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Geological Distribution of Potentially Suitable Shale in the U.S.: Concepts and Literature

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Geological Distribution of Potentially Suitable Shale in the U.S.: Concepts and Literature

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Abstract

Shale is one of the geologic environments that is under consideration for used nuclear fuel disposal. Disposal in shale has many favorable attributes that limit the possibility of communication to the environment, including low permeabilities and the potential for self-sealing, based on its ductility properties. Although current studies of shales and other fine-grained sedimentary materials are still at the generic stage, considering what will be necessary to move toward more definitive studies and concepts is important. In the United States (U.S.), defining shale behavior at depths and pressures likely to be encountered when constructing a working waste repository is a major consideration for an underground research laboratory (URL). Evaluating the justification for a U.S. URL begins with a summary of geological units classified as shale. Existing European URLs provide an invaluable resource for advancing understanding, but knowledge gaps still exist. The rationale for a U.S. URL in shale is based on its ability to fill these gaps.

Comparing experiments in individual shale units and other fine-grained-sedimentary rocks can be complicated by currently used classification systems. Fine-grained geological

units encompass a wide range of materials, but variations in the physical properties and physical environment contribute to the behaviors of individual units. A number of classification systems describe fine-grained geological units. A knowledge of these different systems can help researchers avoid misunderstandings when communicating between disciplines. A detailed, geological description is valuable for understanding differences in lithological structure that may affect behavior and are not obvious from a description of physical properties. This characterization is the basis for accurately describing empirical relationships that define behaviors and for assessing the transferability of concepts between dissimilar units and environments.

Fine-grained geological units encompass a wide range of materials. Many variations in the physical properties and physical environment contribute to the behavior of individual units. The Cretaceous-age Pierre Shale from the Midcontinent region of the U.S. was used as a representative shale formation to compare to the European shale-hosted URLs of Mont Terri, ANDRAS, and Bure (Mol). The greatest material differences for the European URLs are between the nonindurated Boom Clay and the more indurated formations (Callovo-Oxfordian and Opalinus). Properties of the Pierre Shale often fall between the Boom Clay and the more indurated formations. Poorly indurated formations, such as the Boom Clay, have relatively high porosity, high water content, low elastic properties, and low strength properties (cohesion and friction). By contrast, the more indurated formations have lower porosity and, therefore, lower water content, higher elastic properties, and higher strength properties.

The numerical modeling of a preliminary design for a shale-hosted URL by using the properties of the Pierre Shale accentuates many of the existing knowledge gaps, which include:

- Understanding the development and sealing of fractures.
- Physical factors affecting radionuclide sorption and solubility.
- Relationships describing coupled THMC processes.
- Transferability of concepts between dissimilar materials.

The justification, design, and implementation of a shale-hosted URL in the U.S. must meet a number of major and minor milestones. The first major milestone is the general justification of a need for a U.S. URL, which depends on current knowledge gaps and the ability to fill those knowledge gaps through available means. If available means are considered insufficient and a U.S. URL in shale is considered justified, the second major milestone consists of general siting identification. This effort will define broad areas with qualifying conditions and omit areas with disqualifying conditions. Once broad areas have been defined, the effort of the third major milestone is the more specific classification and ranking of favorable and potentially unfavorable conditions. The more detailed classification of the third milestone includes physical properties, the physical system, and construction considerations.

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1. Introduction

The current project Statement of Work for the United States Department of Energy (USDOE) Shale Project consists of two main tasks:

1. The development of a detailed plan necessary for constructing and implementing an Underground Research Laboratory (URL) in shale and identifying long-term goals for work in shale repositories.
2. Compiling and evaluating existing concepts and information for the disposal of nuclear waste in fine-grained media.

Both tasks were addressed primarily in the main document associated with this project, *Preliminary Planning for Development of an Underground Research Laboratory in Shale*, which has been prepared under a separate cover. Assembling available information regarding shales in regard to nuclear waste issues was necessary to complete the main document, and substantial information on shale distribution, the identification of potential sites that are already developed in shales, and the relation of U.S. shales to those in European URLs was also compiled. Supplemental information not included in the main document is included herein.

This report consists of four chapters, and the first is the introduction. The second chapter briefly describes three European URLs developed in fine-grained geologic materials. The third chapter consists of a compilation of mines in the U.S. that can be used to evaluate the possibilities of developing a URL in shales intersected by their workings. The fourth chapter includes a compilation of properties of U.S. shales and acts as a resource tool.

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2. European Underground Research Laboratories Developed in Shales and Fine-Grained Geologic Media

The European experience with URLs in fine-grained geologic media is extensive and ongoing. Although several URLs are operating in Europe, the ones that are most applicable to the shale initiative are at Mont Terri in Switzerland, Bure in France, and Mol in Belgium. The geologic units investigated in underground laboratories span a range of geologic ages from the Jurassic to the Paleogene and include both relatively undeformed sedimentary rocks and rocks that have been involved in tectonic disturbances associated with the formation of the Alps. These URLs, which are also described in the main document, are summarized below.

2.1 Mont Terri Underground Research Laboratories, Switzerland

The underground rock laboratory at Mont Terri is located in the western Alps in Switzerland. This laboratory was established in conjunction with the construction of the Mont Terri tunnel and, therefore, has horizontal access, which simplifies operations substantially. The laboratory is developed in a formation, named the middle Jurassic Opalinus Clay, in a tectonically deformed unit. Figure 2-1 shows the location of the laboratory (labeled as “Felslabor” in the diagram). The Mont Terri laboratory is dedicated only to research and is not contemplated as a potential disposal facility.

The laboratory is located at a depth of 250 meters (m) below the surface, as shown in Figure 2-2, and has approximately 600 m of associated drifts. A wide variety of experiments, including deformation resulting from the excavation process, have been conducted in the laboratory. In particular, this laboratory has been a place to investigate the development of the Excavation Damaged Zone (EDZ) that results from the stresses induced at the free face when an excavation is produced at depth (Corkum and Martin, 2007).

2.2 Bure Underground Research Laboratories, France

The French URL is located toward the eastern margin of the Paris Basin, as shown in Figure 2-3, in a sequence of subhorizontal sedimentary rocks that were deposited in marine conditions during the upper Jurassic. Although most of the sequence consists of calcareous rocks, the laboratory is located in the lower part of the Oxfordian Formation shown in Figure 2-4 (Callovo-Oxfordian), and has a high clay content. Figure 2-5 shows an isometric view of the laboratory location in relation to the stratigraphy and local fault systems.

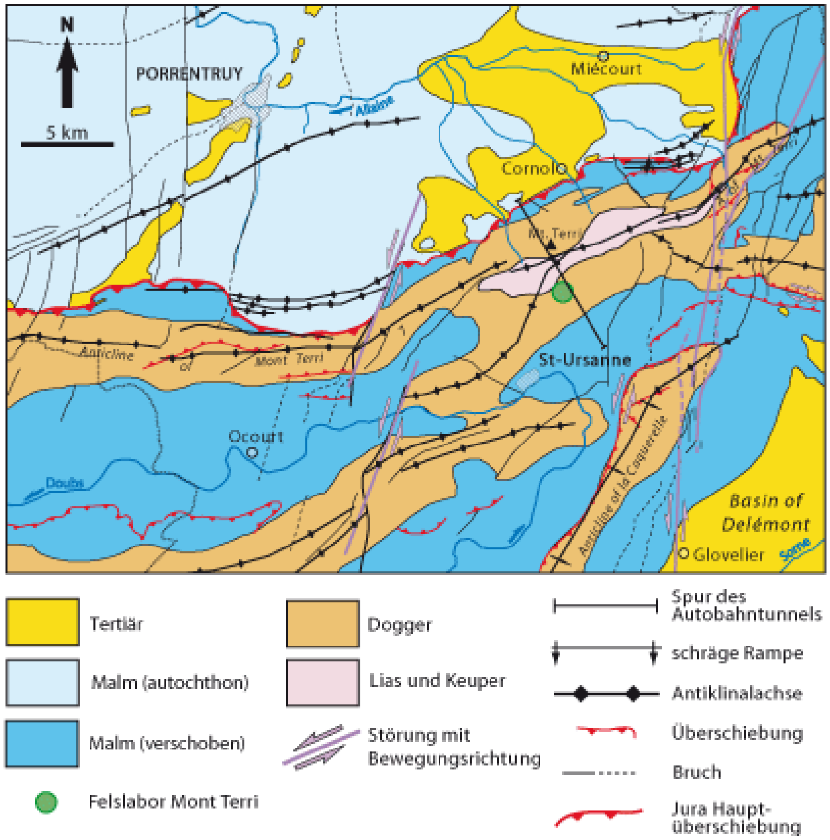


Figure 2-1. Geologic Map of the Location of the Mont Terri Laboratory (Felslabor) (The Laboratory is Developed in a Side Gallery of the Mont Terri Tunnel in a Middle Jurassic Claystone *http://www.mont-terri.ch*).

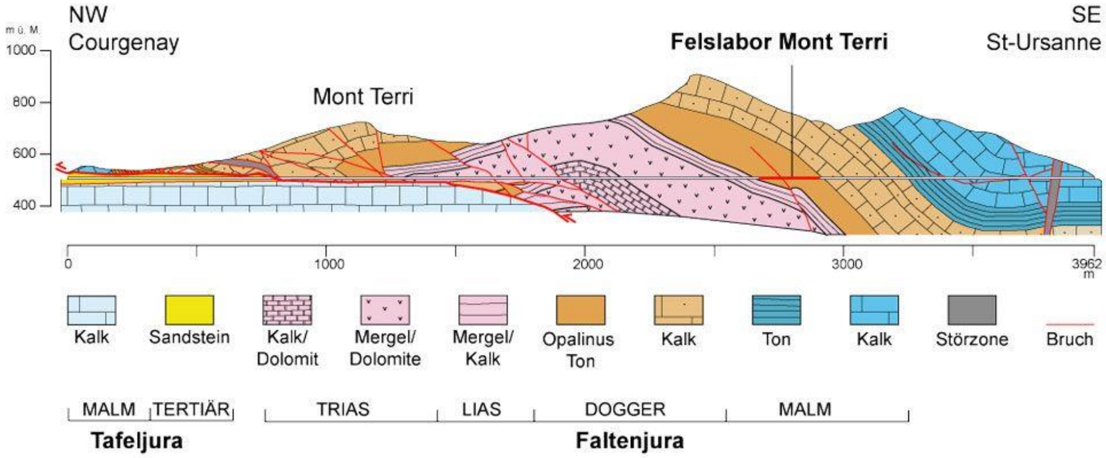


Figure 2-2. Cross Section Showing the Position of the Mont Terri Laboratory (Felslabor) With Respect to the Faulting That Deforms the Stratigraphic Section (*http://www.mont-terri.ch*).

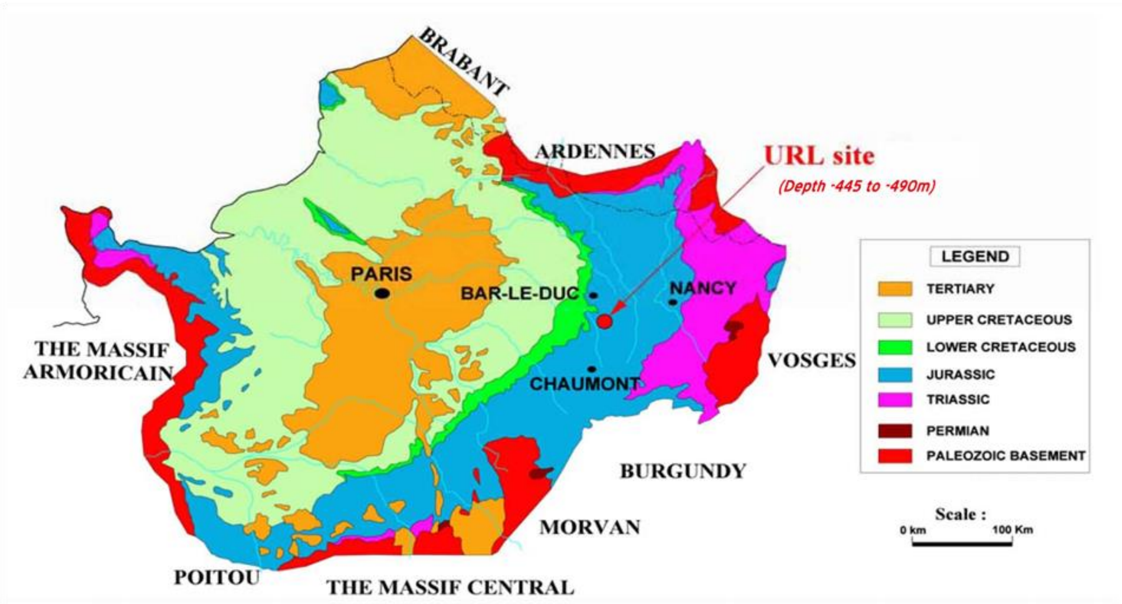
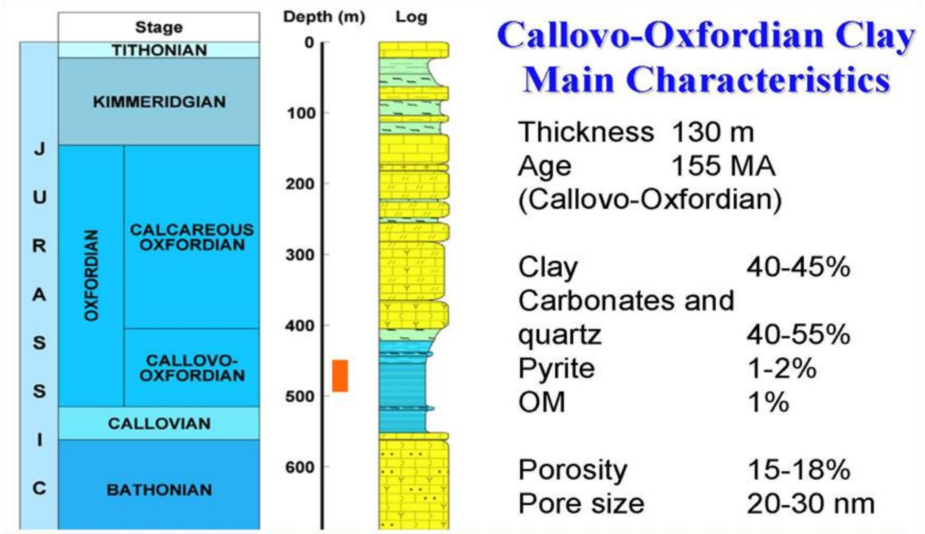


Figure 2-3. Location of the French Underground Research Laboratory ANDRA Along the Eastern Margin of the Paris Basin (After Delay, 2006).



Callovo-Oxfordian Clay
Main Characteristics

Thickness	130 m
Age	155 MA (Callovo-Oxfordian)
Clay	40-45%
Carbonates and quartz	40-55%
Pyrite	1-2%
OM	1%
Porosity	15-18%
Pore size	20-30 nm

Figure 2-4. Stratigraphic Section Associated With the French Underground Laboratory. The laboratory is located in a thick section of clay-rich upper Jurassic sedimentary rocks (rectangle shown adjacent to the depth scale) with a composition that is dominated by clay minerals with subordinate carbonates and quartz content (After Delay, 2006).

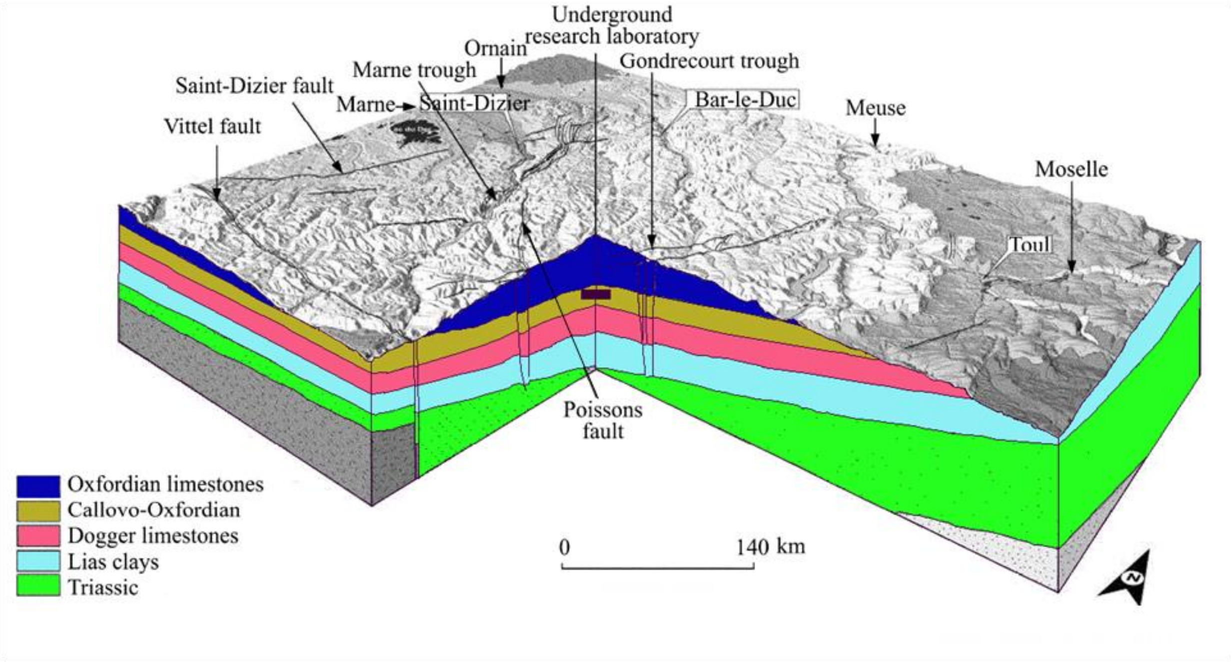


Figure 2-5. Isometric View of the ANDRA Facility in Northern France Showing the Relation of the Stratigraphic Section and Local Geology. The laboratory is developed in clay-rich deposits of Upper Jurassic age in the Paris Basin (Delay et al., 2010).

2.3 HADES, MOL, Belgium

This URL being developed in Belgium is located in the Boom Clay, which is a shallow marine Lower Oligocene unit and is shown in Figure 2-6. It consists of an alternating series of clays and clayey silts with occasional carbonate-rich layers and concretions (Lagrou et al., 2004). Even though the clays and silts tend to be plastic, some fracturing is present. Although the mechanism for forming the fractures is not well established, possibilities include regional tectonic uplift followed by erosion or possibly a combination of compaction and consolidation (Mendoza, 2004).

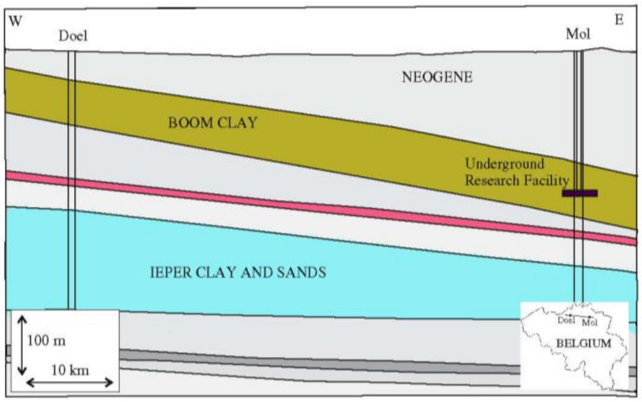


Figure 2-6. East to West Geological Profile of North Belgium Showing the Location of the Doel Borehole, the Mol-1 Borehole, and the Underground Research Laboratory (Huysmans and Dassargues, 2006).

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3. Investigation of Abandoned and Producing Mines for Disposal of Nuclear Wastes

The disposal of high-level radioactive waste in an underground location within shale host rock is being considered by several international organizations, including the French National Radioactive Waste Management Agency (ANDRA), the Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF), and the Swiss National Cooperative for the disposal of Radioactive Waste (NAGRA). To study this possibility in the U. S., an underground testing facility, similar to the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, may need to be located and established. Site characteristics relevant for this goal include depth, host formation thickness, areal extent, tectonic stability, and hydrologic conditions.

To identify potential locations for a U.S. URL in shale, a preliminary exploration of the available mine and stratigraphic data across the country, specifically in the Midwest, was performed. This supplemental report outlines relevant resources that have been identified and their extents and limitations. These resources include the Mineral Resource Data System (MRDS), the National Mine Map Repository (NMMR), the U.S. Geological Survey (USGS) National Coal Resource Assessment, the U.S. Energy Information Administration Annual Coal Report, and several other state and federal agencies. Additionally, some of the methods of searching for, and organizing the data, are included.

3.1 Mineral Resource Data System: http://mrdata.usgs.gov/mrds/

The MRDS is a product produced by the USGS that describes metallic and nonmetallic mineral resources throughout the world. The database can be accessed both with the USGS online search tool or downloaded as an excel file. The database includes deposit name, location, commodity, description, geologic characteristics, production, reserves, resources, and references. The MRDS contains 305,447 sites globally and 267,482 of them are located in the U.S.. Figure 3-1 shows the contiguous U.S. with red dots representing each mine or similar site recorded in the MRDS database.

These sites include large corporate mining operations, historic mining prospects, gravel pits, and many other related facilities. Coal mines, however, which are particularly interesting, because they are commonly associated with sedimentary rock like shale, are relatively absent within the MRDS.

Despite the sheer volume of data within the MRDS, it is limited in several pertinent areas. Although the depths of the underground mines listed in the database are an important consideration in site selection, it is not specifically addressed but it is ambiguously alluded to with a “production size” entry found on approximately 27 percent of entries. Additionally, stratigraphic information is limited within the MRDS. The gangue and host rock type of the underground sites are found in approximately 3 percent and 4 percent of entries, respectively. The MRDS does not include information regarding stratigraphic layering. The mine properties that are available within the database include:

- Region
- MRDS I.D.
- Site Name
- Region
- Country
- State
- County
- Commodity Type
- Commodity 1
- Commodity 2
- Commodity 3
- Operation Type
- Deposit Type
- Production Size
- Development Status
- Ore
- Gangue
- Other Materials
- Ore Body Form
- Work Type
- Model
- Alteration
- Concentration Processes
- Previous Name
- Ore Controls
- Reporter
- Host Rock Unit Name
- Host Rock Type
- Associated Rock Unit Name
- Associated Rock Type
- Structural Characteristics
- Tectonic Setting
- References
- Year of First Production
- Year of Last Production
- Discovery Year
- Production Years
- Discoverer.

The MRDS was used to organize mines according to characteristics relevant to nuclear waste disposal, such as operation type, production size, development status, and host rock type.

3.2 National Mine Map Repository: http://mmr.osmre.gov/

The NMMR, established by the Federal Coal Mine Health and Safety Act of 1969, is charged with maintaining an archive of all closed and abandoned mine maps throughout the U.S. Upon identifying mines of interest with the MRDS dataset, the corresponding mine maps were accessed within the NMMR when available. The vast majority of these maps are microfilm scans that lack information regarding stratigraphy. Figure 3-2 shows a map of Silver Wind Mine in Colorado and represents the quality and style of the maps located within the NMMR.

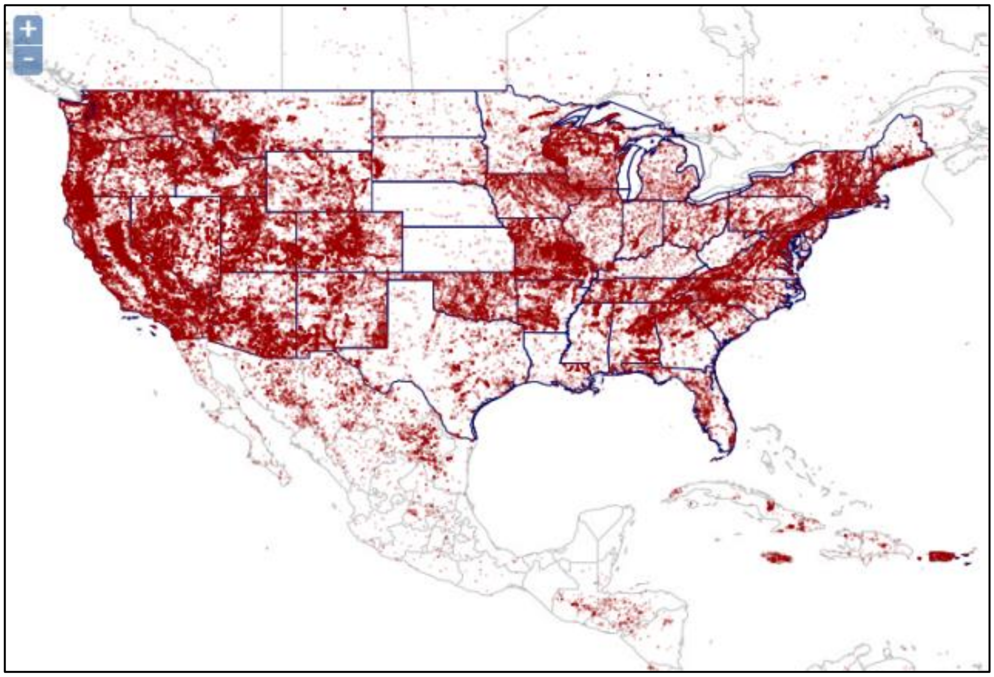

Figure 3-1. All Sites Recorded Within the Mineral Resource Data System Dataset in the Contiguous United States.

Figure 3-2. Representative Mine Map From the National Mine Map Repository.

3.3 U.S. Geological Survey National Coal Resource Assessment: http://energy.usgs.gov/Coal/AssessmentsandData/CoalAssessments.aspx

The USGS National Coal Resource Assessment contains folders with excel spreadsheets that describe drill hole data from 18,000 oil and gas wells in five different basins in the Northern Rocky Mountains and Great Plains Region: Carbon, Green River, Hanna, Powder River, and Williston. Figure 3-3 shows the full extent of the assessment's consideration, including those regions outside of the Northern Rocky Mountains and Great Plains.

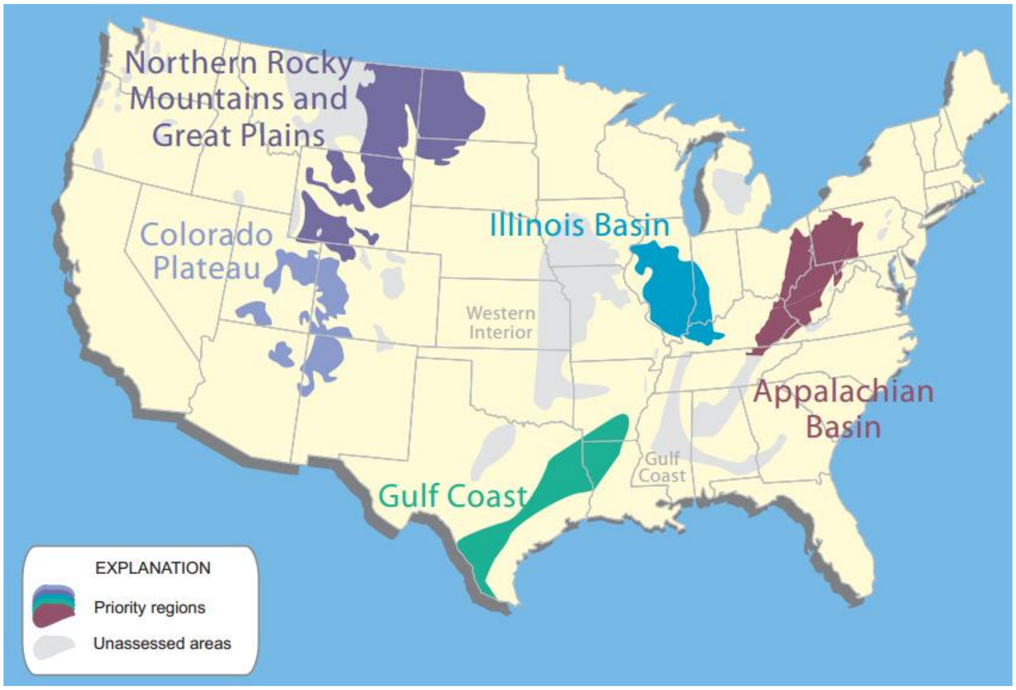

Figure 3-3. Map of the U.S. Geological Survey National Coal Resource Assessment Regions of Consideration Repository.

The assessment's information contains drill hole data including basin zone, location (elevation, latitude/longitude, northing/easting, township/range/section, county, and state), lithology type at depth, depth of bore hole, and data source. It also contains USGS Professional Paper 1625-A (*http://pubs.usgs.gov/pp/p1625a/*), which has chapters corresponding to information on each of the basins, including biostratigraphy, framework geology, land use and ownership, coal resources, and coal quality.

This information was used to develop and estimate the stratigraphy of mines by using the assessment's borehole data. Two boreholes located on roughly opposite sides of a given mine were compared and used to produce an estimate of the stratigraphic layering for the site of the mine. This linear interpolation method of estimating the stratigraphy at a particular site is approximate, but, given the data limitations, it is necessary.

Figure 3-4 is a map of an example mine, the Fire King Deposit, with boreholes JB80042 located to the northeast and JD900001CS to the southwest of the mine.

Figure 3-4. Google Maps Image of Two Boreholes (Red) and a Mine Between Them (Green).

Using the stratigraphic data available through the assessment from the two boreholes, the stratigraphy of the Fire King Deposit Mine was roughly interpolated by juxtuposing the two borehole stratigraphy graphs and connecting similar layers. The estimated stratigraphy of the Fire King Deposit was then developed according to the similar layer connections shown in the Figure 3-5 interpolation.

According to the linear interpolation method used, the stratigraphy of the Fire King Deposit mine can be expected to be similar to stratigraphy shown in Figure 3-5 with coal seams at approximately 140 feet and 170 feet. The depths and extents of sandstone, siltstone, and claystone would also be expected to be present in a similar fashion. This type of investigation can be used to assess the likely stratigraphy of mines where potential shale units have been identified. More advanced interpretation methods may be used to better define the thickness of applicable units.

The USGS National Coal Assessment's borehole data contains some of the stratigraphic information lacking in other sources. Pertaining only to the Northern Midwest and Rocky Mountains, the data is somewhat limited in its geographic area of coverage, but it is still beneficial for establishing a broader stratigraphic catalog.

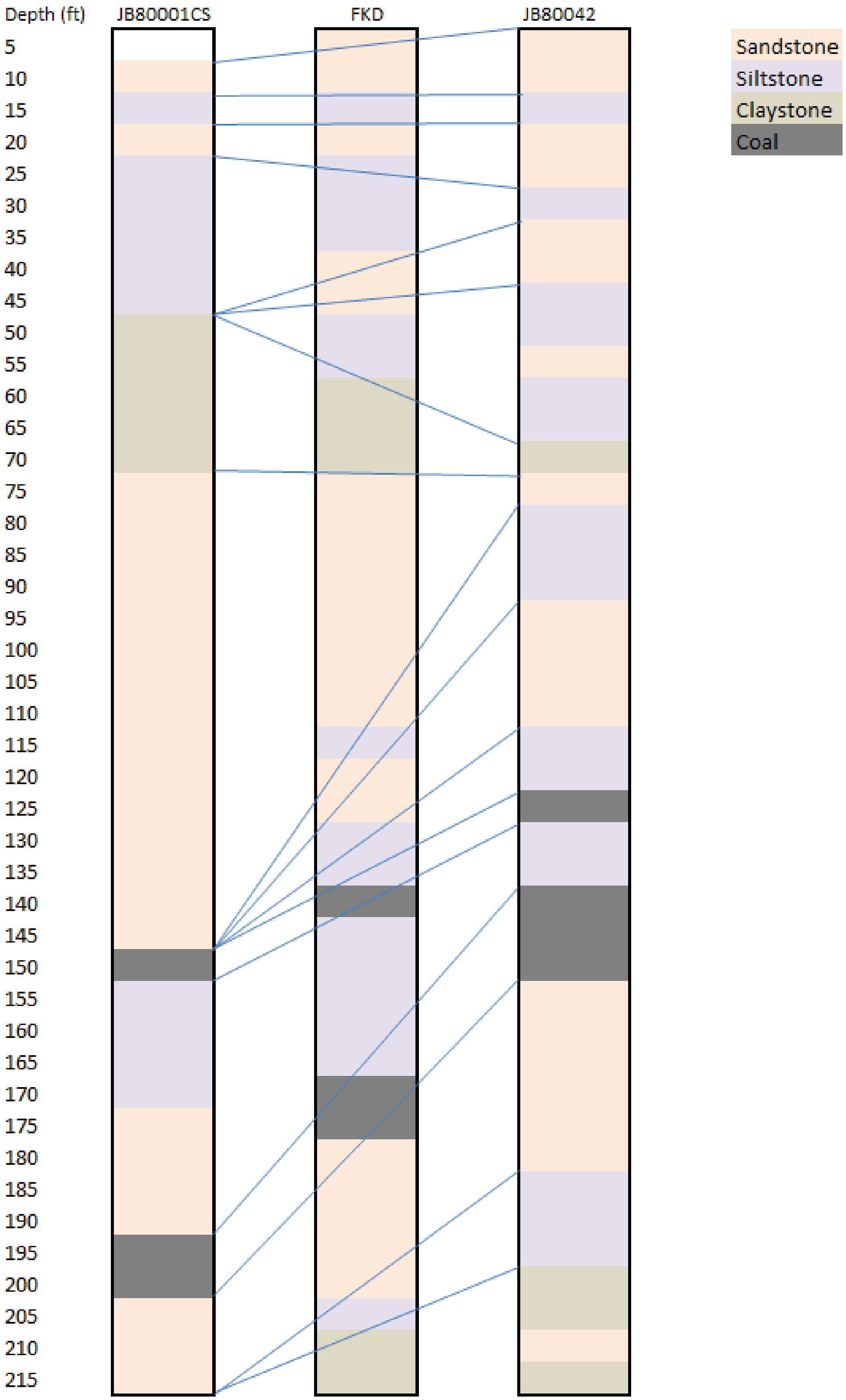

Figure 3-5. Interpolation of Fire King Deposit Mine Stratigraphy.

3.4 United States Energy Information Administration Annual Coal Report: http://www.eia.gov/coal/annual/

The ACR provides information about U.S. coal production, the number of mines, prices, productivity, employment, productive capacity, and recoverable reserves. The report is published by the U.S. Energy Information Administration (EIA). The 2011 report, published in November 2012, is the most current and most of the information provides a broader contextual understanding of current coal mine activity and production in the U.S.

The report is, in part, a summary of all currently producing coal mines in the U.S. and details 1,296 mines; 77 are west of the Mississippi. In addition to this summary, the report also outlines the mines' production, capacities, recoverable reserves, employment, productivity, domestic markets, average mine sales prices, and average consumer prices. Most of the focus of the report is on production. Figure 3-6 shows a comparison of the number of underground and surface coal mines in the U.S. from this 2011 report.

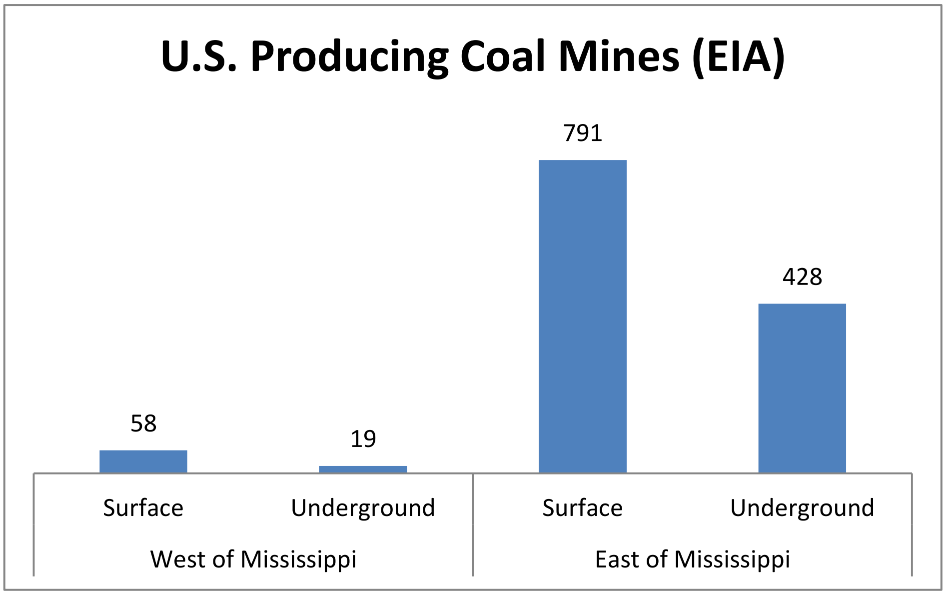

Figure 3-6. United States Producing Coal Mines to the East and West of the Mississippi River.

In conjunction with the information located within the MRDS, the EIA coal report provides a better understanding of the underground and surface mines in the U.S. As shown in Figure 3-6, the vast majority of currently producing coal mines, both underground and surface, are located east of the Mississippi River and are not located in the Midwest.

3.5 State and Other Government Mining Bodies

The following is a list of state and other government mining bodies that could serve as additional sources of information regarding mines and potential nuclear waste disposal sites:

- **Colorado**
  - Division of Reclamation, Mining and Safety – responsible for mineral and energy development, policy, regulation, and planning in Colorado. Operate under the division of the Office of Mined Land Reclamation and Office of Active and Inactive Mines. (*http://mining.state.co.us/Pages/Home.aspx*)
  - Colorado Geological Survey – has an extensive collection of publications pertaining to coal reserves and mines within the state. (*http://geosurvey.state.co.us/Pages/CGSHome.aspx*)
- **North Dakota**
  - North Dakota Geological Survey – The Geological Survey publishes maps and reports on the mineralogical, paleontological, and geochemical resources of North Dakota, including oil and gas, coal, uranium, clay, sand and gravel, volcanic ash, potash, and other salts. In addition to mapping subsurface resources, the survey is actively mapping the surface geology throughout the state with an emphasis on urban areas and identifying geohazards, such as landslides. (*https://www.dmr.nd.gov/ndgs/*)
- **Montana**
  - Montana Bureau of Mines and Geology (MBMG) – A nonregulatory state agency, the Bureau provides extensive advisory, technical, and informational services on the state's geologic, mineral, energy, and water resources. MBMG is increasingly involved in the studies of environmental impacts to land and water caused either by past practices in hard-rock mining or by current activities in agriculture and industry. (*http://www.mbmg.mtech.edu/*).
- **South Dakota**
  - South Dakota Geological Survey – Provides environmental monitoring and natural resource assessment, technical and financial assistance for environmental projects, and environmental regulatory services. (*http://www.sdgs.usd.edu/*)
- **Utah**
  - Department of Natural Resources – Divisions include the Geological Survey and Oil Gas & Mining. (*http://naturalresources.utah.gov/*)

- **U.S. Department of the Interior**
  - Office of Surface Mining (OSM) Reclamation and Enforcement – Responsibility includes establishing a nationwide program to protect society and the environment from the adverse effects of surface coal mining operations. OSM works with colleges and universities and other state and federal agencies.

3.6 Conclusions Regarding the Mine Database Compilation

Those resources and methods described in this report are reliable, government-sponsored sources of data and information pertaining to mines and potentially nuclear waste disposal. The MRDS is the most robust resource of mine data, because it is well supplemented by the NMMR, the USGS National Coal Resource Assessment, the U.S. Energy Information Administration ACR, and many other state and federal agencies.

4. Distribution and Properties of Shales in the United States

Clay and shale sites pose great potential for limiting the transport of radionuclides (Boisson 2005; Hansen et al., 2010). Their low hydraulic conductivities, high sorption properties, and reducing conditions make this geological media very favorable for nuclear waste disposal. In addition, they are typically highly ductile, which would help to seal fractures quickly, if they are created during excavation.

Radionuclides are transported through porous media by advection or diffusion, depending on the properties of the host rock and the individual radionuclides. Low hydraulic conductivity slows the advective transport of radionuclides. Fractures in the host rock will be created during excavation, which creates a region of enhanced hydraulic conductivity through the fractures. Rocks that exhibit ductile behavior are considered capable of sealing these fractures after excavations are backfilled, which limits the duration of fracture-enhanced conductivity. Clay minerals often possess a high, specific surface area, which allows sorption of radionuclides onto these surfaces and limits transport. Reducing conditions are beneficial, because most radionuclides possess low solubilities under these settings.

Fine-grained geological units are abundant and occupy over 50 percent of all sedimentary rocks in the preserved geological record (Boggs, 1995). Figure 4-1 illustrates numerous shale formations across the U.S.

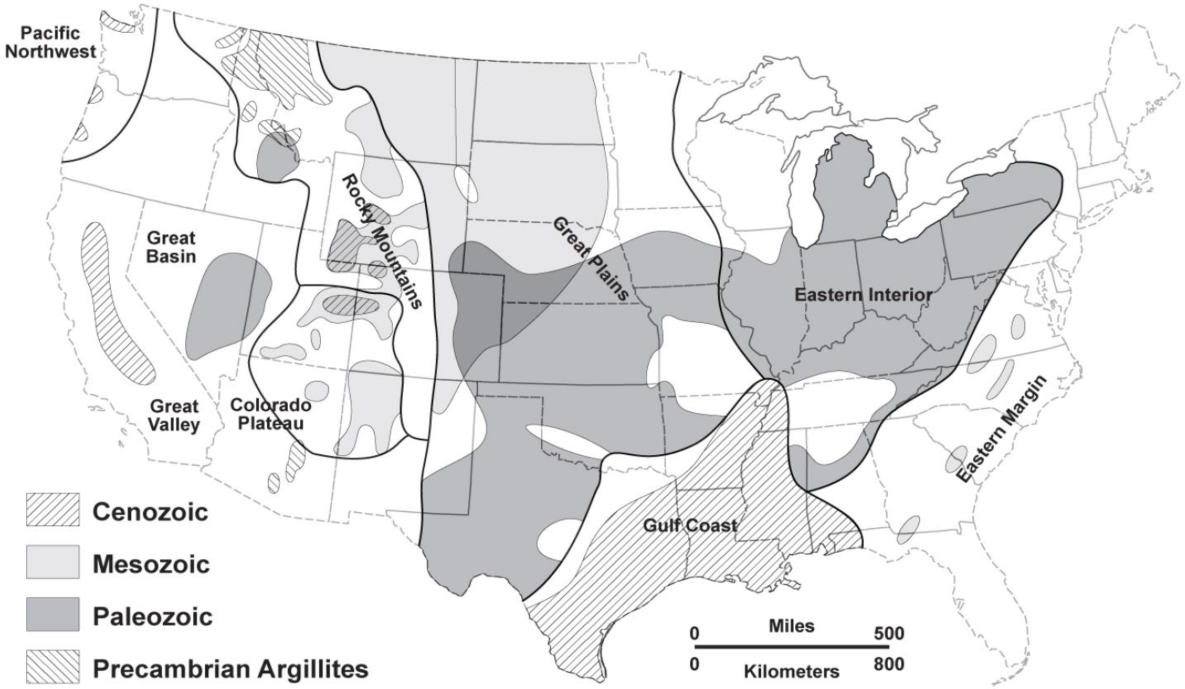

Figure 4-1. Areal Extent of Major Shale Formations in the United States.

It is very important to conduct an extensive literature review on the physical and chemical behaviors of shale media that exist in the U.S. before designing a nuclear waste repository. Only certain shale formations can be considered to host nuclear waste repository. The selection of host shale media highly depends on its location, physical, and chemical properties. This part of the study will summarize the information obtained from previous literature regarding existing shale formations in the U.S., their location, and physical and chemical properties.

4.1 Shale Media in the United States

4.1.1 Pierre Shale

Pierre Shale is one of the most widespread lithological units in the Northern Plains (Gries and Martin, 1985). It occupies the Mesozoic section of the Great Plains Province (Figure 4-1) and possesses many of the desirable features of a potential nuclear waste repository site. In many locations within the Northern Plains, the top of the Pierre Shale is less than 500 m below the surface and has a total thickness between 200 m and 800 m (Shurr, 1977). The Pierre shale is Cretaceous in age and is a highly overconsolidated clay with abundant slickensides and fissures (Neuzil et al., 1984).

The majority of information on evaluating shale media to host nuclear waste has been collected from the studies conducted in the 1970s and 1980s. These studies focused primarily on performing laboratory tests on different shale media to characterize their mechanical, hydrological, thermal, physical, and chemical properties (Kopp, 1986; Gilliam and Morgan, 1987; Ho and Meyer, 1987). The following tables and figures summarize many of the physical and chemical properties of the shale formations collected from previous studies. Table 4-1 indicates the general information regarding the physical and chemical properties of Pierre Shale. This information was obtained from Nopola (2013) and reports the range of the parameters and the average values. Table 4-2 represents the mineralogy and physical properties of Cucaracha Shale obtained from Alonso and Pineda (2006).

4.1.2 Eagle Ford Shale

Eagle Ford Shale (EFS) is in the southern region (Texas) of the U.S. The thickness of the ESF in Ellis County, Texas, varies between 91.4 and 129.5 m (300–425 feet) (Dutton et al., 1994). It has a high swelling potential because its smectite content is high (Hsu and Nelson, 2002). Its color is tan/brown near ground surface. Hsu and Nelson (2002) indicated that EFS has a high swelling potential, compressibility, and creep deformation. It is classified as high plasticity clay (CH) according to the Unified Soil Classification System (USCS). Table 4-3 shows that ESF has a high plasticity index. The physical/chemical properties of ESF were obtained from Hsu and Nelson (2002) and are also summarized in Table 4-3. Hsu and Nelson (2002) also provided mechanical properties of EFS. It is classified as extremely weak to weak rock, and Tables 4-4a and 4-4b summarize the index mechanical properties.

Table 4-1. Typical Properties of Pierre Shale Media

Geological Unit	Rock Classification	Mineralogy				Organic Content (%)	Porosity (%)
		Content of All Clay Minerals (%)	Content of Smectite (%)	Content of Mixed Layer of Smectite/Illite (%)	Content of Carbonate (%)		
Pierre Shale	Bedded Clay Shale	35–80 (75)	0–60 (11)	5–60 (40)	0–90 (5)	05–13	10–40

Table 4-2. Index Properties of Cucaracha Medium

Geological Unit	Location	Clay Content (%)	Liquid Limit (%)	Plastic Limit (%)	Montmorillonite Content (%)	Other (%)
Cucaracha Shale	Panama Canal	32	55	27	Majority	Minority

4.1.3 Bearpaw Shale

The Bearpaw Shale also occurs over a large portion of North America (Pinyol et al., 2007). It has a high amount of montmorillonite clay minerals and has the highest plasticity (Wong, 1998). Table 4-5 summarizes the index properties of Bearpaw Shale medium in the U.S.

Table 4-3. Index Properties of Eagle Ford Shale

	Liquid Limit (%)	**Plasticity Index (%)**	**$CaCO_3$ (%)**	**Water Content (%)**	**Clay Content (%)**	**Smectite Content (%)**
Average	87	58	10	16	—	Approximately 50
Standard Deviation	20	18	7	2	—	
Coefficient of variation	0.23	0.31	0.7	0.13	—	
Range	39–140	16–113	2–39	4–25	38–88	
Sample numbers	377	377	119	1100	—	

Table 4-4a. Brazilian Tensile and Uniaxial Compressive Strength of Eagle Ford Shale

	Brazilian Tensile Strength (MPa)	**Uniaxial Compressive Strength (MPa)**	**Inclined Uniaxial Compressive Strength (MPa)**
Average	0.93	2.07	0.86
Standard Deviation	0.11	0.9	0.44
Coefficient of Variation	0.12	0.43	0.51
Range	0.72–1.12	0.44–5.82	0.06–1.65
Sample numbers	23	121	14

Table 4-4b. Undrained Shear Strength of Eagle Ford Shale

Confining Pressure (psi)	**1–50**	**100**	**200**	**300**	**400**	**500–-600**
Average	273	345	353	407	394	521
Standard Deviation	118	118	100	138	86	141
Coefficient of Variation	0.43	0.34	0.28	0.34	0.22	0.27
Range	106–577	114–642	124–579	129–781	269–525	322–850
Sample numbers	43	54	74	44	11	12

Table 4-5. Index Properties of Bearpaw Shale Medium (Pinyol et al., 2007)

Geological Unit	Location	Clay Content (%)	Liquid Limit (%)	Plastic Limit (%)	Montmorillonite Content (%)	Other (%)
Bearpaw Shale	North America	52	110	22	60	40

4.1.4 Barnett, Haynesville, and Fort Saint John Shale

Sone and Zoback (2011) provide some information on the clay contents and chemical compositions of the Barnett, Haynesville, and Fort Saint John Shale media and Table 4-6 lists this information. This data was obtained from laboratory experiments that were conducted on the samples collected from four different gas reservoirs. Sone and Zoback (2011) claimed that high clay content (35–40 percent) yields higher creep deformation, regardless of carbonate content. This study also indicates that creep strain does not depend on the confining (overburden) pressure.

Table 4-6. Clay Content and Chemical Compositions of the Barnett, Haynesville, and Fort Saint John Shale

Shale Media	Clay Content (%)	Carbonate Content (%)	Quartz-Feldspar-Plagioclase-Pyrite (%)	Total Organic Carbon Content (%)
Barnett–dark	30–45	0–6	48–61	4–5.8
Barnett–light	2–7	39–81	16–53	0.4–1.3
Haynesville–dark	34–43	21–29	34–38	2.8–3.2
Haynesville–light	22–24	51–54	23–26	1.7–1.8
Fort Saint John	34–42	3–6	54–60	1.6–2.2

4.2 Information About Index Properties of Multiple Shale Media and Their Locations

Stark and Eid (1994) conducted extensive laboratory testing to determine the drained residual strength of cohesive soils (32 samples). This study also focused on many different shale formations, and their index properties are summarized in Table 4-7.

Table 4-7. Index Properties of Shale Samples Obtained From Stark and Eid (1994)

Shale Medium	Locations	Water Content (%)	Unit Weight (kN/m³)	Liquid Limit (%)	Plastic Limit (%)	Clay Content (%)	Activity (PIICF)
Duck Creek	Fulton, IL	5.3	24	37	25	19	0.63
Chinle (red)	Holbrook, AZ	10.9	22.7	39	20	43	0.44
Colorado	Montana, MN	5.6	21.2	46	25	73	0.29
Mancos	Price, UT	4.9	24.5	52	20	63	0.51
Panoche	San Francisco, CA	12	20.2	53	29	50	0.48
Comanche	Proctor Dam, TX	11.5	23.1	62	32	68	0.44
Bearpaw	Billings, MN	15.7	21.8	68	24	51	0.86
Patapsco	Washington, D.C.	21.6	20.7	77	25	59	0.88
Pierre	Limon, CO	24.3	20.1	82	30	42	1.24
Lower Pepper	Waco Dam, TX	21	20.3	94	26	77	0.88
Cucaracha	Panama Canal	18.4	20.7	111	42	63	1.1
Otay Bentonite	San Diego, CA	27	17.6	112	53	73	0.81
Denver	Denver, CO	30.5	18.7	121	37	67	1.25
Oahc firm	Oahc Dam, SD	27.6	20.1	138	41	78	1.24
Claggett	Benton, MN	11.7	22.7	157	31	71	1.78
Taylor	San Antonio, TX	35.2	18	170	39	72	1.82
Pierre	Reliance, SD	42.8	17.7	184	55	84	1.54
Oahe bentonite	Oahe Dam, SD	35.4	18.9	192	47	65	2.23
Bearpaw	Ft. Peck Dam, MN	15.8	21.8	288	44	88	2.77

4.2.1 Del Rio Clay, Eagle Ford Shale, Taylor Marl, and Navarro Shale

Youn and Tonon (2010) worked on the effect of air-drying duration on the engineering properties of four clay-bearing rocks in Texas: Del Rio Clay, Eagle Ford Shale, Taylor Marl, and Navarro Shale. The locations of these media are shown in Figure 4-2.

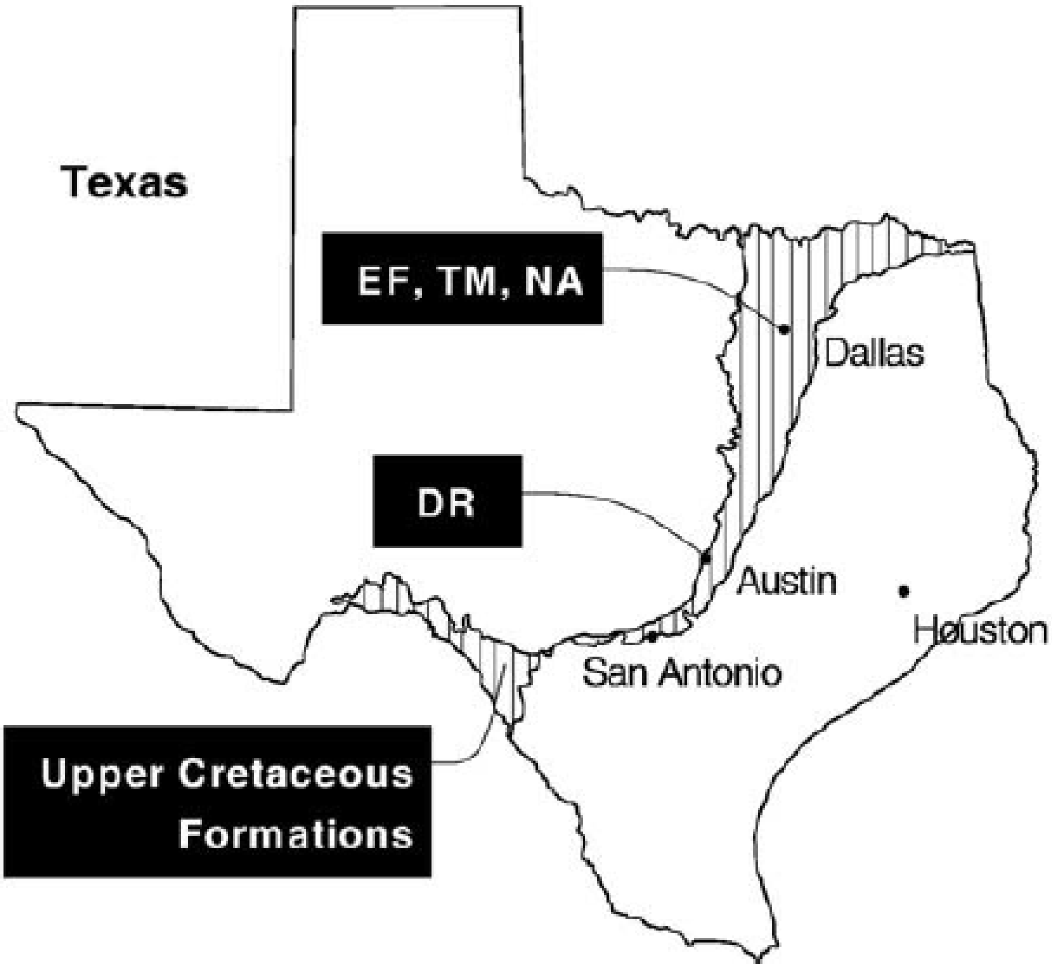

Figure 4-2. Locations of the Del Rio Clay, Eagle Ford Shale, Taylor Marl, and Navarro Shale (Youn and Tonon, 2010) (EF = Eagle Ford Shale, TM = Taylor Marl, NA = Navarro Shale, DR = Del Rio Clay).

Tables 4-8 and 4-9 summarize the physical/index properties and durability properties of these four different clay formations, respectively. Table 4-9 lists the durability strength of formations in a ranking system. "1" represents the most durable formation while "4" represents the least durable formation.

4.2.2 Lea Park Shale

Lea Park Shale consists of dark grey shale of upper Cretaceous age and lies immediately above the Colorado Group (Larsen, 2011). This shale is stratigraphically similar to the Pierre Shale that lies over a large portion of central North America. Physical properties and chemical compositions of the Lea Park Shale are presented in Tables 4-10 and 4-11.

Table 4-8. Index and Engineering Properties of Four Different Clay Formations

		Formations			
		Del Rio Clay	**Eagle Ford Shale**	**Taylor Marl**	**Navarro Shale**
Mineralogy	Illite (%)	38	30 (6–54)	8–16	2–5
	Kaolinite (%)	38	24 (3–48)	1–10	1–4
	Smectite/Montmorillonite (%)	25	45 (14–74)	66-82	89-93
Unit Weight (kN/m^3)		21.1	19.8	20.4	19.7
Dry Unit Weight (kN/m^3)		17.9	16.8	17	15.8
Water Content (%)		18.5	17.7	20	24.4
Liquid Limit (%)		52 (42–56)	47 (43–49)	56 (54–58)	64 (60–68)
Plastic Limit (%)		23 (21–24)	28 (25–31)	28 (26–30)	32 (31–34)
Cation Exchange Capacity (Meq/100 g)		23	20	29	41
Slake Durability Index (%)		32.3	66.9	57	0
Percent Water Loss as a Result of 48-Hour Air Drying		46	60	41	33

Table 4-9. Durability Properties of the Formations

Formation	**Durability**						
	Swelling Mineral Content	**CEC LL WC**	**Rate of Water Loss**	**SDI**	**Young’s Modulus**	**Fissile**	**Shear Strength**
Del Rio Clay	2	2	2	3	1	No	2
Eagle Ford Shale	1	1	1	1	4	Yes	1
Taylor Marl	3	3	3	2	3	Moderately when fresh	3
Navarro Shale	4	4	4	4	2	No when fresh	4

CEC = cation exchange capacity, LL = liquid limit, WC = water content, SDI = slake durability index.

Table 4-10. Chemical Composition of Lea Park Shale (Larsen, 2011)

	Quartz (%)	Feldspar (%)	Dolomite (%)	Calcite (%)	Clay Content (%): 23.7			Organic Material (%)
					Kaolinite (%)	Illite (%)	Smectite (%)	
Lea Park Shale	41.9	4.7	5.3	2.7	32.8	30.4	25.8	5

Table 4-11. Index Properties and Permeability of Lea Park Shale (Larsen, 2011)

	Liquid Limit (%)	Plastic Limit (%)	Water Content (%)	Total Dissolved Solids (g/L)	pH	Electrical Conductivity (mS/cm)	Permeability (nd)
Lea Park Shale	94.7	22.5	17	7.57	8.5	12.75	8-46

4.2.3 Colorado Shale

The Colorado Shale formation is located in Rocanville, Saskatchewan, Canada. This data is included in this report because it may be important to record the Colorado Shale physical properties. There is a large amount of Colorado Shale in the U.S., and the findings of this data might provide valuable input for further studies. Therefore, the results of Larsen (2011) are presented here, even though the studies are not conducted on the shale materials sampled in the U.S. Table 4-12 provides the chemical compositions and permeability of Colorado Shale collected from Rocanville, Saskatchewan, Canada. Larsen (2011) also provided detailed literature on the permeability of other similar types of shale media and these data are shown in Table 4-13.

Table 4-12. Chemical Composition and Permeability of Colorado Shale (Larsen, 2011)

	Quartz (%)	Calcite (%)	Pyrite (%)	Clay Content (%): 4.2			Phosphate (%)	Organic Material (%)	Permeability (nd)
				Kaolinite (%)	Illite (%)	Smectite (%)			
Colorado Shale	0.3	48.3	2.3	43.4	45.9	10.7	9.2	35.6	8–46

Table 4-13. Permeability Values of Similar Shale Formations

Formation	Test Type	Location	Permeability (nd)
Shale	L	Beaufort-Mackenzie Basin	0.2–19
Shale	L	North Sea	3–317
Shale	L	Scotian Shelf	0.1–16
Pierre Shale	L	Local	500
Pierre Shale	F	Regional	6,000
Pierre Shale	L	Local (Pulse Testing)	30–300
Pierre Shale	F	Regional (In Situ Testing	300–3,000
Lea Park Shale	L	Weybum, SK	0.1–1

L = laboratory testing, F = field testing, detailed information can be found in Larsen (2011).

4.2.4 Permeability of Green River Formation, Pierre Shale, and Devonian Shale

Myer and Christian (1987) studied the permeability and hydraulic conductivity of the Green River Formation under the different temperatures and pressures that are provided in Table 4-14. In contrast, Neuzil et al. (1984) indicated that the permeability of Pierre Shale and similar formations ranged from 10^{-18} to 10^{-19} m^2, and hydraulic conductivity of Pierre Shale is 2×10^{-12} meters per second (m/sec) .

Table 4-14. Hydraulic Conductivity and Permeability of Green River Formations Under Different Conditions (Meyer and Christian, 1987)

Test No.	Temp. (°C)	P_P (MPa)	P_C (MPa)	PP (MPa)	Hydraulic Conductivity (m/s)	Permeability (m^2)
1	24	10	20.7	6.4	1.61×10^{-16}	1.5×10^{-23}
2	74	11.2	20.7	6.2	4.83×10^{-16}	2×10^{-23}
3	130	10.5	21	6.9	4.23×10^{-15}	1×10^{-22}
4	137	11.1	21	6.6	5.96×10^{-15}	1.5×10^{-22}

P_P = pore pressure, P_C = confining pressure, PP = instantaneous pressure pulse.

4.2.5 Pierre I and Arco Shale

Al-Bazali et al. (2008) focused on the impact of strain rate on the failure characteristics of shales and provided detailed information on physical and chemical information for the Pierre I and Arco Shale formations. In this study, the Pierre I shale was an outcrop of soft shale with high moisture content, and the Arco shale possessed low moisture content and collected from a well in the northern U.S. Table 4-15 provides the chemical composition of these two shales. Table 4-16 represents the strength and Young's modulus of the two shales in different salt solutions.

Table 4-15. Mineralogical Composition of Pierre I and Arco Shale (Al-Bazali et al., 2008)

Components		Arco Shale	Pierre I Shale
Quartz		23.6	19
Feldspar		4	4
Calcite		—	3
Dolomite		1.2	7
Pyrite		2.4	2
Siderite		4.1	1
Clay	Chlorite	3.6	2.6
	Kaolinite	5.7	7
	Illite	15	12.2
	Smectite	11	10.9
	Mixed Layer	29.4	31.3
	Total	64.7	64
Water Activity		0.78	0.98

4.2.6 General Properties of Shale

Nataraj (1991) provides the general information about shale media presented in Table 4-17. The study is focused on Pierre Shale, Rhinestreet Shale and Typical Illite Shale.

Table 4-16. Strength and Young's Modulus of Pierre I and Arco Shale (Al-Bazali et al., 2008)

Shale	Solutions	Strength (psi)	Young's Modulus ($\times 10^5$ psi)
Pierre I	Natural	5,570	1.65
	Water	4,934	1.38
	$0.95 a_w$ NaCl	5,789	1.44
	$0.85\ a_w$ NaCl	6,556	1.83
	$0.75\ a_w$ NaCl	8,948	2.13
	$0.95\ a_w$ $CaCl_2$	6,258	1.56
	$0.85\ a_w$ $CaCl_2$	8,061	1.98
	$0.75\ a_w$ $CaCl_2$	9,600	2.12
Arco	Natural	6,000	2.62
	Water	1,600	1.28
	$0.95 a_w$ NaCl	2,600	1.4
	$0.85\ a_w$ NaCl	4,600	2.31
	$0.75\ a_w$ NaCl	4,700	2.47
	$0.95\ a_w$ $CaCl_2$	2,650	1.12
	$0.85\ a_w$ $CaCl_2$	3,300	1.92
	$0.75\ a_w$ $CaCl_2$	3,590	2.02

Table 4-17. Mechanical Properties of Pierre Shale, Rhinestreet Shale, and Typical Illite Shale

Shale	Pierre Shale	Rhinestreet Shale	Illite Shale
Bulk Density (kg/m^3)	0.02	0.02	0.02
Unconfined Compressive Strength (MPa)	6.5	25	30
Cohesion (MPa)	1	10	20
Friction angle (°)	10	15	20
Modulus of Elasticity (MPa)	200	3,500	2,000
Poisson's Ratio	0.2	0.2	0.02

4.2.7 Thermal Properties of Shales

Förster and Merriam (1997) studied the heat flow in the Cretaceous of northwestern Kansas and the implications for regional hydrology. They summarized the thermal properties of different shales, such as temperature gradient, thermal conductivity, and heat flow. Table 4-18 lists these properties for different shale formations and their lithologies obtained from Förster and Merriam (1997).

Table 4-18. Temperature Gradient, Thermal Conductivity, and Heat-Flow Density for Stratigraphic Units of Different Shale Formations (Förster and Merriam, 1997)

Shale	Lithology	Temperature Gradient (°C)	Thermal Conductivity (W/mK)	Heat-Flow Density (mW/m²)
Pierre Shale	Shale	65.8±4	1.2	79±2.2
Carlile Shale	Shale	51.4±2.1	1.2	61.7±1.6
Graneros Shale	Silty Shale	45.2±2.9	1.2–1.3	54.2-58.8±1.9
Kiowa Formation	Shale	49±3.5	1.2	58.8±2

4.2.8 Organic Carbon Content of Shale Media

Ho et al. (1987) provided detailed information on the organic carbon contents of the different shale media. This study specifically included Paleozoic Shales, Mesozoic Shales, and Cenozoic Shales. Tables 4-19 and 4-20 provide the organic carbon content of shales reported in Ho et al. (1987).

Table 4-19. Organic Carbon Content of Paleozoic Shales (Ho et al., 1987) (Page 1 of 4)

Shale	Location	Average Organic Carbon Content (%)
Woodford Shale	Oklahoma	8.9
Caney Shale	Oklahoma	7.2
Wolfcamp	Texas	4.08
Devonian Shale of Southwestern New York		
Angola	Chautauqua Co. (Core Samples)	0.31–1.31
Dunkirk	Chautauqua Co. (Core Samples)	0.73–2.8
Hamilton	Chautauqua Co. (Core Samples)	0.61–1.73
Hanover	Chautauqua Co. (Core Samples)	~0.4
Marcellus	Chautauqua Co. (Core Samples)	3.02
Pipe Creek	Chautauqua Co. (Core Samples)	0.45–5.09
Rhinestreet	Chautauqua Co. (Core Samples)	0.52–3.01
Angola	Cattaraugus Co. (Core Samples)	0.18–0.36
Cashaqua	Cattaraugus Co. (Core Samples)	1.38
Dunkirk	Cattaraugus Co. (Core Samples)	0.14–0.69
Geneseo	Cattaraugus Co. (Core Samples)	0.71–1.58
Hamilton	Cattaraugus Co. (Core Samples)	0.41–2.34
Hanover	Cattaraugus Co. (Core Samples)	0.17–0.93
Marcellus	Cattaraugus Co. (Core Samples)	1.31–5.09
Middlesex	Cattaraugus Co. (Core Samples)	1.71
Penn Yan	Cattaraugus Co. (Core Samples)	2.21
Pipe Creek	Cattaraugus Co. (Core Samples)	0.23
Rhinestreet	Cattaraugus Co. (Core Samples)	0.44–2.48
West River	Cattaraugus Co. (Core Samples)	1.58–1.8
Devonian Shale of Southwestern New York		
Angola	Erie Co. (Core Samples)	0.29–0.61
Cashaqua	Erie Co. (Core Samples)	0.52
Dunkirk	Erie Co. (Core Samples)	1.35–1.84
Hamilton	Erie Co. (Core Samples)	0.49–2.91

Table 4-19. Organic Carbon Content of Paleozoic Shales (Ho et al., 1987) (Page 2 of 4)

Shale	Location	Average Organic Carbon Content (%)
Java	Erie Co. (Core Samples)	0.69–2.9
Marcellus	Erie Co. (Core Samples)	2.62
Middle Sex	Erie Co. (Core Samples)	3.46
Rhinestreet	Erie Co. (Core Samples)	1.76–2.85
Cashaqua	Wyoming Co. (Core Samples)	0.63–0.77
Geneseo	Wyoming Co. (Core Samples)	1.84
Hamilton	Wyoming Co. (Core Samples)	0.44–1.41
Marcellus	Wyoming Co. (Core Samples)	6.23
Rhinestreet	Wyoming Co. (Core Samples)	1.78
West Falls	Wyoming Co. (Core Samples)	1.71–2.15
Cashaqua	Allegany Co. (Core Samples)	0.35
Dunkirk	Allegany Co. (Core Samples)	0.19–0.87
Geneseo	Allegany Co. (Core Samples)	3.41
Hamilton	Allegany Co. (Core Samples)	0.7–1.04
Marcellus	Allegany Co. (Core Samples)	4.45
Middlesex	Allegany Co. (Core Samples)	1.13
Penn Yan	Allegany Co. (Core Samples)	1.69
Pipe Creek	Allegany Co. (Core Samples)	0.2–0.98
Rhinestreet	Allegany Co. (Core Samples)	0.3–0.72
West River	Allegany Co. (Core Samples)	1.1
Geneseo	Livingston Co. (Core Samples)	0.14–1.81
Hamilton	Livingston Co. (Core Samples)	0.35–2.45
Marcellus	Livingston Co. (Core Samples)	6.67–14.23
Renwick	Livingston Co. (Core Samples)	0.21–0.38
Cashaqua	Steuben Co. (Core Samples)	0.28–0.55
Dunkirk	Steuben Co. (Core Samples)	0.7
Geneseo	Steuben Co. (Core Samples)	0.67–2.23
Hamilton	Steuben Co. (Core Samples)	0.3–3.09
Marcellus	Steuben Co. (Core Samples)	1.92

Table 4-19. Organic Carbon Content of Paleozoic Shales (Ho et al., 1987) (Page 3 of 4)

Shale	Location	Average Organic Carbon Content (%)
Middlesex	Steuben Co. (Core Samples)	0.44–1.52
Penn Yan	Steuben Co. (Core Samples)	0.85
Rhinestreet	Steuben Co. (Core Samples)	0.21–0.85
Geneseo	Yates Co. (Core Samples)	1.39
Hamilton	Yates Co. (Core Samples)	0.11–1.11
Marcellus	Yates Co. (Core Samples)	2.32
Devonian Shale *of* Southwestern New York		
Ashbed	Tompkins Co. (Core Samples)	0.26
Geneseo	Tompkins Co. (Core Samples)	0.54–1.21
Hamilton	Tompkins Co. (Core Samples)	0.25–1
Marcellus	Tompkins Co. (Core Samples)	0.51–8.8
Renwick	Tompkins Co. (Core Samples)	0.23–0.86
Geneseo	Cortland Co. (Core Samples)	0.8–1.31
Hamilton	Cortland Co. (Core Samples)	0.2–2.08
Marcellus	Cortland Co. (Core Samples)	1.89–5.18
Geneseo	Broome Co. (Core Samples)	0.43
Hamilton	Broome Co. (Core Samples)	0.14–0.47
Marcellus	Broome Co. (Core Samples)	1.3–6.86
Hamilton	Chenango Co. (Core Samples)	0.23–0.61
Marcellus	Chenango Co. (Core Samples)	0.65–2.24
Hamilton	Branagan Co. (Core Samples)	0.27–0.36
Marcellus	Branagan Co. (Core Samples)	0.65–3.68
Hamilton	Delaware Co. (Core Samples)	0.41
Marcellus	Delaware Co. (Core Samples)	1.63–2.81
Devonian Black Shale	Overton Co. Tennessee (Core Samples)	4.8–13.5
Black Shale	Rowan Co. Kentucky (outcrop samples)	0.4–15.5
Black Shale	Perry Co. Kentucky	4.3
Black Shale	Appalachian Basin	0.5-20
Black Shale	New York	4

Table 4-19. Organic Carbon Content of Paleozoic Shales (Ho et al., 1987) (Page 4 of 4)

Shale	Location	Average Organic Carbon Content (%)
Ohio Shale	Ohio	~ 25
Chattanooga Shale	Virginia	~25
New Albany Shale	Illinois	1–15.6
Blocher Shale	Illinois	1–15.6
Selmier Shale	Illinois	1–15.6
Gassy Creek Shale	Illinois	1–15.6
New Albany Shale-Kentucky	Rockcastle Co. (Core Samples)	10.3
New Albany Shale-Kentucky	Pulaski Co.	13.2
New Albany Shale-Kentucky	Adair Co.	12.9
Excello Shale	Midcontinent and Illinois Basin	10–15

Table 4-20. Organic Carbon Content of Mesozoic Shales (Ho et al., 1987)

Shale	Location	Average Organic Carbon Content (%)
Frontier Shale	Wyoming	1.99
Chinle Red Shale	Utah	0.02
Pierre Shale	Sharon Spring Member	8
Mowry Formation Shale	Wyoming	1-3
Frontier Shale	Powder River Basin, Wyoming	0.2–4.3
Colville Group Shale	Alaska	1–2
Pebbe Shale	Alaska	2–4
Torok Formation Shale	Alaska	1–2
Eagle Ford Shale	Dallas, Wood, Rusk, Denten Counties, Texas	15

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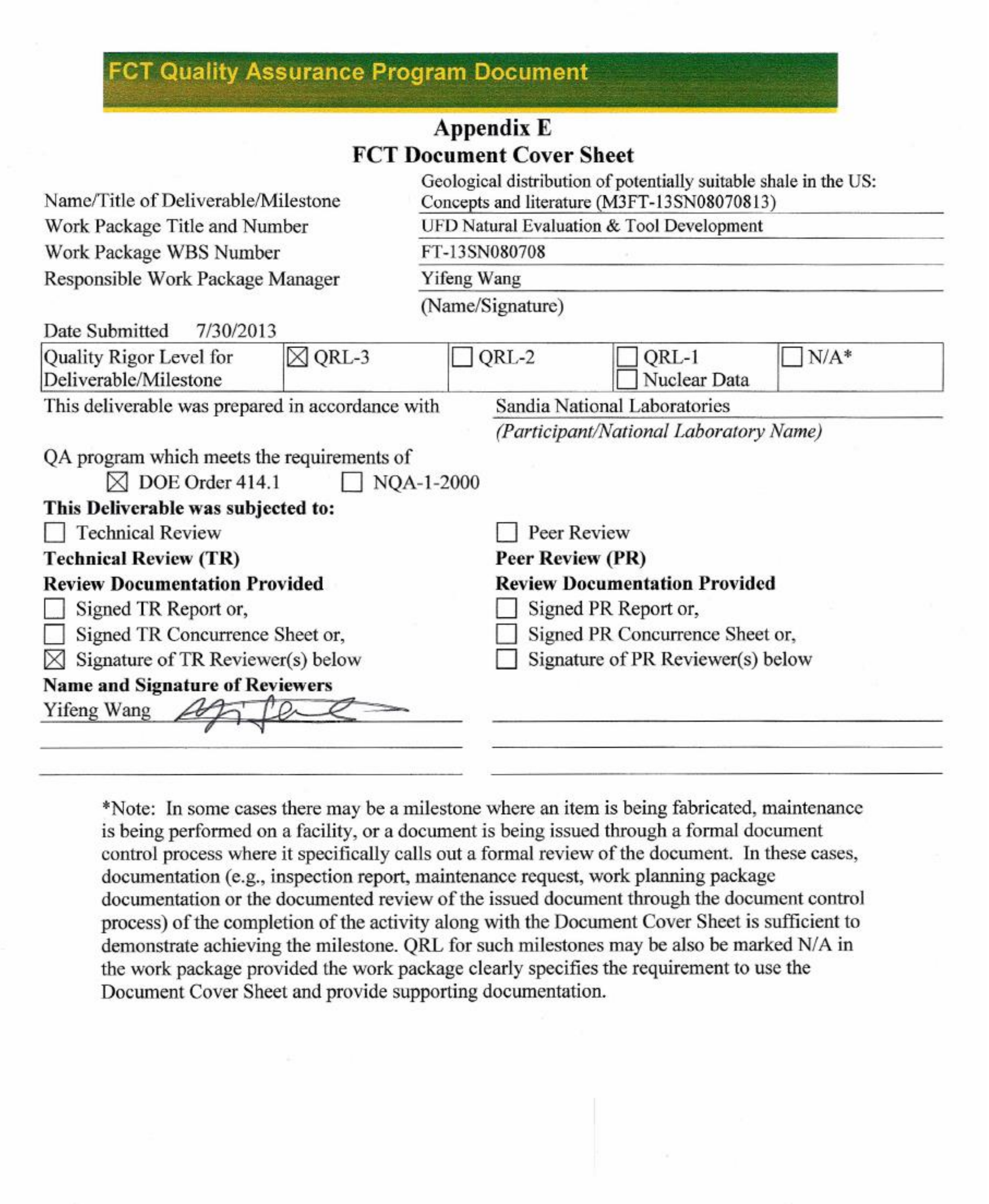
FCT Quality Assurance Program Document

Appendix E
FCT Document Cover Sheet

Name/Title of Deliverable/Milestone: Geological distribution of potentially suitable shale in the US: Concepts and literature (M3FT-13SN08070813)
Work Package Title and Number: UFD Natural Evaluation & Tool Development
Work Package WBS Number: FT-13SN080708
Responsible Work Package Manager: Yifeng Wang
(Name/Signature)

Date Submitted 7/30/2013

Quality Rigor Level for Deliverable/Milestone	☒ QRL-3	☐ QRL-2	☐ QRL-1 ☐ Nuclear Data	☐ N/A*

This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of
☒ DOE Order 414.1 ☐ NQA-1-2000

This Deliverable was subjected to:

☐ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below

Name and Signature of Reviewers
Yifeng Wang

*Note: In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity along with the Document Cover Sheet is sufficient to demonstrate achieving the milestone. QRL for such milestones may be also be marked N/A in the work package provided the work package clearly specifies the requirement to use the Document Cover Sheet and provide supporting documentation.