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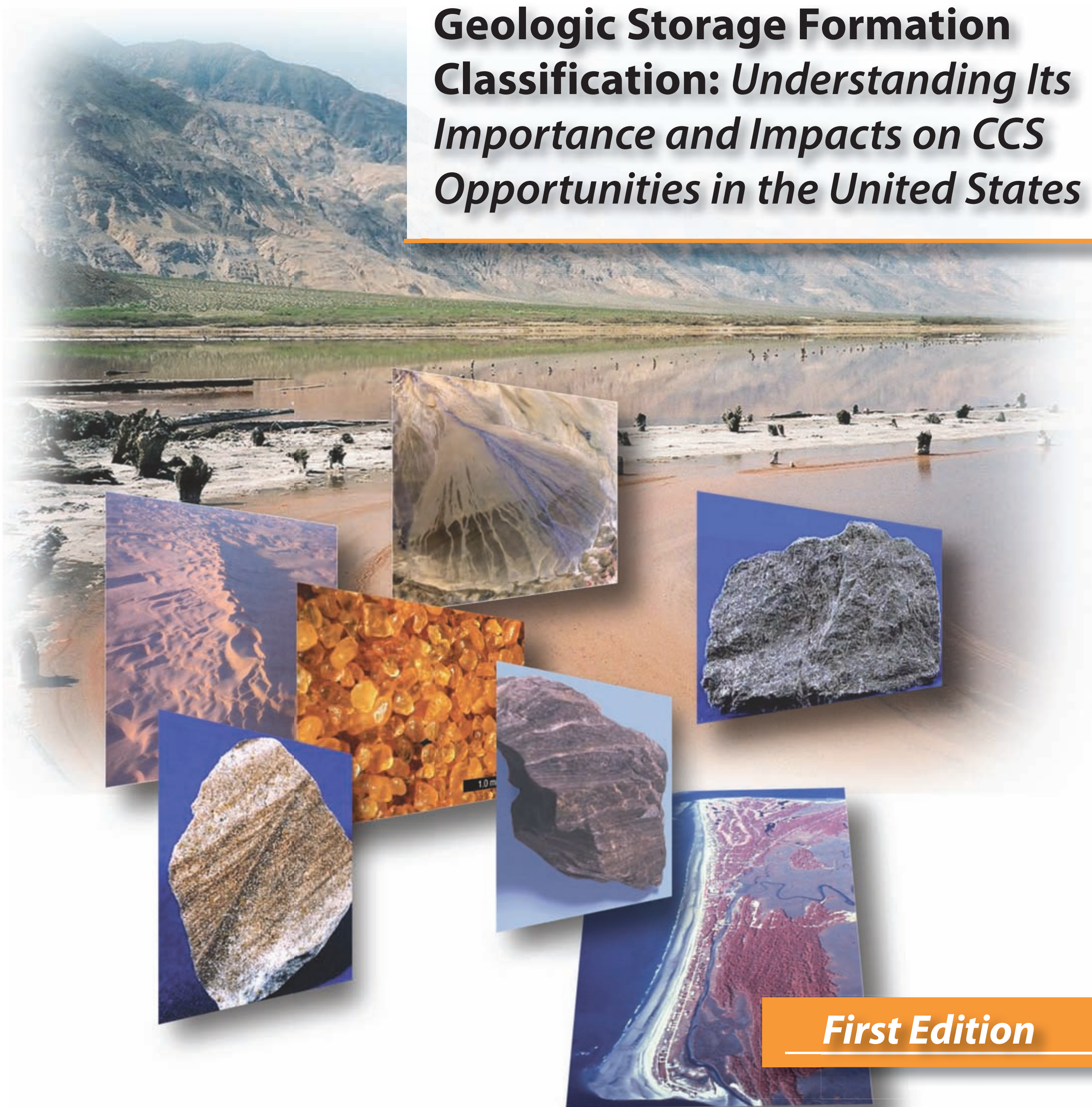
BEST PRACTICES for:

Geologic Storage Formation Classification: *Understanding Its Importance and Impacts on CCS Opportunities in the United States*



First Edition

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

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Geologic Storage Formation Classification:

Understanding Its Importance and Impacts on CCS Opportunities in the United States

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NETL

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List of Acronyms and Abbreviations

Acronym/Abbreviation	Definition
ARRA	American Recovery and Reinvestment Act of 2009
Big Sky	Big Sky Carbon Sequestration Partnership
Btu	British thermal unit
CBM	Coalbed Methane
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon Dioxide
$CaCO_3$	Calcium Carbonate
DOE	U.S. Department of Energy
ECBM	Enhanced Coalbed Methane
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse Gas
GIS	Geographic Information Systems
HFC	Hydrofluorocarbon
LIP	Large Igneous Provinces
MGSC	Midwest Geological Sequestration Consortium
MORB	Mid-Ocean Ridge Basalts
MRCSP	Midwest Regional Carbon Sequestration Partnership
MWh	Megawatt Hour(s)
N_2O	Nitrous Oxide
NRDC	Natural Resources Defense Council
NETL	National Energy Technology Laboratory
OIB	Ocean Island Basalts
OOIP	Original Oil in Place
PCOR	Plains CO_2 Reduction Partnership
ppm	parts per million
RCSP	Regional Carbon Sequestration Partnership(s)
RD&D	Research, Design, and Demonstration
SECARB	Southeast Regional Carbon Sequestration Partnership
SWP	Southwest Regional Partnership on Carbon Sequestration
TDS	Total Dissolved Solids
USGS	U.S. Geological Survey
WAG	Water Alternating Gas
WESTCARB	West Coast Regional Carbon Sequestration Partnership

Executive Summary

A need exists for further research on carbon storage technologies to capture and store carbon dioxide (CO_2) from stationary sources that would otherwise be emitted to the atmosphere. Carbon capture and storage (CCS) technologies have the potential to be a key technology for reducing CO_2 emissions and mitigating global climate change.

Deploying these technologies on a commercial-scale will require geologic storage formations capable of: (1) storing large volumes of CO_2; (2) receiving CO_2 at an efficient and economic rate of injection; and (3) safely retaining CO_2 over extended periods. Eleven major types of depositional environments, each having their own unique opportunities and challenges, are being considered by the U.S. Department of Energy (DOE) for CO_2 storage. The different classes of reservoirs reviewed in this study include: deltaic, coal/shale, fluvial, alluvial, strandplain, turbidite, eolian, lacustrine, clastic shelf, carbonate shallow shelf, and reef. Basaltic interflow zones are also being considered as potential reservoirs.

DOE has recently completed this study which investigated the geology, geologic reservoir properties and confining units, and geologic depositional systems of potential reservoirs and how enhanced oil recovery (EOR) and coalbed methane (CBM) are currently utilizing CO_2. The study looked at the classes of geologic formations, and their potential to serve as CO_2 reservoirs, distribution, and potential volumes.

This study discussed the efforts that DOE is supporting to characterize and test small- and large-scale CO_2 injection into these different classes for reservoirs. These tests are important to better understand the directional tendencies imposed by the depositional environment that may influence how fluids flow within these systems today, and how CO_2 in geologic storage would be anticipated to flow in the future. Although diagenesis has modified fluid flow paths during the intervening millions of years since they were deposited, the basic architectural framework created during deposition remains. Geologic processes that are working today also existed when the sediments were initially deposited. Analysis of modern day depositional analogs and evaluation of core, outcrops, and well logs from ancient subsurface formations give an indication of how formations were deposited and how fluid flow within the formation is anticipated to flow.

The distribution of the different depositional environments that NETL is investigating is presented below. The field activities are in various stages of investigation with

Matrix of Field Activities in Different Formation Classes

Geologic Formation Classes	High Potential					Medium Potential				Lower or Unknown Potential	
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Aluvial	Turbidite	Coal	Basalt (LIP)
Large Scale	–	1	–	–	1	3	–	1	–	–	–
Small Scale	3	2	4	1	2	–	–	2	–	5	1
Characterization	1	–	8	6	–	3	3	2	2	–	1

Notes:
The number in the cell is the number of investigations per depositional environment.
Large Scale Field Tests – Injection of over 1,000,000 tons of CO_2.
Small Scale Field Tests – Injection of less than 500,000 tons of CO_2.
Site Characterization – Characterize the subsurface at a location with the potential to inject at least 30,000,000 tons of CO_2.
Reservoir potentials were inferred from petroleum industry data and field data from the sequestration program.

some completed and others just underway. Additional investigations, including small- and large-scale injection tests, will be needed to be completed on all of the different depositional environments. This will provide the information on the behavior and flow of CO_2 in the different reservoirs.

Referring to the Distribution of Field Activities for CCS/ Geologic Storage matrix, characterization has not been completed for a shelf clastic, reef, and coal environments. Small-scale injection tests (<500,000 tons of CO_2) have not been performed on fluvial deltaic, eolian, and turbidite depositional environments. Large-scale injection tests (>1,000,000 tons of CO_2) have not been performed on deltaic, strandplain, shelf carbonate, eolian, turbidite, basalt Large Igneous Providences (LIP), and coal. Three highly experimental reservoirs that are not included on the matrix because they have not been investigated are fractured shales, Mid Oceanic Ridge Basalts (MORB), and offshore turbidites.

Understanding the impacts of different reservoir depositional classes on storage of CO_2 will support DOE's efforts to develop the knowledge and tools necessary for future commercialization of carbon storage technologies throughout the United States.

1.0 Introduction and Background Geology

Geologic storage of CO_2 is a complex issue involving a number of variables, including capturing the greenhouse gas (GHG) emissions from stationary sources, developing the infrastructure to transport the CO_2, and selecting underground reservoirs for CO_2 storage. This desk reference is based in part on a DOE report, titled, "Depositional Systems for CO_2 Geosequestration (DOE/ NETL-2009/1334 Olsen et al., 2009)."

This desk reference is intended to:

- Assist with an understanding of basic geological principles and terminology associated with potential CO_2 geologic storage in formations.

- Show the importance of geologic depositional systems in determining the internal architecture of such formations, thus making it possible to predict the behavior of the injected CO_2.

- Establish the importance of using the geological depositional system to assess existing and future research, design, and demonstration (RD&D) needs related to storing CO_2 in different depositional environments.

A goal of DOE's Research and Development (R&D) program in carbon storage is to classify the depositional environments of various formations that are known to have excellent reservoir properties and are amenable to geologic CO_2 storage. Using lessons learned from the behavior of CO_2 in reservoirs from previous geologic investigations and their known depositional environments is important in developing an understanding for similar depositional environments being considered for storage, and predicting the expected behavior of CO_2 within these proposed reservoirs without having to duplicate the time, effort, and funds that were expended on the original projects. This is being accomplished through the implementation of 28 CO_2 injection field projects in collaboration with the Regional Carbon Sequestration Partnership (RCSP) Initiative and 10 American Recovery and Reinvestment Act of 2009 (Recovery Act) projects that are focused on the characterization of geologic formation as sites for possible commercial carbon capture and storage (CCS) development. DOE has completed this review of geologic depositional classification system to better understand how the field work being conducted today fulfills the need to test these different classes of depositional systems and determine what future R&D projects are still needed.

According to the U.S. Environmental Protection Agency (EPA), total GHG emissions were estimated at 7,100 million metric tons (7,800 million tons) CO_2 equivalent in the United States in 2006. This estimate included CO_2 emissions, as well as other GHGs, such as methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Annual GHG emissions from fossil fuel combustion, primarily CO_2, were estimated at 5,600 million metric tons (6,200 million tons), with 3,800 million metric tons (4,200 million tons) from stationary sources. Carbon dioxide stationary sources are largely related to power production (Carbon Sequestration Atlas of the United States and Canada, 2008).

Carbon dioxide is a byproduct of the oxidation of hydrocarbons and is generated from the natural decomposition of organic material, accelerated oxidation (burning of fossil hydrocarbons or biomass), and geologic sources (e.g., volcanoes). Carbon dioxide is also the product of decomposition of rocks, like limestone (calcium carbonate [$CaCO_3$]), in cement manufacturing. Geologic storage of CO_2, in underground formations as part of CCS, is one possible long-term/permanent storage solution for the reduction of anthropogenic CO_2 from the atmosphere. This approach involves the capture and stabilization of large volumes of CO_2 in underground carbon sinks (storage locations) (Baines and Worden, 2004). Some variants of these underground sinks are shown in **Figure 1-1,** including the surface infrastructure and the different types of reservoirs that are available.

Prior to implementing CCS, site developers and owners will utilize the results from existing storage projects to develop risk assessments and business models for their individual facilities. The existing data, developed by DOE's National Energy Technology Laboratory (NETL) and others, will allow an individual site to be evaluated to better define the costs for geologic storage, determine the type and quality of geologic sinks that are available in the region, and evaluate the type and quality of transportation infrastructure that is required.

NETL has pioneered and developed practices for the evaluation, installation, and operation of CCS facilities. These practices were developed to both help reduce the costs of implementing CCS and to protect human health and the environment from adverse effects of CO_2. CCS will allow the viable use of coal-fired power plants while helping to stabilize climate changing CO_2 emissions. Coal fuels the majority of power generation capacity in the United States and in many other areas of the world. Coal is an abundant domestic energy resource and the primary source of baseload power generation in the United States, generating 1,986 million megawatt hours (MWh) in 2008. At the 2008 rate of consumption, coal could meet the United States' needs for more than 234 years. Since 1976, coal has been the least expensive fossil fuel used to generate electricity when measured based on the cost per British thermal unit (Btu [a unit of energy content]). Although the cost of generating electricity from coal has increased, it is still lower than generating electricity from either natural gas or petroleum in most areas. The number of coal-fired power plants is expected to increase in the future. Existing facilities can be retrofitted with CCS technology to allow for the continued use of coal without emitting CO_2 emissions into the atmosphere.

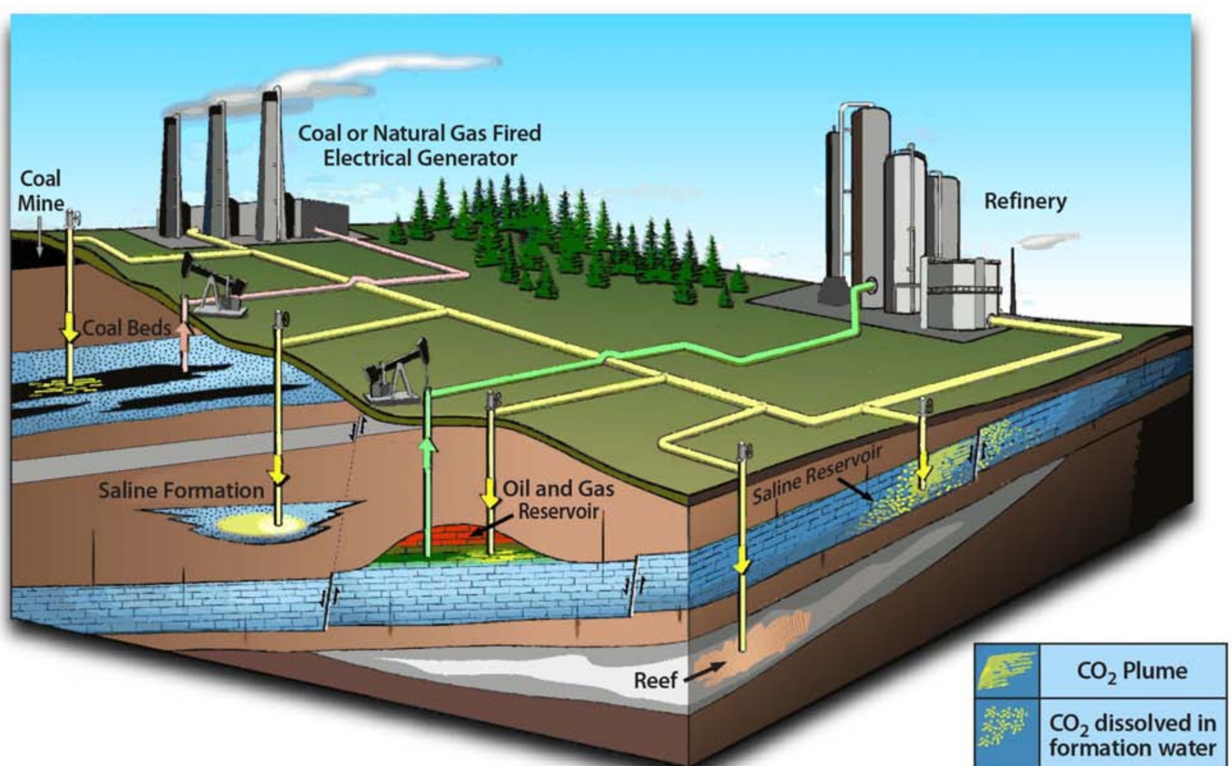

Figure 1-1. Schematic of CO_2 from a Thermoelectric Power Plant and Refinery being stored in Various Geologic Formations. (Adapted from original figure, courtesy of Dan Magee, Alberta Energy Utilities Board, Alberta Geologic Survey, 2008.)

In the oil and natural gas industry, the injection of CO_2 underground has been occurring for approximately four decades. As discussed later in this document, CO_2 is used to extract previously unrecoverable oil and increase oil and gas production. This has resulted in millions of dollars of additional revenue to local and state economies. In this application, CO_2 is considered a commodity.

Although it is also important to consider non-geologic factors for successful large-scale deployment of CCS technologies, including geographic location (source to sink matching), economic factors, public acceptance, and the capture portion of CCS, this report focuses on evaluating the depositional environment of potential geologic reservoirs for future CCS projects.

1.1 Geologic Background

There are three major types of rock that future developers of CCS projects might target for storage formations, including: **igneous, metamorphic, and sedimentary**. Each major type of rocks was formed under different conditions, and their potential for CO_2 storage varies based on the necessary criteria of:

- **Capacity,** which is based on the porosity or openings within a rock, often called "pore space."
- **Injectivity,** which is dependent on the permeability or the relative ease with which a fluid or gas can move within the pore space(s) of a rock.
- **Integrity,** or the ability to confine a fluid or gas within a geologic unit, is of primary importance, because without impermeable seals, fluids will take the path of least resistance and move to a lower-pressure area, including the surface.

The answers to questions concerning capacity, injectivity, and integrity can be learned, in part, by reservoir characterization of the formations in the area of the proposed geologic storage site. Reservoir characterization is an evolving science that integrates many different scientific disciplines (geology, geophysics, mathematical modeling, computational science, seismic interpretation, well log and core analysis, etc.) in order to build a conceptual model of a formation. The decision to select a particular geologic unit for geologic storage usually depends on having a detailed understanding of the reservoir characteristics and the behavior and fate of the injected fluids and their impact on the geologic strata receiving the fluids. Critical factors include: economic analysis of the location of the site, the distance from the CO_2 source to the site, the depth of the reservoir (which influences drilling and injectivity of CO_2), the volume of CO_2 that the site can contain, the trapping mechanism and sealing capacity, and the ultimate fate of the

What is Supercritical CO_2?

Carbon dioxide can be stored in either a gas phase or in a liquid (supercritical) phase. The volume to store gas in a gas phase is huge compared to storage in the liquid (supercritical) phase. To get CO_2 into a supercritical phase requires that the gas be compressed.

If the CO_2 is injected into the reservoir as a liquid the area near the well is cooled but at some distance from the wellbore the liquid takes on the temperature of the reservoir. CO_2 injected at depths below approximately 800 meters (2,600 feet) is at a pressure and temperature that will allow the CO_2 to remain as a supercritical fluid. By maintaining the pressure as presented in the figure below, the volume required for geologic storage is a fraction of what is required for lower pressures.

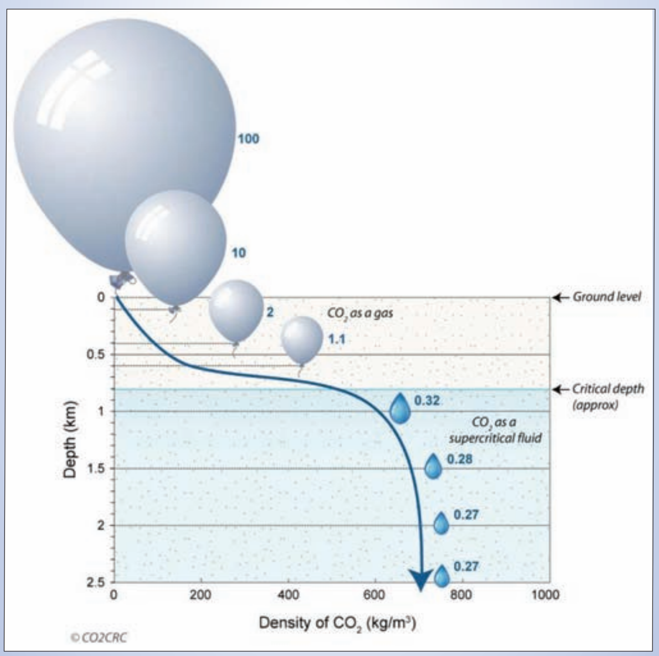

Illustration of Effect of Pressure on CO_2. (Image courtesy of CO2CRC www.co2crc.com.au/imagelibrary/)

stored CO_2. Many of these issues will be affected by the different classes of reservoirs that are being targeted for injection.

Time plays an important role in the formation of reservoirs, because rocks have been formed, eroded, and reformed many times in the history of the Earth before reaching the present configuration of continents and oceans. Reservoirs are strongly affected by these changes. Processes such as compaction of the rock, dissolving and enlarging pore spaces, or filling these pore spaces with sediments or new minerals from solution alters the amount of porosity and permeability of potential CO_2 storage reservoirs.

Most CO_2 geological storage targets are sedimentary rocks (clastics and carbonates), where CO_2 storage is in the pore space between grains, which are most often filled with undrinkable saline water. Igneous formations, which cover more of the Earth's surface than sedimentary formations, offer potentially great geologic storage sites because of their total volume both on continents and under the oceans, but are mostly untested. Coalbeds are a group of rocks that are considered both sedimentary and metamorphic and have their own unique properties. The most important storage mechanism for coal is its preferential ability to adsorb CO_2 directly on its surface. This situation differs from other sedimentary and igneous formations where the CO_2 occupies the pore space. It is anticipated that CO_2 will be injected as a supercritical fluid in the majority of reservoirs. To better understand how these rocks are formed and their potential for CO_2 storage, brief discussions of the different rock types are summarized in **the next three sections**.

1.2 Igneous Rocks

Igneous rocks (from the Latin *ignis*, fire) are formed by the solidification of cooled **magma** (molten rock). All rocks on Earth originated from igneous sources. Igneous rocks make up approximately 95% of the upper part of the Earth's crust. Elevated planetary temperatures during the Earth's formation produced widespread melting that continues today. The melt originates deep within the Earth and is seen in the crust near active plate boundaries or hot spots. Igneous rocks have unique compositions, because the same elements form different minerals and different rock types based on the temperature and pressure of the magma when they solidify.

Figure 1-2 shows the formation and distribution of igneous rock at divergent plate boundaries and subduction zones (where convergent plate boundaries meet). The movement of these different plates is called plate tectonics. The system is powered by heat convection as hot magma moves upward toward the Earth's crust and then flows out (cools) away from the divergent plate boundary. Cooler rock tends to sink and gets pulled down into large convection cells. The crust floats on the mantle (83% of Earth's volume) of melted rocks that extends down about 2,900 kilometers.

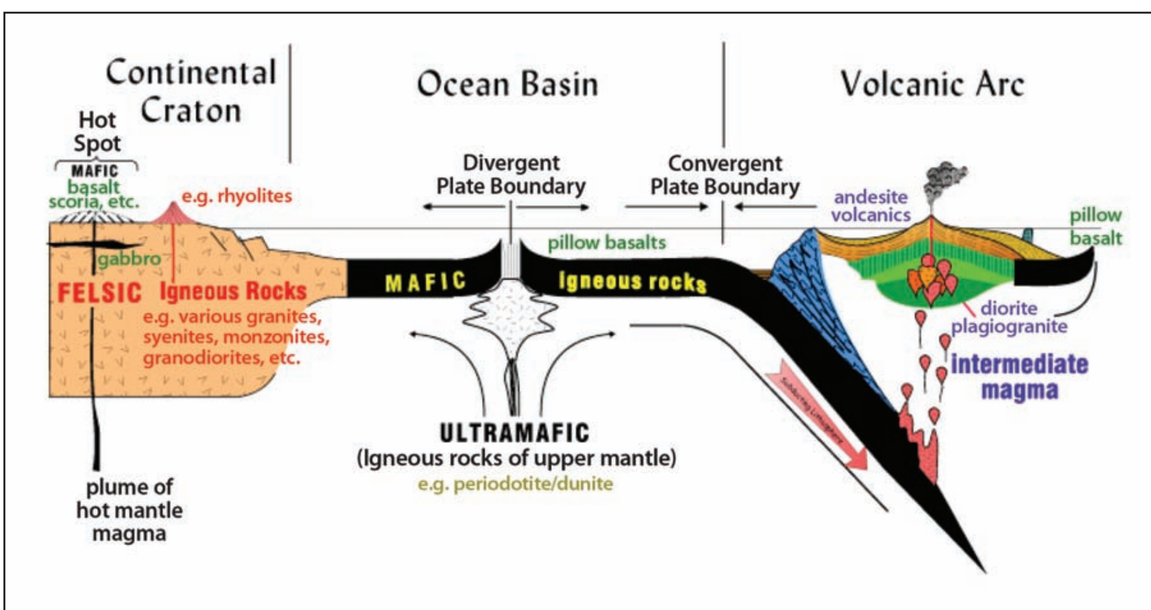

Figure 1-2. Formation and Distribution of Igneous Rock in the Earth's Crust. (Fichter, 2000.)

There are two types of igneous rocks: intrusive and extrusive. In particular, extrusive types offer some unique potential for CO_2 storage. Their high porosity and mineralogy offer opportunities for high volume storage and reactive chemistry that could convert the CO_2 into solid carbonates and essentially trap the CO_2 in the rocks forever.

- **Intrusive Igneous Rocks** (plutonic) are formed from magma that cools and solidifies within the Earth. The most common intrusive rocks are granite (**Figure 1-3**), which vary considerably in color depending on the minerals present. These rocks may be fractured and have low porosity and permeability, making them unlikely targets as storage formations.

- **Extrusive Igneous Rocks** (volcanic igneous rock) are produced when magma exits and cools quickly outside of, or near, the Earth's surface. The quick cooling means that mineral crystals do not have much time to grow, so these rocks have a fine-grained or

Figure 1-3. Cut and polished granite showing pink and white quartz crystals and black mica.

Figure 1-4. Basalt. (Courtesy of USGS Rock Library.)

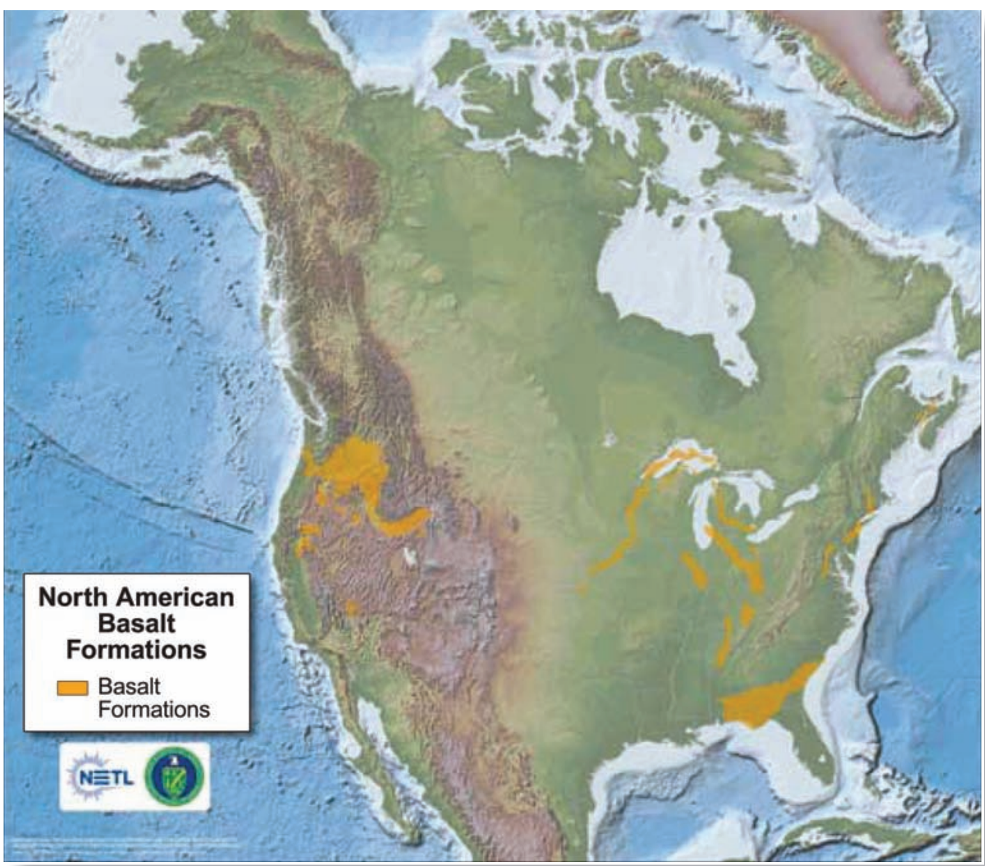

Figure 1-5. Distribution of Known Basalt Formations in the United States and Canada (in yellow) Investigated by NETL (2008).

even glassy texture. Hot gas bubbles are often trapped in quenched lava, forming a bubbly, vesicular texture and lots of porosity. In particular, basalts (**Figure 1-4**) are extrusive igneous rocks that offer opportunities for CO_2 storage. **Figure 1-5** shows the geographic extents of basalt formations in the United States.

1.3 Metamorphic Rocks

Metamorphic rocks are formed from pre-existing rocks (igneous, sedimentary, or other metamorphics). Metamorphic rocks are created from these pre-existing rocks through processes that generate heat and pressure resulting from deep burial and tectonic (mountain building) activity (**Figures 1-6** and **1-7**). For the most part, metamorphic rocks are of little interest as geologic targets for CO_2 storage due to their low porosity (little pore space between sediment grains) and low permeability (near zero interconnectivity of these pore spaces that allows fluids to flow through the rock).

Figure 1-6. Slate, a fine-grained, foliated, metamorphic rock that was formerly shale. (Courtesy of USGS Rock Library.)

Figure 1-7. Schist a metamorphic rock where heat and pressure have elongated individual minerals. Elongated quartz crystals are white in photo. (Courtesy of USGS Rock Library.)

However, a metamorphic rock that has some potential for CO_2 storage potential is anthracite coal. Anthracite has progressed through three stages of coalification. Anthracite coal is classed as metamorphic rock, based on the temperatures and pressures required to form this dense coal from softer sedimentary coal. Anthracite is not an abundant form of coal and represents a relatively small opportunity for CO_2 storage.

1.4 Sedimentary Rocks

Sedimentary rocks are formed from fragments of pre-existing rocks that are transported and held together (cemented) through natural agents, such as chemical precipitation from solution or secretion by organisms. Over geologic time, weathering or erosion of rock formations at a higher elevation produces sediment that is carried by water, wind, ice, and gravity to lower elevations and deposited as sands and silts intermixed with organic materials as sedimentary deposits. The various environments in which this takes place are depicted in **Figure 1-8** for clastic (consisting of fragments) rocks. A comparable schematic representation of the depositional environments for carbonates is provided in **Figure 1-9 .**

- Clastics, like sandstone (**Figures 1-10, 1-11, and 1-12) and shale (Figure 1-13),** are deposited as sand, silt, gravels, or with organic materials on beaches (tidal flats, shelfs, and barrier islands), in river channels (fluvial), in lagoons and swamps, in desert dunes (eolian) (**Figure 1-11**), in lakes (lacustrine), or as offshore submarine fans (turbidite). These deposits can form fans, sand bars, deltas, braided or meandering streams, or dunes, each having a distinct depositional pattern and a unique internal architecture that controls fluid flow within the reservoir body (see **Figure 1-8**). Bituminous coal is also an important sedimentary rock that offers opportunities for CO_2 storage and enhanced coalbed methane (ECBM) recovery.

- Carbonate rocks (**Figure 1-9)** are the product of both biological and chemical systems (e.g., corals formed in reefs, oyster shell banks, or as chemical precipitates) (**Figure 1-14**). They are also classified as sedimentary rocks. Carbonate deposition occurs in seawater and is highly dependent on water depth and sunlight, which allow organisms to grow.

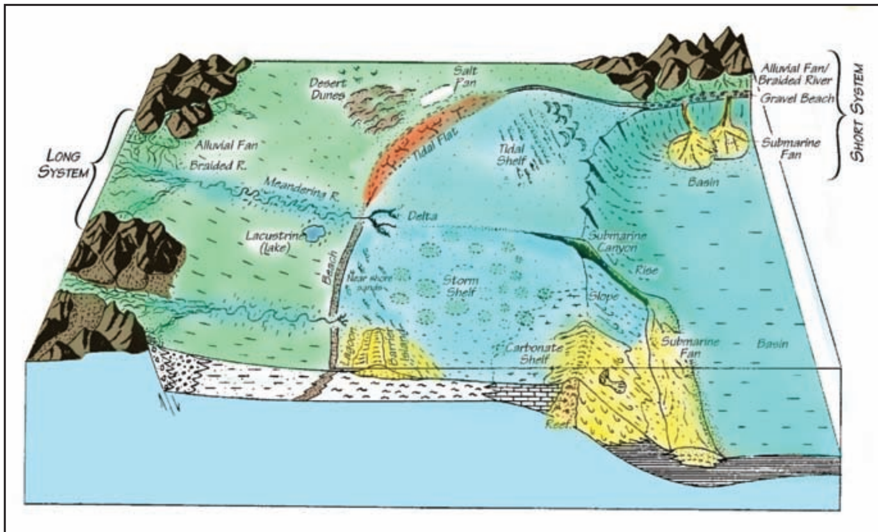

Figure 1-8. Environments for Weathering and Deposition of Rocks that can Produce Sedimentary Clastic Deposits. (Courtesy of Professor L. S. Fichter, 2000.)

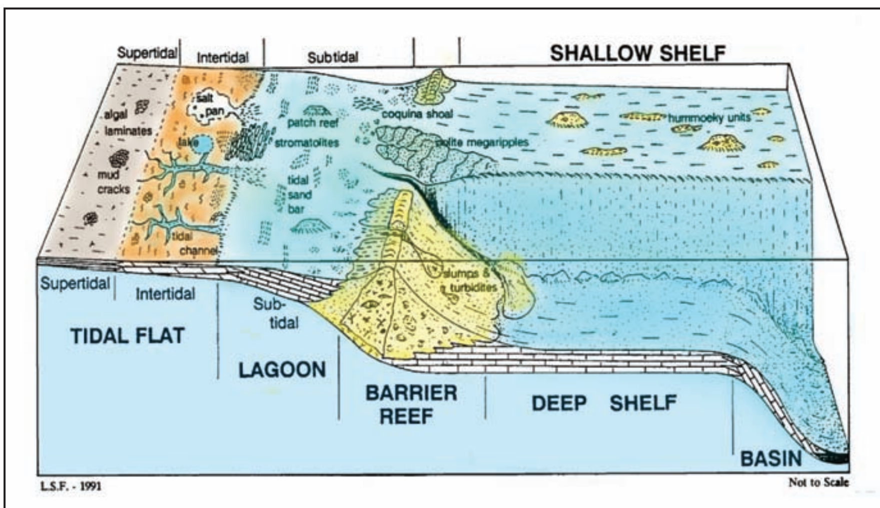

Figure 1-9. Environments for Formation of Carbonate Rocks. (Courtesy of Professor L. S. Fichter, 2000.)

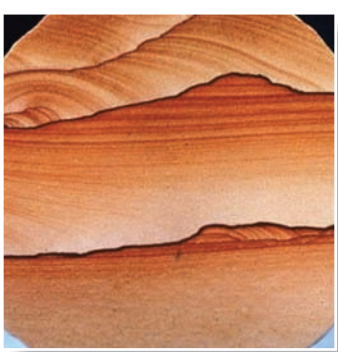

Figure 1-10. Cut sandstone core (cut horizontal) from Eolian deposit showing banding. (Courtesy of Ken Hammond, USDA Rock Library.)

Figure 1-11. Close-up of coral pink sandstone from Eolian formation where sand grains have been rounded and lightly cemented together. (Courtesy of Professor Mark Wilson.)

Figure 1-12. Coarse sandstone showing bedding planes originally deposited horizontally. (Courtesy of USGS Rock Library.)

Figure 1-13. Shale with parallel bands or layers. (Courtesy of USGS Rock Library.)

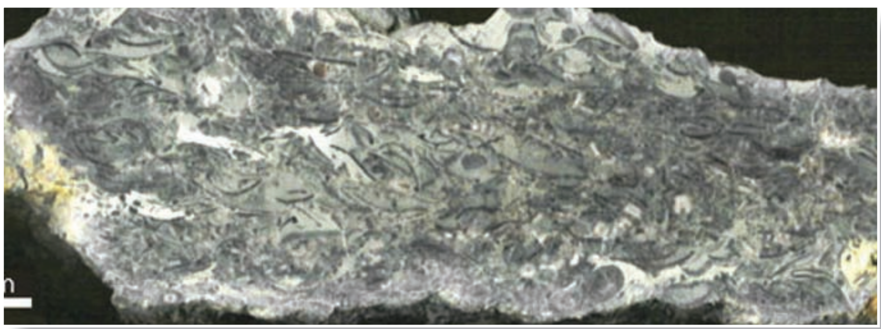

Figure 1-14. Etched limestone showing shells and calcareous debris (calcium carbonate) from Kope Formation, Ohio. (Courtesy of Jim Stuby.)

Most corals that are reef forming species live in shallow water. At shallow water depths, the primary carbonate forming species are microscopic size, one-cell plankton. Carbonate sediments formed in offshore basins and in oceans are the result of tiny shells drifting down and accumulating as thick ooze on the seafloor. The ooze is transformed into carbonate shale or chalk over time. Carbonates also include a subclass of rocks, called "evaporates," which include salts, gypsum, and anhydrite that are formed when saline water evaporates, leaving layers of dense, low permeability salts that often form seals to other high permeability formations. Water has reacted with carbonate rocks in some areas to create porosity and permeability (solution channels) making these rocks of interest for CCS.

Both clastic and carbonate rocks possess geologic storage potential because of the relatively high porosity and permeability developed during their formation. However, the unique changes that occur as sediments are transformed into today's rock determine the exact nature and potential of a clastic or carbonate reservoir for fluid flow and storage. Changes that occur following deposition are termed post-deposition or diagenetic changes and can impact the porosity and permeability of the rock and have some impacts on the injectivity, fluid flow, and capacity of the formations. Understanding these changes and their impacts on storage is critical to transferring the results of DOE's field projects to other portions United States that have similar types of depositional environments.

During the development of the regional characterization for geologic storage sites, NETL through its regional carbon sequestration partners (RCSPs) identified and examined the location of potential injection zones in different basins throughout the United States and Canada. Initial resource estimates were calculated for the primary storage formations and have been reported in the 2008 version of the Carbon Sequestration Atlas of the United States and Canada. These estimates are refined as NETL and the RCSPs continue to validate storage potential in each respective region. Conservative estimates of storage potential in North America show the potential for hundreds of years of CO_2 storage in deep geologic formations bearing saline fluids and oil and gas. These geologic formations and reservoirs are made up of the different geologic classes discussed in this report.

These sedimentary formations contain layers of porous or fractured rocks that are saturated with brine, oil, and gas. Brine is a highly saline solution that contains appreciable amounts of salts that have either been leached from the surrounding rocks or from sea water that was trapped when the rock was formed. The U.S. EPA has determined that a saline formation used for CO_2 storage must have at least 10,000 parts per million (ppm) of total dissolved solids (TDS, - salts), compared to sea water, which currently has approximately 34,000 ppm of TDS. Most drinking water supply wells contain a few hundred ppm or less of TDS. Any higher concentrations in drinking water would have an unacceptable, salty taste (Price, Allen, and Unwin). Oil and gas reservoirs are often saline formations that have proven traps and seals allowing oil and gas to accumulate in a trap over millions of years. With the exceptions of multiple manmade wellbores, there is little reason to believe that these same formations would leak if the oil and gas was replaced with CO_2. Many oil and gas fields containing stacked formations (different reservoirs) have characteristics that make them excellent target locations for geologic storage, including good porosity. The regions of various sedimentary basins where saline formations, oil and gas fields, and unmineable coal seams that have been assessed for storage potential are shown in **Figures 1-15** and **1-16**.

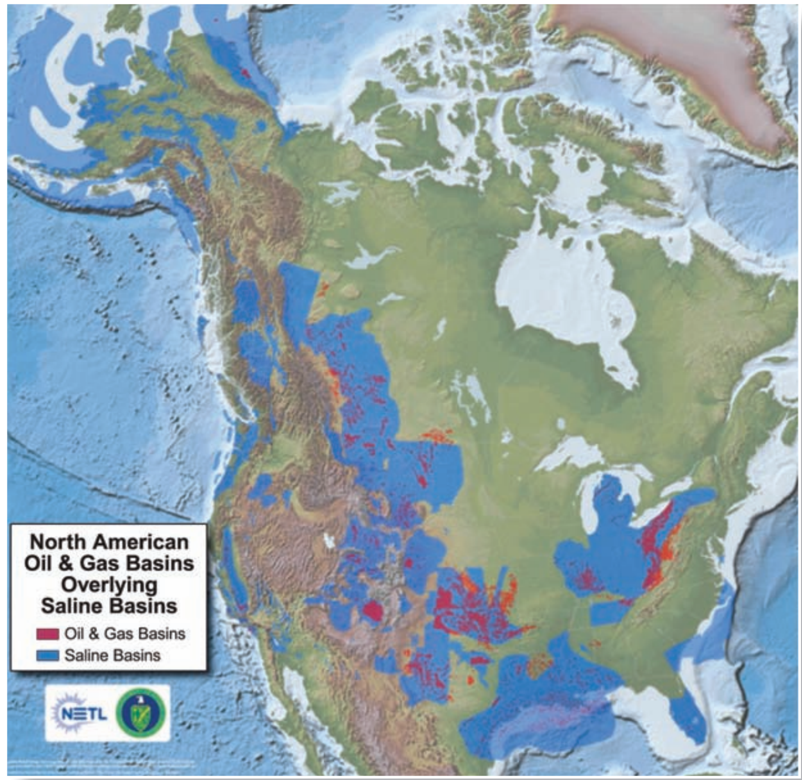

Figure 1-15. Map of Oil and Gas Fields (red) Superimposed on Saline Basins (blue) of North America. (NATCARB, 2008.)

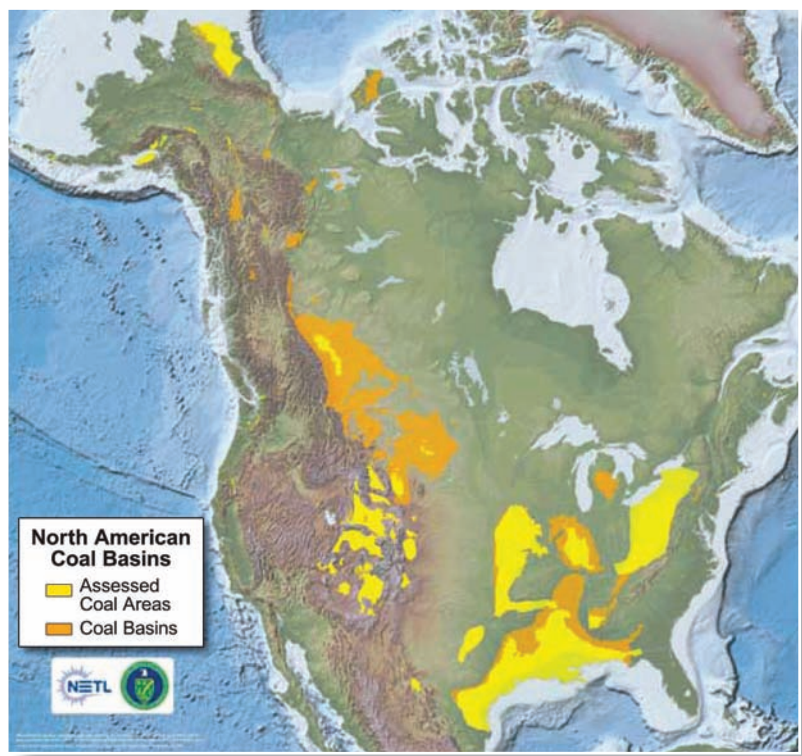

Figure 1-16. Distribution of Known Coal Basins Investigated by NETL. (NATCARB, 2008.)

2.0 Characteristics of Storage Reservoirs and Confining Units

Reservoir characterization, as applied in this report, is based on the hypothesis that what is learned from the depositional environment of a reservoir can be used to develop a geological/reservoir model. The model will describe (in part) the characteristics and performance of another reservoir deposited in the same type of depositional environment. In general, three types/groups of reservoirs have been historically evaluated for potential geologic storage of CO_2: depleted oil and gas reservoirs, deep coalbeds unavailable to conventional mining, and saline formations. Additionally, research is being performed to evaluate the potential for geologic storage in fractured basalts and shales. These reservoirs are made up of multiple depositional environments and have been grouped together based on their reservoir content and geology.

The characteristics of geologic formations or reservoirs that help make them potential geologic storage targets include: porosity; permeability; adequate volume for storage; seals; and a trapping mechanism(s) to confine the CO_2 for safe, long-term storage. Porosity and permeability are primarily dependent on the depositional system and post-depositional processes or diagenesis.

Most geologic storage targets are sedimentary rocks where CO_2 storage is trapped in the pore space between grains. Igneous formations have great potential for CO_2 because of their huge expanse, but have only recently started to be studied as potential storage reservoirs. Coalbeds are a group of rocks that have their own unique properties (cleats) that control fluid paths and a rock matrix where physical adsorption in the matrix would be the principal means of capturing CO_2.

2.1 Reservoir Properties

Rocks are often not as solid as they appear to the naked eye. Microscopically, there are voids or pore spaces among the sediment grains forming a rock, not unlike the space surrounding marbles in a jar. Porosity is the first essential element of a reservoir, shown schematically in **Figure 2-1** and microscopically in **Figure 2-2**. Permeability, which involves the interconnectedness of the individual pores, is the second essential element (**Figures 2-1** and **2-2**). Permeability is the capacity of a rock to transmit fluids through interconnected pores on a microscopic scale. Permeability depends on the size and shape of the pores, especially the pore throats (narrow channels between pores) that control interconnections, and the extent of these interconnections.

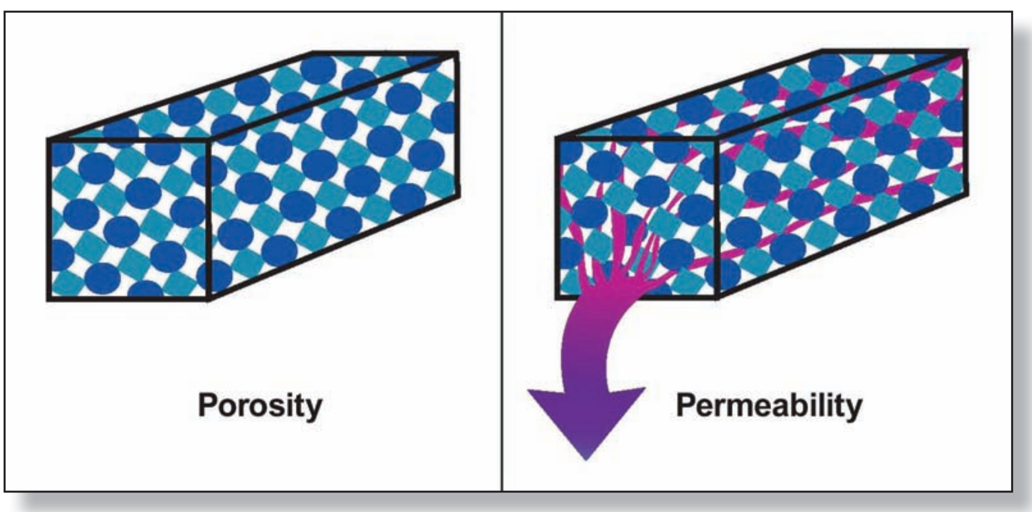

Figure 2-1. Porosity in Rocks and Rock Permeability.

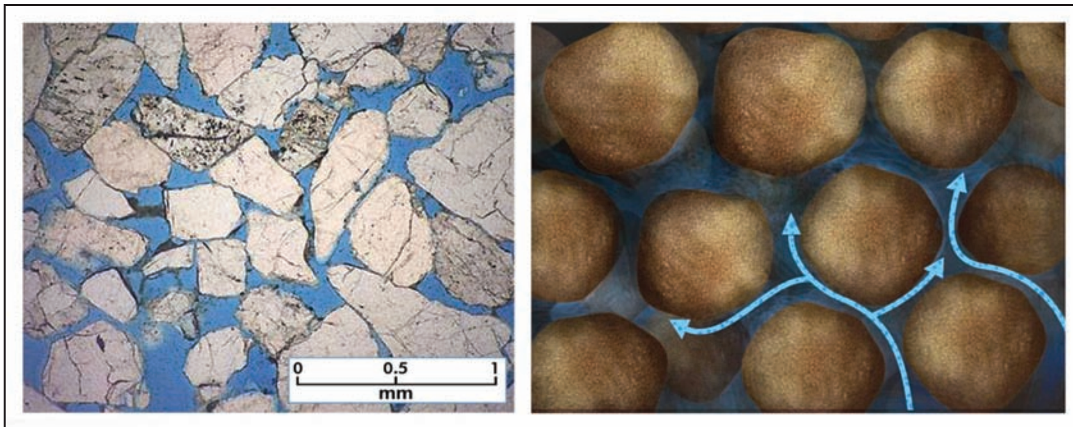

Figure 2-2. Microscopic Schematic of Rock Porosity and Permeability.

There are predictable trends in porosity and permeability in reservoirs related to the depositional environment where sediments were deposited. Reservoirs associated with delta formations, rivers and flood plain deposits (fluvial), submarine canyons and slumps—deltas in deep water (turbidites), and carbonate reefs are known for their good porosity and permeability. Rock units formed by windblown sand (eolian) both along sea shores and in deserts are also good reservoirs. Diagenesis over millions of years tends to alter the trends initially established by their depositional pattern. However, paths of fluid flow follow the path of least resistance. For the most part they are predictable. Thus, injected CO_2 would be anticipated to abide by the reservoirs internal architecture. The reservoir is not one large uniform sand box, but rather has defined boundaries and barriers initially defined by the depositional environment in which it was deposited.

Both porosity and permeability (generation, magnitude, and distribution) differ considerably between igneous, metamorphic, and sedimentary (clastic and carbonate) reservoirs. Diagenetic changes can create or destroy the original porosity and permeability, or create barriers to fluid flow. Porosity, usually caused by fracturing and/or dissolution of the original rock matrix, is often referred to as secondary porosity. In some cases, the secondary porosity considerably increases the porosity of the rock matrix and is the primary mechanism for fluid storage and fluid flow. Geologic storage of CO_2, regardless of other factors, must have sufficient areal extent and reservoir volume to hold large volumes, possibly requiring several stacked formations (often deposited over hundreds of thousands of years or millions of years within the same named formation) and their respective trapping mechanisms and seals.

2.2 Sealing and Trapping Mechanisms

Since the density of CO_2 is less than saline water, it tends to float upward; therefore, a seal (frequently called the caprock) above the storage unit is required. Seals have to significantly retard the movement of fluids (Couples, 2005). Without a seal, hydrocarbons (oil) generated at depth would have long ago migrated toward the surface and either biodegraded to heavier oil or escaped to the atmosphere. In the same manner, injected CO_2 will not remain in a storage reservoir unless adequate seals are present. Analysis of seals involves assessment of their thickness, lateral extent, permeability, and geomechanical properties (rock mechanics), such that their effectiveness can be quantified. Factors that may influence the integrity of a caprock include lithology (type of sediment), thickness, burial depth, ductility (ability to stretch or flow without breaking), permeability, and lateral continuity (Allen and Allen, 2005). Clays, claystones, shales, chalks, and evaporites formed by evaporation of salt water, such as gypsum, anhydrite, and halite, are favorable lithologies for sealing (Grunau, 1987). A rock that has been drilled from a deposit that was laid down at the bottom of a shallow lake over a few tens of thousands of years is shown in **Figure 2-3** (left). Individual bands of fine clay (dark brown) are visible, as well as courser sand (light tan), a high organic content fine sediment (decomposition of years of algae growth - black layer), a grey/white layer of salt (the lake dried out), followed by more sediment deposited in the lake in more recent time. Fluid flow would be anticipated to flow horizontally through the small zones if the permeability is high enough but would be greatly restricted from moving vertically because of the bedding plains (fine shale and anhydrite) layers. Fluid flow would be anticipated to be higher in the course sand layer than in the layers composed of finer silt and clay. This shale core, if thick enough, may be a seal for geologic storage. Well-sorted beach sand is shown in **Figure 2-3** (right) would make an excellent reservoir; reservoirs are rarely as uniform except on a small scale of less than inches as depicted with this photo.

Figure 2-3. Shale, sand, and anhydrite core from Colorado (left) and well-sorted beach sand (right). (Courtesy of USGS.)

Trapping mechanisms are primarily stratigraphic or structural depending on the physical processes by which they isolate an area or formation. Stratigraphic traps are the result of lithology (rock type) changes. Common stratigraphic sealing units are thick layers of shales or evaporites, which function as hydraulic resistant seals, as shown on microscopic level in **Figure 2-4**. Structural traps can be divided into three forms: anticline trap, fault trap, and salt dome traps. Anticline traps are formed by folding, causing isolation of reservoirs in high points (**Figure 2-5** – left). Anticlinal traps are important in petroleum exploration and could just as easy be for geologic storage. Fault traps are formed by faulting with parallel rock sections moving so that impermeable rock types trap the migrating fluids within a reservoir (**Figure 2-5** – center). Salt dome reservoirs are formed by salt domes or diapirs intruding into sedimentary layers and isolating areas along the flanks of the salt structure (**Figure 2-5** – right).

If both the seal and storage unit outcrops at some extended distance from where the CO_2 is injected, the "seal" may not provide containment for the time period necessary for CO_2 storage.

Seals have been classified into two main types:

- Membrane seals that rely on capillary processes.
- Hydraulic resistance seals that rely on low leakage rates (Brown, 2003).

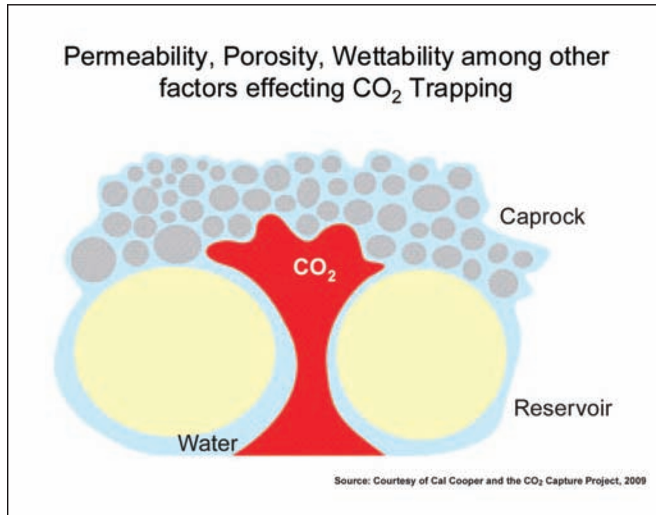

Figure 2-4. Capillary trapping of CO_2 occurs in narrow pore throats, which prevents the CO_2 from migrating up from the larger pores in the rock matrix. The strength of capillary trapping depends on the width of the pore radii and on the interfacial tension at the interface between the two fluids (water and CO_2). (CO_2 Capture Project, 2009.)

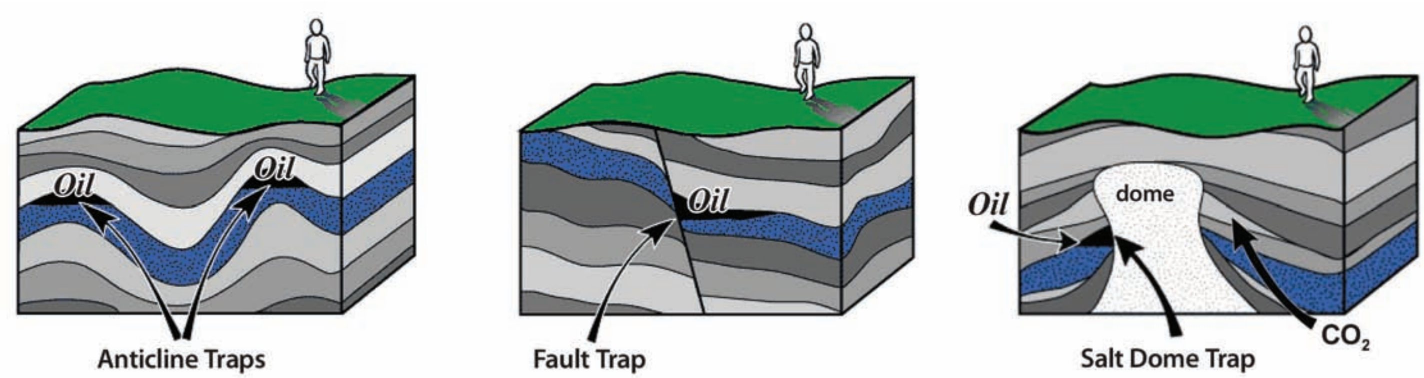

Figure 2-5. Structural traps: (left) Anticline, (center) Fault, (right) Salt Dome as trap. (Modified from Petroleum Research Institution Website, 2008.)

3.0 Depositional Environments

The majority of geologic units being considered for geologic storage are sedimentary, having been formed in freshwater lakes or saline oceans, known as basins. The current rock formation (reservoir) architecture is the result of millions of years of sediment deposition in these basins. The orientation of the original deltas, beaches, reefs; how the basins were filled; and what has happened in the intervening time since the deposition (called diagenetic alteration) influence the flow of fluids like CO_2.

Each type of geologic formation has different opportunities and challenges. While geologic formations are infinitely variable in detail, they have been classified by geologists and engineers in the petroleum industry by their trapping mechanism, the hydrodynamic conditions (mechanical forces that produce), lithology (physical characteristics), and more recently by their depositional environment (how they were formed). The depositional environment influences how formation fluids are held in place, how they move, and how they interact with other formation fluids and solids (minerals). These properties may allow the formation to be labeled as reservoirs, which in a broad sense permits the containment of liquids or gases. For the purposes of geologic storage, the geologic formation/reservoir classification system has been expanded to include unconventional reservoirs, such as coalbeds, and igneous formations, such as stacked basalts. By understanding the depositional environments of potential reservoirs, correlations can be drawn from similar depositional environments around the world. This could potentially eliminate some of the site-specific characterization requirements for similar depositional systems. The reservoir classification scheme developed for CO_2 storage, based on depositional environments, is presented as **Table 3-1**. For some systems like granite an igneous rock or metamorphic rocks there is little or no porosity or permeability except occasional fracture systems, which are often solution filled with other minerals, leaving them with little or no storage potential these system are not discussed in this document. The reservoirs internal architecture governing flow characteristics, potential chemical reactions, and geomechanical processes from the injection of CO_2 into different types of reservoir depositional environments are summarized in **Table 3-2.**

For fluid flow in porous media, knowledge of how depositional systems formed and directional tendencies imposed by the depositional environment can influence how fluids flows within these systems today and how CO_2 in geologic storage would be anticipated to flow in the future. Although diagenesis has modified fluid flow paths in the intervening millions of years, the basic *architectural* framework created during deposition remains. Geologic processes that are working today also existed when the sediments were initially deposited. Analysis of modern day depositional analogs, evaluation of core, outcrops, and well logs from ancient subsurface formations provide an indication of how formations were deposited and how fluid flow within the formation is anticipated to flow.

Compartmentalization is graded on how effective the baffles between adjacent areas of deposition are. This is dependent on the permeability of the material and the amount of fluid flow.

Table 3-1. Reservoir Depositional Classification Schematic.

Rock Classification: Lithology	Geoscience Institute for Oil and Gas Recovery Research Classification in 1991			DOE's Oil Reservoir Classification from 1990's	Sequestration Formation Classification 2010: Storage	Sequestration Formation Classification 2010: Seals
Sedimentary	**Clastic Reservoirs**	Delta	Delta/Fluvial-Dominated	Class I Reservoirs	Deltaic	**Shales** *(fine terrigenous materials—clays as well as from carbonates)* Deposited in Lacustrine, Fluvial, Alluvial, Near Shore and Open Ocean Marine Environments
			Delta/Wave-Dominated			
			Delta/Tide-Dominated		Coal/Shale	
			Delta/Undifferentiated			
		Fluvial	Fluvial/Braided Stream	Class 5 Reservoirs	Fluvial	
			Fluvial/Meandering Stream			
			Fluvial/Undifferentiated			
		Alluvial Fan			Alluvial	
		Strandplain	Strandplain/Barrier Cores and Shorefaces	Class 4 Reservoirs	Strandplain	
			Strandplain/Back Barriers			
			Strandplain/ Undifferentiated			
		Turbidites	Slope-Basin	Class 3 Reservoirs	Turbidite	
			Basin			
		Eolian — *Wind Blown: Clastics and/or Carbonates*			Eolian	
		Lacustrine — *Lake Deposited: Clastics, Carbonates, Evaporites*			Lacustrine	**Evaporites** *(from various Lithology Deposited in Arid Settings)*
		Shelf			Shelf	
	Carbonate Reservoirs Carbonate (>50% Carbonate content but can contain Terrigenous materials — sand, feldspar, non-carbonate boulders and evaporites)	Peritidal	Dolomitization			
			Massive Dissolution			
			Other			
		Shallow Shelf/ Open	Dolomitization	Class 2 Reservoirs	Shallow Shelf	
			Massive Dissolution			
			Other			
		Shallow Shelf/ Restricted	Dolomitization			
			Massive Dissolution			
			Other			
		Reef	Dolomitization		Reef	
			Massive Dissolution			
			Other			
		Shelf Margin	Dolomitization			
			Massive Dissolution			
			Other			
		Slope-Basin	Other			
Igneous	**Basalts**				Basaltic Interflow Zones	
	Granitic					
Metamorphic						

Table 3-2. Characteristics of Depositional Reservoirs.

Classification	Primary Flow Direction of Injected Fluids	Composition	Characteristic Deposition Pattern	Potential CO_2 Interactions	Chemical Interactions with CO_2	Compartmentalization[1]
Deltaic	Parallel to stream or delta axis when deposited. Fluids flow in high permeability paths	Ranges from course sand in channel bottoms to fine clays in seals, but formed within predictable ranges of deposition for types of deltas	Dependent on delta type and where within delta.	Interaction dependent on carbonate content and clay barrier (shales) within	Moderate chemical reactivity depending on clays	Depends on where in depositional environment
Coal	Parallel to axis of least stress imposed by diagenesis on the cleat network	Highly variable content with organic content showing remains of plant materials, as well as various clays and sand	Highly variable, but deposited in layers	Adsorption dominates	Adsorption dominates, but little chemical reactivity	Controlled by cleat network
Shale	Flow direction controlled by diagenesis after deposition. Little flow- low porosity and permeability	Mostly fine to very fine clays, fine sand, organic matter, and/or fine carbonate fragments	Deposited as layers in low flow environments causing drapes over higher permeability larger sediment	Forms seals	Slow chemical reactions with clays in shale	Few compartments, forms seals and barriers within and between other formations.
Fluvial	Parallel to axis of stream when deposited. Fluids flow in high permeability paths	Ranges from course sand in channel bottoms to fine clays in seals, but formed within predictable ranges of deposition for rivers	Fining upward in channel	Interaction dependent on carbonate content and clay barrier (shales) within	Moderate chemical reactivity depending on clays	Highly variable depending on where within fluvial system
Alluvial	Parallel to axis of alluvial fan when deposited	Wide mix of poorly sorted materials, size, and composition	Fan thinning to distal end	Highly variable based on rock composition	Highly variable based on rock composition	Little
Strandplain	Parallel to beach front	Principally quartz sands	Parallel to the beach and perpendicular to the beach	Little interaction	Little chemical reactivity as mostly quartz sand	Moderate
Turbidite	Parallel to axis of deposition of fan	Variable composition and ranges from finer carbonate, sand, fine clays to very fine clays	Repeated layers of fining upward. Fine materials toward distal end	Interaction dependent on carbonate content	Chemical reactivity dependent on carbonate, quartz sand, and clay composition	Highly
Eolian	Parallel to prevailing wind direction at time of deposition	Mostly well-rounded quartz sands, few fines	Pattern depends on dune type, but within dune type are usually consistent	Little interaction	Little chemical reactivity as mostly quartz sand	Highly

Classification	Primary Flow Direction of Injected Fluids	Composition	Characteristic Deposition Pattern	Potential CO_2 Interactions	Chemical Interactions with CO_2	Compartmentalization[1]
Lacustrine	Parallel to horizontally depositional bedding plane Flow direction controlled by diagenesis after deposition. Little flow	Fine clays, silt, sand, organics, windblown fines, evaporites, and carbonates	Highly layered depositional pattern, often reflecting seasonal variations	Interaction dependent on carbonate, evaporite, and clay content within	Highly variable dependent on composition of rock.	Highly layered
Shelf Clastic including Barrier Island	Highly variable and controlled by diagenesis after deposition	Mix of terrestrial material (quartz, clays, etc.) and <50% carbonate materials	Often highly mixed by tides, waves, currents, and sea dwelling animals	Interaction dependent on carbonate content and clay barrier (shales) within	Chemical reactivity highly dependent on carbonate content and little interaction with quartz, reaction with clays slow	Depends on depositional environment
Shallow Shelf Restricted and Open Carbonate	Highly variable and controlled by diagenesis after deposition	Highly variable mix of carbonate materials and <50% terrestrial materials quartz sands and clays	No characteristic pattern. Original depositional structure modified by diagenesis	In presence of water dissolved near well carbonate, precipitates form downstream in presence of ions, such as sulfate	Fast reaction with carbonates and then sulfates	No consistent pattern
Reef	Flow direction controlled by diagenesis after deposition	Principally carbonates, limited terrestrial material	Dominated by reef original structure, modified by diagenesis	In presence of water dissolved near well carbonate, precipitates form downstream in presence of ions, such as sulfate	Fast reaction in carbonates	No consistent pattern
Basalt	Dominated by flow in interflow zone, little flow through basalt	Composition of MORB is remarkably uniform throughout the world, and different from ocean island basalts (OIB) or LIP, but within LIP similar patterns in basalt flows at different scales. Interflow zones in LIP have highly variable composition	Structure of basalts different for MORB, OIB, or LIP, but within LIP similar patterns in basalt flows at different scales. Interflow zones are highly variable.	CO_2 will help seal fractures within basalt.	High chemical reactivity within basalt, but reactions are slow; interflow zone mixed composition, thus variable reactivity	Interflow zone different from within basaltic in LIP and different than MORB

[1] *Compartmentalization is graded on how effective the baffles between adjacent areas of deposition are. This is dependent on the permeability of the material and the amount of fluid flow.*

3.1 Deltaic Reservoir Properties

Deltaic Depositional Environment

Deltas are composed of clastics, which are rock fragments from original geologic units that are re-deposited. There are several groups of deltaic reservoirs, fluvial (river)-dominated, wave-dominated, tide-dominated, and undifferentiated deltas (Fowler, Rawn-Schatzinger, et al., 1995). Each of these different depositional environments will have distinctive fluid flow patterns due to their internal architecture. The components of a delta system are presented in **Figure 3-1**. Deltaic reservoirs are created by stream or river fed systems that deposit sediments rich in organic matter into standing bodies of water (lakes, bays, lagoons, oceans, etc.), resulting in an irregular expansion of the shoreline. These deltas and rivers meander (move laterally) over time based on the amount and type of deposition, river flow, and flooding (**Figure 3-2**). In general, all deltas are marked by a thickening wedge of sediment at the interface of land and water. This is formed by the rapid influx and deposition of sediment at a rate that exceeds its removal and redistribution by wave and tidal action.

A fluvial-dominated delta environment is associated with streams and rivers eroding sediments and rocks, the transportation, and deposition of sediments (**Figure 3-3**). The upper delta plane is the area where fluvial, lacustrine (lake), and swamp sediments occur. The nature of the deposits is dependent on the type of river and the climate. Sediments in fluvial dominated delta environments are usually described as fining upward, meaning that coarse sediments are on the bottom and fine material is deposited on top. These types of deltas tend to form fingers of delta front sands and the general distribution of major sands tends to be perpendicular to the shoreline. The lower delta plane channels become more numerous as they divide into smaller distributaries.

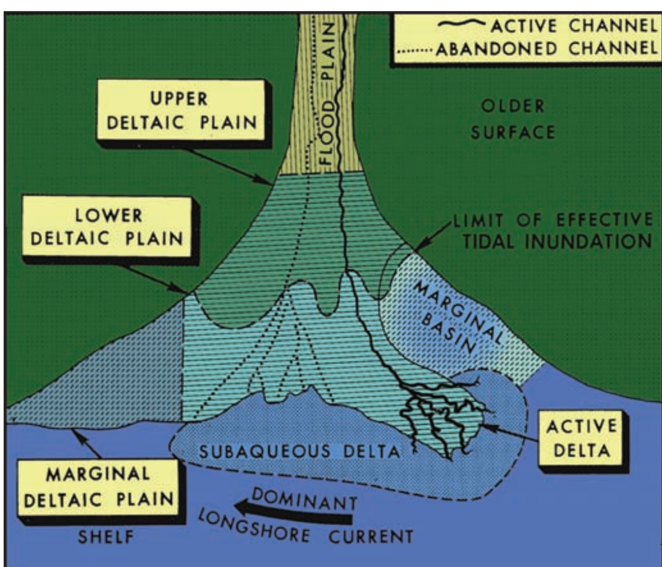

Figure 3-1. Components of a Deltaic System. (Coleman and Prior, p. 139, 1982.)

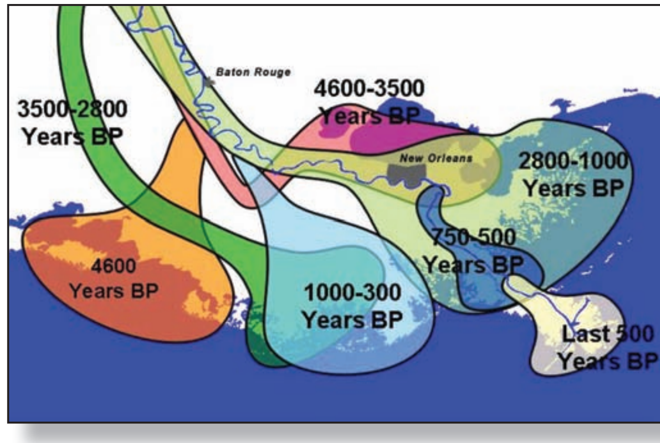

Figure 3-2. Mississippi River Delta, United States, Lobe Development over the Last 5,000 years. (Frasier, 1967.)

Figure 3-3. Mississippi River Delta, United States. A Recently Developed Elongated Shaped Delta that is River-Dominated. Photo taken by the ASTER Instrument on the Terra Satellite, May 24, 2001. (Courtesy of NASA.)

Other depositional features include levees, which are long and narrow ridges on either side or between streams and can develop bays between the channels. In addition, marshes and swamps are usually extensive between the bays and channels. The preferential flow through this depositional environment is along the ancient river channels.

A wave-dominated delta environment is associated with large waves that run over the top of spits or sand bars and down the landward side **Figure 3-4** and **Figure 3-5**. The sands tend to be reworked into numerous coastal barriers that are orientated roughly parallel to the shoreline. Wave-dominated deltas have a broad outer mound of beach material separated by crescent-shaped troughs. A coarsening upward sequence is produced through wave-dominated delta growth, but the sands of the upper part of the sequences should show low-angle cross bedding and planar bedding through wave action on beaches, and some onshore-directed cross bedding from dunes in the shoreface zone. Clear channels are not as evident as river-dominated deltas and sediment is deposited more parallel to the shore than away from the shore and the channel flow is oblique or parallel to the shore.

Figure 3-4. Nile River Delta, Egypt. A Lobe Shaped Delta that is Wave-Dominated. North is top of image. Photo taken from MISR Satellite, January 30, 2001. (Courtesy of NASA.)

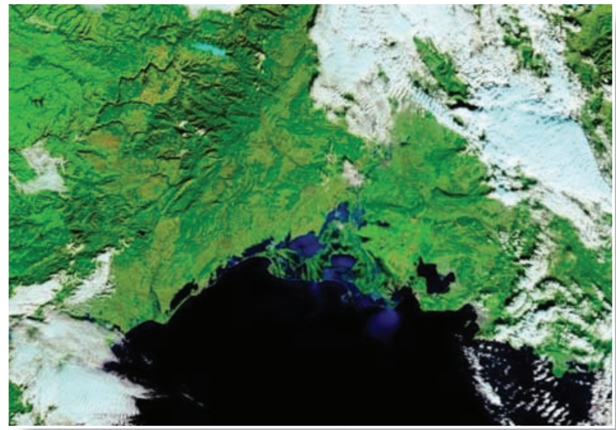

Figure 3-5. Rhone River, France. A Wave-Dominated Elongated Delta. Flooding in Southern France, the worst in decades carried sediment tinting the otherwise black Mediterranean Sea a bright blue. (Photo from Terre MODIS Satellite, NASA Earth Observation Collection, December 1, 2003, courtesy of NASA.)

A tide-dominated delta is where sedimentation at the delta front is controlled by the high and low tides (**Figure 3-6**). Multiple small-folded ridges are developed in a linear pattern parallel to the direction of tidal currents, which may be perpendicular or parallel to the delta front. The lower delta plain will have extensive tidal flats where mud is deposited. The tidal-dominated delta

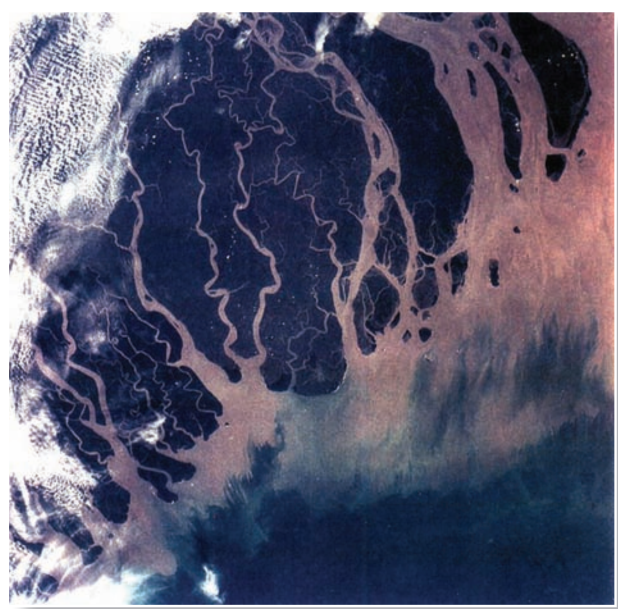

Figure 3-6. Ganges/Brahmaputra River Delta, Bangladesh. This is a Tidal-Dominated Delta - the Largest Inter-Tidal Delta in the World. North is top of image. (Photo from MISR Satellite, November 6, 1994, courtesy of NASA.)

should have a thick coarsening upward sequence. Muds should be present in sands showing tidal structures, cut through by major channels filled with sands. Due to the eroding effect of tides, the sands display cross-bedding, the sand ridge field can be truncated through erosion, and the tributary channel sediments contain more slack-water mud drapes than usual. Thus, fluid flow within these sediments shows fewer high-permeability channels and more compartmentalization with fine clays as barriers.

Undifferentiated-deltas may be either a complex combination of any or all of the three major types, or deltas for which insufficient classification information exists.

Coals are deposited over a narrow range of depositional sedimentary environments, including swamps, marshes, and flood plain deposits. In all cases, fresh organic plant material was buried quickly and protected from oxidation (anoxic conditions), otherwise it becomes CO_2. The younger sediments rest on the older material. As coal evolved from soft plant and woody debris into hard coal, the coal ranking increased as the amount of moisture decreased (**Figure 3-7**). Coal rank is a measure of the maturity of the coal as it changes from peat, to soft coal (bituminous), and eventually hard coal (anthracite). Coal rank increases with heat content, hardness, and carbon content. Maturation is the geological processes of compaction, applying heat, and pressure to the coal over time, which, under suitable conditions, transforms the coal into successively higher ranks. Carbon dioxide storage in coal seams or carboniferous shale is accomplished differently than in other geological settings. Instead of occupying pore space, the CO_2 is adsorbed into the matrix of the coal and locked in place. Generally, CO_2 that enters coal is held so tight that it will remain in place without caprock(s).

Coal will preferentially adsorb the CO_2 and drive out the methane. The practice of using CO_2 to boost methane production in Coal Bed Methane (CBM) recovery is called Enhanced Coal Bed Methane (ECBM). The range in the

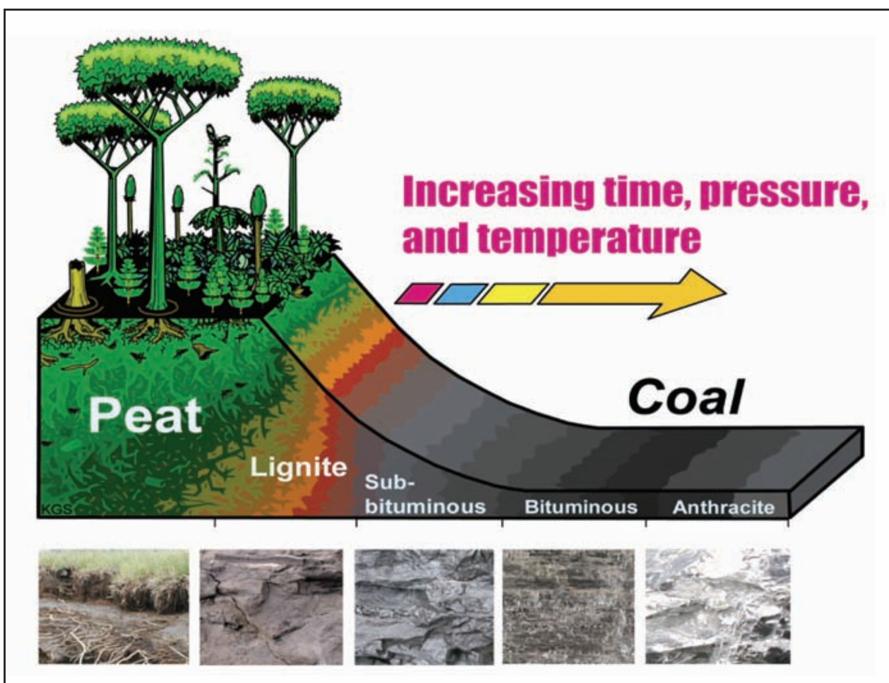

Figure 3-7. As Time, Heat and Pressure Increase during Coalification, the Lignite Changes into Bituminous and Finally Anthracite Coal. (Courtesy of Steve Greb, Kentucky Geological Survey, 2008.)

adsorption capacity is based on the exposed surface area of the coal, which is usually governed by diagenetic processes. Coal seams tend to have low permeability and the majority of the porosity and permeability is the result of fracturing/cleats (**Figure 3-8**). One issue that is still being investigated is coal swelling in the presence of CO_2, which may reduce or cutoff the flow of CO_2 or methane.

Shale, the most common type of sedimentary rock, is characterized by thin, horizontal layers of rock with low permeability in both the horizontal and vertical direction. Shale is composed of fine clay particles that are packed so closely together that fluids cannot move between the particles. Clays are naturally occurring materials made up of fine-grained minerals derived from igneous rocks. Fluid flow is governed by fractures that could be formed after deposition and other diagenetic processes. In general, vertical fluid flow is negligible when compared to horizontal fluid flow occurring along the bedding plane surfaces. Most of the fluid is transmitted along fractures parallel to the horizontal bedding planes. In many cases, because of the low permeability of shale, it is considered a caprock or sealing formation for other types of reservoirs.

Many shales contain 1 to 2% organic material in the form of hydrocarbons, which provide an adsorption substrate for storage similar to coal seams. Additional research is needed to focus on achieving economically viable CO_2 injection rates, given shale's low permeability. It is possible that this research may lead to the conclusion that it is not feasible to use fractured, organic-rich shales as reservoirs for geologic storage.

Currently, these tight organic rich shales are being developed as gas and oil shale plays, such as the Marcellus Shale, and are a significant contributor to the domestic natural gas resource. The shale is artificially fractured to allow the release of the natural gas. This may provide a potential storage reservoir for CO_2 once the natural gas has been removed.

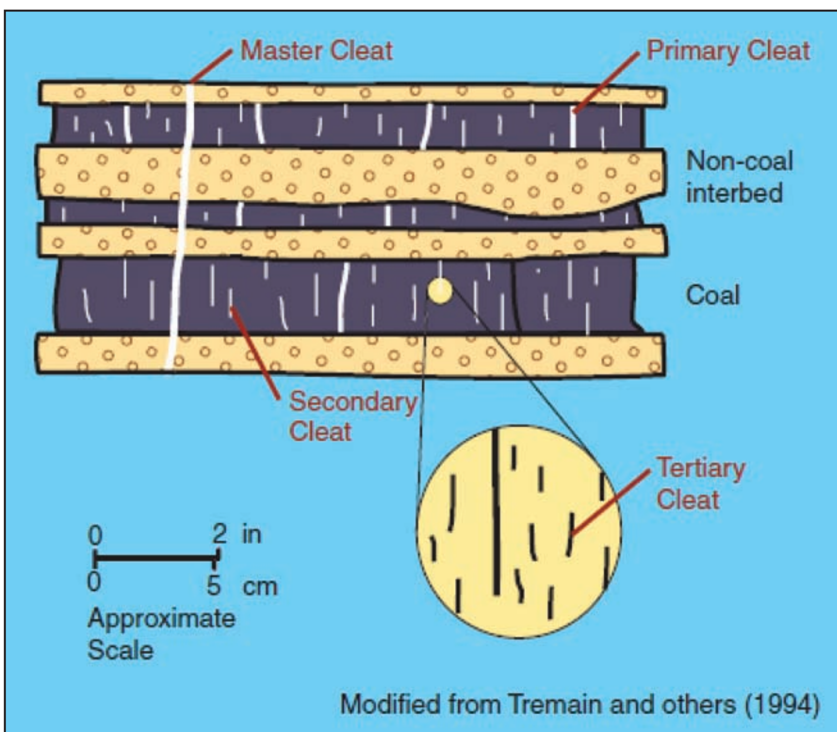

Figure 3-8. Structure of coal and the cleat system within. The frequency of cleats is generally higher in coal than in the shale layers separating coalbeds. Cleats provide the pathway for fluids to move through the coal. (Tremain et al., 1994; Dallegge and. Barker, 2009.)

3.2 Carbonate Reservoir and Reef Reservoir Properties

Carbonate Depositional Systems

Most carbonate material comes from the growth and demise of organisms that live in oceans on continental shelfs. The organisms make their hard parts out of carbonate by extracting calcium and magnesium ions, and CO_2 from seawater. Over 90% of carbonates formed in modern environments are thought to be the skeletal remains of biological organisms that formed under marine conditions favorable for their growth. These conditions include light, temperature, salinity, substrate, and presence/absence of clastics high in silicon.

The main controls on carbonate sedimentation are tectonic movement and climate (Tucker and Wright, 1990). The organisms that are the biological building blocks of carbonate reefs have specific tolerances to light, temperature, and water depth. Sea level changes associated with mountain building and glaciers cause sea transgression and regression that can control sedimentary deposits that may cover carbonate generating systems. The wide variety of depositional environments possible for carbonate deposits is shown in **Figure 3-9**.

Four aspects of carbonate deposition differ from clastic sedimentation: (1) shallow water marine carbonate buildups are similar through geologic time; (2) they form *in situ* in shallow water with warm tropical conditions; (3) carbonate muds are extensively preserved during compaction; and (4) early diagenesis effects that occur just after deposition. Carbonate buildups have been accumulating in different locations for approximately 545 million years (Demicco and Hardie, 1994).

Shapes of carbonate deposits include:

1) Isolated banks with flat tops and walls that slope steeply down into the ocean. A modern example is the Bahamas Bank.

2) Continental shelf deposits. Modern examples are the shelves of the Belize (Belize) and Great Barrier Reef (Australia).

3) Ramp-like shelves that slope into shallow ocean basins. A modern example is the southern shelf of the Arabian Gulf.

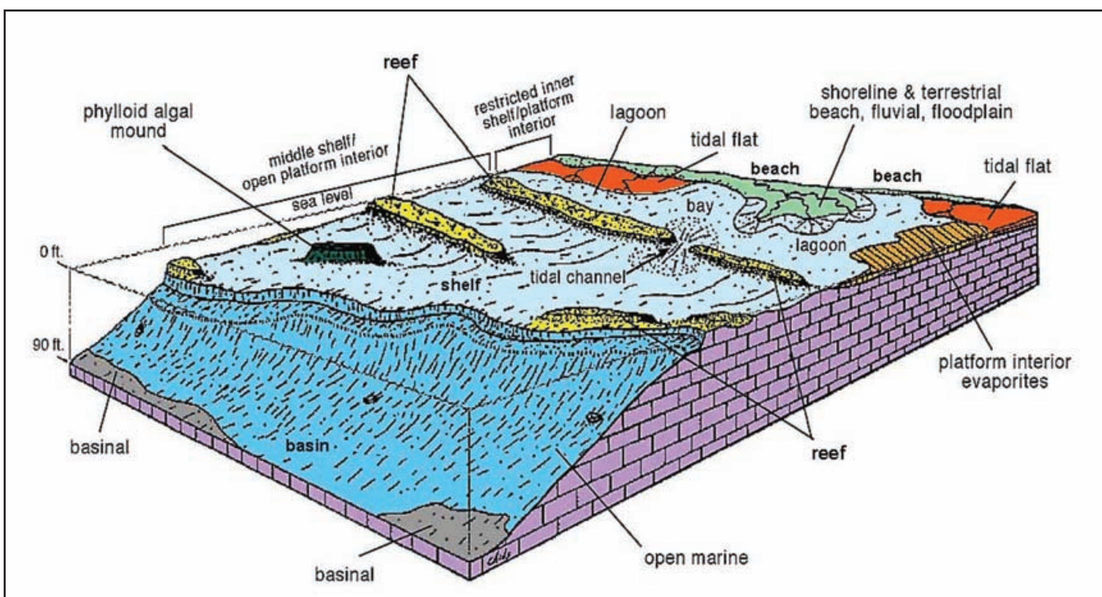

Figure 3-9. Carbonate Depositional System. An idealized block diagram of carbonate depositional environments based on Pennsylvanian carbonates in southeastern Utah. (Modified from Chidsey, 2007.)

As compared to clastic sedimentation, carbonate sedimentation is much more influenced by faulting, fracturing, precipitation, and solution channels after initial deposition. In carbonates, there are far fewer recognizable trends in direction of fluid flow imposed by the initial deposition system (reef, shallow shelf, etc.). Most of the trends in fluid flow are the result of changes to the rock occurring after deposition (Budd, *et al.*, 1995). There are three carbonate depositional environments that are being considered for geologic storage: Peritidal, Shallow Shelf/Open, and Shallow Shelf/Restricted.

Peritidal carbonate depositional environments are defined as the area between the highest tide to the area exposed during the lowest tide. The term peritidal is generally used to describe a variety of carbonate environments associated with low-energy tidal zones, especially tidal flats (Folk, 1973). The orientation and size of these depositional environments is based on the size of the tides and the fluctuation of sea levels. Ancient peritidal carbonates commonly form stratigraphic traps for hydrocarbons as a result of onlap and offlap geometries, creating pinch-out structures (Shinn, 1983a). These carbonate units have usually undergone changes to the rock, including fracturing that causes secondary porosity.

Shallow shelf open and restricted carbonates describe the original carbonate rocks that were deposited either in shallow waters on open shelves, restricted lagoons, deeper water on the shelf margin, or basin slopes as precipitates. As aforementioned, changes in the rock significantly impact the porosity and permeability of the rock over time, which also affects reservoir quality both for oil and gas accumulation and for potential capacity as a CO_2 storage reservoir. The flow patterns of water above (vadose zone) and below the water table (phreatic zone) are shown in **Figure 3-10**; this is important to understanding how secondary porosity controls fluid movement.

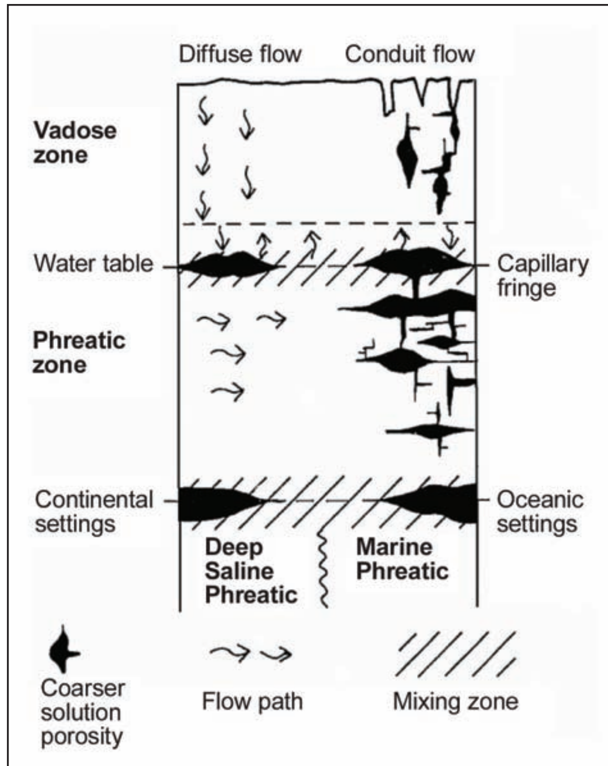

Figure 3-10. Groundwater zones. Flow may be through pore networks, or fractures. Dissolution and mixing occurs in the vadose zone and the lower phreatic zones. (Tucker and Wright, 1990, pp 337.)

Reef Depositional System

The geometry of a reef basin and its tectonic history affect the porosity, permeability, and development of carbonate reservoirs (Klovan, 1974). Reef development corresponds to the overall history of a basin, which is related to tectonic movements and the rise and fall of sea level. Similar controls affect recent and ancient reefs and allow for analogies between depositional settings with similar features. For example, pinnacle reefs developed in response to gradual and continual subsidence, with the reefs growing upward to obtain light as the sea level rises. The development of pinnacle reefs found in Alberta is illustrated in **Figure 3-11**. The restricted basin had barriers that limited water circulation, which prevented development of more massive reefs that result from higher amounts of nutrients.

Isolated banks and reefs form on small up-faulted blocks related to early opening of ocean basins, along the margins of uplifted continental margins, and as fringing reefs on volcanic islands. The huge ancient carbonate continental shelf that rimmed the North American continent during the (Cambrian-Ordovician period, 100 million years BP) is an example of a shelf deposit on a stable, passive margin.

3.3 Turbidites Reservoir Properties

Turbidite Depositional System

Turbidites are downslope gravity flows operating at water depths of greater than 150 feet and form slope, shelf, and basin deposits. Much like alluvial deposits that occur at the base of many mountain ranges, these are the subsea equivalent, but originate at the margin between shallow water shelf and deeper basins at the continental margins, as shown in **Figures 1-8** and **1-9**. They can be composed of both clastic- and carbonate-derived rock.

Major rivers do not stop at ocean boundaries, they can continue hundreds of miles out to sea as subsurface rivers (turbidity flows), across the continental shelf, and travel down submarine canyons to the basin floor. Large fluvial inputs beyond river deltas are enhanced during floods of major rivers; the larger flow volume of sediment-laden (i.e. turbid) water scours storm shelfs and lagoons, becoming more and more turbid, carrying dense, sediment-rich water into the ocean where it flows downhill. Turbidites occur in both submarine canyons and on the continental slope. On slopes, they can flow downslope, forming a submarine fan that looks a little like an underwater delta. The place of origin on the continental shelf often refills with sediment and is later scoured off again, causing another layer to be deposited at the base of the slope. Two different shaped of turbidites are formed based on the velocity of the flow, the sediment size, the width of the coastal plane and the basal slope angle **(Figure 3-12)**. Turbidites tend to

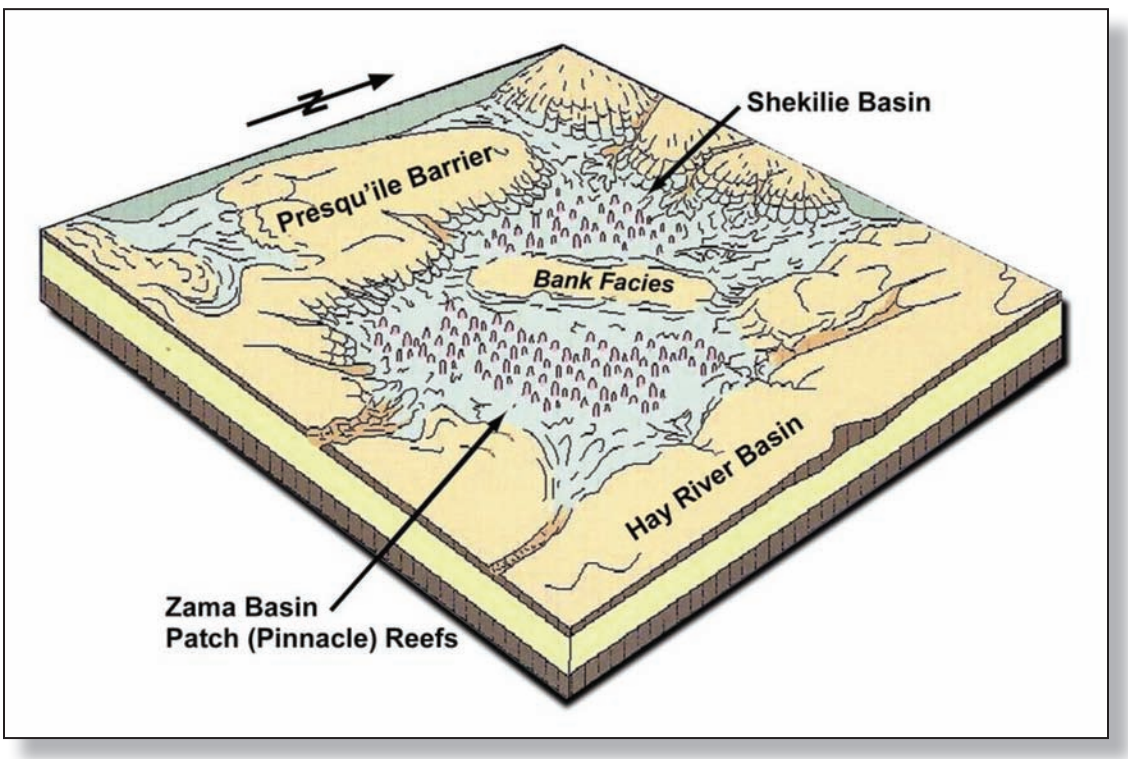

Figure 3-11. Pinnacle Reef Development in Alberta. (Alberta Energy Utility Board, 2004.)

become stacked from repeated sequences of deposition down canyons or from scouring of the continental slope and many form at nearly the same point of origin.

Since the flow of sediment is mostly water, turbidite sediment is well sorted when deposited on the basin floor. Turbidites can be divided into coarse-grained (more sand) and fine-grained (more mud and less sand) flows where the sand and mud produced different sediment distribution patterns and a different internal architecture as a result. As compared to many other slow geological processes, sand and mud flowing down a submarine canyon causes heavier sediment to fall out faster and lighter sediment to travel farther. Turbidites that separated from their place of origin on the edge of the continental slope and then deposit on the basin floor

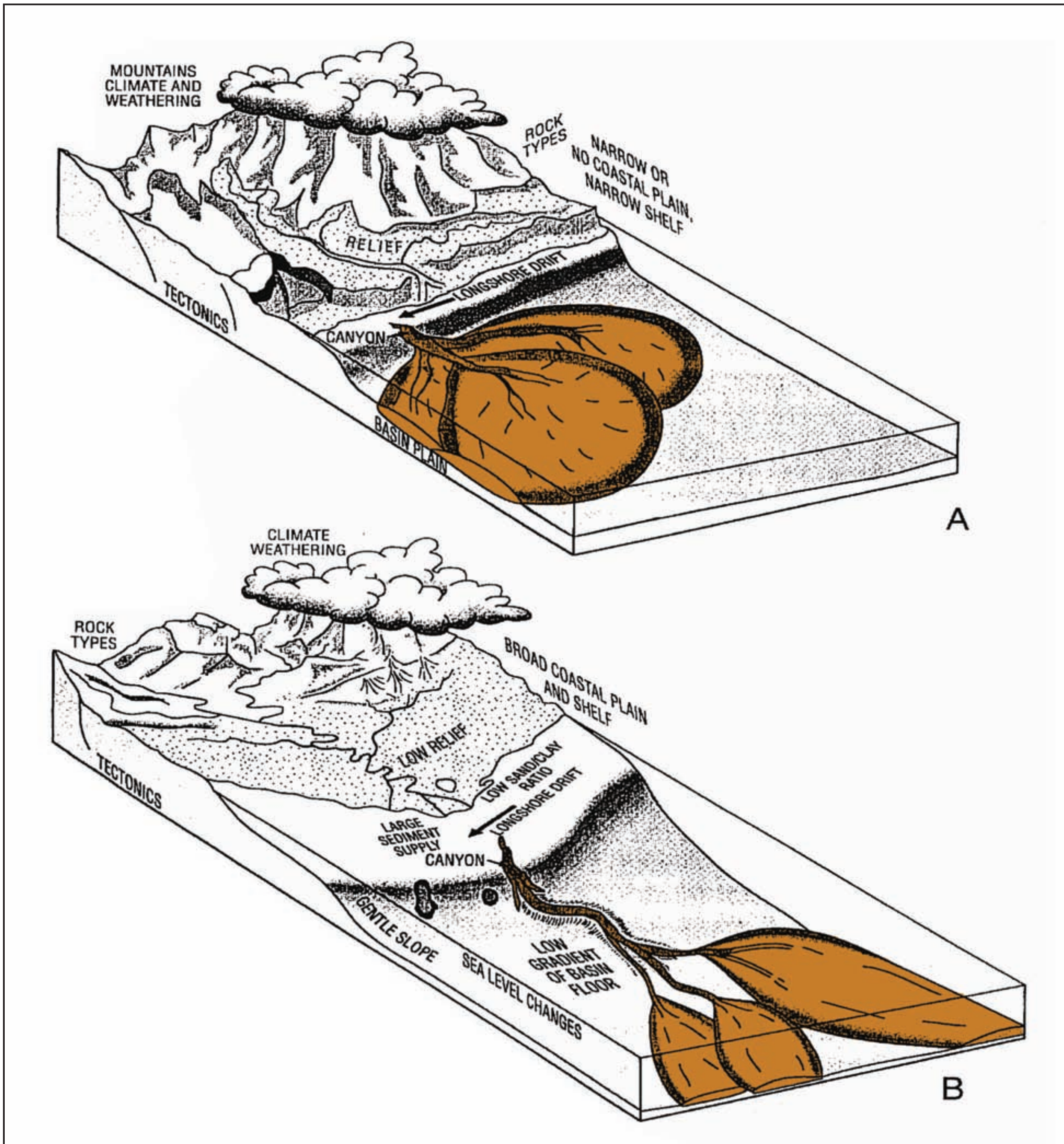

Figure 3-12. A. Coarse-Grained, Sand-Rich Turbidite (brown) System, B. Fine-Grained, Mud-Rich Turbidite (brown) System. (Bouma, 2000.)

are thickest at the base of the slope and thin as they move outward into the basin (Pratson, *et al.*, 2000). Turbidites at the base of the submarine canyon tend to become stacked from repeated sequences of deposition. The preferential fluid flow path within a turbidite is parallel to the axis of the mass flow (LaBlanc, 1972).

3.4 Strandplain Reservoir Properties

Strandplain Depositional System

Coastal strandplain and barrier island deposits are laid down along a shoreline where wave and tidal forces dominated the transport of sediments (Rawn-Schatzinger and Lawson, 1994). Strandplains typically are created by the redistribution of coarse sediments by waves and long-shore currents on either side of a wave-dominated delta. Tectonics and sediment supply rate control the thickness, lateral extent, and formation of strandplain deposits (modern analogs are shown as **Figures 3-13** and **3-14**).

Strandplain deposits are formed by sediments moving outward into a sea (the sea level elevation is falling). The shoreface builds seaward and is shaped by waves and currents, which spread out in broad continuous stacked beach deposits along coastlines (DOE/Bartlesville Project Office, 1994). Two forms of strandplain – sand-rich and mud-rich – are distinguished by sediment type. Sand-rich strandplain deposits are continuously deposited parallel and perpendicular to the shoreline and have higher permeability. The sands within mud-rich strandplains are not continuous in the perpendicular direction to the shoreline and have low permeability. Lagoonal deposits (muds and fine silt that form shale) are usually not associated with strandplains because the waves moved fine sediment up the coast and often out to sea. A strandplain with dozens of old beach ridges seen in **Figure 3-14** from Kitikmeot Region, Nunavut, Canada can be dated back about 10,000 years when the last glaciers in the area retreated. At the end of the last glaciation, the beach level can be seen in the low, dark cliff line at the foot of the slope of the plateau. The resulting clean sand is often well sorted and has high permeability and porosity. Preferential fluid flow is in the direction paralleling the axis of the deposit.

Figure 3-13. Strandplain Deposit along the South Carolina Coast (infrared satellite image). Note the linear sand ridges building toward the ocean as the strandplain builds through sand brought by long-shore currents. The layered appearance results from the accumulation of new strandlines. (Hayes, 1989.)

Figure 3-14. Strandplain near the mouth of the Kugaryuak River, Coronation Gulf, Southwest Kitikmeot Region, Nunavut, Canada. (Reproduced with the permission of Natural Resources Canada 2010, courtesy of the Geological Survey of Canada. Photo 2002-377 by Daniel Kerr.)

Barrier Island Depositional System

The depositional processes that influence barrier island formations are a combination of wave/tidal action and long-shore currents (DOE/Bartlesville Project Office, 1994). Sediments are normally carried along the coast by currents; commonly the source of the sediments is from deltas. Wave action sorts the sediments based on grain size and will deposit the larger sized particles on the sea side of the barrier island first and smaller particles later. The deposition is based on the amount of energy generated by tidal influences, the strength of currents, and the strength of the waves. During storms, finer grained sediment may be carried up and over the barrier island to be deposited in the mudflats and lagoons on the land side of the barrier island.

Two modern analogs of barrier island deposition are shown in **Figures 3-15** and **3-16**. Barrier islands are easily susceptible to storm degradation, which can erode the sand, move the sand in the direction of the current and waves, and overtop the island (they are unstable land masses). Ancient barrier island deposits encountered the same forces (McCubbin, 1982) and preferential fluid flow (highest permeability) within the (Cole, *et.al.,* 1994) barrier island formations is highly variable and controlled by changes to the rock after deposition.

Figure 3-15. Barrier Island with Beach and Back Dune areas visible, South Carolina. (Photo courtesy of Richard Schatzinger, Consulting Carbonate Sedimentologist.)

Figure 3-16. Barrier Island along the Texas Coast with ocean to the left, shoreline, beach and dune ridges, mudflats and lagoon before marshes on mainland on right of photo. (Photo Courtesy of the University of Texas.)

3.5 Alluvial and Fluvial Fan Reservoir Properties

Alluvial Depositional Systems

Alluvial depositional systems, like most depositional systems, are gravity driven. In general, an alluvial sediment source comes from higher elevations, such as mountains, and is deposited in valleys. The sediment source and depositional locations are closer together than in other depositional environments. **Figures 3-17** and **3-18** show typical alluvial fan system where water has washed sediment from the face of the mountain downhill. Near the heal of the deposit, the material is poorly sorted, coarest grained. The toe of the fan is also poorly sorted, but is finer grained. Prograding fans (where the valley bottom is declining in elevation as compared to the adjacent mountains) lead to a coarsening upward sequence from repeated alluvial deposits. There is no dominant preferential fluid flow path (identifiable and predictable high permeability trend as compared to other depositional environments) in most ancient alluvial deposits.

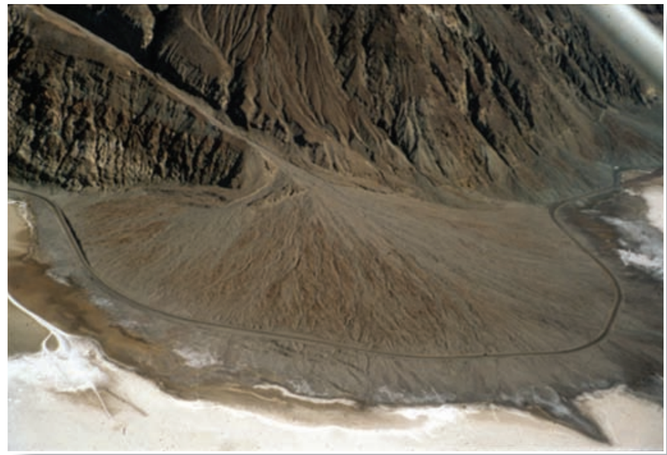

Figure 3-17. Badwater Fan, Death Valley, California. Oblique air photo looking SSW The Black Mountains in the background provide the source material. Road encircling fan provides scale. (Courtesy of Paul Heller, 2006.)

Fluvial Depositional Systems

Fluvial depositional systems are mechanisms where gravity and water carry sediment from higher to lower elevations. Streams and rivers in the mountains remove material and deposit their sediment load downstream in low lying, flatter terrain. In the lower stretches of rivers, deposition occurs on a temporary basis as streams meander, dropping part of their sediment load only to be picked up and washed farther downstream at a later time. At lower elevations where the river velocity slows, increased deposition occurs (red square in **Figure 3-19** and magnified in **Figure 3-20**), forming braided streams (**Figure 3-21**).

Fluvial depositional systems often leave characteristic clues of how the sediments are transported, direction of river flow, and the relative velocities of the stream in the subsurface sediments. Heavier sediments fall out first and lighter sediments are carried downstream (to deltas and the ocean) to calmer water where they are deposited. During floods, fine muds are often sent miles away from the normal river channel covering the surrounding lands, while river channels get scoured and redirected by

Figure 3-18. Large alluvial fan (covers an area of 56.6 x 61.3 kilometers) blossoms across an otherwise desolate landscape between the Kunlun and Altun mountains, XinJiang Province, China (image is centered near 37.4° N, 84.3° E). Right side is the active part of the fan where water currently flows in the many small streams. (Photo by NASA/GSFC/METI/ERSDAC/ JAROS Satellite, May 2, 2002. Courtesy of U.S./Japan ASTER Science Team.)

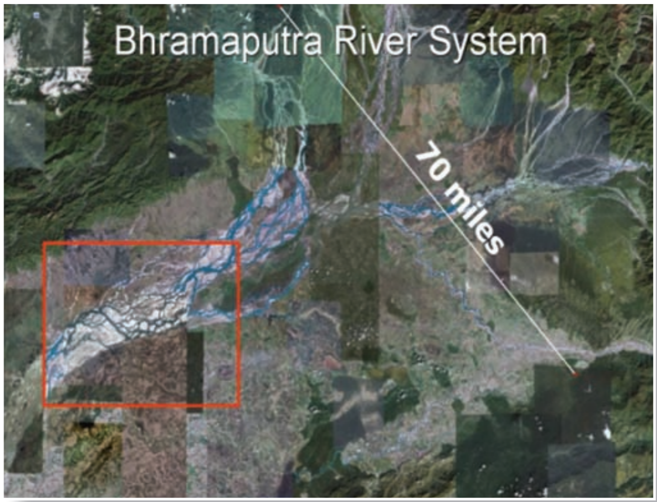

Figure 3-19. Google Earth Image of Bhramapura River System, Bangladesh showing Braided stream system depositing sediment from the Himalayan Mountains. North is top of image. (Google Earth Image modified from Hannes Leetaru, 2009.)

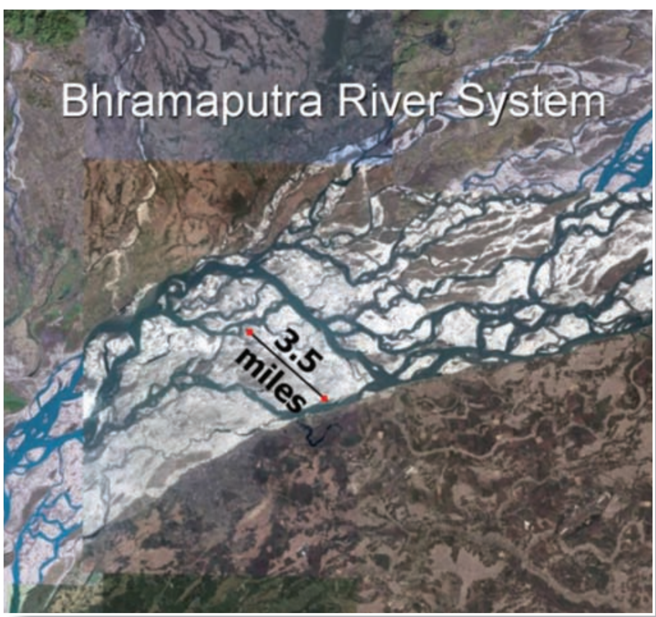

Figure 3-20. Closer Image of Braided River Fluvial Depositional System showing the area in red in previous figure. (Google Earth Image modified from Hannes Leetaru, 2009.)

higher velocity flows. This leaves characteristic course-grained sediment on the bottom (higher permeability) and fining upwards signature. Over time, the river will start to meander (migrate and form snake-like pattern) (**Figure 3-22**). The meandering is controlled by the river velocity, sediment load, areas that are being scoured, and areas of deposition.

Figure 3-21. Braided River Flowing on a previously Glaciated Flat near Peyto Lake, Banff National Park, Canadian Rockies, Alberta, Canada. (Google Earth, July 2008.)

Ancient fluvial depositional systems have often been reworked and tend to develop individual compartments in portions of the depositional system where the bottom is composed of course sediment that fine upward. This is often sealed by a fine silt/clay layer (future shale) that acts as a barrier to fluid flow. These stacked, compartmentalized sediments may or may not be connected. One would anticipate that injection of CO_2 would take the path of least resistance and travel along the higher permeability channels located along the axis of the original river system where the compartmentalization is not as prevalent.

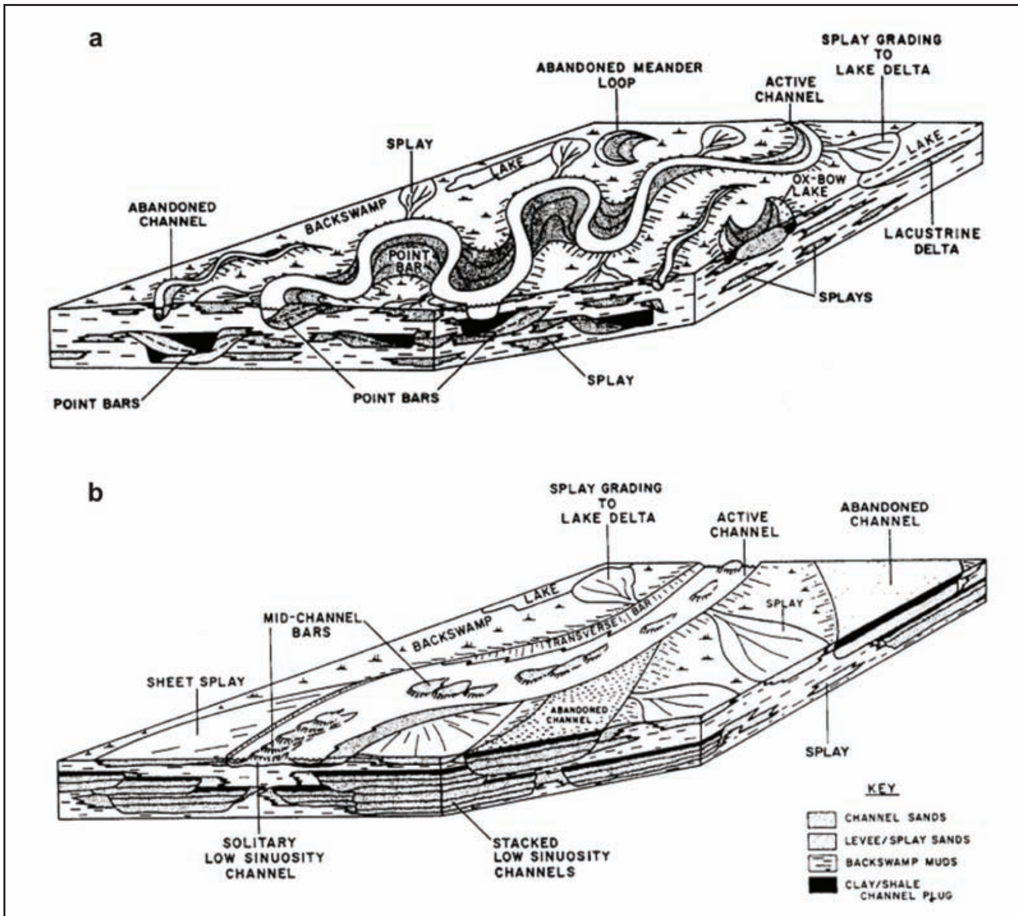

Figure 3-22. Block diagram of a meandering stream (a) and braided stream (b) showing lateral migration of channel and point bar sequence and environmental relationships. (Davies, et al., 1996.)

3.6 Eolian Reservoir Properties

Eolian Depositional Systems

Eolian deposits are unique formations that are formed under arid conditions where wind is the main force that controls the processes and shape of sand formations (Reineck and Singh, 1975). Eolian deposits usually form in interior basins, often in subsiding basins that are dry, coastal areas where a large supply of sand-sized particles exists. The sediments are well sorted, and have the characteristic of coarser stones and larger sand grain sizes between areas of finer grained sand dunes and sand sheets. Dunes are hills of sand with a single summit or crest and a distinct slip face (**Figure 3-23**). Fine material from the sand dunes is often blown thousands of miles away as is evident from satellite imagery of storms that blow across the Sahara Desert of North Africa and whose clay fines (dust) are deposited downwind as far west as the Caribbean Sea.

Some eolian deposits also contain carbonate-derived materials (ground coral, limestone, shell), but are normally derived from clastic rock sources. Eolian deposits formed in deserts with no source of water-borne sediments often form large migrating sand dunes with distinct shapes defined by wind patterns. Internal features of these large dunes include horizontal bedding, common on the windward slopes of the dunes and cross-bedded, which are formed by avalanches on the slip face of the dune (Reineck and Singh, 1975). Stratigraphic sequences of sand dunes typically show truncation of one unit and deposition of stacked units as erosion and deposition alternate. The prevalent fluid flow direction within these reservoirs is usually parallel to the wind direction when the unit was deposited.

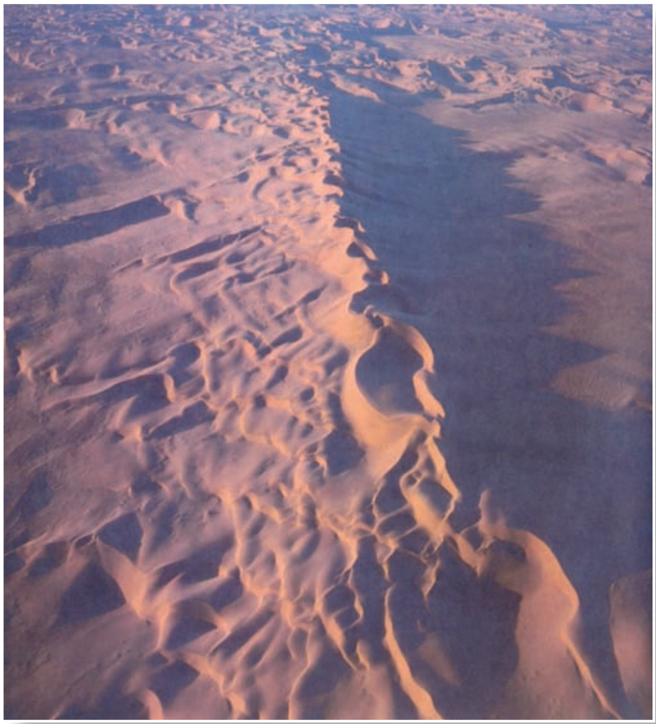

Figure 3-23. Namib Desert, Southwest Africa. The Namib Desert Dune Ridge System is an analog for the Triassic Wingate Formation, Uinta Basin, Utah. Interdune facies are represented by the flat areas lateral to the dune ridge. (Eckels, et al., 2005. Photo by E. Tad Nichols – in McKee, 1979.)

3.7 Lacustrine Reservoir Properties

Lacustrine Depositional Systems

Lacustrine depositional systems evolve in hydrologically closed systems, such as freshwater fed lakes. These lakes may become hypersaline with time because there is no outlet to the sea. They generally have depositional rates higher than open systems. They contain clastic sediments washed into the basin by fluvial (river and stream) systems and flooding, where course material is deposited closer to the sediment source and finer-grained sediment (silt and clay) is deposited in deeper areas of the lakes. They may contain carbonates; evaporites, which form when water is evaporated; and organic material from algae. With little turbulence in the lake, sediments are often horizontally deposited.

A lacustrine formation being deposited in a hydrologically closed system is shown in **Figure 3-24**. Crusts of evaporite salt form at the edge of an intermittent lake in Saline Valley, California. Red algae bloom near shore and clastic sediments get washed into the basin, with course material settling out first in deltas and fine material covering the deeper areas of the lake bottom. Fine airborne dust contributes to the sediment load as most

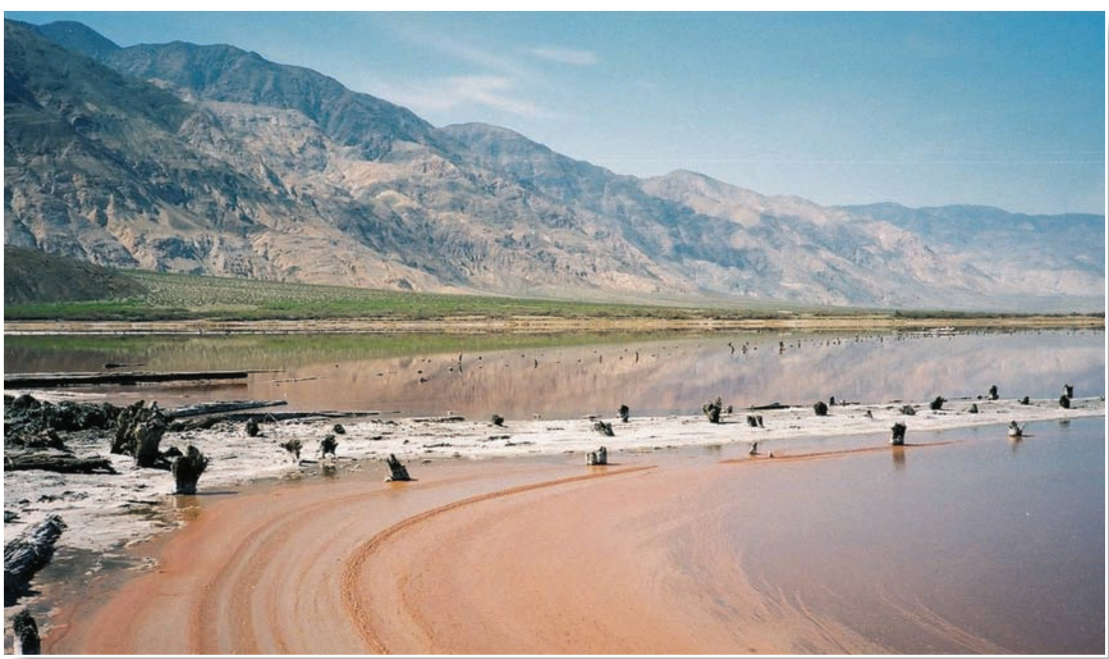

Figure 3-24. A Lacustrine Formation Being Deposited in a Hydrologically Closed System. Crust of Evaporite Salts Forms at the Edge of a Lake in Saline Valley, California. (Photo courtesy of Tim Lowenstein, SUNY at Binghamton, March, 2004.)

Lacustrine formations had an airborne contribution. In the case of the Green River Formation of the western U.S., volcanic eruptions associated with the building of the Rocky Mountains, deposited enormous volumes of ash that settled out of the air and were also washed downstream and eventually filled the large lakes.

Lacustrine formations have little porosity or permeability and are often considered as seals, rather than CO_2 storage formations. Being horizontally bedded, the fluid flow would be anticipated to be parallel to the bedding plane. Changes to the rock and compaction may leave zones that have been or are hydraulic aquifers that have dissolved part of the salts contained within the formation, causing preferential flow paths unrelated to the initial deposition (Choquette and Pray, 1970; Tucker, and Wright, 1990).

Evaporites Depositional System

One subclass of carbonate rocks is represented by evaporite deposition (Dean and Schreiber, 1978). Evaporites can be considered a subset of a lacustrine depositional system and are formed when an aqueous solution is totally or largely evaporated (**Figure 3-25**). Although some evaporites can be formed in inland lakes, most of the world's extensive evaporite deposits have been formed from seawater. The fundamental constituents of evaporites are from the ions that were dissolved in the evaporated water. These ions form sodium, calcium, chlorine, sulfate, and carbonate. When evaporation takes place, the salts are deposited in a predictable order that is controlled by the solubility of the salts and the composition of the solution. Evaporites are formed in four different depositional environments: (1) craton/continental crust; (2) shallow epeiric sea; (3) stable continental margin/continental crust; and (4) rifted continental margin/oceanic crust.

Evaporites are often considered a seal for more porous formations. Their ability to slowly flow around and encapsulate materials makes them an ideal storage site for sources of low-level nuclear waste. They have little porosity or permeability.

Figure 3-25. Evaporite Deposits being formed on the Caribbean Island of Bonaire. Shallow water salt pans concentrate hypersaline water, which evaporates to form salt. The white line in the middle of the photo is a froth of salt. (Photo courtesy of Richard Schatzinger, Consultant Carbonate Sedimentologist.)

3.8 Basalt Reservoir Properties

Igneous rocks represent an uncommon formation type for petroleum reservoirs; however, because of their widespread coverage of the Earth's surface, they represent a large potential CO_2 storage formation. There are two different types of basalts: Mid-Ocean Ridge Basalts (MORB) and Large Igneous Provinces (LIP). More study is needed to evaluate the flow in MORB. Studies of LIP flows show that there is a typical internal structure that consists of four sections: the flow top, the entablature, the colonnade, and the flow base (**Figure 3-26**). The movement of fluid through a basalt formation is governed by numerous factors. For basalts flows, these factors include: the topographic surfaces over which the basalts originally flowed as lava; the erosion that occurred before, during, and after extrusion of the lava; the deposition of interbeds (sediments and materials that were deposited between lava flows); tectonic activity; and diagenetic processes. The lateral continuity, thickness, and composition of individual flows (particularly interflow zones) are highly varied.

Basalts form extremely heterogeneous aquifer units that transmit water most readily through the broken vesicular (old gas bubble pockets) and scoriaceous (material that appears like volcanic cinders). Interflow zones that commonly constitute 5 to 10% of the thickness of an individual basalt flow (Saar and Manga, 1999). Interflow zones represent periods between successive basalt flows where the original material is altered and sediments are deposited. The interflow zones are separated by the less transmissive and more massive entablature and colonnade (**Figure 3-26**), in which fractures are more or less vertical. Lateral groundwater movement in the entablature and colonnade is probably negligible when compared with the volume of water that moves laterally through the interflow zones.

The potential for geologic storage in basalts also depends on the physical and chemical reactions between the CO_2 and the host rock mineralogy (Matter, *et al*., 2007). Basalt consists mainly of calcium and magnesium silicate minerals that have an ability to neutralize acids. The minerals in basalt can form stable carbonate minerals by reaction with CO_2. These chemically stable carbonates can form chemical seals to retain CO_2 in the basalt (Matter, *et al*., 2007; Rochelle, *et al*., 2004). As a result of this property, basalts have the potential to permanently lock away CO_2 by forming stable minerals, but these reactions may take hundreds to thousands of years to occur after CO_2 exposure.

Few basalt formations in the United States have been examined. NETL and its partners are still calculating the volume of geologic storage potential in these formations. Much larger areas of basalts underlie today's oceans and are associated with movement of the Earth's crust (continental drift). Fluid flow studies within these deep sea formations are in its infancy. Uncertainties remain on the hydrology (study of fluid flow) and the reservoir potential in basaltic formations.

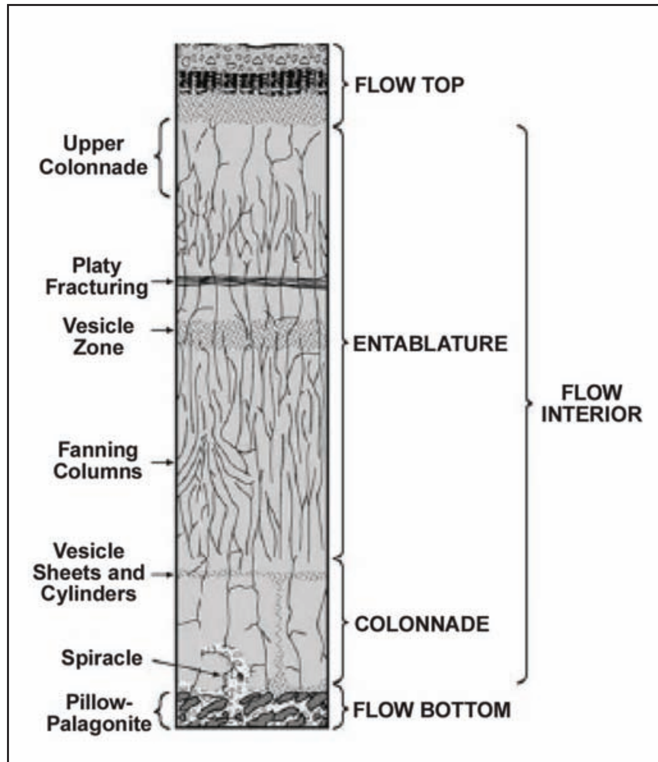

Figure 3-26. Major Internal Features of a Columbia River Basalt Group (North America) Lava Flow. (McGrail, et al., 2006.)

4.0 The Road to Commercialization

NETL is currently gathering data to develop a database of regional reservoir and associated properties for each type of depositional environment. As mentioned earlier, this data will be utilized by site developers and property owners to develop risk assessments and business models for CCS and to better define costs for geologic storage and determine the type and quality of geological sinks in a region. It is unlikely that a property owner would spend the necessary money to develop this baseline data that is being provided by NETL even though it is required for a risk assessment or business model of CCS. A list of NETL-developed CO_2 projects is shown below according to their geological classifications and lithology (**Table 4-1**).

Table 4-1. CO_2 Geosequestration Projects with Lithology and Geologic Classification.

Basin	Location	Partnership / Operator	Phase II	Phase III	ARRA Program	Principal Target Formation(s)	Lithology	Geologic Classification
Michigan	Michigan	MRCSP	II			Bass Island Dolomite/ Bois Blanc	Carbonate	Shallow Shelf Restricted
Cincinnati Arch	Kentucky	MRCSP	II			Mt. Simon	Clastic	Strandplain
Appalachian	Ohio	MRCSP	II			Oriskany, Middle Salina, Clinton	Clastic Carbonate Clastic	Shelf Clastic, Shallow Shelf Restricted, Shelf Clastic
Michigan Basin	Michigan	MRCSP		III		St. Peter	Clastic Sandstone	Shelf Clastic
Williston	North Dakota	PCOR	II			Fort Union	Coal	Coal
Williston	North Dakota	PCOR	II			Madison Group, Mission Canyon	Carbonate	Shallow Shelf Open
Powder River Basin	Montana	PCOR		III		Muddy	Clastic	Fluvial Deltaic
Alberta Basin	British Columbia	PCOR		III		Elk Point Group	Carbonate	Barrier Reef Complex
Illinois	Illinois	MGSC	II			Cypress Sandstone	Clastic	Delta Tide Dominated
Illinois	Illinois	MGSC	II			Springfield Coal	Coal	Coal
Illinois	Indiana	MGSC	II			Clore Sandstone	Clastic	Fluvial Channel
Illinois	Kentucky	MGSC	II			Jackson Sandstone	Clastic	Shelf Clastic
Illinois	Illinois	MGSC		III		Mt. Simon	Clastic	Strandplain in Upper and Braided Fluvial in Lower
Gulf Coast	Mississippi	SECARB	II			Tuscaloosa Formation Mississippi Site	Clastic	Delta
Appalachian	Virginia	SECARB	II			Coals in the Pocahontas and Lee Formations	Coal	Coal

Basin	Location	Partnership / Operator	Phase II	Phase III	ARRA Program	Principal Target Formation(s)	Lithology	Geologic Classification
Gulf Coast	Mississippi	SECARB	II			Tuscaloosa Formation Cranfield Site	Clastic	Fluvial
Black Warrior	Alabama	SECARB	II			Black Creek, Marry Lee & Pratt Coal Seams	Coal	Coal
Gulf Coast	Mississippi	SECARB		III		Lower Tuscaloosa Formation	Clastic	Fluvial/Deltaic
Gulf Coast	Alabama	SECARB		III		Paluxy Formation	Clastic	Fluvial/Deltaic
Paradox Basin	Utah	SWP	II			Desert Creek & Ismay Formation	Carbonate	Shallow Shelf Restricted
Permian	Texas	SWP	II			Cisco-Canyon	Carbonate	Reef
San Juan	New Mexico	SWP	II			Fruitland	Coal	Coal
Uinta	Utah	SWP		III		Entrada & Navaho	Clastic	Eolian
Colorado Plateau [1]	Arizona	WESTCARB	II			Tapeats Sandstone	Sandstone	Shelf Clastic
Colorado Plateau [2]	Arizona	WESTCARB	II			Naco & Martin	Carbonate	Shallow Shelf Restricted
Sacramento Valley [1]	California	WESTCARB	II			Domengine	Sandstone	Fluvial-deltaic
						Hamilton	Sandstone	Shallow Shelf
						Anderson	Sandstone	Deltaic
						Martinez	Sandstone	Shallow Shelf
						Martinez 123	Sandstone	Shallow Shelf
Newark	New York & New Jersey	Sandia Technologies, LLC			X	Stockton & Passaic	Clastic	Fluvial & Alluvial
						Basalts	Basalt	Interflow Zones in Basalts
Illinois & Michigan	Illinois & Michigan	University of Illinois			X	St. Peter	Clastic	Strandplain
						Knox	Carbonate	Shallow shelf/ open
Ozark Plateau	Kansas	University of Kansas Center for Research, Inc.			X	Arbuckle	Carbonate	Shallow Shelf
						Mississippian chert/ dolomite	Carbonate	Metamorposed Shallow Shelf

Basin	Location	Partnership / Operator	Phase	Phase	ARRA Program	Principal Target Formation(s)	Lithology	Geologic Classification
			II	III				
Gulf of Mexico Miocene Age	Texas	University of Texas at Austin			X	Multiple within Fleming Group including Lagarto & Oakville Formations	Clastic	Fluvial-deltaic, Strandplain/ Barrier Bar, Turbidite
Los Angeles	California Offshore	Terralog Technologies USA Inc.			X	Pico	All Clastic	Strandplain, Turbidite
						Puente		
						Multiple		
Green River	Colorado	University of Utah			X	Weber	All Clastic	Eolian
						Dakota		Strandplain
						Entrada		Strandplain / Eolian
Black Warrior	Alabama	University of Alabama			X	Pottsville, Parkwood & Pride Mountain	Sandstone	Deltaic / Strandplain
						Bangor & Tuscumbia	Limestone	Shallow Shelf / Open
						Hartselle	Sandstone	Strandplain
South Georgia Rift	Georgia	South Carolina Research Foundation			X	Interflow Zones Basalts	Sandstone and Basalt	Fluvial/Alluvial between the Basalt Flows
Rock Springs Uplift & Moxa Arch	Wyoming	University of Wyoming			X	Tensleep	Sandstone	Standplain
						Weber	Sandstone	Eolian
						Madison	Carbonate	Shallow Shelf - Open
						Bighorn	Carbonate	Shallow Shelf
Powder River	Wyoming	North American Power Group, Ltd.			X	Madison	Carbonate	Shallow Shelf - Open
						Bighorn	Carbonate	Shallow Shelf
Michigan	Michigan	Board of Public Works			X	Upper Mt. Simon	Clastic	Strandplain/ Fluvial

Notes:

1 - The Anderson formation is the primary injection horizon. The other formations are secondary formations.

2 - Site Characterization well.

NETL's goal is to characterize the different depositional environments with drilling, subsurface geophysics, chemical analysis, and geomechanical analysis of the rocks and conduct both small- (<500,000 tons) and large-scale (>1,000,000 tons) CO_2 injections. The different storage projects that are completed or underway and their associated major geologic depositional environments/ classifications are presented in **Table 4-1.**

As shown above, NETL is investigating a distribution of the different depositional environments, but additional investigations, including reservoir characterizations and small- and large-scale injection tests, are needed on the majority of the depositional environments. This will provide information on the behavior and flow of CO_2 in the different reservoirs that can be used to, in general, predict the behavior and flow in similar depositional environments.

The potential of different storage reservoirs are ranked in accordance to the 1990's Oil Reservoir Classification methodology (**Table 3-1**), but differ in significant ways. The 1990's classification grouped the different reservoirs into classes based on estimates of the largest oil in place strata at that time. The CO_2 storage classification is ranked in accordance to potential storage volume, which is controlled by the porosity and permeability of the reservoir material, frequency, and aerial extent of the different reservoir types.

Referring to the matrix (**Figure 4-1**), reservoir characterization (with the ability to store >30 million tons of CO_2) has not been completed for a shelf clastic, reef, and coal environments. Small-scale injection tests (<500,000 tons of CO_2) have not been performed on fluvial deltaic, eolian, and turbidite. Large-scale injection tests (>1,000,000 tons of CO_2) have not been performed on deltaic, strandplain, shelf carbonate, eolian, turbidite, basalt Large Igneous Providences (LIP), and coal. Three highly experimental reservoirs that are not included on the matrix are fractured shales, basalts (MOR), and offshore turbidites, as they have not been investigated. The projects listed in **Figure 4-1** are in various states of completion with some investigations that are completed and some just started. Understanding the impacts of different reservoir classes on CO_2 storage will support DOE's efforts to develop the knowledge and tools necessary for future commercialization of carbon storage technologies throughout the United States.

Matrix of Field Activities in Different Formation Classes

Geologic Formation Classes	High Potential					Medium Potential				Lower or Unknown Potential	
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Aluvial	Turbidite	Coal	Basalt (LIP)
Large Scale	–	1	–	–	1	3	–	1	–	–	–
Small Scale	3	2	4	1	2	–	–	2	–	5	1
Characterization	1	–	8	6	–	3	3	2	2	–	1

Notes:
The number in the cell is the number of investigations per depositional environment.
Large Scale Field Tests – Injection of over 1,000,000 tons of CO_2.
Small Scale Field Tests – Injection of less than 500,000 tons of CO_2.
Site Characterization – Characterize the subsurface at a location with the potential to inject at least 30,000,000 tons of CO_2.
Reservoir potentials were inferred from petroleum industry data and field data from the sequestration program.

Figure 4-1. Matrix of NETL CO_2 Geosequestration Projects and Depositional Environments.

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