A Summary of CO_2-Enhanced Oil Recovery Options in the Illinois East Sub-Basin

Topical Report

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Curt Blakley, Nathan Webb, Yaghoob Lasemi, Zohreh Askari, Christopher Korose, Nathan Grigsby, and Carl Carman

Prairie Research Institute
University of Illinois
Urbana-Champaign, IL 61820

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CARBONSAFE ILLINOIS EAST SUB-BASIN

Principal Investigator: Dr. Hannes Leetaru
Business Contact: Illinois State Geological Survey
615 E. Peabody Drive
Champaign, IL 61820-7406

Executive Summary

Illinois Basin oil fields have an estimated CO_2 storage resource of 140 to 440 million metric tons, 58 to 180 million metric tons of which are in reservoirs with conditions suitable for miscible CO_2-EOR (Finley, 2005). Untapped reserves remain locked in established mature oil fields as well as prospective greenfields waiting for development. CO_2-EOR recovery in the ILB has the potential to be economically significant by improving oil recovery and providing possible storage of anthropogenic CO_2, and CO_2-EOR reservoirs could potentially be co-located (stacked) with saline storage options. CO_2-EOR interests in the wider region may assist the economics of a storage project long-term, via potential revenue from sale of CO_2 for EOR and/or by taking advantage of Carbon Capture and Storage (CCS) tax credits under 26. U.S. Code § 45Q (and 2018 FUTURE Act amendments). Pilot scale injection tests have been performed at a few locations across the ILB with positive indications of oil response, but there have been no field-scale applications of CO_2-EOR in the ILB. Enhanced ILB oil field miscibility classification maps show additional reservoir-level detail and help expand the screening area for CO_2-EOR opportunities in the East Sub-Basin. Examination of the oil fields and their productive reservoirs revealed the presence of several carbonate and siliciclastic candidates for miscible/near miscible and immiscible CO_2-EOR in the East Sub-Basin study area. In addition, related studies have identified and assessed residual oil zones (ROZs) in sandstone and carbonate formations throughout the region. These results and ongoing work highlight key reservoirs in primary fields of interest and provide the basis for targeted oilfield and site-specific work in assessing the feasibility of industrial-scale CO_2 storage and CO_2-EOR in the Illinois East Sub-Basin study area.

Introduction

This report summarizes CO_2-EOR opportunities that may be available to supplement deep saline storage in the CarbonSAFE Illinois East Sub-Basin pre-feasibility study area (Figure 1). The goal of the US DOE CarbonSAFE program is to determine the feasibility of a commercial-scale geological storage complex that is capable of storing in excess 50 million metric tons of industrially-sourced CO_2.

Any 50+ million metric ton CO_2 storage operation in the Illinois Basin (ILB) would primarily target thick saline reservoirs capable of storing this large volume at a single location. However, CO_2-EOR interests in the wider region may assist the economics of a storage project long-term, via potential revenue from sale of CO_2 for EOR and/or by taking advantage of Carbon Capture and Storage (CCS) tax credits under 26. U.S. Code § 45Q (and 2018 FUTURE Act amendments). In the ILB, oil fields have an estimated CO_2 storage resource of 140 to 440 million metric tons, 58 to 180 million metric tons of which are in reservoirs with conditions suitable for miscible CO_2-EOR (Finley, 2005). Thus, CO_2-EOR reservoirs could potentially be co-located (stacked) with saline storage options, or the EOR reservoirs could be offsite and require pipeline transport.

This report discusses the potential for CO_2-EOR in the CarbonSAFE Illinois East Sub-Basin pre-feasibility study area. The following sections present a brief overview of oil production in the ILB from initial discovery to implementation of CO_2-EOR in field studies and outline the geologic setting of the East Sub-Basin study area in the context of previous CO_2-EOR assessment work. Regional maps and cross-sections characterizing the distribution of reservoirs with estimated CO_2-EOR and storage resources are presented showing the potential for a new direction in residual oil zone (ROZ) CO_2-EOR studies.

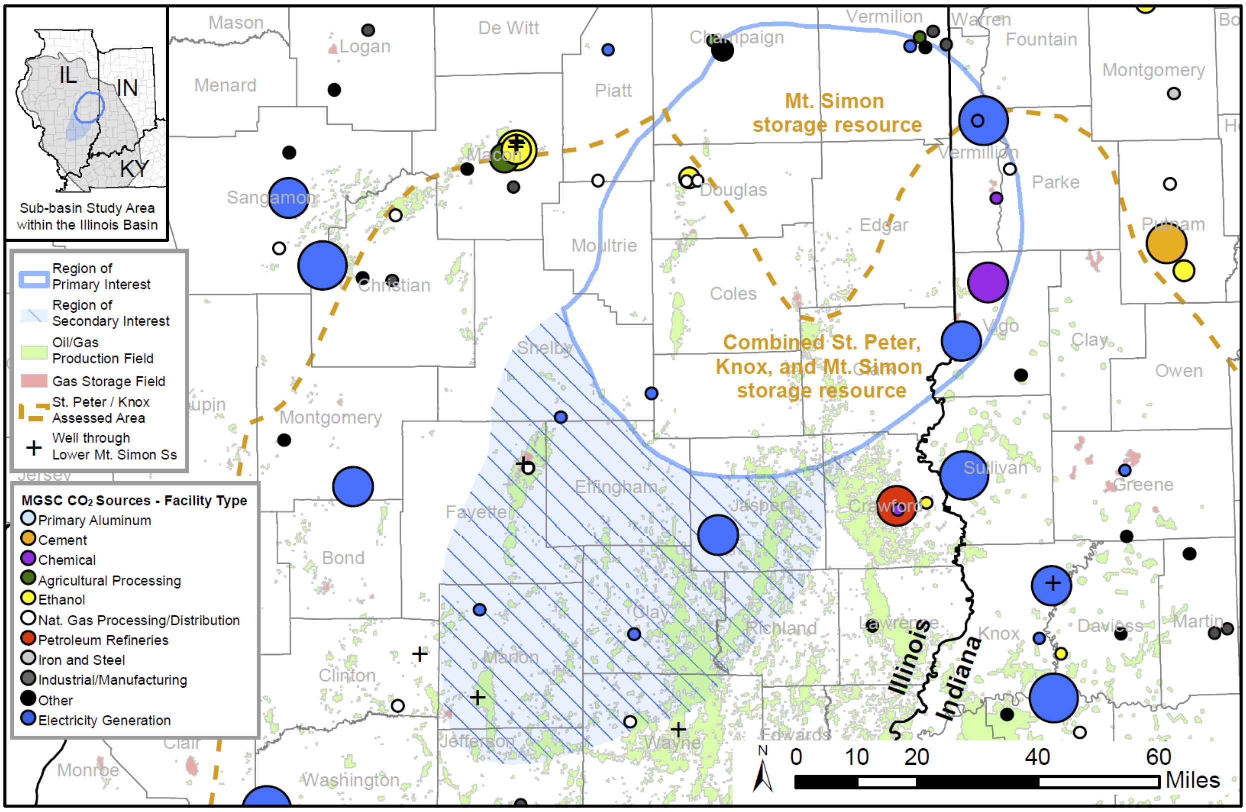

Figure 1. Pre-feasibility study area, CarbonSAFE Illinois East Sub-Basin. Major sources of CO_2 in the broad region are shown as circles, sized by relative emissions (modified from US EPA, 2017), and the area contains saline storage complexes as discussed in other reports. The blue-shaded region of secondary interest is the focus area for the East Sub-Basin CO_2-EOR summary presented in this report.

Oil Production in the Illinois Basin

In 1865, wild-catting in Clark County, about eight miles north of Casey, Illinois, identified oil reservoirs although the lack of proper casing halted significant field developments in the area (Blatchley, 1913). Around the same time, oil was discovered in the Pennsylvanian rocks on the western shelf of the ILB near Litchfield, Illinois, in the pursuit of coal resources and oil production began in the area in 1889.

Between 1904 and 1910 the ILB became an important national oil producer when several large, shallow oil fields were discovered and rapidly developed in Pennsylvanian to Ordovician rocks along the La Salle anticlinal belt in east-central Illinois (Mylius, 1927). Peak production (Figure 2) of approximately 150 million barrels of oil per year (MMBO/year) was reached in the early 1940s, due in large part to the successful application of seismic exploration technology in the ILB and the subsequent discovery of many new fields in the central, deeper portion of the Basin. Production declined with less new oil field discovery reducing primary production from established fields until the application of hydraulic fracturing and waterflooding in the 1950s. These secondary recovery techniques increased production to around 80 MMBO/year during the 1950s and 1960s.

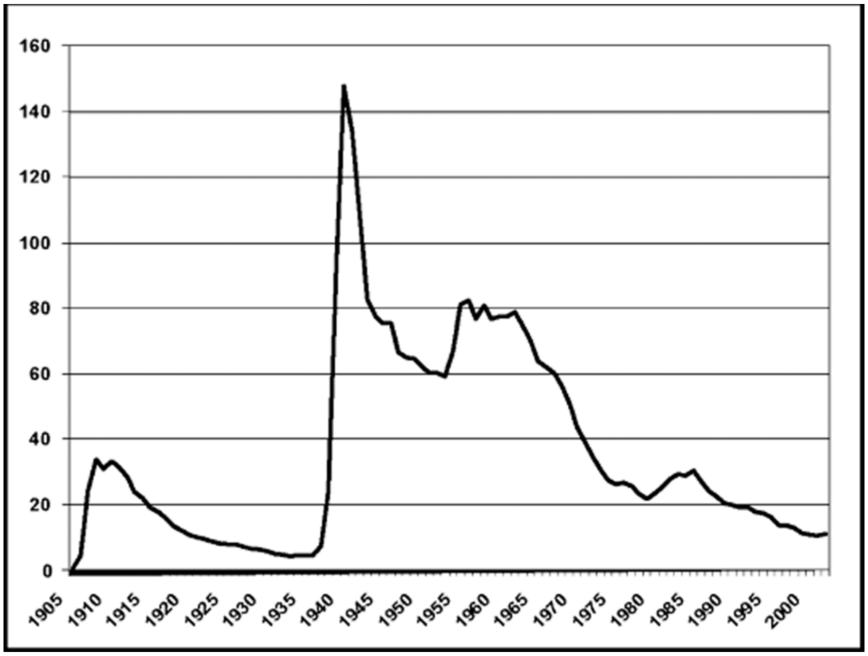

Figure 2. Overall production of liquid hydrocarbon in the Illinois Basin plotted in millions of barrels per year (Knepp, 2009)

Petroleum production has been in a steady decline since the mid-1960s, except for a short increase in the 1980s and 1990s resulting from increased activities due to the higher prices of oil. Active secondary oil recovery efforts and some tertiary EOR projects have improved declining production; many of these mature fields are reaching production limits. Application of CO_2-EOR to fields in the Basin could increase oil production in mature fields and provide storage of anthropogenic CO_2 (MGSC, 2005).

CO_2-EOR has been used outside the ILB commercially for many years. In particular, decades of experience in West Texas have produced some general "rules of thumb" for CO_2 utilization specifically related to observations of predominantly miscible CO_2 flooding in carbonates of the Permian Basin (Knepp, 2009). Pilot scale injection tests have been performed at a few locations across the ILB with positive indications of oil response, but there have been no field-scale applications of CO_2-EOR in the ILB.

Early CO_2-EOR Studies in the ILB

In the early 1990s, a CO_2-EOR pilot study was performed at Mattoon field, Coles County, Illinois. The Mississippian Cypress Sandstone reservoir was selected for the purpose of investigating the application of CO_2 for recovery of bypassed oil in fluvial-deltaic reservoirs in mature fields. The Cypress Sandstone at Mattoon Oil Field has been studied previously (Oltz, 1994). In Mattoon field, the Cypress Sandstone is a predominantly siliciclastic formation consisting of sandstone and shale occurring at an average depth of 1850 ft (565 m) with an average thickness ranging from 65-150 ft (20 - 46 m).

A single well CO_2 injection field test, known as a "Huff-and-Puff" (HNP), was implemented in the Mattoon study. The huff-and-puff is divided into: a) the injection period ("huff"), b) the soak period, when the well is shut-in to allow the CO_2 to diffuse into the formation thereby reducing oil viscosity and increasing formation permeability through mineral grain dissolution, and c) the production stage ("puff"). Extensive CO_2-oil-water core flood experiments, CO_2-oil phase interaction experiments, integrated geological modeling, reservoir simulations, project methodology, and assessment of results are presented in the Mattoon field study final report (Baroni et al., 1995). The report concluded that single-well HNP operations may be the most cost-effective in mature ILB oil fields given the age of many of the wells and potential for well integrity issues. Injectivity results demonstrated that oil production can be significantly increased with the introduction of CO_2 for EOR, though reservoir characterization is essential to designing a successful injection project.

The Midwest Geological Sequestration Consortium (MGSC) was established to assess the best regional approaches for carbon capture, transportation, and injection into less economic coal resources, mature oil fields, and deep saline reservoirs within the ILB with potential for long term storage or enhanced hydrocarbon recovery. During the project Characterization Phase (2003–2005), regional data assessments were completed to determine potential geologic reservoirs for CO_2 injection projects.

A study entitled, "CO_2 Sequestration and Enhanced Oil Recovery Potential in Illinois Basin Oil Reservoirs" was published that evaluated the potential efficacy of CO_2-EOR and CO_2 sequestration development in the ILB. The assessment classified oil fields on the basis of CO_2 miscibility using available temperature and pressure data. Geological mapping, reservoir modeling, and flow simulation were completed on several candidate fields to test EOR potential with results extrapolated basin wide. Reservoir modeling and flow simulation determined that potential additional oil recovery attainable through the use of CO_2 flooding ranges from 0.86 to 1.3 billion bbl (BB) (Knepp, 2009).

Based on results from the extensive characterization studies and secondary screening criteria, three field sites were selected for the Validation Phase (2005-2009) to assess CO_2 storage feasibility and CO_2-EOR potential. Field site screening, reservoir characterization, and ranking from test site portfolios are discussed at length in Phase II Final Report (MGSC, 2012), and the results from the CO_2-miscible and CO_2-immiscible test reservoirs were compared to documented miscible carbonate floods in the Permian Basin (West Texas). The three field test studies are briefly described below.

EOR I — Loudon Oil Field (Huff-and-Puff)

The following is a synopsis of results presented in the final report (MGSC 2009). The immiscible CO_2-EOR I pilot study (HNP) injected into the Mississippian Cypress Sandstone in southern Louden Oil Field, Fayette County, Illinois. In Louden Field, the Cypress Sandstone is very fine to fine-grained sandstone consisting of thin (6-10 feet or 2-3 m), lenticular stacked sand bodies separated by shale interbeds with potential for net sandstone thicknesses up to 100 ft. (30 m) in areas where the sand bodies may coalesce. A total of 43 tons (40 metric tons) of gaseous CO_2 was injected into a converted oil well to a depth of approximately 1,500 feet (460 m) over a one-week period at a rate of 5-10 tons per day. A shut-in period of one week was observed before the well was returned to active production. Oil production increased to a consistent 1-2 barrels of oil per day (bbl/day) above pre-injection production of 0.5-1.0 bbl/day.

EOR II - Mumford Hills Oil Field, Indiana

The following is a synopsis of results presented in the final report (Frailey, 2012). The miscible CO_2-EOR II pilot study injected into the Mississippian Clore Formation in Mumford Hills Oil Field, Posey County, Indiana. In Mumford Hills, the Clore Formation is fine-grained, elongate sandstone 15-20 ft. (5-6 m) thick with core characteristics indicative of fluvial or deltaic channel environment. A total of 6,950 tons (6,300 metric tons) of liquid CO_2 was injected into a converted oil production well to a depth of approximately 1,900 feet (580 m) at a rate of 20-35 tons/day over a 12-month time period. Fluids were produced and monitored from four surrounding wells (inverted 5-spot pattern). Estimated improved oil recovery was 2,590 bbl. Model projection of full-field CO_2 injection over 20 years shows the potential for 12% (170,000 stock tank barrel [stb]) incremental oil recovery.

EOR III pilot — Sugar Creek Oil Field, Kentucky

The following is a synopsis of results presented in the final report (Frailey, 2012). The immiscible CO_2-EOR III pilot study injected into the Mississippian Jackson Sandstone in Sugar Creek Oil Field, Hopkins County, Kentucky. In Sugar Creek, the Jackson Sandstone consists of fine-grained lenticular sandstone bodies, 5- 20 feet (1.5-6 m) in thickness, interbedded with shale. Geophysical log interpretation and core characteristics indicated a depositional environment similar to tidal shoal deposits identified in other Mississippian reservoirs in the ILB. A total of 7,230 tons (6,560 metric tons) of liquid CO_2 (converted to gaseous state *in situ*) was injected into an existing water injection well to a depth of approximately 1,850 feet (565 m) at a rate of 20-30 tons per day over a 12-month time period. Fluids were produced from eight surrounding wells in the flood area with CO_2 detected at one well two weeks after injection, which led to well shut-in. Estimated improved oil recovery was 9,900 bbl. Model projection of full-field CO_2 injection over 20 years shows the potential for 5.5% (174,000 stb) incremental oil recovery. Oil production was nearly 10 bbl/day above pre-injection but lost production from the shut-in well prevented accurate measurement of the total increase in production from EOR activities.

<u>CO_2-EOR and Storage Possibility in Illinois East Sub-Basin</u>

The ILB is a hydrocarbon-bearing intracratonic basin with regionally significant CO_2 storage resources and commercial development potential. In terms of CO_2 storage resources, the ILB has 1.6 to 3.2 billion metric tons of estimated storage in coal seams, 140 to 440 million metric tons in mature oil reservoirs (US DOE 2012), and 41 to 421 billion metric tons of estimated CO_2 storage resources in saline reservoirs (US DOE 2015). The conventional oil reservoir resource target for CO_2-EOR in the ILB is 0.9 to 1.3 billion barrels recoverable (MGSC 2005), not including potential residual oil zones (ROZs).

Enhanced oil recovery through miscible, near miscible, and immiscible CO_2 flooding in the ILB can be economically significant because it would improve recovery from oil fields and will result in storage of anthropogenic CO_2. The Ordovician through Pennsylvanian succession in southern Illinois consists of alternating carbonate and siliciclastic units (Figure 3). The succession contains several sandstone, limestone, and dolomite reservoirs that are prolific oil producers (Figure 3) in a number of oil fields in which both stratigraphic and structural controls were responsible for petroleum entrapment.

From 2003-2005, the MGSC assessed oil reservoirs and fields in the Illinois Basin (Finley, 2005) and estimated 240 to 380 MMBO are potentially recoverable in CO_2-miscible reservoirs, with a miscible-CO_2-flooding storage potential of 58 to 180 million metric tons. As part of the study, data were assessed at the reservoir level, e.g. average reservoir properties to estimate original oil in place (OOIP) and temperature and pressure gradients were applied to average reservoir depths to estimate miscibility classification (see Table 1 and Table 2). Similarly, CO_2 storage and oil recovery factors (derived from oil production results and simulation work) were applied to the OOIP values, based on reservoir groupings of similar lithologies and whether the CO_2-miscibility type was miscible or immiscible. The combinations of temperature and pressure creating the largest near-miscible range were used as criteria for assigning miscibility classes to the oil reservoirs based on depth. For basin-wide categorization, reservoirs with average depths <2,100 feet (<640 m) were classified as immiscible, 2,100 to 2,900 feet (640 to 884 m) were near-miscible, and >2,900 feet (>884 m) were miscible.

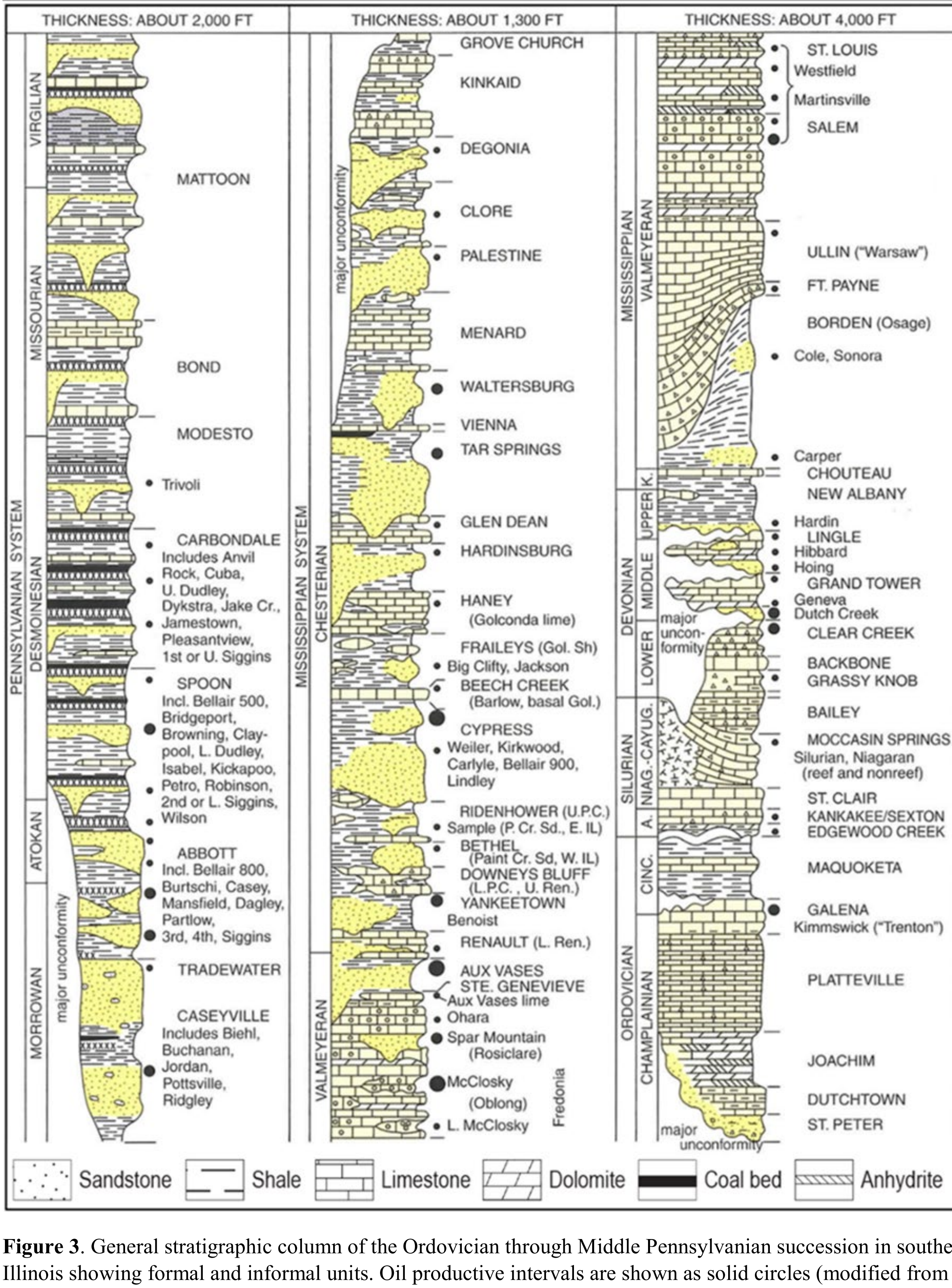

Figure 3. General stratigraphic column of the Ordovician through Middle Pennsylvanian succession in southern Illinois showing formal and informal units. Oil productive intervals are shown as solid circles (modified from Huff and Seyler, 2010).

The MGSC regional CO_2-EOR results have largely been presented, in map form, at the field-summary level—which leveraged a bulk volume weighted oil field depth in order to estimate a predominant miscibility classification per field. This representation has been an effective tool for illustrating the regional CO_2-EOR overview in the ILB, but it tends to draw a focus to the deeper center of the basin where fields with predominantly miscible conditions are located. Field-level representation masks additional conditions for miscibility in the outer-lying (and generally, shallower) belts of predominantly near-miscible and immiscible oil fields. For example, by supplementing the field representations with reservoir-level results, fields outside the predominantly miscible zone in the deeper center of the ILB (Figure 4, i.e. predominantly near-miscible and some predominantly immiscible fields) are shown to have at least one reservoir with miscible conditions for CO_2 flooding. Similarly, the deeper fields in the center of the basin shown to be predominantly miscible (e.g. Clay City Consolidated) also contain shallower reservoirs in the near-miscible and immiscible categories.

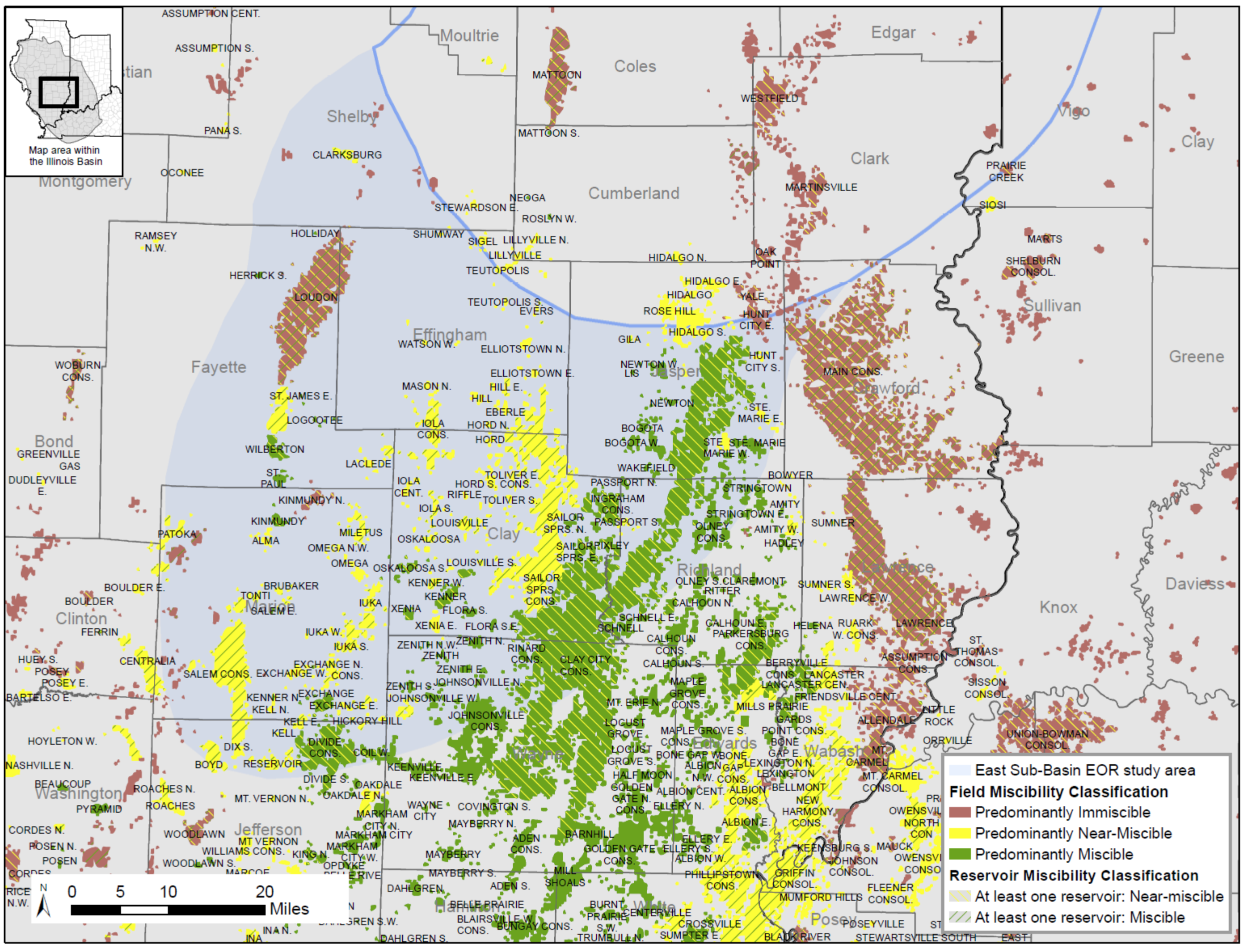

Figure 4. CarbonSAFE Illinois East Sub-Basin CO_2-EOR area of study. Field-level results (solid colors) from MGSC Phase I work (Finley, 2005) were supplemented with reservoir-level results (hachured lines), showing an additional level of CO_2-miscibility information for oil fields in the area.

Table 1. Depth ranges of each miscibility class* calculated based on a temperature ±2°F of the critical temperature (86 to 90°F) and two temperature gradients (Finley, 2005).

Condition	Classification	Criteria	Gradient (°F/ft)	Depth range (ft)
1	immiscible	$T_c < 86$ °F	1.0 °F/100	< 2,500
	near miscible	86°F ≤ T_c < 90°F	1.0 °F/100	2,500 ≤ D < 2,900
	miscible	$T_c \geq$ 90°F	1.0 °F/100	≥ 2,900
2	immiscible	$T_c <$ 86°F	1.2 °F/100	< 2,100
	near miscible	86°F ≤ T_c < 90°F	1.2 °F/100	2,100 ≤ D < 2,433
	miscible	$T_c \geq$ 90°F	1.2 °F/100	≥ 2,433

Table 2. Depth ranges of each miscibility class* calculated based on pressures roughly ±100 psia of the critical pressure (Pc=1,000 to 1,200 psia) and two pressure gradients (Finley, 2005).

Condition	Classification	Criteria	Gradient (psia/ft)	Depth range (ft)
3	immiscible	$P_c <$ 1,000 psia	0.433	D < 2,310
	near miscible	1,000 psia ≤ P_c < 1,200 psia	0.433	2,310 ≤ D < 2,770
	miscible	$P_c \geq$ 1,200 psia	0.433	D ≥ 2,770
4	immiscible	$P_c <$ 1,000 psia	0.800	D < 1,250
	near miscible	1,000 psia ≤ P_c < 1,200 psia	0.800	1,250 ≤ D < 1,500
	miscible	$P_c \geq$ 1,200 psia	0.800	D ≥ 1,500

*The criteria used to assess miscibility conditions at depth were based on temperature and pressure "windows" around the critical point of CO_2. The combinations of temperature and pressure creating the largest near-miscible range were used as classification criteria for assigning miscibility classes to Basin-wide oil reservoirs/fields, and it was concluded that temperature was the controlling factor determining CO_2 miscibility in reservoirs in the Illinois Basin.

Examination of the oil fields and their productive reservoirs in the East Sub-Basin study area revealed the presence of several carbonate and siliciclastic candidates for miscible/near miscible and immiscible CO_2-EOR. Using available data, a miscibility cross-section displaying the well-developed and extensive reservoir intervals was prepared for the southern part of the CO_2-EOR study area (Figure 5).

Carbonate reservoirs selected for CO_2-EOR include the reservoir intervals developed in the Ordovician "Galena/Trenton" (Kimmswick Limestone), Devonian Geneva Dolomite Member of the Grand Tower Limestone, and Mississippian Ullin, Salem, St. Louis, and St. Genevieve limestone units. Siliciclastic reservoirs including, Aux Vases, Yankeetown ("Benoist"), Bethel, and Cypress sandstones are also good candidates for miscible/near miscible CO_2-EOR (Figure 5). In the northern part of the study area, however, except for the Galena/Trenton Limestone, most of the Mississippian and all of Pennsylvanian reservoirs occur in shallow depth and are suitable for immiscible CO_2-EOR.

For miscible CO_2-EOR and storage, a reservoir depth of over 3,000 feet (915 m) is commonly favored (e.g., Verma, 2015). Miscible liquid CO_2 floods in reservoirs having temperatures less than the critical temperature of CO_2 (87.7°F), called low-temperature oil reservoirs (LTORs), are common in the ILB. All recent slim tube-measured minimum miscibility pressure of ILB LTOR oils follow closely to the vapor pressure of pure CO_2. Thus miscible liquid CO_2 floods are possible if reservoir pressure is maintained above the vapor pressure of pure CO_2. In addition to depth, pressure, and temperature, screening of reservoirs for CO_2-EOR and associated storage should also consider reservoir thickness and areal extent, oil gravity, and distance to CO_2 source considering the cost of CO_2 capture, transportation, and injection.

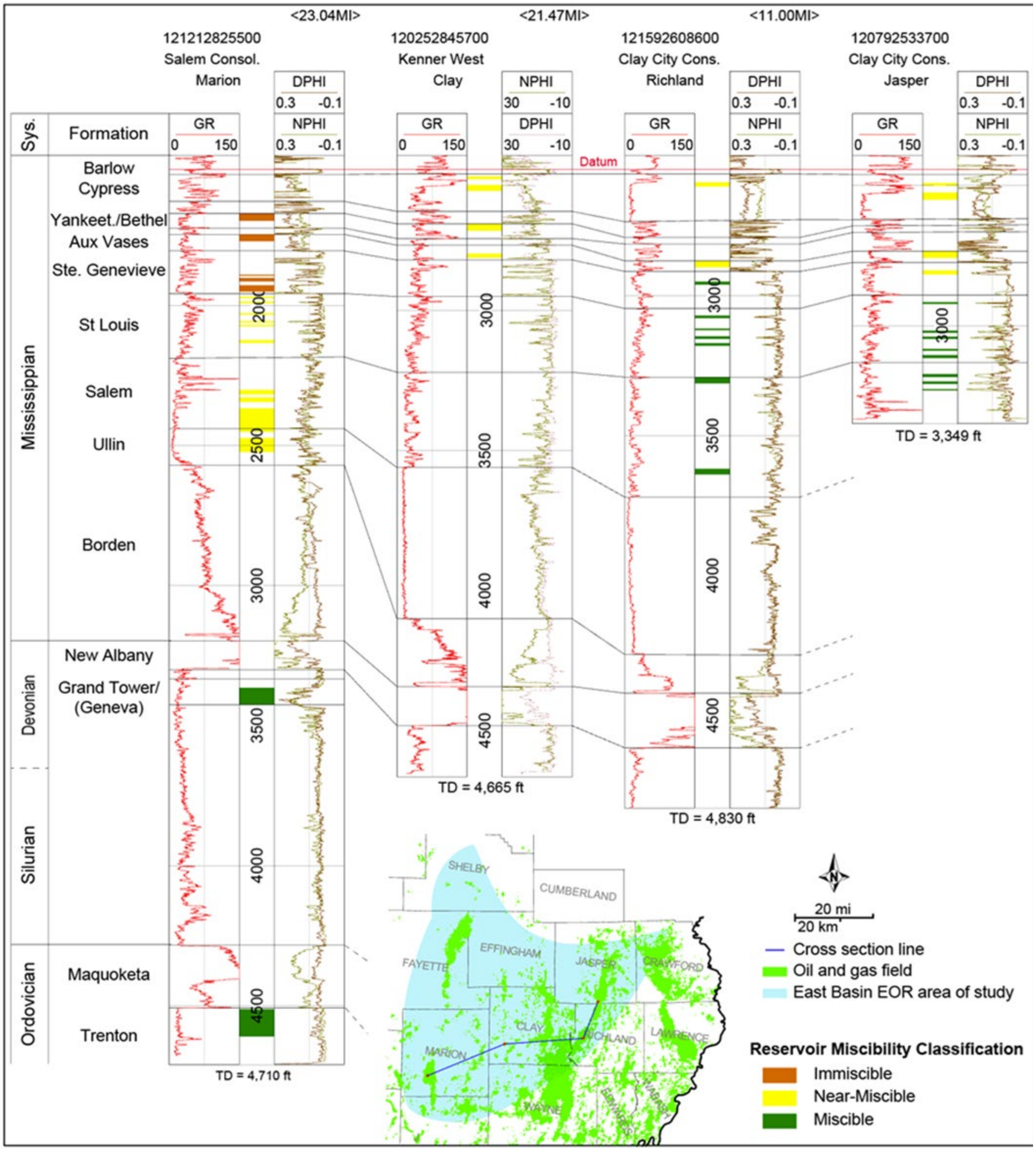

Figure 5. Stratigraphic cross-section displaying the reservoir miscibility in the Ordovician through Middle Pennsylvanian strata in CarbonSAFE East Sub-Basin area.

Current EOR Research

Research is underway in the ILB to identify residual oil zones (ROZs) which would be a new potential resource for CO_2-EOR and associated storage. ROZs are volumes of rock of significant scale into which oil accumulated and was later naturally displaced, leaving behind a low, largely immobile remaining oil saturation (West 2014). Oil saturation (S_o) in ROZs ranges between 20% and 40%, making them functionally similar to conventional reservoirs that have been depleted by decades of waterflooding and are therefore well-suited to tertiary oil recovery processes like CO_2 flooding (Harouaka et al.; 2013). ROZs are anticipated to substantially increase oil resource estimations due to increases in thickness and lateral extent of the oil-bearing rock at many oil fields.

Certain formations in the ILB form extensive, well-connected fairways of porous and permeable rock that contain conventional oil reservoirs in anticlines, but also have potential for non-conventional brownfield and greenfield (fairway) ROZs. Chesterian sandstones, including the Cypress, Benoist, Hardinsburg, and Waltersburg Sandstones (Figure 3), have analogous lithology and texture, and form thick and extensive sandstone belts in the ILB. Likewise, thick, coarser textured sandstone belts with thin oil reservoirs and vast CO_2 storage potential are also known to occur, albeit at shallower depths, within the Caseyville and Tradewater Formations of the Lower and Middle Pennsylvanian. Additional ROZ potential exists in thick, water-bearing Lower and Middle Mississippian and Lower Paleozoic formations as well. The Carper Sandstone is an example of this type of reservoir, which, despite some oil production in brownfield settings, is relatively understudied. Finally, certain carbonate formations such as the Mississippian Ullin Limestone and the Devonian Geneva Dolomite (Figure 3) are also thick and extensive with characteristics indicative of ROZs, including oil shows with high water cut in areas where production is attempted.

ROZs have proven to be economically viable targets for CO_2-EOR in the Permian Basin. However, they also have large associated storage potential, especially because they are believed to occur in regional fairways with multiple, stacked, porous and permeable formations separated by laterally extensive caprocks. ROZs do not exist in isolation: because potential ROZ fairways in different formations overlap, there is potential for vertically stacked ROZs at any given site. For example, sites outside of established oilfields may exhibit stacked greenfield ROZ fairways, or sites within oil fields may host a combination of stacked depleted reservoirs and a brownfield ROZ. Research to systematically characterize depleted conventional oil reservoirs in areas that overlap with brownfield or greenfield ROZs is being conducted to strengthen the value proposition of stacked CO_2-EOR and storage potential in the ILB. This research aims to quantify the target oil and subsurface storage resource and highlight sites that minimize the spatial impact and cost of infrastructure of potential EOR projects.

With a focus on miscible conditions for CO_2-EOR, the enhanced ILB oil field miscibility classification maps showing additional reservoir-level detail helps expand the screening area for CO_2-EOR opportunities in the East Sub-Basin. Related cross section development, and the identification and assessment of ROZs, highlight key reservoirs in primary fields of interest and provide the basis for targeted oilfield and site-specific work in assessing the feasibility of industrial-scale CO_2 storage and CO_2-EOR in the Illinois East Sub-Basin study area.

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