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## **Moving Permian Basin Technology to the Gulf Coast: the Geologic Distribution of CO<sub>2</sub> EOR Potential in Gulf Coast Reservoirs**

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### **Abstract**

The Permian Basin in West Texas has seen a long history of CO<sub>2</sub> enhanced oil recovery (EOR). Over 65 sandstone, limestone, and dolomite reservoirs have been subject to miscible CO<sub>2</sub> floodings in the last 30 years. However, the experienced gain has not been extended to the much more porous and permeable clastic depositional systems of the Gulf of Mexico Coast. Proximity to possible anthropogenic CO<sub>2</sub> sources, enabling reduced costs and infrastructure, and the petrophysical character of these sandstones are just two of the many attributes that showcase the Gulf Coast formations as an attractive option for this type of tertiary recovery.

A large oil reservoir database was analyzed to determine the geologic distribution of CO<sub>2</sub> EOR potential in Gulf Coast oil reservoirs. Key factors to screen reservoirs in which miscible CO<sub>2</sub> displacement is feasible are minimum miscibility pressure (MMP) and cumulative oil production. Oil reservoirs that were screened out as potential candidates have the following characteristics: an initial reservoir pressure greater than the MMP, water drive or secondary recovery, cumulative production greater than 1 million stock tank barrels (MMSTB).

Analysis shows that the miscible CO<sub>2</sub> EOR resource potential along the Texas Gulf Coast is 2.7 billion stock tank barrels (BSTB), and the total Gulf Coast potential, including Mississippi, Louisiana, and Alabama, is 4.5 BSTB. Results of this assessment indicate that mature Gulf Coast clastic oil reservoirs are a new large potential target for CO<sub>2</sub> EOR when experi-

### **Methods and Sources of Data**

Our methodology separates volumes of CO<sub>2</sub> that could be sold for EOR from volumes that could be stored as waste product. For this assessment, we first screened reservoirs for those that were likely to be economic targets. Other

reservoirs, including abandoned reservoirs, gas reservoirs, or those which are not suitable for CO<sub>2</sub> miscible floods, are for purposes of this assessment, included in the volume of sub-economic brine-filled porosity. We first describe the methodology for quantifying economic tar-

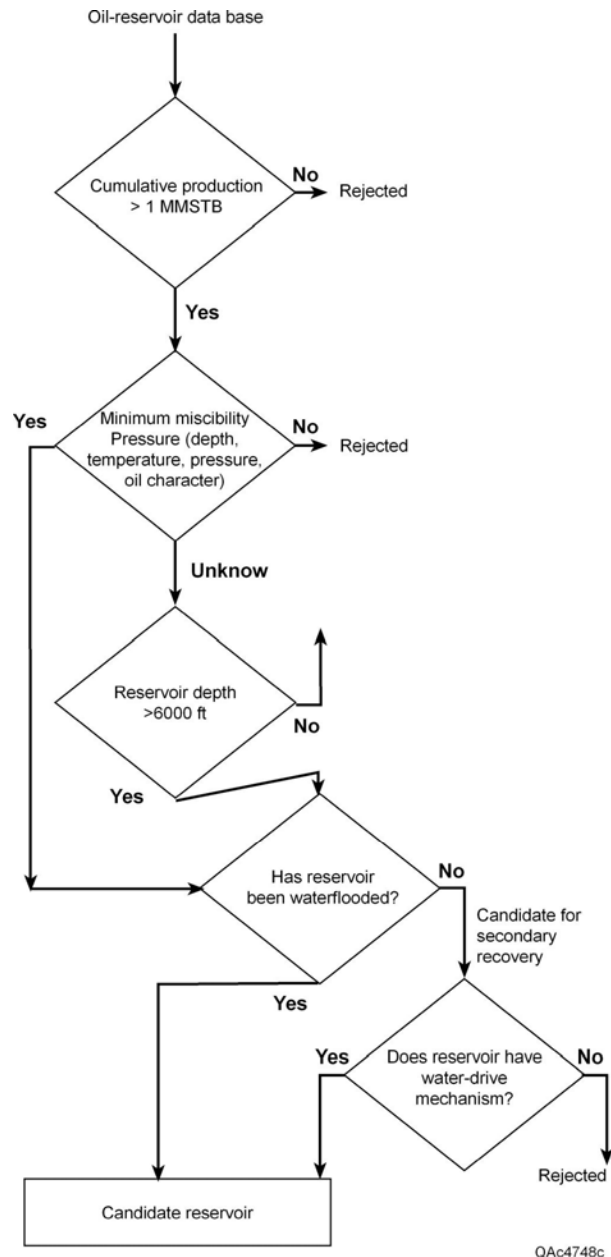
gets, then the methods used for description of brine-filled formations.

There are three broad reservoir characteristics that can be applied as screening criteria to determine the feasibility of CO<sub>2</sub> EOR. These criteria include minimum miscibility pressure (MMP), injectivity, and reservoir heterogeneity. The most critical detailed constraint for the applicability of miscible CO<sub>2</sub> EOR is the MMP. Minimum miscibility pressure is a function of oil properties, reservoir temperature, reservoir pressure, and the purity of the injected CO<sub>2</sub>. Other screening criteria include injectivity, which controls the rate at which CO<sub>2</sub> can be put into the reservoir, and storage capacity (described in terms of total porosity). Geologic heterogeneity affects both early CO<sub>2</sub> breakthrough and thus volume of CO<sub>2</sub> recycled. For determining candidate reservoirs MMP was the only reservoir characteristic applied. No reservoirs were included as candidates for CO<sub>2</sub> EOR unless the MMP was less than the initial reservoir pressure.

Several other reservoir properties are important to consider in the screening and process design phases. Broadly speaking, oil viscosity, oil API-gravity, reservoir depth, reservoir oil saturation, and reservoir heterogeneity are among the most important. Cracoana (1982) suggest oil viscosity values of 1 centipoise (cp) or less and an API-gravity of greater than 40°. Stalkup (1984) suggests reservoirs should have oil gravities greater than 27° API-gravity, and should be no shallower than 2500 ft (762 m). Others have suggested that API oil gravity should range between 11 and 30 degrees. Both viscosity and API-gravity are constraints controlled by the minimum miscibility pressure. Residual oil saturation is primarily an economic screen and values of 20 to 25% have been suggested by Stalkup (1984).

The approach to determining the best possible CO<sub>2</sub> EOR miscible flood candidates in the Gulf Coast region was to construct an oil reservoir database and develop a screening method. The oil reservoir database covers the states of Alabama, Mississippi, Louisiana, and Texas. The screening criteria were based on that of Holtz et. al, (2001).

Screening proceeded according to a decision tree which chooses large reservoirs with miscible CO<sub>2</sub> flood potential as candidates (Fig 1).



**Figure 1.** Decision tree to identify gas-displacement-recovery candidate reservoirs.

General reservoir screening constraints were applied to cull out reservoirs that were not yet at the stage of their production life where CO<sub>2</sub> EOR would be the proper option. Reservoirs that are candidates for CO<sub>2</sub> EOR are those that are at an advanced stage of waterflooding or aquifer encroachment. At this production stage most of the mobile oil has been produced and the remaining significant volume of oil is residual oil that can not be produced without EOR. To identify reservoirs at an advanced stage of production, screening constraints that were grounds for rejection from the candidate set included:

- 1) reservoirs that were not initially water driven;
- 2) reservoirs that were at an early stage of waterflooding; and
- 3) reservoirs that had not yet been waterflooded.

However, previous waterflooding was not applied as a requirement for large, deep reservoirs where vaporizing gas-drive-miscibility can be achieved. The literature (SPE-EOR Field Reports [1982-1992]) shows that these reservoirs have had gas displacement EOR applied directly after primary production.

An extensive database that includes major oil reservoirs in Texas, Louisiana, Alabama and Mississippi was developed for screening. An unpublished BEG Texas oil reservoir database was combined with Louisiana and Mississippi data from the TORIS database, as well as reservoir data on Mississippi from the Alabama Geologic Survey. Data for Texas reservoirs were generated by gathering engineering information from numerous sources, including the Atlas of Major Texas Oil Reservoirs (Galloway and others, 1983), Atlas of Major Texas Gas Reservoirs (Kosters and other, 1989) and hearings reports from the Railroad Commission of Texas. The database includes petrophysical, fluid characteristics, and geological information, along with production information and location data. Reservoirs were grouped by plays. The Louisiana Geological Survey (LGS) provided field outlines and field names for Louisiana.

We first assess which reservoirs are most likely to be economic, then estimate a minimum volume

capacity using simplified assumptions for how much CO<sub>2</sub> could be stored, then calculate the net usage, which is an estimated volume that an operator would need to purchase to recover the oil. This methodology was developed by Gulf Coast Carbon Center (GCCC) industry-academic collaborative as part of the match provided to SE-CARB.

### Estimating Minimum Miscibility Pressure

The key criterion to determine if a CO<sub>2</sub> EOR-flood is likely to be economic is miscibility of CO<sub>2</sub> in oil. Miscibility increases with depth and with oil gravity. Using available data and empirical equations, we determined the minimum miscibility pressure (MMP). Typically MMP is defined as the minimum pressure above which recovery of oil exceeds 90-percent in slim tube tests. Although this pressure is less than that required for complete miscibility, any further pressure increase will not significantly change final oil recovery.

A two-step approach has been taken to estimate a reservoir's MMP. First, the molecular weight of C5+ components of the reservoir oil must be determined. A correlation between oil API-gravity and C5+ oil molecular weight published by Lasater (1958) should be made (figure 2). This correlation can be empirically determined by applying equation 1.

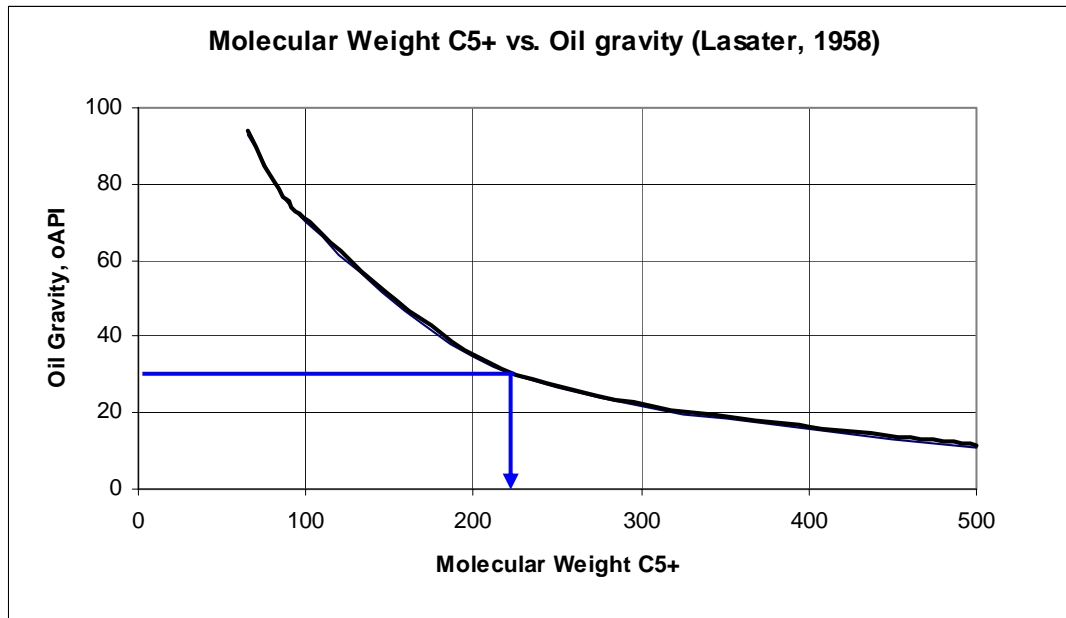
$$MW = \left( \frac{7864.9}{G} \right)^{\frac{1}{1.0386}} \quad (1)$$

where MW = C+5 molecular weight, and  
 G = API oil gravity.

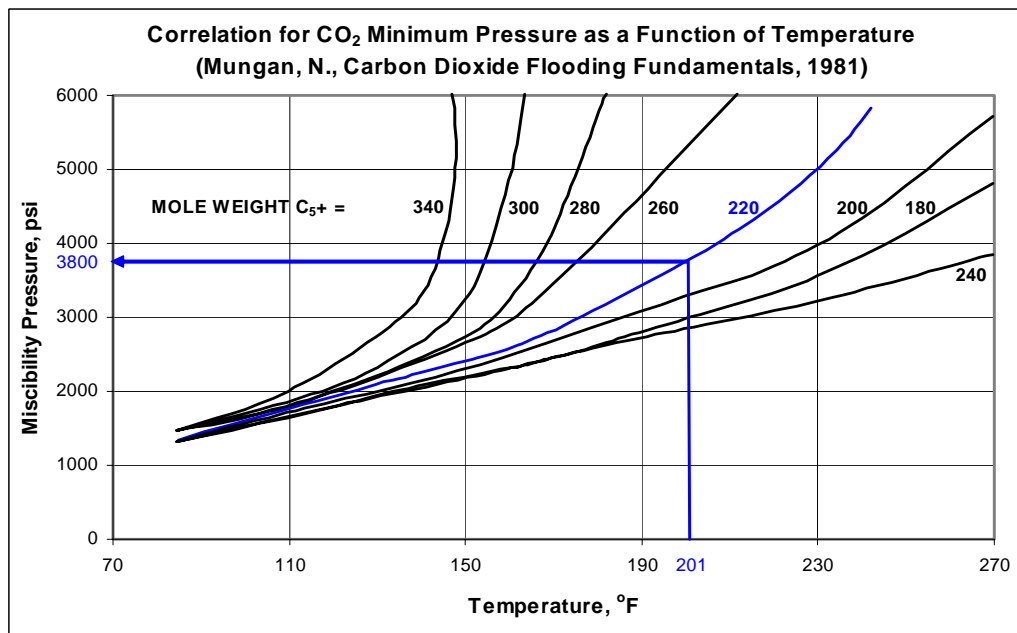
Second, MMP from reservoir temperature and C5+ oil molecular weight must be determined.

A relationship published by Holm and Josendahl (1982) and extended by Mungan (1981), which estimates MMP from molecular weight of the C5+ components of reservoir oil and reservoir temperature (Figure 3), was applied. This relationship was used by developing an equation through nonlinear multiple regression that allowed us to estimate MMP (Equation 2).

$$MMP = -329.558 + (7.727 * MW * 1.005^T) - (4.377 * MW)$$



**Figure 2.** Correlation between oil gravity and the molecular weight of an oil's C+ 5 components.



**Figure 3.** Nonlinear relationship between temperature and C+5 oil molecular weight and minimum miscibility pressure. (From Mungan, 1981)

### Quick-Look Total CO<sub>2</sub> Storage Potential (CO2QLSP)

To accurately assess the capacity of a reservoir to store CO<sub>2</sub> one needs to compile reservoir properties and determine how much of the volume would be filled by CO<sub>2</sub> during an injection, and how much would be by-passed. The quick-look approach is a spread sheet solution used when not enough data are available to calculate pore volume from reservoir parameters.

A quick-look CO<sub>2</sub> storage potential (capacity) can be obtained by analyzing cumulative production of an oil field. Here we assume that the pore volume represented by oil production is available in the reservoir for CO<sub>2</sub> storage. Stock-tank oil volumes are converted back to reservoir volumes, and resultant pore volumes are converted to the amount of CO<sub>2</sub> that could be put into that volume at initial reservoir conditions (Equation 3).

$$\text{CO}_2\text{QLSP (metric tons)} = 0.05259 \cdot N_p \cdot B_{oi} / B_{\text{CO}_2} \quad (3)$$

where  $N_p$  = Cumulative oil production (STB),  
 $B_{oi}$  = Oil formation volume factor (rbbl/STB), and  
 $B_{\text{CO}_2}$  = CO<sub>2</sub> formation volume factor (RCF/SCF).

An empirical equation was derived to obtain  $B_{\text{CO}_2}$ . Data for this equation were obtained from Jarrell et al. (2002). The equation is a set of statements and 2<sup>nd</sup>- and 3<sup>rd</sup>-order polynomials.

Often in a large reservoir database, oil formation volume factor is a data field that is not populated. To overcome this problem, we make assumptions and apply empirical equations. Oil formation volume factor can be estimated from an equation by Standing (1947) (Equation 4).

$$B_o = 0.972 + 0.000147F^{1.175} \quad (4)$$

Where

$$F = R_{so} \left( \frac{\gamma_g}{\gamma_o} \right) + 1.25T$$

$$\gamma_o = \frac{141.5}{131.5 + API}$$

$\gamma_g$  = Gas specific gravity  
 API = oil API gravity  
 Rso = Solution gas-oil ratio

When applying this Standing correlation the gas gravity and solution gas-oil ratio are needed. When these parameters are not known an estimate can be made. In this report, we applied a average 0.75 gas gravity and used a second Standing correlation to estimate Rso (Equation 5).

$$R_{so} = \gamma_g \left( \frac{P}{18(10)^{\gamma_g}} \right)^{1.204} \quad (5)$$

where,

$\gamma_g = 0.00091T - 0.0125API$   
 $T$  = Temperature, (°F)  
 $P$  = Pressure, (psi)

### Quick-Look Net Total CO<sub>2</sub> Usage Potential (CO2EORP)

For an economically-driven CO<sub>2</sub> sequestration scenerio focused on EOR, the most important parameter is the amount of CO<sub>2</sub> that would be purchased from a source in order to recover additional oil. This is a different value than the volume stored because significant volume of CO<sub>2</sub> would be cycled to recover oil.

A quick-look method to determine the net CO<sub>2</sub> needed for a CO<sub>2</sub>-enhanced oil recovery (EOR) project is based on reservoir cumulative production and CO<sub>2</sub> utilization rates, which are the amount of CO<sub>2</sub> used to recover a barrel of oil. First, a total CO<sub>2</sub> usage rate is applied, along with a recycle rate. For this quick-look method, original oil in place (OOIP) is estimated from cumulative production and primary + secondary recovery (Equation 6). Each reservoir is assumed to be close to its ultimate primary + secondary recovery. Furthermore, a basin-average primary + secondary recovery factor is applied. For the Gulf Coast with its strong water-drive oil reservoirs, a

50% primary + secondary recovery factor is assumed.

$$OOIP = N_p / R_{ps} \quad (6)$$

Target CO<sub>2</sub> EOR reserves are determined by applying a recovery factor, and the ultimate recovery factor from CO<sub>2</sub> EOR is taken as a percent of OOIP (Equation 7). EOR reservoir recovery is assumed to be 15% of the OOIP of each of the basins.

$$N_{CO_2} = OOIP * R_{CO_2} \quad (7)$$

The final step in calculating net CO<sub>2</sub> used in an EOR project is to apply utilization rates. Volume of CO<sub>2</sub> needed is obtained as a function of the total EOR volume target and net utilization rate (Equation 8). For Gulf Coast high-permeability sandstone reservoirs, the gross utilization rate was set at 4.5 MSCF/STB and the recycle rate at 2 MSCF/STB.

$$CO_2 \text{ EORP} = N_{CO_2} (U_{CO_2T} - U_{CO_2R}) \quad (8)$$

where OOIP = Original oil in place (MSTB)  
N<sub>p</sub> = Cumulative oil production (MSTB)  
R<sub>ps</sub> = primary + secondary recovery  
N<sub>CO<sub>2</sub></sub> = Cumulative CO<sub>2</sub> EOR target  
R<sub>CO<sub>2</sub></sub> = Ultimate recovery factor from CO<sub>2</sub> EOR (% of OOIP)  
U<sub>CO<sub>2</sub>T</sub> = Total CO<sub>2</sub> utilization (MSCF/STB)  
U<sub>CO<sub>2</sub>R</sub> = CO<sub>2</sub> utilization recycled (MSCF/STB)  
CO<sub>2</sub> EORP = Net CO<sub>2</sub> used in EOR project

### Waterflooded Reservoirs in Texas: Recovery Factors

To estimate average waterflood efficiency of Gulf Coast Tertiary sandstone reservoirs we conducted a survey of major Texas oil reservoirs that have undergone secondary-recovery waterflood operations. Only those reservoirs that had undergone waterflood secondary recovery were included. Data were obtained from the Atlas of Major Texas Oil Reservoirs (Galloway and others,

1983). Non-Gulf-Coast reservoirs in Texas were also surveyed to establish a total range of possible values of waterflood recovery efficiency and to place Gulf Coast values of ultimate recovery in perspective. Recovery efficiency values were reported in percent of OOIP. Total range in recovery efficiency values was reported, as well as an average value, which was not weighted by OOIP of each reservoir, but was considered equally on a reservoir-by-reservoir basis. However, the average value for the East Texas Woodbine play was weighted by OOIP value from the East Texas field because it dominates the play and accounts for the bulk of the play's oil production.

Reservoirs were summarized primarily by depositional origin and secondarily by individual play. Principal producing Tertiary Gulf Coast plays in southeast Texas that have undergone waterflood secondary-recovery operations are from three plays: Yegua Deep-Seated Salt Domes, Frio Deep-Seated Salt Domes, and Frio Barrier/Strandplain Sandstone (Galloway et al., 1983). Play-average recovery efficiencies in these three plays range from 50.2 to 58.5%, with a total range for individual reservoirs from 28 to 61%. On the basis of these data, an average 50% recovery factor for waterflooded reservoirs in the Gulf Coast area is reasonable for averaging. One should remain aware that recovery efficiency is highly variable, depending on reservoir properties and the optimization of the flood engineering.

### Brine storage database compilation

For the brine storage phase of the project, we focused on compiling, assessing, and digitizing published and compiled sources of data about distribution of potential sequestration targets in the subsurface. This approach was selected because (1) high quality published data are abundant for the high capacity target of the region, and (2) compiling new data from primary subsurface data (for example wireline logs, sample logs, seismic lines) for this complex subsurface geology over this large region would have required effort disproportionate with level of funding. We focused on two types of regions, those with significant to very large capacity in Gulf and Atlantic

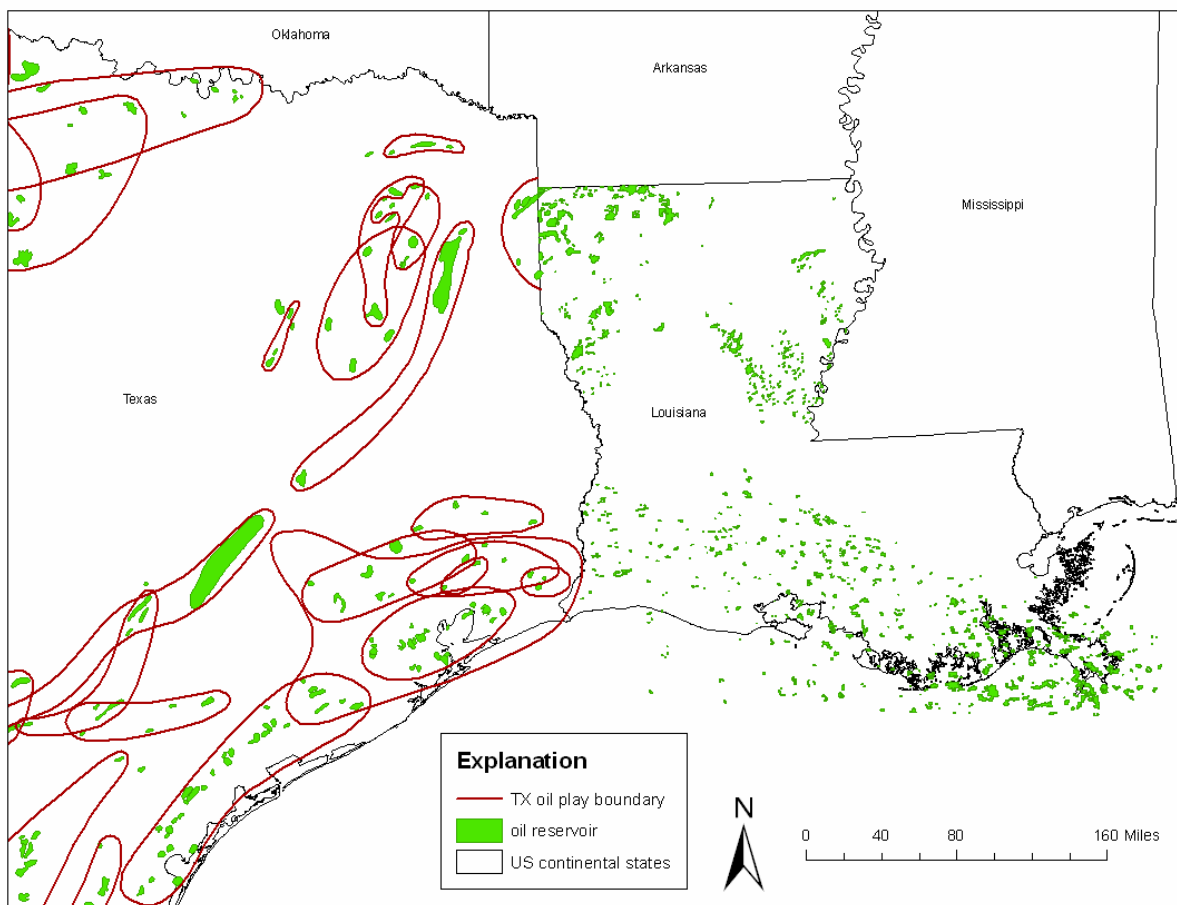
Coastal areas, and those which could quickly be assessed to have little or no storage capacity. Some areas that likely had some- to good-capacity were deferred.

### Geographic Information System (GIS) Description

Reservoir and brine formation data were managed and mapped in a GIS system. Depending on original data type, different procedures of shapefile creation (digitization or analysis) were followed using ArcGIS software to arrive at the final package of shapefiles. All data are projected to Contiguous USA Albers Equal Area Conic pa-

rameters. This information is provided in .PRJ-files contained in the GIS\_data folder. Metadata files are included in the GIS database to provide additional information about shapefiles. XML metadata files, which are stored as part of the shapefile in the GIS\_data folder, can be viewed using ArcCatalog. Metadata have also been exported as HTML-files that can be viewed using an Internet browser. Figure 4 shows a sample of the oil reservoir database developed from BEG, GCCC, and Louisiana Geological Survey (LGS) data.

### Results and Discussion



**Figure 4.** GIS data sample: distribution of oil reservoirs in Louisiana and major reservoirs and plays in Texas.



## Gulf Coast Region Miscible Oil Reservoirs

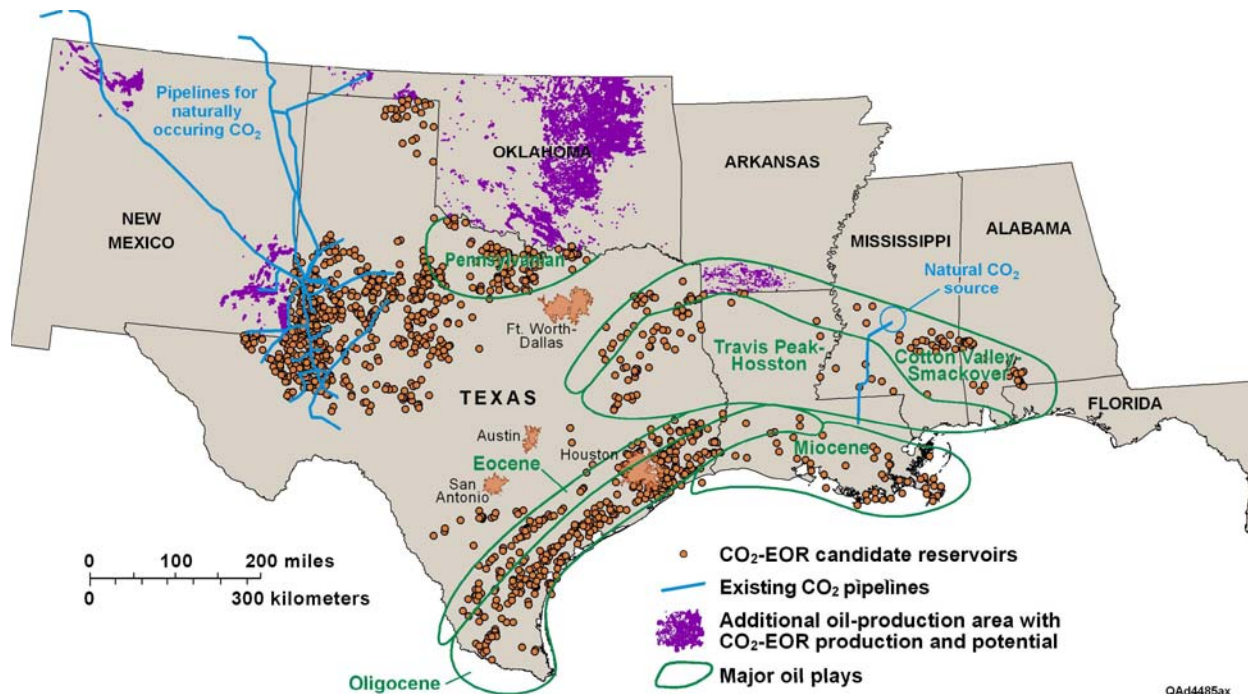
The Permian Basin in West Texas has seen a long history of CO<sub>2</sub> enhanced oil recovery (EOR). More than 65 sandstone, limestone, and dolomite reservoirs have been subject to miscible CO<sub>2</sub> flooding in the last 30 years, and this economically viable, low risk activity provides a prototype for beneficial use of large volume of CO<sub>2</sub> with storage. However, the experienced gain has not been extended to the much more porous and permeable clastic depositional systems of the Gulf Coast. Proximity to possible anthropogenic CO<sub>2</sub> sources and the petrophysical character of these sandstones are just two of the attributes that are favorable for the Gulf Coast formations.

Analysis shows that the miscible CO<sub>2</sub> EOR resource potential along the Texas Gulf Coast is 2.7 billion stock tank barrels (BSTB), and the total Gulf Coast potential, including Mississippi, Louisiana, and Alabama, is 4.5 BSTB. Results of this assessment indicate that mature Gulf Coast clastic oil reservoirs are a new, large potential target

for CO<sub>2</sub> EOR when experience in the Permian Basin is retooled for this setting.

Six major groups of oil plays have been identified containing candidates for CO<sub>2</sub> miscible displacement in the Gulf Coast (fig. 5). Oligocene and Eocene plays extend from central Louisiana, southwestward and parallel to the present-day coastline, all the way to the Mexico border. The Miocene play completely covers southern Louisiana and the Mississippi delta in a west-east trend. The Travis Peak-Hosston and the Cotton Valley-Smackover major plays extend from the eastern side of the Gulf Coast region, in south Alabama and the west Florida Panhandle, to East Texas, covering southern Alabama, southern Mississippi, northern Louisiana, and central east Texas. Finally, the Pennsylvanian play is found in central north Texas, east of the Texas Panhandle and northwest of Dallas-Fort Worth.

The majority of the CO<sub>2</sub> EOR candidate reservoirs in southeast Texas are located along the Oligocene play. The large cumulative oil produc-



**Figure 5:** Map of CO<sub>2</sub> EOR Miscible Potential in the Gulf Coast

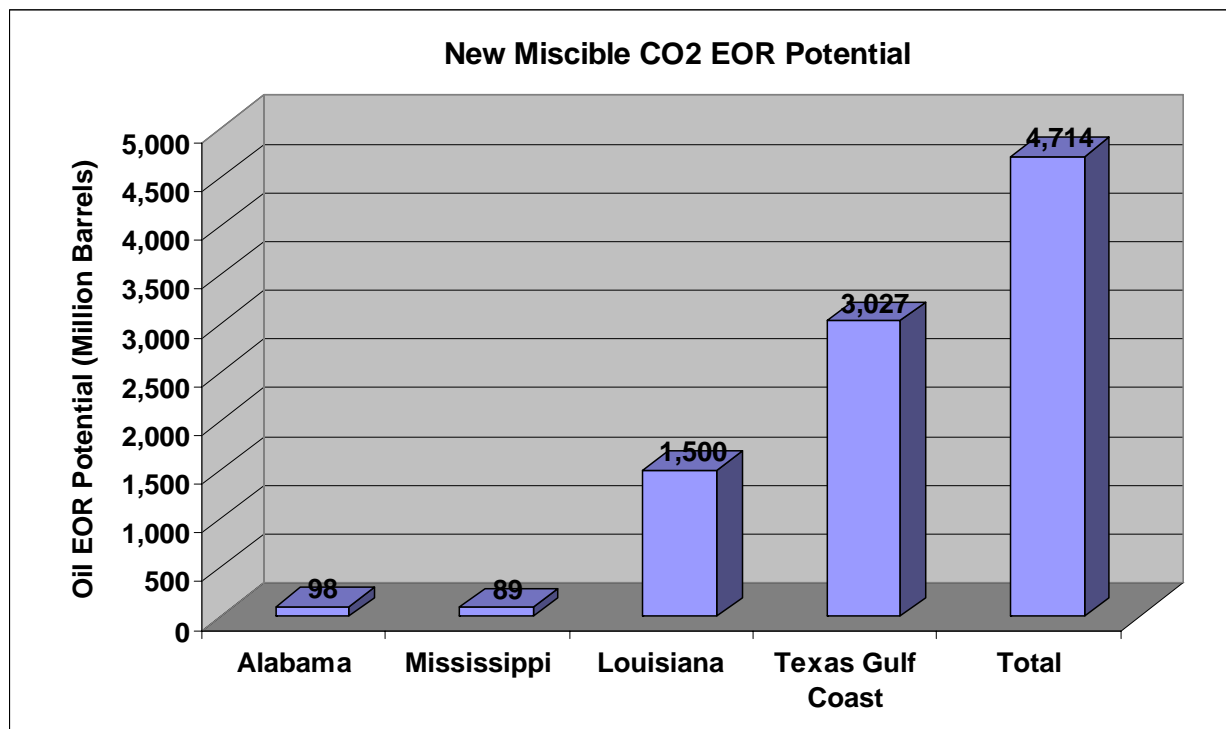
tion of the biggest fields in this region comes from reservoirs in the Frio deep-seated salt domes and the Yegua salt-dome flanks. A major group of candidate reservoirs is located in northeast Texas, distributed along the west ends of the Travis peak-Hosston and Cotton Valley Smackover plays. A third concentration of reservoirs is located in north Texas bordering the Oklahoma and follows the Pennsylvanian oil reservoir play trends (Galloway et. al., 1983). According to our analysis, the Texas Gulf Coast CO<sub>2</sub> EOR resources (excluding the Permian basin) sum to 3 billion stock tank barrels (BSTB).

In Louisiana, Miocene plays are mainly located in the Mississippi delta and along the coastline. The rest of the reservoirs are scattered throughout the state and dispersed in different plays. The Bay Marchand reservoirs have been responsible for the largest cumulative oil production in Louisiana. The state is endowed 1,500 million stock tank

barrels (MMSTB) of CO<sub>2</sub> EOR resources according to the assessment.

In Mississippi the candidate reservoirs are mainly located along the Cotton Valley - Smackover plays. Only 10 other reservoirs can be found south of the major group, lying in the Travis Peak - Hosston play. The Smackover Formation and the Tuscaloosa Group have provided the State with the majority of the cumulative oil production. Brookhaven is the largest candidate field in Mississippi and produces from the Tuscaloosa group. The analysis for the state indicates 89 MMSTB of CO<sub>2</sub> EOR resource potential

In Alabama all the Gulf Coast candidate reservoirs are found in the Cotton Valley - Smackover play. Like in Mississippi, the gross cumulative volumes have been produced from the Smackover Formation. The largest candidate field in the State is Citronelle and produces from the



**Figure 6:** Bar graph of miscible CO<sub>2</sub> EOR resource potential in the Gulf Coast

Rodessa formation. The analysis for Alabama indicates 98 MMSTB of CO<sub>2</sub> EOR resource potential.

The largest potential and economic incentive for use for CO<sub>2</sub> to EOR is found in the Texas Gulf Coast, followed by Louisiana (Fig. 6). The magnitude of the resources in the Texas Gulf Coast make the Alabama and Mississippi results appear small, however 187 MMSTB still represents an attractive resource to attract development of use of CO<sub>2</sub> for EOR.

#### CO<sub>2</sub> Storage Capacity associated with Miscible CO<sub>2</sub> EOR

Use of CO<sub>2</sub> for EOR results in retention of large volumes the reservoir. The volume of this storage is highly dependent on the engineering practices and the sequestration incentives or cost of CO<sub>2</sub>. During oil production, CO<sub>2</sub> is produced with oil, and this produced CO<sub>2</sub> usually is separated from

oil and brine, compressed, and cycled back into the reservoir to stimulate additional production. This cycled volume cannot be counted as part of the storage capacity. In current (high cost of CO<sub>2</sub>) market conditions, at the end of production, the CO<sub>2</sub> is usually produced as a commodity and used in another part of the field. In a future market where storage of CO<sub>2</sub> had value, this CO<sub>2</sub> could be left in the reservoir at abandonment. As a quick-look method of estimating this capacity, we assume that the produced oil is replaced on a volume-for-volume basis by CO<sub>2</sub>.

The estimated volume of storage at abandonment in the EOR candidates is over 2,500 million metric tons (MMT) of CO<sub>2</sub> (Fig. 7). The largest sequestration capacity in these economic EOR reservoirs is in Texas with over 1,300 MMT of sequestration capacity. Louisiana also contains a large capacity of over 1,100 MMT. Mississippi and Alabama account for smaller but significant volumes of sequestration capacity. These results

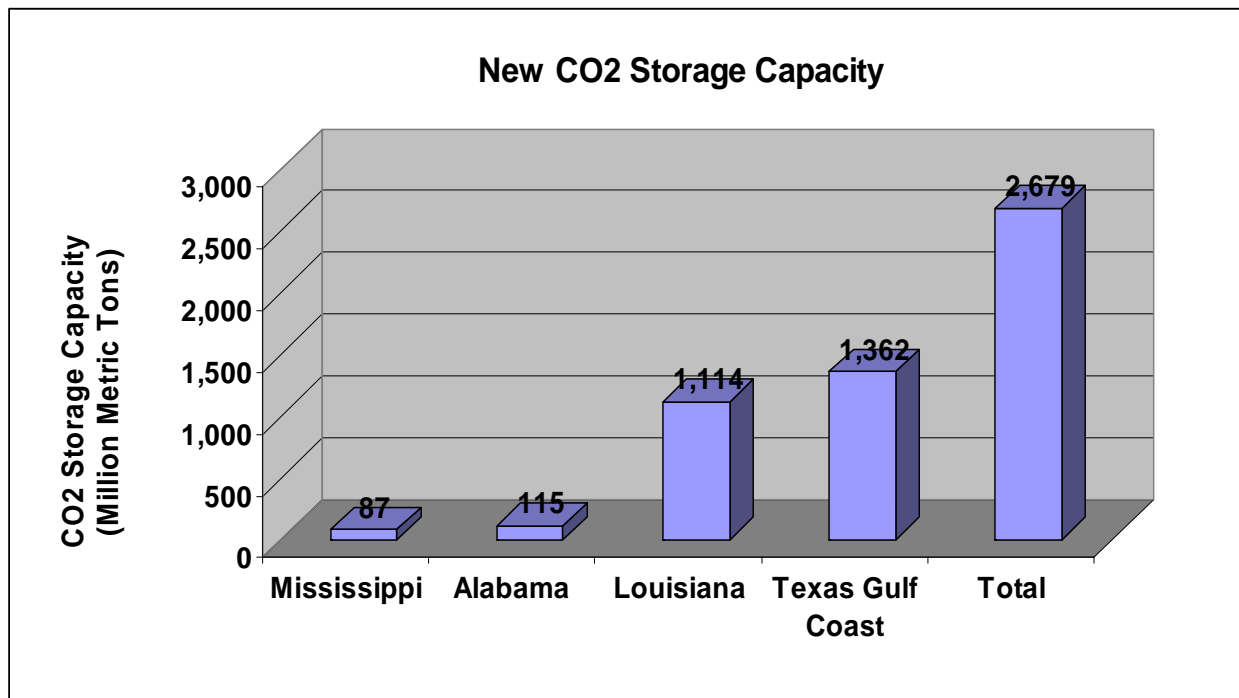


Figure 7: CO<sub>2</sub> Sequestration capacity in miscible oil reservoirs along the Gulf Coast

indicate that Oligocene and Miocene oil reservoirs contain a large target for sequestering CO<sub>2</sub> at the end of CO<sub>2</sub>-EOR

### Summary

A large potential for reserve growth lies along the Gulf Coast through the application of CO<sub>2</sub> miscible enhanced oil recovery. Results indicate that there is the potential for approximately 4.7 BSTB of additional oil reserves. This resource lies between the Pennsylvanian and Miocene aged strata, with the main portion of the resource within the Oligocene and Miocene aged reservoirs. With the Gulf coast states, Texas contains the greatest oil CO<sub>2</sub> EOR potential with a target of over 3 BSTB. These large resource will likely be exploited when a large volume of CO<sub>2</sub> is made available in this oil province.

### Acknowledgments

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