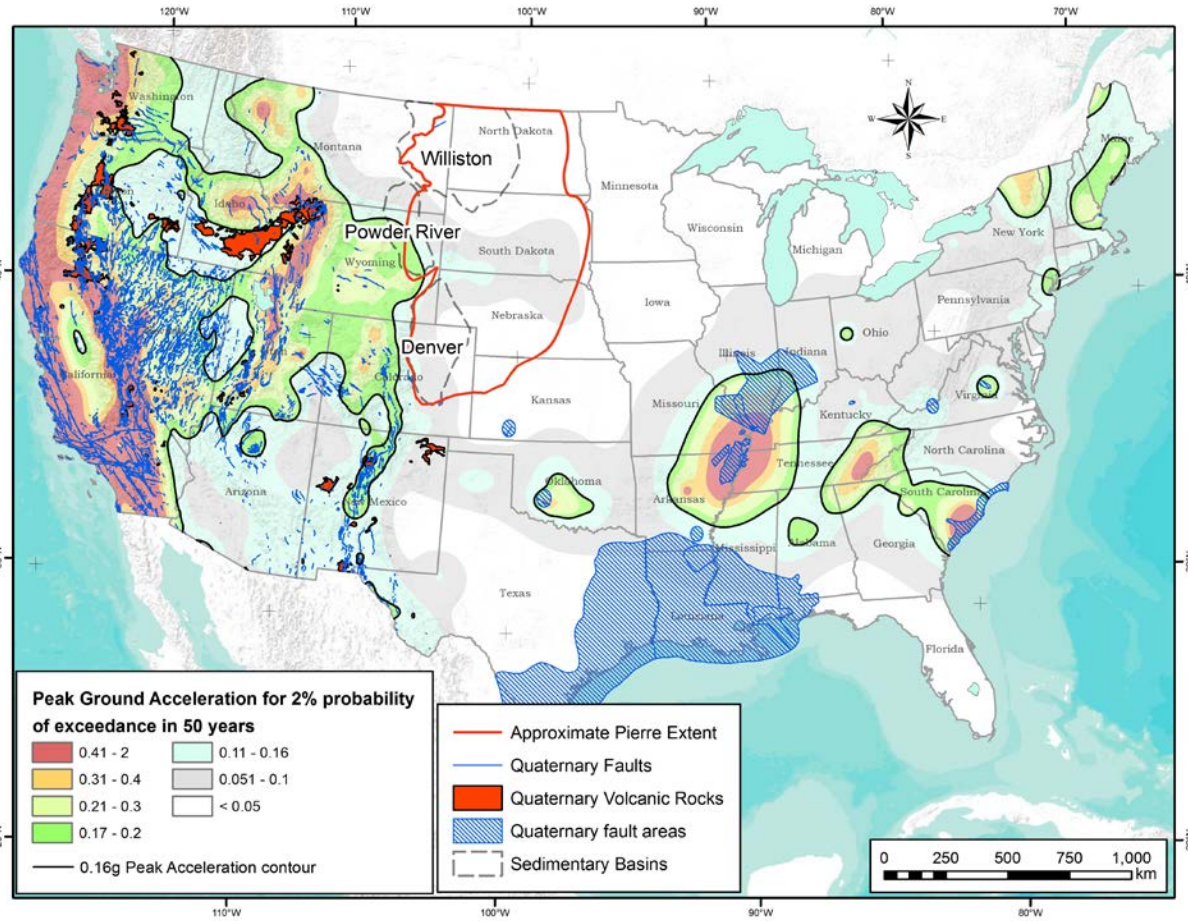


**Figure 4-12.** Map of seismic hazard overlain with the distribution of Quaternary faulting and Quaternary volcanic rocks in the contiguous US. In combination, these features indicate areas in the US that are considered tectonically active. The geographic extent of the Pierre Shale is outlined in red.

encompasses the geographic extent of the Pierre Shale, is part of the tectonically stable mid-continent region that has no evidence of significant tectonism in the past several hundred million years (Figure 4-12). Areas of higher seismic hazard associated with the Pierre Shale include an east-west zone that coincides with the South Dakota-Nebraska state line and the area near the western edge of the Pierre Shale along the Colorado Front Range and the Laramide uplifts in Wyoming (Figure 4-12). These zones have a peak ground acceleration potential of between ~0.05 and 0.16 g, which equates to a maximum Modified Mercalli intensity value of VI, or the ability to slightly damage ordinary buildings.

### 4.3.6 Population Distribution and Density

Except for a few large cities, most of the geographic extent of the Pierre Shale lies in rural agricultural areas with sparse population (Figure 4-13). Exceptions are areas of high population density east of the Front Range in central Colorado and southern Wyoming along the southwestern margin of the Pierre Shale (Figure 4-13). The largest towns within the interior portions of the Pierre Shale are Bismarck, North Dakota and Rapid City, South Dakota with populations in excess of 70,000. It is generally accepted that HLW repositories should be sited in areas that are sparsely populated.

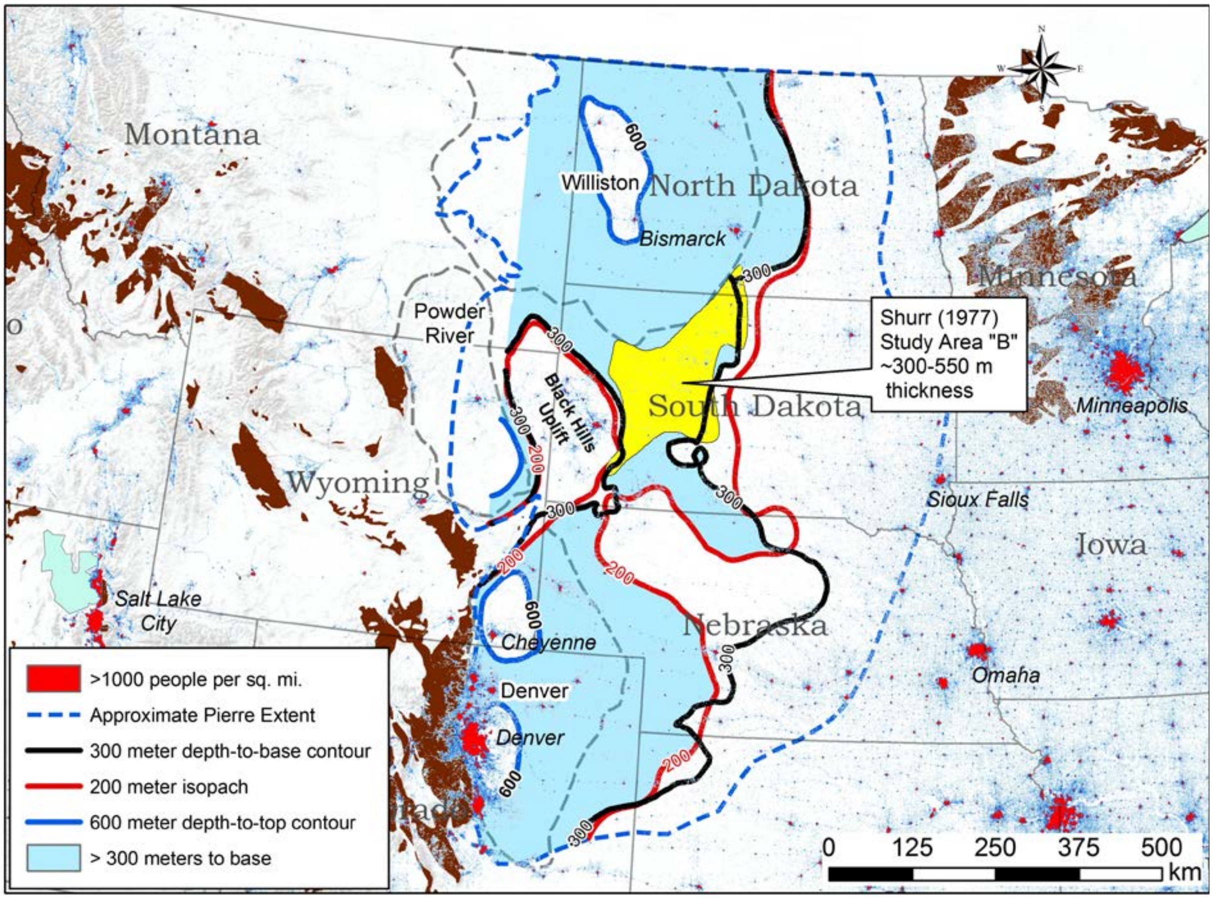


**Figure 4-13.** Map of population distribution and density and the geographic extent of the Pierre Shale. Red areas indicate square-mile grid cells with population of greater than 1000 people. Blue areas are grid cells with less than 1000 people per square mile. Selected cities are labeled for reference.

# 5. Summary

This research was performed as part of the Defense Waste Repository (DWR) project. Based on revised DOE priorities in mid-2017, the development of a DWR has been discontinued; current work unique to the development of a DWR is being closed out and documentation will be completed by the end of fiscal year (FY) 2017. Implementation of any recommendations made in this report for further research regarding a DWR would require resumption of the DWR project at some future time.

We have completed a regional geologic evaluation of the Pierre Shale in the northern Great Plains. This evaluation focused on understanding the geologic and hydrologic characteristics of the sedimentary sequence that surrounds and includes the Pierre Shale as well as siting guidelines that would impact the long-term safety of HLW waste disposal in this region.

The Pierre Shale has a large geographic extent that encompasses most of the northern Great Plains of the US. This region, in the mid-continent, is tectonically stable with relatively low seismic risk and no evidence of recent faulting or volcanism. Topographic relief is low with the exception of the Black Hills uplift. Recharge in the Black Hills, Rocky Mountains and topographic slope to the east drives groundwater flow from west to east in semi-confined sandstone aquifers interlayered with less permeable shales. Permeabilities of the Pierre Shale measured at the laboratory and borehole scale are in the range of $10^{-20}$ to $10^{-21}$ $m^2$, with evidence of regional, formation-scale permeability as high as $10^{-16}$ $m^2$ due to transmission of groundwater through sparse fractures (Bredehoeft et al., 1983). At smaller length scales of a few kilometers, unfractured blocks of shales have permeabilities are likely to be equivalent to those measured at small scales, as evidenced by preservation of low fluid-pressure anomalies over long time scales (Neuzil, 1993; 2015). Thus, while the Pierre Shale is not impermeable over regional scales, it appears possible through site-specific studies to identify unfractured large blocks with low permeabilities.

Evaluations of siting guidelines using modern GIS tools are consistent with previous evaluations (Shurr, 1977). The formation depth and thickness constraints applied in this report (see Figure 4-8) identify a large area of shale that includes the preferred geologic study area "B" of Shurr (1977), which was based on similar criteria as well as other criteria including the number of boreholes and uniformity of the shale. The lithology of the Pierre Shale in the eastern half of its geographic extent is more likely to be comprised of fine-grained claystone ("offshore marine shale") compared to areas farther west (Shurr, 1977; Schultz et al., 1980; Figure 4-3).

Drilling for oil and gas is concentrated in major sedimentary basins, with areas to the east of the basins having a relatively low density of boreholes. Heat Flow is low throughout most of the region with the exception of area of anomalously high heat flow in south-central South Dakota. This heat flow anomaly is attributed to advective eastward flow through the Dakota aquifer from recharge areas to the west (Black Hills, Rocky Mountains) and upwards leakage from the Dakota through the Cretaceous shale section, consistent with regional-scale vertical flow of groundwater through a sparse fracture system.

Finally, to support a generic shale repository reference case, we developed a representative stratigraphic sequence based on the stratigraphic sequence that includes the Pierre Shale. This sequence includes sandstone aquifers above and below the Pierre Shale and representative permeability values for each of the sedimentary formations based on published reports or articles.

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