Regional Geology and Tectonic Hazards – FY 2011 Status Report

Fuel Cycle Research & Development

Prepared for U.S. Department of Energy
Used Fuel Disposition Campaign

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October 2011
FCRD-USED-2012-000002

Los Alamos Unclassified Release LA-UR 11-06562

FCT Quality Assurance Program Document

Appendix E
FCT Document Cover Sheet

Name/Title of Deliverable/Milestone: Regional Geology and Tectonic Hazards-FY11 Status Report

Work Package Title and Number: Regional Geology & Tectonic Hazard, FT-12LA080701

Work Package WBS Number: 1.02.08.07

Responsible Work Package Manager: Frank Perry Frank Perry
(Name/Signature)

Date Submitted 10/26/2011

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

This deliverable was prepared in accordance with Los Alamos National Laboratory
(Participant/National Laboratory Name)

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

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,
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ACRONYMS

BRC	Blue Ribbon Commission on America’s Nuclear Future
DOE	Department of Energy
EIA	Energy Information Administration
FY	Fiscal Year
GIS	Geographic Information System
HLW	High-Level Waste
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
MIT	Massachusetts Institute of Technology
NWMO	Nuclear Waste Management Organization (Canada)
R&D	Research and Development
SMU	Southern Methodist University
UFDC	Used Fuel Disposition Campaign
UK	United Kingdom
UNF	Used Nuclear Fuel
US	United States
USGS	United States Geological Survey

REGIONAL GEOLOGY AND TECTONIC HAZARDS – FY 2011 STATUS REPORT

1. Introduction

The Used Fuel Disposition Campaign (UFDC) has identified the need to build a spatial database to manage and analyze information concerning regional geology neccessary to support the site screening and site evaluation decision points identified in the Used Fuel Disposition Campaign Disposal Research and Development Roadmap (Nutt,2011).

This report documents initial work in FY11 for the Regional Geology and Tectonic Hazards work package. The objective of this work package is to construct a geographic information system (GIS) database for geologic features and potential siting factors. The database will provide information on alternative host rock that could serve as a feasible host for a high-level waste (HLW) repository, in terms of appropriate areal extent, depth and thickness. In following years, the information will be expanded to include additional information on the surrounding rock units and characteristics of the potential host formations. The GIS database will also incorporate data on siting factors and conditions that could potenially impact site selection and site characterization.

The UFDC is considering three alternative geologic host rocks for mined repositories (grantic, salt and clay-bearing rock) and crystalline (granitic) basement rock for deep borehole disposal (Nutt, 2011). Much of the work completed in FY11 was exploratory in nature to identify available and suitable spatial data for these alternative host rocks, identifying data for siting factors that would influence siting decisions, and exploring spatial analyis methods to visualize and analyze the intersection of geologic host rocks and other siting factors (e.g., tectonic hazards). At this early stage of the UFDC, and keeping with a philosophy of generic research and development (R&D), this work will make no attempt to design a site screening tool to screen specific sites or to suggest a specific set of siting guidelines. Instead, the objective of this work is to create a tool to better understand the distribution of suitable alternative host rocks at the regional scale and the potential siting factors or guidelines that could impact future siting screening and site selection activities and decision points.

Alternative geologic host rocks for the disposal of HLW have not been studied as part of DOE-sponsored R&D since passage of the Nuclear Waste Policy Act in 1987. Much of the original regional reconnaisance work to understand salt, shale and granitic rocks was before the advent of the widespread use of GIS. Therefore, the resulting data was not in digital format or stored in computer systems would allow a spatial analysis to be conducted today. These data (currently in the form of published maps and report figures) can be recovered, however, and digitized and converted to an appropriate GIS format for spatial analysis. In addition, much new data for alernative host formations (in particular shale) has become available in the past few years, much of it already in GIS format, that can be directly imported into a GIS database.

A GIS allows visualizaion and quanitative analyis of data layers and how features represented by the data layers spatially intersect at any length scale. Data layers can represent any data of interest for repository siting and site characterization, including different types of geologic rock types and their physical properties, geologic features and tectonic hazards, as well as cultural and political features including population distribution, transportatoin infrastructure, land ownership, etc. Data utilized in a GIS may already exist in a digital form that can be readily imported into the GIS, or be in an “analog” form such as maps or figures that documented information from earlier disposition studies. These types of data can be digitized and rectified for incorporation into GIS.

2. Data Sources and Adequacy

A review of data sources indicates that currently available data is probably adequate to represent the distribution of suitable alternative host rock formations at the national and regional scale. A large amount of data has been gathered since at least the early 1960s by the USGS, the DOE and its predecessors, university researchers and the oil and gas industry. More modern sources of data are often available as GIS formatted data and are readily imported into the GIS database. Older sources of data, including most of the previous regional survey work of potential host rocks by supported by DOE in the 1970s and 1980s are not in GIS format and must be digitized and converted to a suitable GIS format (see Section 3 of this report). A modern digital map of North America (Garrity and Soller, 2009) is available as a GIS database (http://pubs.usgs.gov/ds/424/) and is readily imported in the GIS to display crystalline plutonic and metamorphic (i.e., granitic) rocks or other potential host rocks exposed at the surface (Figure 2-1, 4-1). Digital maps are also available for all states if a greater level of detail is needed at the regional scale (http://tin.er.usgs.gov/geology/state/). In some cases, older geological data, such as depth to crystalline basement rock (Figure 4-2), has been digitized for use in applications such as geothermal energy R&D and is available by contacting university research groups (http://smu.edu/geothermal/).

We are incorporating individual formation-level data for sedimentary rocks (salt and shale) at the basin scale (Figure 2-2). Data for salt and shale is inherently more difficult to acquire because it is largely subsurface data. Exposures at the surface are often poor or non-existent (as is always the case for salt, and often the case for shale) and therefore geologic map data has limited use. The challenge with these rocks is to identify formations that have suitable depth and thickness to host a mined repository. Subsurface information on depth and thickness is generally dependent on drilling data that is most often obtained by the oil and gas industry and is generally proprietary. Synthesis of drilling data to determine depth and thickness of formations on broad regional scales has been done in the past by state geological surveys or bureaus of economic geology, or in regional surveys by the USGS. DOE contractors have synthesized data at the regional scale for salt and shale, but these data were published before the advent of widespread use of GIS and are presented as figures and maps that require digitization and conversion to appropriate GIS data format (see Section 3.2). A wealth of new subsurface data on shale formations has become available in the past few years due to increased exploration and production of natural gas from shale. Some of these data are available in GIS format (see Figure 4-5) from sources such as the USGS Energy Resources Program (e.g., National Oil and Gas Assessment Project (http://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment.aspx).

Data for regional and site conditions that could potentially be applied as siting guidelines are readily available in GIS format from well-established government or university sources. These data include seismic hazard data (USGS), natural resources data (USGS, EIA), population (census) data, digital elevation models for topographic analysis, geothermal gradient and land use (federal or protected lands), among others.

Figure 2-1. Geologic map of North America available as GIS formatted data (from Garrity and Soller, 2009).

Figure 2-2. Organic-rich shale basins of the United States (from NETL, 2010). Major bedded salt formations are associated with marine shales in many of these basins. Sedimentary basins are the organizing framework for gathering information on individual sedimentary formations for this work package.

3. Database Creation and Methods

Documentation of data will be implemented through creation of a GIS that will allow management, querying, analysis and display of relevant information that will impact future site screening and site evaluation decision points. GIS datasets were created for granitic rock distribution, depth to crystalline basement and selected occurrences of salt and shale using ArcGIS Desktop, Version 10.0. Work this year focused on identifying national and basin-scale data availability and importing these data into the GIS system for visualizing the spatial distribution of geologic data and siting factors. Methods were tested to visualize and analyze the intersection of geologic data and potential siting factors to begin documenting siting issues that could impact the site screening, site selection, and site characterization decision points (Nutt, 2011)

3.1 Database description

GIS databases for the geologic parameters discussed above are being constructed using the ArcGIS “file geodatabase” format. The file geodatabase uses an efficient data structure that is optimized for performance and storage. This system allows easy importation of spatial and tabular data from many different native formats and allows for easy extraction of data into many formats for future customer use. File geodatabases have no storage size limit. Individual datasets within a file geodatabase, such as a feature class or table, have a size limit of 1 TB, allowing for nearly unlimited attribution of data. In addition, both raster and vector data can be stored in the geodatabase. Much of the data obtained to date is already in an electronic format that can be loaded into the file geodatabase. These formats included ArcGIS coverages and shapefiles, Microsoft Excel tables, DBF files, or delimited text files. If electronic media is not available, paper media or published figures are processed by means of digitizing as described below.

3.2 Digitization methods

Published maps and figures showing various spatial parameters for features important to understanding regional geology and siting factors are being digitized and incorporated into the GIS databases. Paper maps are scanned at high resolution, saved as bitmaps (JPEG, TIFF, etc.) and loaded into the GIS software for on-screen digitizing. Figures from published sources are likewise imported into GIS software for on-screen digitizing. If the maps are available in digital format, they are loaded directly into the GIS software. The map images are rectified into spatial coordinates based on whatever system the map or figure was produced, if known. Intersection points of known latitude and longitude, if present, are used to rectify the image. Otherwise, other known geographic points such as state or county boundaries, cities, landmarks, etc. are used. Once the images are properly rectified, the data is then digitized using ArcScan, (a sub-program of ArcGIS) into points, lines or polygons and loaded into the file geodatabase as spatially correct features. The features are assigned attributes based on what parameters they represent (rock type, thickness contours, depth, etc.).

3.3 Projections

Geologic data and data for siting factors that have been included in the database to date are typically in a geographic coordinates system (i.e., degrees of latitude and longitude) that is straightforward to import into a GIS system. However, some of the datasets obtained are in various projected coordinate systems that are applicable to a continental scale, such as Lambert

Conformal or Albers Equal Area. The coordinate system and the projection of the data are not significant as long as they are known and properly defined in the GIS system.

Maps and figures produced from the database are typically projected into a system which best depicts the features of interest over the area in which the features exist. Common map projections include Universal Transverse Mercator (UTM) coordinates for local and regional maps and Lambert Conformal or Albers Equal Area for maps covering larger areas.

4. Distribution of Alternative Host Rocks

4.1 Overview

A primary goal of this work package is to populate a GIS system with data for the distribution of alternative geologic host media for disposal of HLW. For granitic host rocks, population of the database is relatively straightforward, and involves identifying surface exposures of appropriate rock types documented in geologic databases or maps and importing these data into the GIS. For salt and shale formations, the problem is more difficult as both types of deposits (particularly salt) are largely subsurface features not well exposed at the surface. It is therefore not simply a matter of bringing information from geologic maps into the GIS. These subsurface data are obtained primarily from drillhole information and interpretation of geologic relationships within sedimentary basins.

4.2 Granitic (Crystalline) Rock

Data for granitic rock in the contiguous United States were obtained from Garrity and Soller (2009), a digital database of the geology of North America (Figure 2-1). Granitic, or crystalline, rocks in this database are broadly divided into granitic (igneous) or gneissic (metamorphic) rock (Figure 4-1). Granitic rock types in the database include granite, felsite, intermediate plutonic rocks, and tonalite. Gneissic rock types include orthogneiss, paragneiss, tonalite gneiss, sedimentary and volcanic gneiss, and undivided gneissic rocks.

As described in Rechard et al. (2011), granitic rocks are found in several distinct geologic and tectonic settings within the contiguous US:

1. **Northern Appalachians:** Large areas of crystalline rocks exposed across much of upstate New York, New Hampshire, and Vermont that are part of the Phanerozoic crystalline rock terrains. The Adirondacks crystalline rocks represent a shield area.

2. Central and Southern Appalachians: Tectonically exposed Precambrian rocks forming considerable topography in the southeastern states of Virginia through Georgia. They are generally deformed and metamorphosed.

3. Central Midwest: Tectonically exposed crystalline basement rocks that form the Ouachita Mountains magmatic province of southern Oklahoma and the Llano uplift of central Texas.

4. Northern Midwest: Large areas of Wisconsin and Minnesota contain Precambrian crystalline rocks that are within the southern Canadian Shield.

5**. Rocky Mountains:** The mountain ranges running from the Canadian border to central New Mexico contain extensive crystalline-rock terrains.

6. Basin and Range: The region contains Phanerozoic crystalline-rock terrains that are highly faulted and covered by Tertiary volcanic rocks.

7. Pacific Coast and the Sierra Nevada: One of the largest regions of the US with outcrops of crystalline rock runs from the Mexican border through California and the length of the Sierra Nevada. There are also blocks along the coast south of San Francisco and across the California-Oregon border. The Cordilleran batholiths are marginal to Precambrian basement.

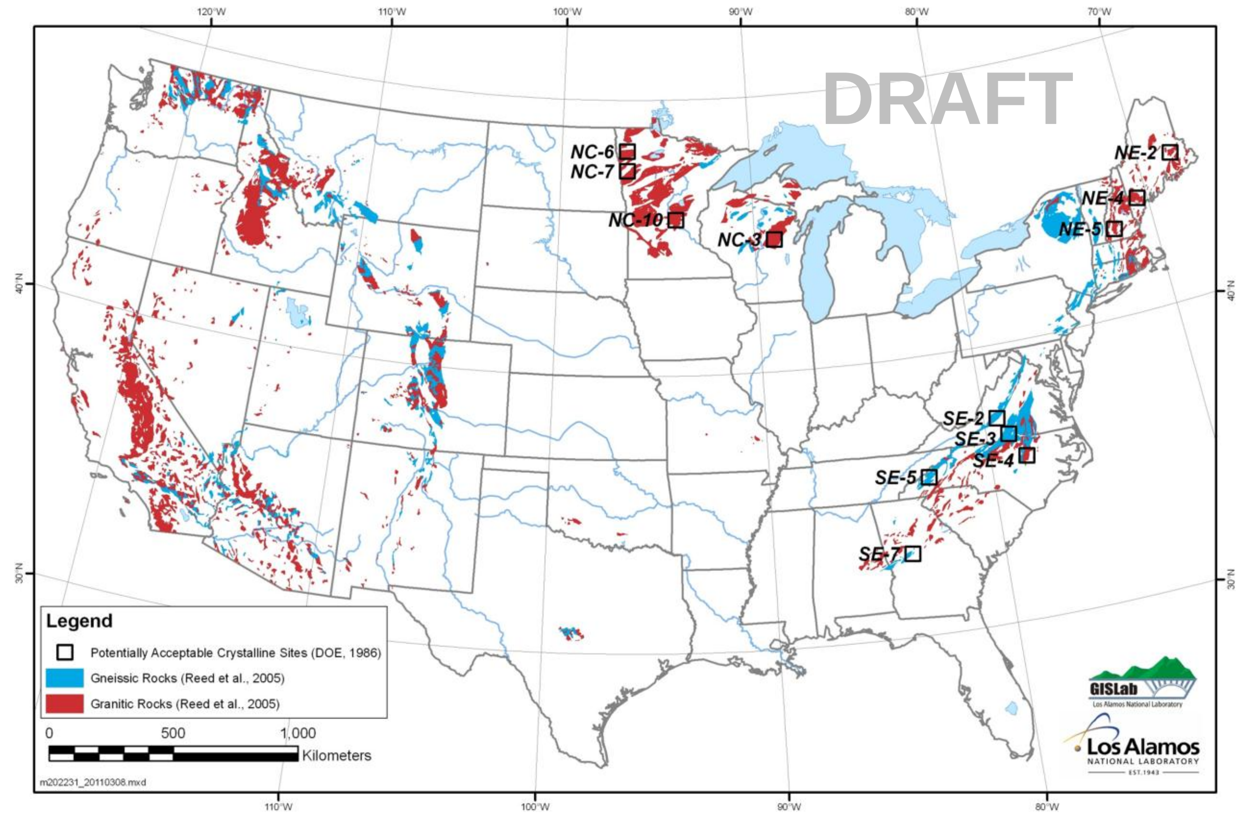

Figure 4-1. Surface exposures of granitic and gneissic crystalline rock in the contiguous United States. Shown for reference are the locations of the twelve Potentially Acceptable Crystalline Sites identified as part of the DOE Crystalline Repository Project of the early and mid-1980s (DOE, 1986).

4.3 Crystalline Basement Rock

Digital data for sediment thickness was obtained by contacting the Southern Methodist University (SMU) Geothermal Laboratory in Dallas (http://smu.edu/geothermal/) and importing the provided data into the GIS (Figure 4-2). This dataset contains approximately 216,000 x,y,z data points spanning much of the US. Each data point is directly equivalent to basement depth at that location. These data are the source for several figures published in recent reports on geothermal energy and deep borehole disposal (MIT, 2006; Brady et al., 2009). Data is not included for the tectonically active regions of the western US because sediment thickness and depth to basement is complex and highly variable over short distances due to intensive faulting. The x,y,z data will be used in GIS to produce a continuous surface model which represents the true elevation of crystalline basement at any location within the data boundaries.

Visualization of the data shows that much of the mid-Continent has crystalline basement rock within 2 kilometers of the surface (red-toned areas, Figure 4-2). This region is in general surrounded by deep sedimentary basins that typically contain salt or shale formations (green and gray-toned areas, Figure 4-2).

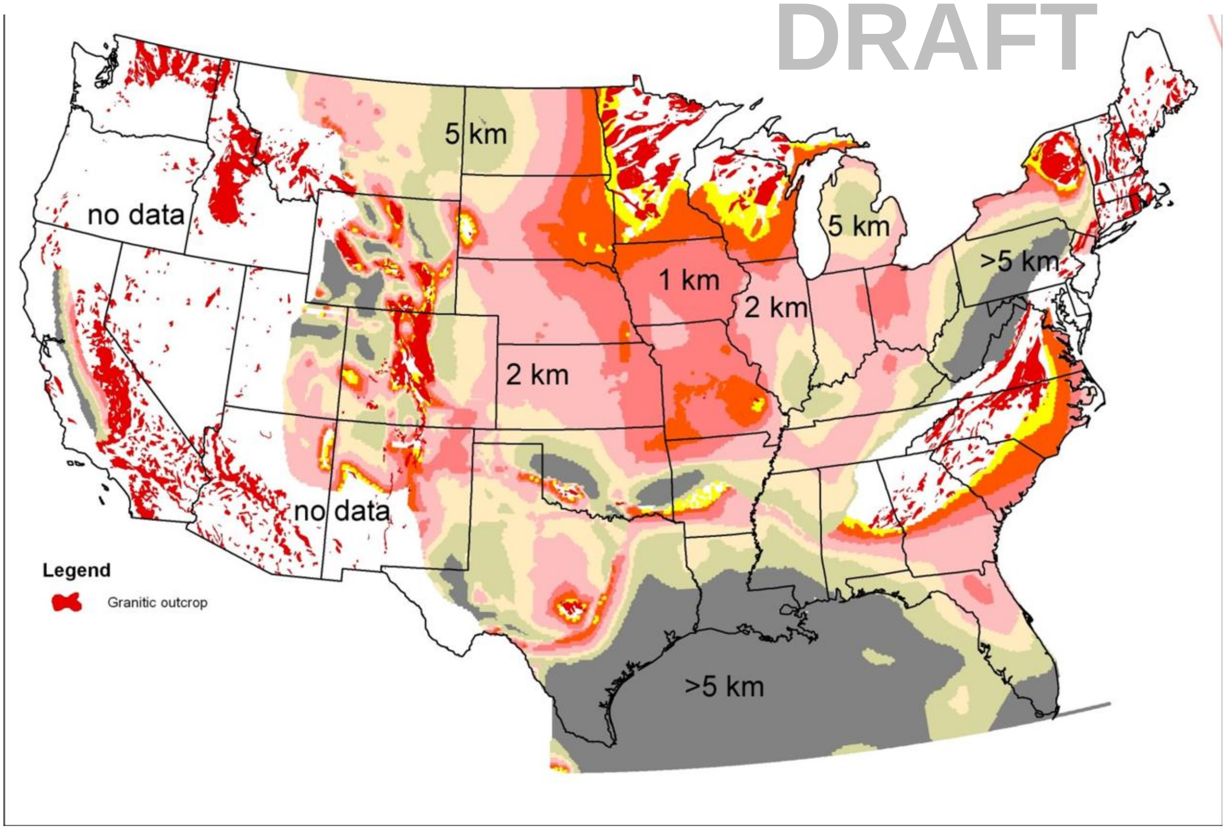

Figure 4-2. Contours for depth to basement and surface outcrops of granitic rocks (red) within the contiguous United States. Data for depth to basement obtained from SMU Geothermal Laboratory.

4.4 Salt

Information on the distribution of salt in the United States for purposes of HLW disposal is described in two major reports by Pierce and Rich (1962) and Johnson and Gonzales (1978). The map of salt deposits in the US presented by Johnson and Gonzales (1978) has been used extensively over the years to communicate salt distribution in the US (e.g., Figure 4-3). While useful as presented to easily communicate the overall distribution of salt in the US, it does not provide information about the true extent of salt or the depth and thickness of individual salt formations within major basins (e.g., the Permian Basin as depicted in Figure 4-3 is actually comprised of several distinct basins with different salt formations). Our goal is to use information provided in available reports and publications to document the actual extent, depth and thickness of individual formations present within the sedimentary basins of the US.

As an example, we are presently digitizing depth and thickness data for two salt units in the greater Permian Basin, the Hutchinson Salt of Kansas and Oklahoma, which lies within the Anadarko Basin, and the Salado Formation of southeastern New Mexico and Texas, which lies within the Midland and Delaware Basins (Figure 4-4, upper). The depth and thickness data were presented as figures in Johnson and Gonzales (1978) and Hovorka (1998). Digitization and importation into the GIS allows us to represent these salt units as three-dimensional bodies (Figure 4-4, lower) in relationship to the earth’s surface and analyze which parts of the units have suitable depth and thickness to potentially host a mined repository. Once the data has been digitized, all or parts of the salt unit can be visualized in a variety of ways (e.g. Figure 4-4, lower).

As part of assessing the regional geology of alternative host rocks, we are reviewing the occurrences of salt formations throughout the sedimentary basins of the U.S., beginning with the large amount of information included in Johnson and Gonzales (1978). This information is summarized in the following sections and in Appendix A. The descriptions are divided into those for bedded salts in major sedimentary basins, other (relatively minor) occurrences of bedded salt, and salt domes.

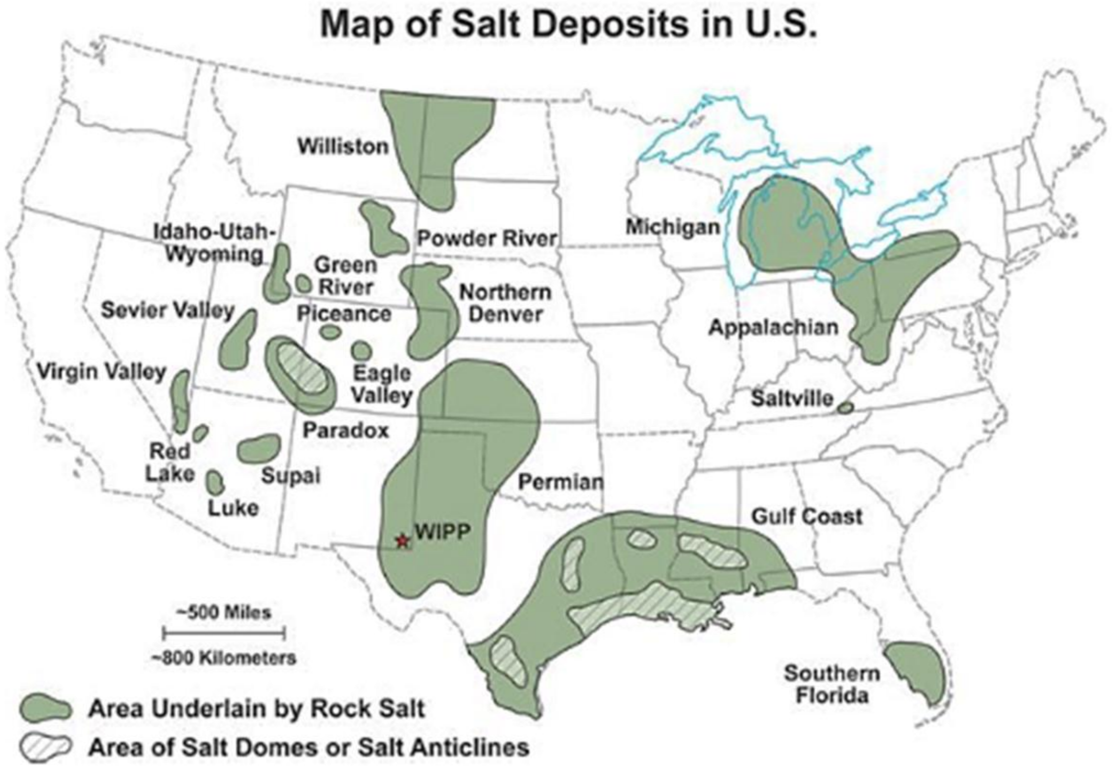

Figure 4-3. Map of salt deposits in the United States (from Hansen and Leigh, 2011, based on Figure 1 of Johnson and Gonzales, 1978).

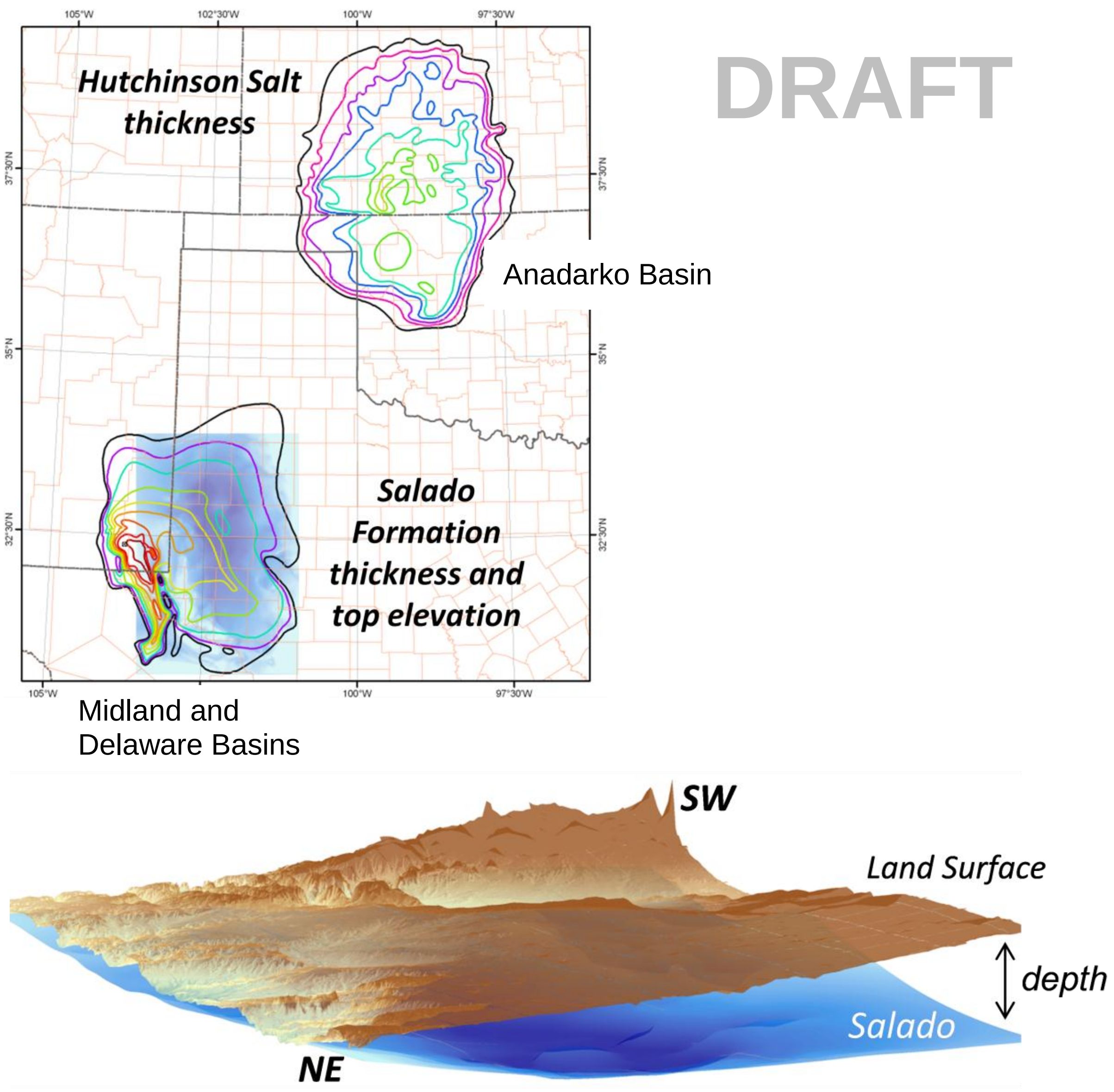

Figure 4-4. Depth and thickness data for the Salado Formation and Hutchinson Salt, Permian Basin. **Upper Figure**: Colored contours represent thickness data from Johnson and Gonzales (1978). Blue-shaded surface represents depth data for part of the Salado Formation (Hovorka, 1998). This work (still in-progress) will allow us to identify those parts of salt formations that have appropriate thickness (~50 meters) and depth (~300-1000 meters) to potentially host a HLW repository. **Lower Figure**: View from the northeast of surface topography and depth to the top surface of the Salado Formation using information depicted in the upper figure. The western edge of the formation in New Mexico is not included in these data.

4.4.1 Bedded Salt Formations in Major Sedimentary Basins

4.4.1.1 Michigan Basin

The Silurian to Devonian age Salinas Group, which contains several major salt beds in flat-lying sedimentary deposits, is about 5000 m thick and occurs across Michigan and parts of Illinois, Indiana, Ohio, and Ontario, Canada (Johnson and Gonzales, 1978). The salt beds, which range in thicknesses from a few meters to more than 150 m, are associated with carbonate, shale, sandstone, and anhydrite deposits. On average, the depth distributions of the salt beds below the ground surface are variable and range from 1800 m in the center of the basin to 150-300 m along the margins. In terms of tectonic history, the Michigan basin is little deformed and has insignificant folding and faulting.

Abundant fresh-water lakes and rivers plus major aquifers at shallow depth (< 100 m) and saline and mineralized waters at deeper sections characterize the hydrological conditions of the Michigan Basin. However, the subterranean water resources are well confined and they do not cause salt dissolution problems. Minor salt dissolution effects were noted in some of the shallow salt beds located along the basin margin. Oil and gas are major resources that occur within the sedimentary deposits that contain the salt beds. However, the resources are mostly confined to defined areas of the basin. Seismic hazard is low within the basin.

4.4.1.2 Appalachian Basin

The Appalachian Basin occupies a major NE-SW-elongated structural depression that was impacted by intense folding and faulting during the late Paleozoic. The Salinas Group of the Michigan Basin is also present within the Appalachian Basin and it consists of dolomite, shale, several salt beds, and anhydrite deposits. The basin covers a large region within the eastern interior from Tennessee through parts of Kentucky, Maryland, Ohio, New York, Pennsylvania, Virginia, and West Virginia (Johnson and Gonzales, 1978). Despite its occurrence close to the intensely folded and faulted Appalachian tectonic zone, earthquake and seismic hazard are low in the basin. Several salt beds occur within the Salinas Group sedimentary deposits and the aggregate thicknesses vary from 150 m at the margin to 750 m at the center of the basin. Individual salt beds are generally thinner (3-50 m) compared with the Michigan Basin deposits. For the uppermost deposits, the depth below the ground surface varies from about 300 to 900 m.

Annual precipitation and springs from glacial drifts dominate the hydrological resources of the Appalachian Basin. Moreover, bedrock aquifers and glacial drifts provide good quality water, indicating the absence of salt dissolution processes in the subsurface. Oil and gas in pre-Salinas Group sedimentary deposits are major economic resources for the region.

4.4.1.3 Williston Basin

Salt formations in the Williston Basin span a long period of geologic time. The halite units occur within the Devonian Prairie Formation, the Mississippian Madison Group, the Permian Opeche Formation, the Permian-Triassic Pine Salt, and the Jurassic Dunham Salt (Johnson and Gonzales, 1978). The basin underlies a large part of the North Dakota, eastern Montana, northwest South Dakota, and part of southern Canada. The Nesson and Cedar Creek anticlines are major structural features within the basin and they are closely associated with oil and gas production. The aggregate salt deposits in the basin vary from about 30 to 150 m and they generally occur about 1,500 m below the ground surface, except for the Permian-Triassic Pine Salt, which is known to occur at shallower depth (~900 m) along the south edge of the basin near the common corner of South Dakota, Montana, and Wyoming. Individual salt deposits over a large part of the basin vary from 12 to 50 m in thickness and pure halite deposits up to 90 m were reported within the Pine Salt deposit. Potash is commonly associated with the halite deposits

4.4.1.4 Permian Basin

The Permian Basin lies within a tectonically stable region with nearly flat-lying Permian and younger sedimentary deposits. The greater Permian Basin, loosely defined, consists of several structural sub-basins, the Delaware, Midland, Palo Dura, Dalhart and Anadarko Basins (from south to north).

The basin contains salts and other evaporites that are associated with red beds and carbonates. The salt deposits and other evaporates occur within the five principal structural sub-basins. Generally, these basins are filled with carbonates (limestone or dolomite), gypsum or anhydrite, salt and potash in ascending stratigraphic order. The Permian Basin has been stable since the formation of the evaporite deposits and there are no records of mountain-building processes or glaciations. However, dike intrusions probably related to the Rio Grande rift are known in the southeastern part of New Mexico. The basin contains eight principal salt-bearing formations with older salts confined to the north and younger salts occurring in the south. The salt beds are commonly interbedded with shale, anhydrite, and limestone or dolomite.

The principal salt deposits are the Hutchinson, Lower and Upper Clear Fork, San Andreas (Blaine) Formation, Artesia Group, Castile Formation, Salado Formation and Rustler Formation in ascending stratigraphic order. The salt deposits vary in thicknesses from 30 to 500 m and generally occur at a depth of 100 to 1800 m. Individual salt beds are generally thin (2 to 20 m) except in the principal salt-bearing Salado Formation, which is more than 600 m thick with individual salt beds 60 to 300 m thick and locally increasing to 500 m. The depth to the top of the bedded salts in the Salado Formation ranges from as shallow as 50 m in the western part of the basin to 300 to 750 m in most other parts of the basin. Salt dissolution at shallow depth occurs in the eastern part of the basin at depths of 150 to 250 m below the surface on the east side of the Permian basin.

East-flowing fresh-water rivers from precipitation and runoff and locally recharged by springs from the Ogallala and from Permian sandstone, gypsum, and dolomite aquifers flow across the Permian Basin. Average annual precipitation ranges from about 40 to 60 cm in the west to about 60 to 75 cm in the east part of the basin. Unlike the surface waters, groundwater in bedrock formations in the region contain strongly saline water within the exception of the Tertiary age Ogallala Formation, which is a major source of ground water throughout the High Plains region. Other fresh water resources occur within sandstone, limestone, and Quaternary terrace and alluvial deposits throughout the basin. Seismic hazard is low in the basin. Widespread occurrences of oil and gas, salt, potash, gypsum, and anhydrite resources occur within the basin.

4.4.1.5 Paradox Basin

The Pennsylvanian Hermosa Group of the Paradox Formation covers a region that is about 30,000 square kilometers in southeastern Utah and southwestern Colorado (Johnson and Gonzales, 1978). The flexural foreland basin that formed along the southwestern flank of the ancestral Rocky Mountain Uncompahgre uplift resulted in several northwest-southeast-trending salt-core anticlines that are mostly confined to the northeastern part of the basin (Trudgill, 2011). The Paradox Formation is about 2500 m thick and consists of salts, coarse clastic rocks, carbonates, shale, and anhydrite deposits. Generally, the depth to salt beds is about 1500 m and becomes relatively shallow along the salt anticlines. However, most of the deformed halite and associated rocks, which vary in thickness from 700 to 4000 m, form the core of the anticline. Salt dissolution occurrences were reported along the southeastern and western edges of the basin as well as along the crest of the salt anticlines. Despite its proximity to Basin and Range Province, the Paradox Basin lies within a region of low seismic hazard.

In the arid Paradox Basin, annual precipitation is very low but the Colorado and Green Rivers provide surface water resources. Quaternary alluvial and terrace deposits provide principal aquifers for good-quality groundwater resources. Apart from salt, potash, and other mineral resources, the Paradox Basin contains oil and gas resources.

4.4.2 Other Bedded Salt Deposits

There are at least thirteen small basins which contain bedded salt. Those located in the western US formed primarily within Tertiary lacustrine basin environments (Figure 4-3). These basins are briefly described below.

1. **The Supai salt basin** (Arizona): Contains salt-bearing deposits that range in thickness from 100 to 300 m. Individual salt beds are at least 6 to 12 m thick and are 300 to 750 m below the surface. The salt deposits have not been folded or faulted. Sinkholes and solution-collapse related to salt dissolution are present in southwestern part of the basin.
2. **Luke Basin** (Arizona) – A thick sequence of halite and shale at depth of 300 to 2000 m. An exploratory well provided information about the subsurface geology of the basin. In descending stratigraphic order, the sequence is 20 m of anhydrite cap rock, 150 m of halite with shale (0.6 to 2.4 m thick), 180 m of argillaceous halite, 150 m of halite alternating with argillaceous halite, 400 m of halite with shale (0.3 to 2 m thick), 60 m of halite, 30 m of halite alternating with argillaceous halite, and nearly 115 m of halite with sparse shale (0.3 to 2 m thick) in descending stratigraphic order.
3. **Red Lake Basin** (Arizona): About 1200 m of salt was drilled in one borehole, and the base of the salt was not reached. Gravity survey indicated that the mass of salt might extend about 20 km and might be as thick as 3000 m.
4. **Virgin Valley** (Nevada-Arizona): The salt deposit formed in an ephemeral lake environment within the Basin and Range Province and it is recent in age. It is associated with sand, silt, and clay. Three test wells indicated that halite was intersected from 620 to 915 m and from 560 to 1100 m and stopped in salt, whereas the third well encountered salt at 260 m and passed out of it at 610 m. The salt and adjacent rocks are locally deformed due probably to Basin and Range tectonics.
5. **Sevier Valley** (Utah): The salt deposit occurs in central Utah. Up to 60 m of salt was exposed at a quarry and estimated to be about 300 m in thickness. Even though the salt is brick red in color due to red clay, it is 95 to 97 percent halite. Exploratory wells intersected the salt deposit at variable depths that ranged from 1800 to 3600 m. The salt layers are generally thin (<20 m) except for the north-central area where more than 600 m of salt was encountered. The salt is generally deformed.
6. **Eagle Valley** (Colorado): The deposit consists of clastic and evaporite rocks on the western side of the Rocky Mountains in northwestern Colorado. Halite occurs 450 m

below the surface in association with anhydrite, shale, and siltstone to a maximum depth of 1600 m. The evaporite deposit is deformed.

7. **Piceance Basin** (Colorado): Two halite-bearing zones associated with nahcolite are known within the Parachute Creek Member of the Early Tertiary (Eocene) Green River Formation. Salt deposits of the Piceance basin are at moderate depth and individual layers are thin. Dissolution of the upper salt is probably an ongoing process.
8. **Green River Basin** (Wyoming): Salt layers of the Green River basin are usually mixed with trona and are thin (<1 m) units of almost pure halite that occur locally as part of a thicker evaporite bed.
9. **Idaho-Utah-Wyoming Borde**r: The halite deposit is interbedded with red shale, anhydrite, and limestone. It is impure and discontinuous and occurs in a structurally complex setting.
10. **Northern Denver Basin**: Rock salt occurs in the northern part of the Denver basin, in parts of western Nebraska, northeastern Colorado, and southeastern Wyoming. It is estimated to be about 200 m thick and it occurs at moderate depth (~900 m) below the surface.
11. **Powder River Basin** (Wyoming): The salt-bearing unit is 30 to 60 m thick and occurs in a deep (2000-4500 m) section in northeastern Wyoming. Individual salt beds are up to 10 m thick.
12. **Saltville Area** (Virginia): The rock salt is impure and heterogeneous and it contains fragments of shale, anhydrite, limestone, and dolomite. It occurs as a tectonic breccia in a tightly folded and faulted setting. Brine production has been active in the area.
13. **Southern Florida**: The thin salt beds (<3 m) are associated with anhydrite, limestone, dolomite, and minor amounts of dark shale. The salt beds were intersected in deep wells more than 3300 m below the ground surface. The depth and thickness of the salt beds are unsuitable to potentially host a mined repository.

4.4.3 Gulf Coast Salt Domes

4.4.3.1 North Louisiana Salt Dome Basin

At 13,000 square kilometers, it is the smallest of five dome-bearing basins that occupies the NW-SE-elongated North Louisiana Syncline. The basin is divided into small and large sub-basins that are separated by an E-W-oriented ridge. Nineteen salt domes, belonging to the Jurassic Louann Salt were found within the basin. Vertical diapirism of the Louann Salt began in the early Cretaceous and ceased by middle Cretaceous. However, local arching and faulting continued into late Tertiary. Studies of Quaternary deposits showed no significant tectonic movements. Four of the domes occur about 1000 m below the ground surface, whereas others occur at shallower depth (<320 m). Some of the domes have been utilized for LPG storage, whereas six of the domes have saline water at the surface. The salt domes are associated with carbonates, marls, chalks, anhydrite, clay, sand, and shale.

With average annual rainfall of 125 cm, one third becomes runoff into four major rivers that flow through the basin. Most domes show a potential for flooding from nearby swamps and lakes. Surface saline occurrences are related to upturned Cretaceous strata. Both fresh and brackish groundwater occurs within Eocene and Cretaceous aquifers, respectively, separated by impermeable Paleocene clays. The Eocene fresh water aquifer is under artesian pressure. No major seismic activity has been recorded within the basin but its proximity to the New Madrid fault zone is noted. Oil and gas are major resources in the basin. Salt, gravel and sand, gypsum, and anhydrite were also mined in the past. Most of the domes (15) are within 100 to 300 m of the ground surface. Some have been used for LPG storage, whereas others were mined for brine production.

4.4.3.2 Northeast Texas Salt Dome Basin

The basin is about 160 kilometers in diameter and major NE-oriented tectonic and depositional features bound the basin. Drilling in the basin identified 18 domes and the presence of an additional five domes is speculated. The domes are 1.5 to 8 km in diameter. Carbonates, evaporates, marls, chalks, anhydrite and sand and gravel occur as cap rocks or hosts to the salt intrusion. The parent Jurassic Louann bedded salt is about 6100 to 6700 m below the ground Four of the deepest salt domes occur at about 1000 m below the surface, whereas seven are at <200 m depth. A 0.006 mm/year uplift rate was estimated for the last 50 Ma and the domes have not been active since the late Tertiary based on detailed studies of Quaternary deposits.

The annual precipitation is about 110 cm, mostly contributing to runoff into major streams. Fresh groundwater is associated with the Eocene-age Wilcox Group that is generally intersected at about 700 m below the ground surface. Saline aquifers are present below at deeper levels but they are separated from the overlying fresh-water aquifer by the impermeable Midway clay. The Midway clay is not penetrated by salt domes.

Outside Alaska, the basin is one of the most prolific oil and gas producers in the US. These resources accumulated along structural and stratigraphic traps associated with Jurassic, Cretaceous, and Tertiary formations. Most domes are barren of hydrocarbon deposits; three are utilized for oil and gas production. Salt production was mostly confined to subsurface mining and salt springs. Other resources include sand and gravel and lignite. LPG was deposited in three of the domes and another is utilized for multiple industry usage. The basin has 18 known salt domes; 14 of them occur 300 to 1000 m below the surface.

4.4.3.3 Mississippi Salt Dome Basin

The basin runs from SE Louisiana across Mississippi to SW Alabama for a distance of 400 km. Uplifted structural blocks and faults bound the NW-SE trending basin. Part of the basin occupies the Mississippi alluvial plain, whereas the rest is within the Gulf Coast plain. The basin contains 77 known and suspected salt domes at various depths and 58 of the domes have cap rocks. Limestone anhydrite, clay, shale, and unconsolidated Quaternary sandstone with minor shale and carbonates are associated with the Jurassic Louann salt intrusion. The parent salt is at 6400 m and at 3165 m along the northern flanks of the basin. About 12 domes occur below 3000 m, whereas the rest are at 300 to 600 m below the surface.

The annual precipitation ranges from 130 cm to 160 cm and most of it is lost to evaporation or to runoff. Surface saline water or salt springs are uncommon in the basin. Fresh groundwater is abundant within Eocene-age sands and other fine-grained sediments in the basin at 750 m to 1200 m below ground surface. Seismic events are rare but the basin is within the same region as the New Madrid fault zone located to the north. Oil and gas are major resources in the basin and 11 of 77 domes are significant producers. Two domes were used for salt production and two others for LPG storage. Other resources in the basin include sand and gravel, clay, brick clay, and limestone for Portland-cement production. About half of the 77 salt domes exceed a depth of 300 to 1000 m below the surface, seven are utilized for industrial usage, and others are more than 600 m below the surface.

4.4.3.4 Texas-Louisiana Coast Salt-Dome Basin

Marine shales and clays dominate the stratigraphic sequence the Gulf Coast basin. The gulf-ward shift of the depositional axis of the basin started in the Jurassic and the center of the depositional environment moved from the Houston Embayment area of south Texas to south Louisiana during the early Tertiary. Sedimentation in the basin was controlled by growth faults. Salt diapirs and flowage have created complex geology in the Texas-Louisiana coastal basin. The basin contains more salt domes compared with the combined number of domes discovered in the four salt-dome basins described above. Stratigraphically, deltaic continental deposits interfingering with marine shales and clays are the dominant lithologic units associated with the salt domes. Most of the salt domes occur at about 1000 m below the surface except for four domes that occur at <360 m depth. One of the domes is shallower at 135 m and it is covered by thick cap rock that ranges in thickness from 80 to 160 m.

From west to east the annual average precipitation ranges from 100 cm to 125 cm and during hurricane season up to 60 cm of rainfall a day can occur. Flooding in the low-lying region is of concern during such occurrences. Principal fresh water aquifers in the Texas portion of the basin occur in 80 to 150 km-wide and 480 to 900 m deep Plio-Pleistocene sands that parallel the coast. Holocene sediments also provide fresh water resources. Seismic risk is low in the basin but the salt domes are considered tectonically unstable compared with those located in the interior basins. The basin provides the most prolific petroleum source in the United States and it is found within Tertiary, Cretaceous and Jurassic rocks. Salt domes and salt tectonics provided the structural traps for the oil and gas resources. Of the known 143 domes, 77 are utilized for industrial usage, including oil and gas storage and salt production. Native sulfur, sand and gravel, limestone, clays, and gypsum are other resources. Even though many salt domes occur within the basin only four out of 139 were considered favorable for additional investigation for storage of waste by Johnson and Gonzales (1978).

4.4.3.5 South Texas Salt-Dome Basin

This basin is the smallest of the coastal basins and is confined to the southeastern part of Texas. The basin occurs within the Rio Grande Syncline bounded by high-angle normal faults with up to 150 m of displacements related to salt flowage. Marine and continental deposits of Tertiary sands, clays, and sandstone associated with salt diapirs constitute the geology of the basin. Six salt domes, one of which is the deepest (4300 m) and the largest in the US, have been identified in the basin. Two other domes are at 1900 m below the ground surface and the shallowest is at 250 to 300 below the surface.

With annual average precipitation of 57 cm, the basin is within a semi-arid climate except for occasional tropical storms (hurricanes) that exceed the annual precipitation, resulting in major flooding. Typical fresh groundwater occurs at about 750 m even though saline water might be encountered at shallow depth. Seismic hazard is low. Major oil and gas production is from Tertiary limestone and sandstone reservoirs and the salt domes. Potash, gypsum, and low-grade uranium are known to occur within the basin.

4.5 Shale and Other Clay-Bearing Rocks

In collaboration with this work package, scientists at LBNL are surveying shale formations in the major sedimentary basins of the U.S. (Lui et. al., 2011, Section 3). As part of this collaboration, LBNL is supplying data on shale formations that will be incorporated into the GIS database to evaluate what formations or portions of formations are at the appropriate depth and have appropriate thickness to potentially host a HLW repository. An initial example is shown for structural contours on the top of the Eocene Green River shale in the Green River, Uintah and Piceance Basins of the Rocky Mountain region of Wyoming, Colorado and Utah (Figure 4-5).

Figure 4-5 displays two other pieces of relevant information, the distribution of granitic rock of the Rocky Mountains (in yellow) and the distribution of producing natural gas and oil fields (in black). This view highlights that shale formations or formations below the potential host formation are often targets of gas and oil exploration and production in sedimentary basins, a potential human intrusion issue for siting that has grown in importance with the recent expansion of natural gas exploration in the US. The risk of human intrusion from oil and gas exploration has been considered in the past few years and implemented as siting guidelines in the UK and Canada (summarized in Rechard et al., 2011, Section 5). See also Section 5.1 of this report.

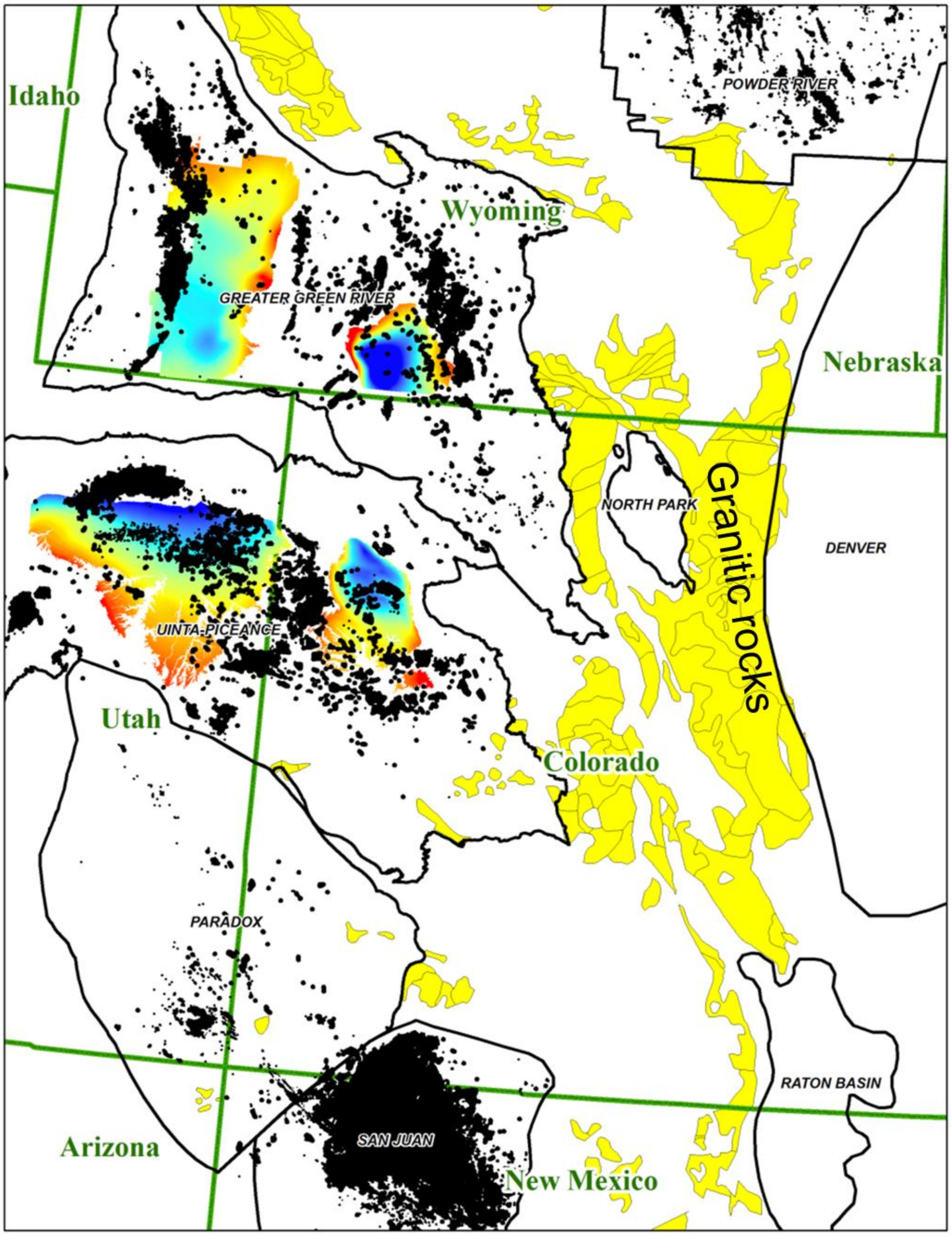

Figure 4-5. Representation of the upper surface of Eocene shale (Green River Formation) in the Green River, Uintah and Piceance Basins of Colorado, Utah and Wyoming. Red to Blue shading represents depth to the top of the formation (Red=shallow, blue=deep). Black patterns represent areas of natural gas and oil production. **Sources:** USGS Digital Data Series DDS-69-Y, DDS-69-BB and DDS-69-DD (USGS, 2010a, b; USGS, 2011).

5. Screening Guidelines and Distribution of Alternative Host Rocks

5.1 Introduction

The Draft Report of the Blue Ribbon Commission on America's Nuclear Future (BRC, 2011) recommended that:

> *Prior to launching a consent-based siting process, the implementing organization should develop a set of basic, initial siting criteria designed to ensure that time and resources are not wasted to investigate sites that are clearly unsafe, unsuitable or inappropriate for waste facility development.*

Other national programs have adapted this approach to siting in recent years, viewing it as an important initial step to create a fair, transparent and open siting process, as well as a method for determining relatively quickly (in a year or less) whether a site meets basic suitability requirements for proceeding to more detailed site selection and site characterization studies. Application of initial siting criteria recently implemented in the UK and Canada are discussed extensively in Section 5 of Rechard et al. (2011).

Siting guidelines adapted by many countries generally focus on the following issues:

- The natural system, including conditions related to geology, hydrology, geochemistry, topography and seismic activity that impact human and environmental safety;
- present and future land use, including conditions related to habitation and population density, resource extraction and agriculture;
- environmentally or culturally sensitive or protected areas such as parks, recreational and archeological sites and habitats of endangered species);

The Crystalline Repository Project (DOE, 1986) used the following criteria to down-select to potential candidate areas in region-to-area screening:

- Deep Mines and Quarries,
- Federal-Protected Lands,
- State-Protected Lands
- Population Density and Distribution

More recently, Canada entered into a consent-based waste management framework with communities expressing interest in undergoing an initial site screening based on the following initial screening criteria (NWMO, 2010):

- The site must have available land of sufficient size to accommodate the surface and underground facilities.
- This available land must be outside of protected areas, heritage sites, provincial parks and national parks.

- This available land must not contain known groundwater resources at the repository depth that could be used for drinking, agriculture or industrial uses, so that the repository site is unlikely to be disturbed by future generations.
- This available land must not contain economically exploitable natural resources as known today, so that the repository site is unlikely to be disturbed by future generations.
- This available land must not be located in areas with known geological and hydrogeological characteristics that would prevent the site from being safe

The initial siting criteria are intended to identify conditions at a potential site that would exclude it from for further consideration in the site selection process.

Siting criteria recently adapted in the UK and intended to be as broad and high-level as possible called for excluding any area that contained exploitable natural resources (coal, oil and gas, oil shale, industrial minerals and metal ores) or freshwater aquifers or shallow porous formations present at potential repository depths (Defra, 2008).

McEwan (2007) in reviewing recent strategies for site selection, concluded that intial siting criteria shoud be framed as relatively simple, high-level guidelines and should not be overly prescriptive

> *It is beneficial for any such criteria or guidelines applied at this stage of a site selection programme to be relatively simple, as for many areas or sites little is likely to be known about their geology and hydrogeology, except in the broadest terms. It is also likely to be counterproductive at this stage to set prescriptive criteria, with a few notable exceptions, and to make the selection process too formal, as this will result in a programme that will be rigid and unresponsive to change. Exceptions to this recommended lack of rigid criteria are provided by countries that have dynamic geological environments, e.g., Japan, where the existence of active faults, and the USA, where current igneous activity, provide obvious constraints on the location of a future repository.*

The planned approach for this work package is to consider siting guidelines that, based on prior experience of the US and other national programs, could reasonably be evaluated across broad regional areas using existing information and data. These guidelines will provide insight into the siting factors that would need to be considered at the site screening and site evaluation stages of repository development. Siting guidelines will be evaluated both singly and in combination with other siting guidelines, to determine their potential impact on the availability of alternative host rock formations at suitable depth and of sufficient thickness to host a mined repository.

5.2 Sensitivity to Siting Guidelines for Granite

Sensitivity studies can be used to quantify how application of siting guidelines could impact the availability of host rocks for different regions of the country. As an example of testing this technique, we calculated the impact of increasing the buffer size around population centers on the availability of granite in eastern and western states. 10 CFR 960.5-2-1, Population Density and Distribution, lists a Potentially Adverse Condition:

> *Proximity of the site to highly populated areas, or to areas having at least 1,000 individuals in an area 1 mile by 1 mile as defined by the most recent decennial count of the US census.*

DOE (1986) used this condition as one of several siting guidelines to screen for potentially acceptable sites for the Crystalline Repository Project (Figure 4-1).

Population density was chosen as an example of a potential siting guideline to explore GIS tools for testing the sensitivity of the availability of granite to variety of siting factors. For population, the contiguous US was arbitrarily divided into eastern and western states along the eastern state lines of Texas, Oklahoma, Kansas, Nebraska, South Dakota and North Dakota. Using census data from 2000, the country was divided into roughly 1 km grids and all areas with population density of at least 386 persons per square kilometer (equivalent to 1000 persons per square mile) were identified (Figure 5-1A). Because we were testing the potential impact of several possible siting guidelines, the granite dataset we used had been previously screened to exclude granitic rocks in areas with a higher probability of significant seismic ground acceleration (Figure 5-1E).

To quantify and visualize the effect of excluding granitic rocks in proximity to population centers, the radius of population buffer zones was varied from 0-50 kilometers in increments and the area of granite outside of buffer zones calculated for each distance increment (Figure 5-1B). The calculations produce curves that define the area of granite available as a function of the size of a buffer around population centers (Figure 5-1F). The curves comparing the eastern and western US show that the availability of granitic rocks in the eastern US rapidly diminish compared to the western states because of higher population in the east, as can be visualized in Figure 5-1B for a 25 km buffer zone.

Sensitivity to other potential siting guidelines can be similarly evaluated and visualized by varying a reasonable range of parameter values for each siting guideline and calculating the effect on the availability of alternative host rocks. In addition to population distribution, the full suite of siting guidelines could incorporate conditions that include seismic hazard, land use (e.g. federally owned or protected), presence of natural resources (e.g., oil and gas), topographic slope, and geothermal gradient, among others (e.g., Figures 5-1C, D and F).

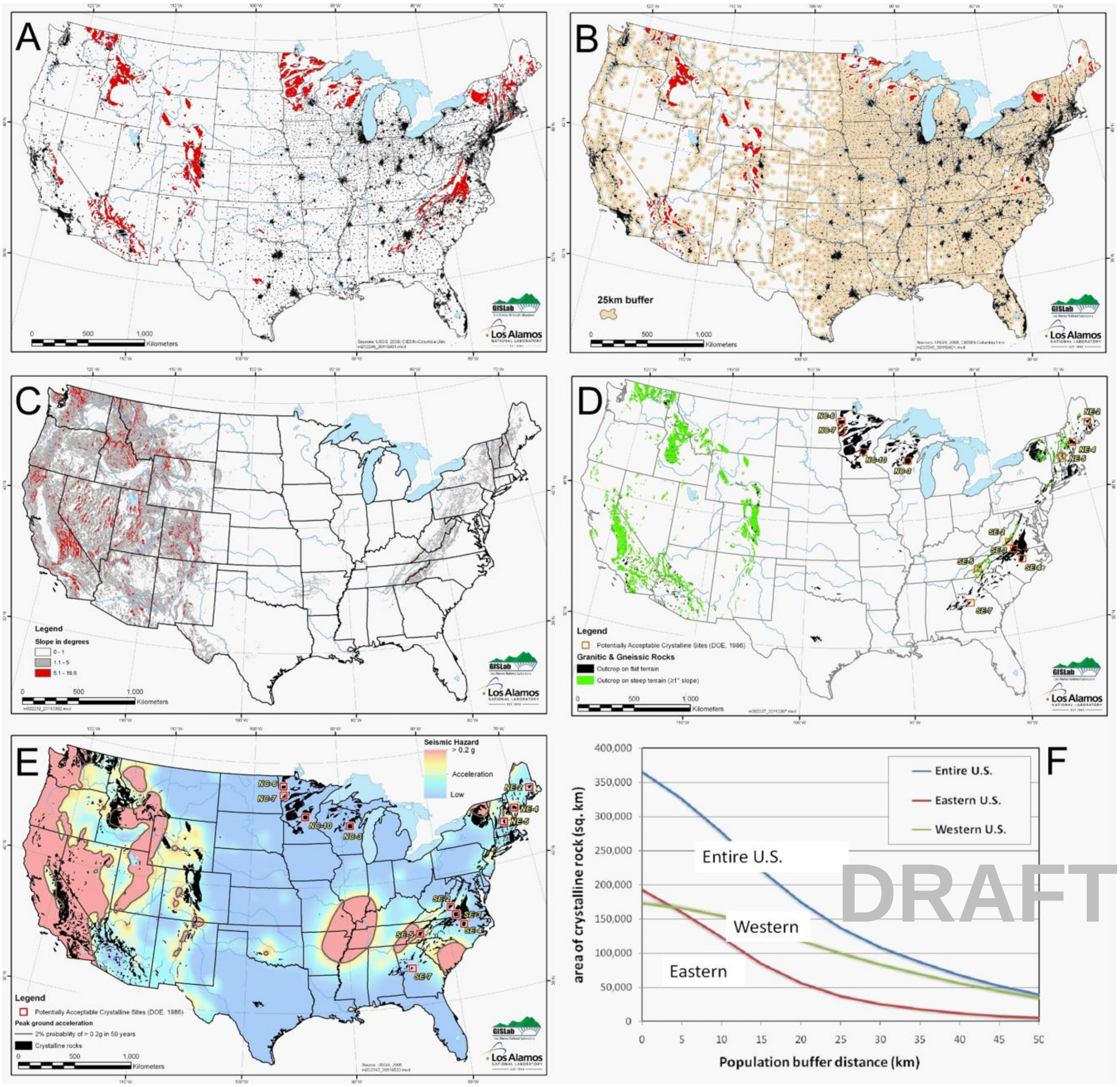

Figure 5-1. Sensitivity to potential siting guidelines for granite. **A.** Granitic outcrops and distribution of population clusters (population density > 1000 persons/square mile); **B.** Impact of a potential siting guideline based on distance from population clusters on available surface granites. Example is for a 25 km population buffer (tan pattern). Granite outcrop beyond 25 km distance shown in red; **C.** Topographic slope calculated from DEM data. Gray pattern indicates slope of 1-5 degrees, red pattern indicates slope of >5 degrees; **D.** Comparison of granitic surface exposures with slopes >1 degree (green pattern) and those on slopes <1 degree (black pattern), showing impact of a potential siting guideline based on topography and hydraulic gradient for different regions of the US; **E.** Seismic hazard in the US (from USGS, 2008). Pink-filled contours indicate areas of highest probability for ground acceleration > 0.2 g. **F.** Population buffer distance versus area of granite for eastern, western and entire U.S. Impact of population density is highest for the eastern States (see discussion in Section 5.2.

6. Concluding Remarks and Future Work

In FY11, we began populating a GIS database with geologic data for granitic, salt and clay-bearing rocks. An initial goal of this work package is to obtain data that will allow identification of potential rock formations or parts of formations that have suitable depth and thickness to host a mined repository. A second goal is to acquire data on potential siting factors and to develop tools that could be used to evaluate host geology against potential siting guidelines and issues. Once these data are brought into the database at a national scale, we will focus on obtaining data at an appropriate regional scale to allow more detailed analysis and comparison of regional geology and siting factors, including tectonic hazards. This work will support future decision points for site screening and site selection as described in the *UFDC Disposal Research and Development Roadmap* (Nutt, 2011). The BRC (2011) stated that:

> *Prior to launching a consent-based siting process, the implementing organization should develop a set of basic, initial siting criteria designed to ensure that time and resources are not wasted to investigate sites that are clearly unsafe, unsuitable or inappropriate for waste facility development.*

Although it is not the goal of this work package to develop siting criteria or guidelines, we will develop tools that will allow evaluation of the impacts of potential guidelines on a site screening and site selection process in the US, in anticipation of future guidelines that may be based partly on recent international siting experiences. These guidelines are likely to address issues of human intrusion, including exploration for natural resources and use of freshwater aquifers, and of constraints imposed by social and cultural factors such as population and land use. The database and analysis tools will allow comparison of future regional siting options to anticipate site screening and site selection issues that could challenge a repository program in certain regions of the US more than others. The database and analysis tools will also facilitate identification of regions that may not warrant a more detailed evaluation in a future siting environment.

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8. Appendix A

Table 1. Comparison of the major characteristic features of bedded salt deposits in the Michigan, Appalachian, Paradox, and the Williston Basins. The geological, tectonic, hydrological, seismic, mineral resources of the basins are highlighted. The individual features of the salt beds are also summarized.

	Michigan Basin	**Appalachian Basin**	**Paradox Basin**	**Williston Basin**
Salt Deposits	Salinas Group Salt (A to G Salt Beds)	Salinas Group Salt (A to G Salt Beds)	Hermosa Group: Paradox Formation	Prairie Formation (Devonian), Madison Group (Mississippian). Opeche Formation [Permian), Pine Salt [Permian-Triassic), and Dunham Salt [Jurassic)
Age	Silurian and Devonian	Late Silurian	Pennsylvanian	Devonian to Jurassic
Areal Distribution and thickness of sedimentary rocks	5000 m of sedimentary rocks across Michigan, as well as parts of Wisconsin. Illinois. Indiana. Ohio, and Ontario.	Extends from Tennessee through parts of Kentucky, Virginia, West Virginia. Ohio, Maryland, Pennsylvania, and New York	30,000 sq km in SE Utah and SW Colorado	Large sedimentary and structural basin that underlies most of North Dakota, the eastern part of Montana, NW South Dakota, and part of southern Canada
Tectonic Setting	Flat-lying sedimentary deposits with insignificant folding and faulting	Elongated sedimentary and structural basin related to the Late Paleozoic Appalachian 'revolution' that resulted in intense folding and faulting in eastern part. No faults or folds reported in basin	Flexural foreland basin developed along the SW flank of the Ancestral Rocky Mountain Uncompahgre uplift. Many NW-SE-trending salt-core anticlines formed along NE side of basin	Nesson anticline, a N-trending structure in NW North Dakota and the Cedar Creek anticline, a structure that extends NW ward into Montana from the common corner of North Dakota, South Dakota, and Montana.
Aggregate thickness of salt	a) >600 m in central part of basin and decreases toward margin in Salinas Group. b) 150 m of eight salt beds of	150-500 m in shallow subsurface and increases to 750 m in deep section.	2500 m of Paradox Formation evaporites with coarse clastics and carbonates	>1260 m of Devonian to Jurassic salt-bearing sedimentary rocks with aggregate thickness of 30 to 150 m of salt in each unit.

	Michigan Basin	Appalachian Basin	Paradox Basin	Williston Basin
	Devonian Detroit River Group.			
Lithologic units	Carbonates. Shale's, salt, anhydrite, and sandstone of Cambrian to Jurassic ages and recent glacial drift	Series of salts, dolomite, anhydrites, and shale deposits	Halite with minor clastic rocks, organic shale's, anhydrite, and carbonates.	Bedded halite and potash
Depth to top of salt	Ranges from 1800 m at center of basin to 150-300 m at margin		In much of the basin, depth to salts is about 1500 m and becomes relatively shallow along salt anticlines.	Most salts are about 1500 m deep from the surface except for the younger deposit, which is about 900 m deep.
Units/Salt Beds and Salt Cores	**A-1 Salt**: Deepest salt bed, halite plus some potash, 60 m thick in basin interior and reaches 150 m in center of basin. Depth to top of A-1 is as much as 2500 m and decreases to 900 m along margin		Major salt-anticline systems are (1) Lisbon Valley-Dolores Valley, (2) Moab Valley-Spanish Valley-Pine Ridge, (3) Gypsum Valley, (4) Castle Valley-Paradox Valley, and (5) Salt Valley-Cache Valley-Fisher Valley-Sinbad Valley and several smaller anticlines. - Typical anticline consists of three parts: floor, central core, and overlying or flanking strata. - Floor consists of 450 to 750 m of faulted, non-evaporite deposits older than the Paradox Formation. - Central core are 700 to 4000 m thick of deformed halite and associated rocks of the Paradox Formation that flowed into the anticline.	1) The **Prairie Formation** in parts of North Dakota and Montana is the oldest unit and it contains nearly 150 m of massive beds of halite and several interbeds of potash with aggregate thickness of 12 m. Depth to salt beds is 1500 to 3600 m. 2) The Mississippian **Madison Group** contains nearly 120 m of salt beds with individual beds ranging in thickness from 10 to 50 m. Depth to salt beds is 1500 to 2700 m except in the east, which ranges from 1000 to 1500 m from the surface. There, the thickness of salt beds ranges from 6 to 12 m. 3) **Opeche Formation:** Impure and lenticular salt bed confined to center of basin and varies in thickness from 30 to 45 m. Depth from surface is 1800 to 2200 m. 4) **Pine Salt** in the middle section
	A-2 Salt: Sits on A-1 A-2 Salt: Sits on A-1 carbonate, 100 m of pure halite in most areas and 150 m in center of basin. Depth to top of A-2 is >2000 m and decreases to 900 to 1200 m along margin			
	B Salt: Separated from underlying A-2 Salt by A-2 carbonate. Lower part is pure but upper part contains thin beds of shale and dolomite. Grades to anhydrite. Thickness varies from 100 m in most parts to 150 m in center of basin. Depth to top of B-salt is >2000 m and drops to 600 - 900 m at basin margin	B Unit: Oldest salt rests on shale, dolomite, and anhydrite of A Unit. Aggregate thickness of unit is 15 to 50 m of interbedded salt, shale, dolomite, and anhydrite. Salt beds are typically 1 to 6 m.		
	D Salt: Contains two moderately thin salt beds separated by dolomite.	**D Unit:** Contains two or more thin salt beds with shale, having a total		

	Michigan Basin	**Appalachian Basin**	**Paradox Basin**	**Williston Basin**
	Varies in thickness from 10 to 30 m.	thickness of 10-40 m.	- Overlying or flanking strata are younger non-evaporite rocks that overlie the Paradox Formation and range in thickness from 1,500 to 4,500 m.	of **Spearfish Formation** is fairly pure and about 90 m thick in two separate basins in North and South Dakota. Depth to salt bed is 1600 to 2200 m (North Dakota) and 900 to 1800 m in South Dakota. 5) Dunham Salt of Jurassic age is about 30 m thick and occurs in two separate areas at a depth of 1500 to 2100 m in western North Dakota.
	F Salt: Youngest deposit of pure and impure salt. Total thickness ranges up to 300 m with individual salt beds of 2 to 6 m except for the two bottom and the upper massive salt beds that range in thickness from 10 to 20 m and locally as much as 30 m. Depth to top of unit is the same as others but drops to about 900 m along the margin.	**E Unit:** Thin beds of salt dominated by shale and dolomite with total thickness of 15-60 m.		
		F Unit: Contains pure salt with alternating beds of shale, dolomite, and anhydrite. Total thickness varies from 60 m (margin) to 300 m in deeper part of basin. Individual salt beds range from 3 to 25 m in Ohio, 20 to >50 m in south-central New York due to deformation and flowage. Depth from the surface ranges from 300 to 900 m.		
	Detroit River Group: youngest (Devonian) deposit in the basin, aggregate thickness of 30 to 150 m in northern part, decreasing toward margin. Salt beds interbedded with anhydrite, limestone, and dolomite. Thicknesses vary from 5 to 25 m except for uppermost bed of 3 m.			

	Michigan Basin	**Appalachian Basin**	**Paradox Basin**	**Williston Basin**
	Depth to top of unit ranges from 1200 m in center of basin to 600-900 m in the north.			
Salt Dissolution	Data not available but B, F and the Detroit River Salts may be affected along the northern north and NE of the basin margin.	Data not readily available even though it might have occurred in certain areas in New York.	Past or present dissolution confined to western and southeastern edges of the salt basin and along crestal areas of the salt anticlines	
Hydrology	**Surface Water:** mostly from precipitation (66 to 92 cm annually) and springs from glacial drifts and bedrock. Numerous lakes present in Lower Peninsula. River and major lakes sources of fresh water .	**Surface Water:** Mostly from annual precipitation (81-102 cm) and springs from glacial drifts and bedrock.	**Surface Water**: The Colorado and Green River drainage systems dominate the basin. Annual precipitation ranges from 20 to 40 cm in low desert areas and up to 75 cm in adjacent mountains. Fault-bound large springs are present in the Paradox Basin	
	Ground Water: Principal bedrock aquifers (i.e., sandstone, limestone, and dolomite) and glacial drifts provide good quality ground water from shallow depth (<100 m) in parts of the basin remote from the major lakes. Saline and mineralized water are present at depth.	**Ground Water:** Good quality water produced from shallow depth of principal bedrock aquifers and glacial drifts.	**Ground Water:** Data is sparse but Quaternary alluvium and terrace deposits are the principal source of good-quality water. Faulted aquifers also provide local supply.	
Seismic Activity	Low level of recorded seismic activity in the basin suggests earthquakes not a problem.	Even though proximal to intensely folded and faulted region of the Appalachian 'revolution', earthquake activity and seismic risk are low in the basin.	Entire Paradox basin has no recorded earthquake activities and it is within Zone 1 of the seismic risk map of the United Sates.	
Mineral Resources	Oil and gas, salt (halite and potash), iron ore, copper, gypsum, building	Oil and gas reservoirs from pre-Salinas salt deposits. Other	Principal oil and gas production from the southern	

	Michigan Basin	Appalachian Basin	Paradox Basin	Williston Basin
	materials, clay, etc.	resources are salt, gypsum, building materials, and clays	part of the basin away from the salt anticlines and exploration is confined to flanks. Salt and potash are far from market centers. Uranium and vanadium mined from Triassic and Jurassic sedimentary rocks.	

Table 2. Summary of the major characteristic features of the five Gulf Coast salt dome-bearing basins in Alabama, Mississippi, Louisiana, and Texas are presented. The geological, tectonic, hydrological, seismic, and economic resources of each basin are also summarized

	North Louisiana Salt-Dome Basin	**Northeast Texas Salt-Dome Basin**	**Mississippi Salt Dome Basin**	**Texas-Louisiana Coast Salt-Dome Basin**	**South Texas Salt–Dome Basin**
Salt Deposit	Louann Salt	Louann Salt	Louann Salt	Louann Salt	Louann Salt
Age	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic
Areal Distribution	At 13,000 square km, it represents the smallest of five dome-bearing basins	160 km in diameter and bounded by major structural features	Runs from SE Louisiana across Mississippi to SW Alabama for a distance of 400 km.	Gulf Coast Basin where stratigraphic units thicken gulfward with more marine shales and clays.	Smaller of the coastal basins and occupies the southeastern-most part of Texas.
Tectonics	NW-SE elongation along the North Louisiana Syncline marked by a series of border faults. Consists of a smaller northern (Minden) and larger southern (Winnfield) basins separated by an E-W-trending structure (ridge). No growth faults and related depositional systems.	NE-oriented tectonic and depositional feature with the Louann Salt thickening toward the center of the basin.	Uplifted blocks and faults bound the NW-SE trending basin. Within the Tertiary sequence, there is no structural expression, which gently dips toward the Gulf of Mexico. The NW part of the basin lies within the Mississippi alluvial plain, whereas the rest is within the Gulf Coast Plain.	Since Jurassic time, depositional axis of the basin has shifted Gulfward and since early Tertiary the center of maximum deposition has moved eastward from the Houston Embayment area of south Texas into south Louisiana. Growth fault controlled sedimentation within the basin	Occurs within the southeastward-plunging Rio Grande syncline or embayment. High-angle normal faults with displacements of up to 150 m are common within the basin caused possibly by salt flowage.
Salt Domes	19 salt dome found in down-warped subbasin in a smaller part of the Northern Louisiana Basin. 4 were used for LPG storage, six have saline water at the surface and several have surface expressions.	18 salt domes discovered by drilling plus five additional domes speculated. Four domes are below optimal depth of 1,000 m, three are prolific petroleum producers, three are LPG storage, and one has multiple industry usage. Domes range 1.5 to 8	Basin contains 77 known and suspected salt domes at variable depths that are irregularly distributed.	Basin contains more salt domes than the other four basins combined. Of the 143 known domes, 73 are utilized for industrial activities. The other 66 are too deep (~1,000 m) for considerations and four occur in Texas close to the coastline that is	Basin contains six salt domes. One of which is the largest and the deepest (4300 m) in the US.

	North Louisiana Salt-Dome Basin	**Northeast Texas Salt-Dome Basin**	**Mississippi Salt Dome Basin**	**Texas-Louisiana Coast Salt-Dome Basin**	**South Texas Salt–Dome Basin**
		km in diameter.		prone to flooding and tropical storms.	
Lithologic units	Salt domes contain cap rocks. Carbonate units with marls, chalks, and other limestone, anhydrite, clay and alternating sands and shale.	Cap rock detected on 11 domes but information is sparse on others. Carbonates, evaporates, marls, chalk, andhydrite, and sands and shale.	About 58 domes have developed cap rock. Limestone, anhydrite, clay, shale, clay, and unconsolidated Quaternary sandstone with minor shale and carbonates.	Dominated by continental deltaic units interfingering with marine shale's and clays.	Dominated by marine and non-marine deposits of Tertiary sands, clays, and sandstones associated with salt diapirs.
Depth to top of salt	4 out of 19 salt domes occur 1000 m or more below the surface; others are shallower at about 300 m. Shallower domes may have saline water at the land surface.	Depth to parent salt is 6,100 to 6,700 m below the surface. Four domes are below optimal depth of 1,000 m and seven are <200 m below surface.	Top of Louann salt is at 6,400 m and drops to 3165 along northern flanks. Tops to 12 domes lie below 3000 m and the rest range between 300 to 600 m from the surface.	Most salt domes are about 1000 m deep except for four domes in Texas that are shallower than 360 m and one of them at 135 m with cap rock thickness of 80 to 160 m.	Deepest dome occurs at 4300 m and two are at 1900 m below the surface. The shallowest is at 250 to 300 m below the surface.
Salt movement	Initial movements were along horizontal dimensions and formed broad pillows and ridges in Jurassic. Salt diapirism begun in early Cretaceous and ceased by mid Cretaceous. Regional vertical movement ceased by early Tertiary but local arching and faulting continued into late Tertiary. Domes have not been active since late Tertiary. Detailed studies of Quaternary deposits above	Uplift rate estimated at 0.006 mm per year in the last 50 Ma. Domes have not been active since late Tertiary. Detailed studies of Quaternary deposits above salt domes provide information on neoteconic activities.	Shallower salt domes occur in the southern part of the basin, whereas in the north no domes are shallower than 600 m.	Salt diapirs and flowage have created complex geology in the Texas-Louisiana Coastal basin of the Gulf of Mexico.	Faulting in the basin attributed to salt flowage in the subsurface.

	North Louisiana Salt-Dome Basin	Northeast Texas Salt-Dome Basin	Mississippi Salt Dome Basin	Texas-Louisiana Coast Salt-Dome Basin	South Texas Salt–Dome Basin
	salt domes could reveal neoteconic activities.				
Hydrology: Surface and ground water resources	Four major rivers drain the basin. Average annual precipitation is about 125 cm with a third ending as runoff and a smaller amount as recharge. Most domes show a potential for flooding from nearby swamps and lakes. Surface saline's appear to be from upturned Cretaceous bed strata,	Average annual precipitation is abut is about 110 cm with most of it ending as runoff into major streams with good drainage except for except for localized swamps and marshes. A dam on one of the major streams created Palestine lake, which covers some of the domes and could potentially cause flooding.	Annual precipitation ranges from 130 to 160 cm and most of it is lost to evaporation or run off southward to the Gulf of Mexico. Unlike the Northeast Texas and North Louisiana basins, the domes in the Mississippi basin lack surface salines or salt springs.	Hydrological studies conducted on areas with shallower salt domes. Annual average rainfall ranges between 100 and 125 cm from west to east. Up to 60 cm of rainfall in a day are known due to tropical storms that lead to severe flooding in low-lying region.	Semiarid climate with annual precipitation of only 57 cm. Occasionally tropical storms (hurricanes) exceed the annual rate, resulting in major floods.
	Ground Water: Fresh water aquifers are Eocene in age and are under artesian pressure, whereas Cretaceous aquifers contain brackish to saline water and are separated from each other by Paleocene clay beds. Hydrologic stability of domes is a contentious issue.	**Ground Water:** The Eocene-age Wilcox Group contains fresh-water aquifers with high-well yields at a depth of about 700 m. The impermeable Midway Clay separates fresh water from underlying saline aquifers. Surface salines above some of the salt domes probably related to active salt dissolution.	**Ground Water:** Fresh ground water is abundant and ranges in depth from 750 m to 1200 m below the surface. Fresh water aquifers are within Eocene deposits of sands and other fine-grained sediments.	**Ground Water:** Principal fresh-water aquifers in the Texas portion of the basin occur in 80 to 150-km wide and 480 to 900- m deep Plio-Pleistocene Willis and Goliad sands. Holocene-age deltaic sediments also provide shallow fresh-water aquifers that extend 100 km inland.	**Ground water:** The Pliocene Goliad sands represent fresh-water aquifer. Even though saline water occurs at shallow depth, typically fresh water exists at a depth of 750 m within the basin.
Seismic Activity	No seismic activity above MM V intensity has ever been recorded in the basin. However, the effect of the New Madrid fault zone of Missouri-Illinois-Kentucky	Basin has low-level seismic activities related to crustal loading from the Sam Rayburn Reservoir. No natural tremors have been reported in the area and the	No seismic events greater than MM V have been recorded within the basin proper. However, the basin is within the sphere of influence of the New	The basin lies within seismic-rick zone 1 and 0 where little or no damage can be expected. However, salt domes within the basin are	Basin occurs within seismic-risk zone 0. No earthquake activity of MM of magnitude V has ever been recorded in the

	North Louisiana Salt-Dome Basin	Northeast Texas Salt-Dome Basin	Mississippi Salt Dome Basin	Texas-Louisiana Coast Salt-Dome Basin	South Texas Salt–Dome Basin
	could be felt this far south.	threat to surface facilities is insignificant.	Madrid Zone located to the north.	regarded tectonically unstable compared with those from the interior basins.	basin.
Mineral Resources	Jurassic to Eocene oil and gas deposits in anticlinal traps created by salt diapirism and faulting. The region mostly known for natural gas. Salt was mined in the past but no active mining exists today. Sand and gravel, gypsum and anhydrite from cap rock quarry are mined.	Basin is one of the most prolific oil and gas producers in the country outside Alaska. Oil and gas produced from Jurassic, Cretaceous, and Tertiary units and occur along structural and stratigraphic traps. However, most domes contain no hydrocarbons. Salt was produced from a subsurface mining and from salt springs. Sand, gravel, and Eocene lignite deposits are abundant within the basin.	11 of 77 domes have significant petroleum output from Jurassic and Tertiary units. Despite many salt domes only two are developed for salt mining and two for LPG storage. Sand and gravel, bentonite clay, common brick clay, and limestone for Portland cement production were mined.	Most prolific petroleum source in the US from Tertiary deposits and from Jurassic and Cretaceous rocks. Salt domes and tectonics provided traps for oil and gas. Salt domes used for LPG and crude-oil storage and for salt mining, which accounts for half of US salt production. Native sulfur mined from cap rocks of salt domes. Sand and gravel, clays limestone, and gypsum mined.	Major oil and gas production from Tertiary limestone and sandstone reservoirs and six salt domes. Appreciable depth of salt domes probably precluded rock salt mining even though a brine field was operated on one of the domes. Potash, gypsum, and low-grade uranium reported in the basin.