APPLICABILITY OF CARBON DIOXIDE ENHANCED OIL RECOVERY TO RESERVOIRS IN THE UINTA BASIN, UTAH

by Zhiqiang Gu and Milind Deo

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Cover photo:
Glen Bench area, looking north towards the Uinta Mountains, Uintah County. Photo by Craig Morgan.

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APPLICABILITY OF CARBON DIOXIDE ENHANCED OIL RECOVERY TO RESERVOIRS IN THE UINTA BASIN, UTAH

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OBJECTIVES

A report titled "Basin Oriented Strategies for CO_2 Enhanced Oil Recovery," compiled for the U.S. Department of Energy (Advanced Resources International, 2006), states that the reservoirs in Utah have 2 billion barrels of stranded oil that is amenable for recovery through carbon dioxide (CO_2) enhanced oil recovery (EOR) method. Recognizing this vast potential, two specific reservoirs in Utah were evaluated for CO_2-EOR. It is well known that successful waterfloods usually lead to successful CO_2-EOR projects. In this project, two of the successful water flooded reservoirs in the Uinta Basin were studied in detail for potential of CO_2-EOR.

Redwash field (figure 1) has produced about 80 million barrels of oil in primary and secondary production (Utah Division of Oil, Gas and Mining production records), and was initially considered to be a good target. However, the field was too complex, producing from a multitude of sands and the producing company was of the opinion that evaluation of CO_2-EOR for the field ought to be deferred. Instead a small 5 million barrel oil field, Glen Bench, which was well delineated was selected for evaluation.

Greater Monument Butte field offered a more distributed target. Primary and secondary recoveries in these reservoirs tend to be low (5% and ~10-20%, respectively (Pennington, et al., 1996)) providing a large target for CO_2-EOR. Thin layered pay zones and low permeabilities make designing these floods challenging.

This simulation study was an attempt to accomplish the following:

- Estimate the post waterflood incremental oil recovery for the two fields using CO_2 injection and water alternating gas (WAG).
- Determine the CO_2 utilization factors. This refers to the amount of CO_2 needed for every incremental barrel of oil produced. It is well known that a utilization factor between 8-12 Mcf of CO_2 per barrel will generally lead to an economic process.
- Establish the sequestration potential of the proposed EOR operations, in million tons of CO_2 sequestered per year.

Based on the results of this project, a more targeted, project design could be undertaken in collaboration with field operators.

BACKGROUND

CO_2 flooding under miscible conditions is an important and widely used process for EOR throughout the world (Christensen, et al., 2001). CO_2 is usually not miscible on first contact with the reservoir oil. However, at sufficiently high pressures, CO_2 achieves miscibility with oil for a broad spectrum of reservoirs. Under favorable conditions, the gas will vaporize the low to medium fractions of the reservoir crude. After multiple contacts between the oil and CO_2, a bank of light hydrocarbons and CO_2 will form, and this mixture promotes miscibility between the CO_2 and the remaining crude oil. The minimum pressure at which this miscibility is achieved is termed the minimum miscibility pressure (MMP). If miscibility is achieved, the flooding will promote an efficient displacement without a residual phase. In theory, this could lead to the recovery of 100% of the oil in place. In practice, in laboratory experiments over 90% recovery is achieved (Yelig and Metcalf, 1980). In addition to the development of miscibility, CO_2 also dissolves in the oil lowering viscosity and increasing volume (the swelling effect). Because of these effects, CO_2 floods are very effective even under immiscible conditions. Whether a CO_2 flood is first-contact miscible, multi-contact miscible, or immiscible depends on the composition of the crude oil, the reservoir temperature, and the pressure under which the flood is carried out.

CRUDE OIL ANALYSIS

Crude oil analysis was performed using the simulated distillation procedure (SIMDIS) on a gas chromatographic column on an oil sample collected at the well head of the 15-25 well (T. 8 S., R. 16 E., section 25) in the Monument Butte Northeast unit. Dead oil viscosities at temperatures of 120°F were in the range of 2 to 4 centipoise (cp). The carbon number distribution of the sample (averaged from two runs) is given in table 1.

A gas-oil ratio of 400 standard cubic feet/stock tank barrel (scf/stb) was used to recombine the oil with dissolved gas and the mole fractions of the standard carbon number components were calculated. The data are shown in table 2.

It is not practical to model the CO_2-EOR displacement with 45 oil components. Hence a lumping study was conducted using the program WINPROP from the Computer Modeling Group in Calgary, Canada. This resulted in representing the oil using 12 components. Lumping results are shown below in table 3. In addition, CO_2 was a component in all the studies.

MINIMUM MISCIBILITY PRESSURE

Minimum miscibility pressure of the oil calculated at 120°F was about 2900 psia. For the simulations carried out at 120°F, the bottom-hole injection pressures were about 4500 psia—as a result, most of the reservoir was at pressures that exceeded the minimum miscibility. The minimum miscibility pressure at 160°F is about 4000 psia. At the same temperature, the minimum miscibility pressure in Rangely field, Colorado, was about 2100 psia (the injection gas at Rangely contained about 5% methane (Graue and Zana, 1981). Thus, from a miscibility view point, higher pressures would be required in Monument Butte field compared to other ongoing CO_2 floods for attainment of complete miscibility.

SIMULATIONS

All the simulations were performed using the compositional simulator, GEM from the Computer Modeling Group, Calgary, Canada. Three different types of simulations were performed for the Monument Butte Northeast (MB-NE) unit. In the first, a fundamental evaluation of the CO_2-EOR potential was undertaken using an idealized system.

Three phase flow calculations in the reservoir require two sets of relative permeabilities: the water relative permeabilities and oil-water relative permeabilities (k_{rw} and k_{row}), and the liquid-gas permeabilities and gas relative permeabilities (k_{rog} and k_{rg}). A generic set of water-oil and liquid-gas relative permeabilities are shown in figure 2. The relative permeability of each phase is calculated using the following relationships. The parameters employed in this fundamental process evaluation are provided in table 4.

The fundamental study was conducted primarily to ascertain the numerical parameters of the complex compositional simulations. Recoveries with CO_2-only injection, and CO_2-WAG (water alternating gas injection) are shown in figure 3. In WAG, CO_2 and water are injected alternatively at two month intervals. In the Monument Butte Northeast 20-foot-thick reservoir, the recovery was determined more by the total amount of CO_2 injected (which was higher in the CO_2-only injection) than by profile control aspects, which are important in WAG applications. In both applications very high recoveries are observed—well over 50% of original oil in place (OOIP). The CO_2 utilization factors were also exceptional: about 4 mcf/stb for the CO_2 flood and about 3 mcf/stb for WAG. The fundamental study demonstrated that miscibility was obtained for the oil in question and that in an ideal, homogeneous reservoir, very high recoveries are theoretically possible.

THE GLEN BENCH STUDY

The geologic information for the Glen Bench study was provided by Craig Morgan of the Utah Geological Survey (UGS). Geologic properties used in constructing the Glen Bench simulation input file are shown in figures 4 and 5. Oil from the field was analyzed using gas chromatography as explained previously. There was no significant difference in lumped oil composition used in the compositional simulator. With the reservoir parameters employed, the OOIP calculated for the Glen Bench field was about 3 million barrels. Recoveries from a CO_2 flood and WAG for the field are shown in figure 6.

The study was conducted using existing wells and infrastructure. The oil recovery rate is low—in 15 years of the CO_2 flood, about 9% of the oil recovered, while about 6.5% OOIP recovery is obtained after 25 years of WAG. The shapes of the curves suggest, however, that a higher well frequency (more closely spaced wells) would increase the rate of recovery, and possibly the ultimate recovery in the field.

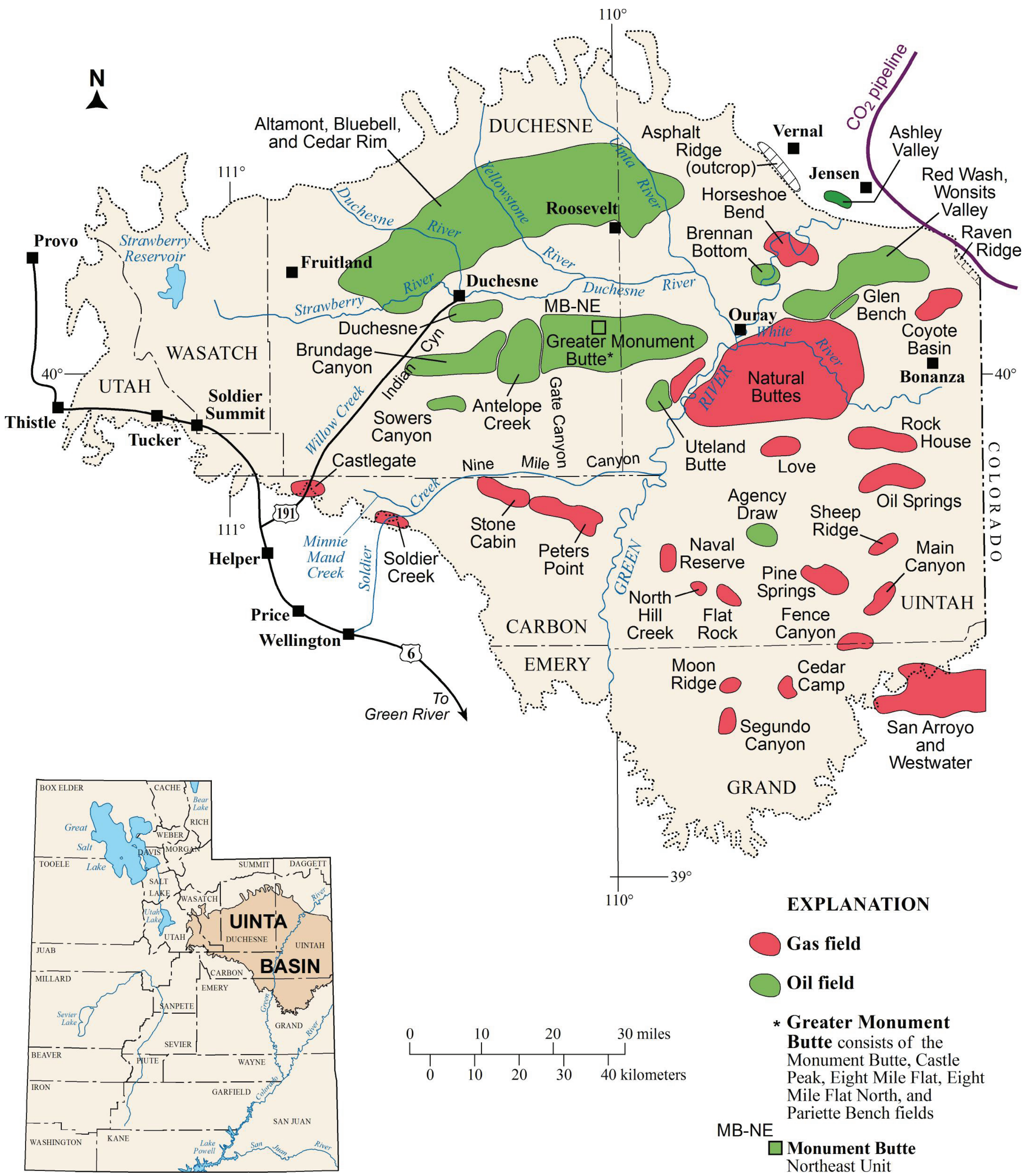

***Figure 1.** Location of major oil and gas fields in the Uinta Basin. Generalized field outlines based on Chidsey, et al. (2004).*

Table 1. *Standard carbon number (SCN) distribution of the oil sample from the 15-25 well (T. 8 S., R. 16 E., section 25) in Monument Butte Northeast unit.*

SCN	6-9	10	11	12	13	14	15	16	17	18
Weight Percentage	4.69	2.36	2.15	1.90	2.59	2.57	2.43	1.99	2.29	2.54
SCN	19	20	21	22	23	24	25	26	27	28
Weight Percentage	2.93	2.30	2.31	2.34	2.35	2.29	2.28	2.39	2.43	2.42
SCN	29	30	31	32	33	34	35	36	37	38
Weight Percentage	2.45	2.01	2.02	1.76	1.54	1.39	1.32	1.25	1.19	1.31
SCN	39	40	41	42	43	44	44+			
Weight Percentage	1.01	1.02	0.93	0.91	0.89	0.78	28.7			

Table 2. *Mole fractions of the various carbon number fractions in the recombined oil, Monument Butte Northeast unit.*

SCN	1	2	3	4	5	6	7	8	9
Mole fraction	32.07	0.736	0.251	0.0476	0.0383	2.986	2.675	2.40	2.122
SCN	10	11	12	13	14	15	16	17	18
Mole fraction	3.854	3.213	2.590	3.246	2.963	2.589	1.962	2.118	2.217
SCN	19	20	21	22	23	24	25	26	27
Mole fraction	2.44	1.838	1.738	1.710	1.650	1.549	1.4808	1.501	1.4822
SCN	28	29	30	31	32	33	34	35	36
Mole fraction	1.427	1.4065	1.117	1.098	0.929	0.791	0.698	0.650	0.601
SCN	37	38	39	40	41	42	43	44	44+
Mole fraction	0.562	0.607	0.457	0.453	0.404	0.388	0.376	0.322	4.252

Table 3. *Concentrations of the 12 components obtained by lumping the original oil components, Monument Butte Northeast unit.*

Hypothetical Components	C1	C2	C3	C4	C5	C6-9
	0.3207	0.0074	0.0025	0.0005	0.0004	0.1018
Hypothetical Components	C10-15	C16-20	C21-25	C26-32	C32-45	CO_2
	0.1845	0.1057	0.0813	0.0896	0.1056	0

Swir	irreducible water saturation	Sgr	residual gas saturation
Sorw	residual oil saturation in water oil system	Sorg	residual oil saturation in the gas oil system
Krw	relative permeability to water	Krgro	gas relative permeability at irreducible water saturation
Krow	oil relative permeability as determined from oil-water two phase relative permeability at Sw	Krog	oil relative permeability as determined from oil water two phase relative permeability at Sg
Krwro	water relative permeability at residual oil saturation	Krg	relative permeability to gas
Kroiw	oil relative permeability at irreducible water saturation		

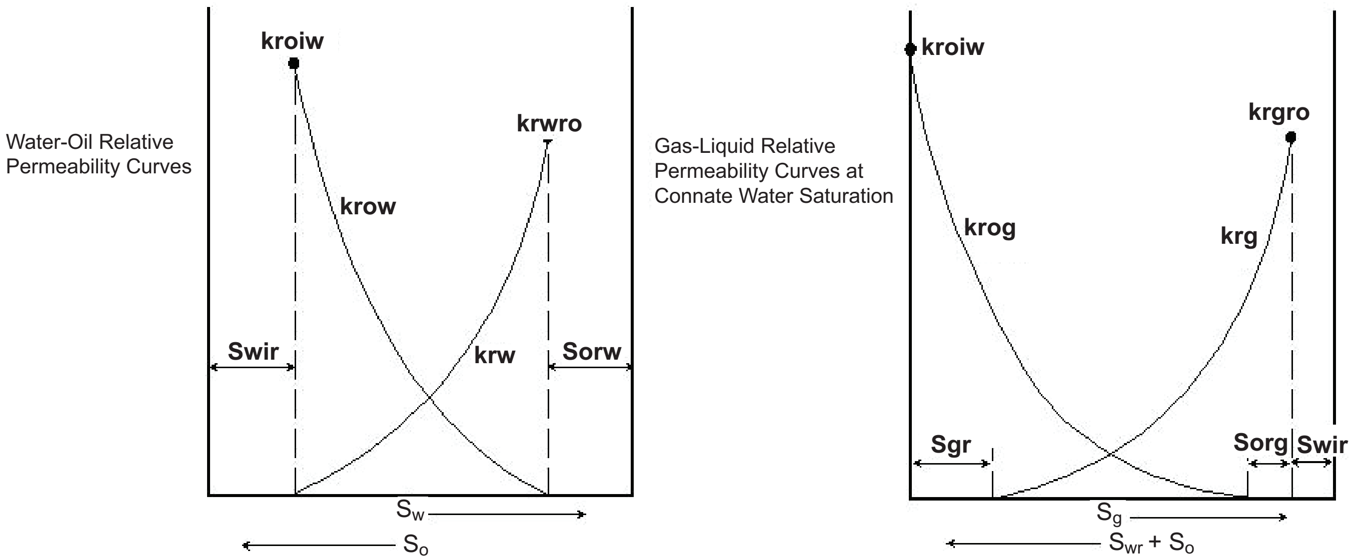

Figure 2. *Generic water-oil and liquid-gas relative permeability curves which are used to calculate the three-phase relative permeabilities.*

Table 4. *Parameters used in the fundamental process evaluation of the CO_2 EOR process.*

Domain: 933.38ft*933.38ft*20 ft
Absolute permeability of domain: 4 md
Injection well: BHP control for P_{BH} = 4500 psi
Production well: BHP control for P_{BH} = 650 psi
Initial condition: T = 120°F, P = 2300 psi, porosity = 0.15

Relative Permeability Table:

*SWT (Water-Oil relative permeability table)

S_w	k_{rw}	k_{row}	p_{cow}
0.22	0.0	1.0	7.0
0.40	0.016	0.68	4.0
0.60	0.032	0.0	3.0
0.80	0.045	0.0000	2.5
1.00	0.07	0.0000	2.0

S_w - Water saturation
k_{rw} - Water relative permeability
k_{row} - Oil relative permeability in water-oil relative permeability set (two-phase)
p_{cow} - Water-oil capillary pressure

*SLT (Liquid-gas Relative Permeability Table)

sl	k_{rg}	k_{rog}	p_{cog}
0.22	1.0	0.0	3.9
0.30	0.9750	0.0	3.5
0.40	0.6	0.0	3.0
0.50	0.504	0.0	2.5
0.60	0.408	0.0	2.0
0.70	0.288	0.02	1.5
0.80	0.12	0.1	1.0
0.90	0.0264	0.33	0.5
0.96	0.0	0.6	0.2
1.0	0.0	1.0	0.0

sl - Liquid saturation
k_{rg} - Gas relative permeability
k_{rog} - Oil relative permeability in gas-liquid relative permeability set (two phase)
P_{cog} - gas-oil capillary pressure

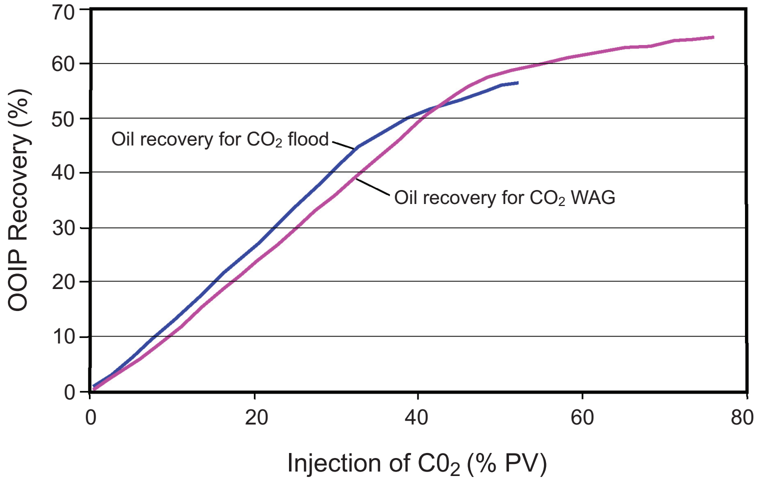

Figure 3. *Comparison of oil recoveries in an ideal 20-foot-thick reservoir with a secondary CO_2 flood and the water alternating gas process. %PV = percent pore volume.*

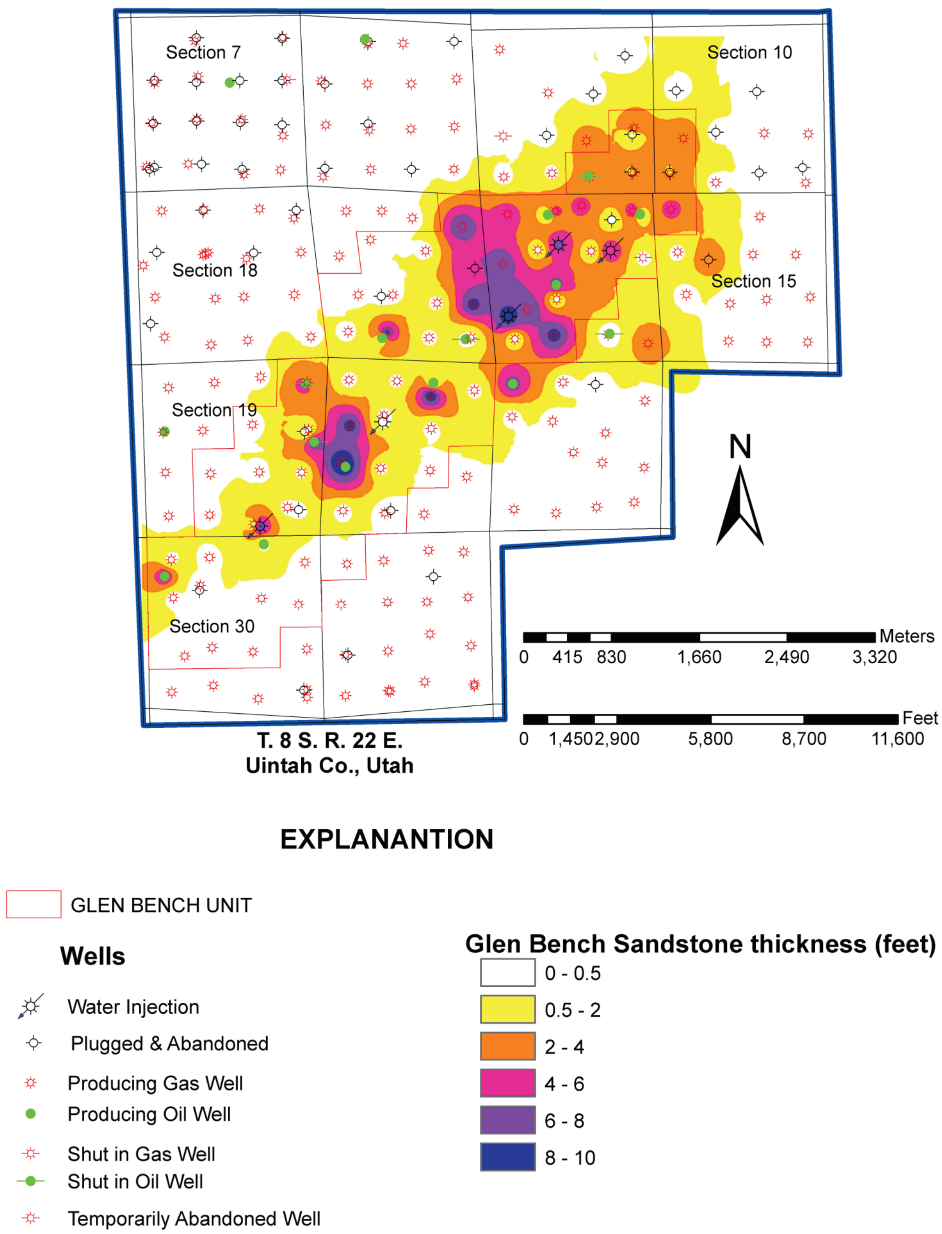

Figure 4. *Isopach map of the Glen Bench Sandstone.*

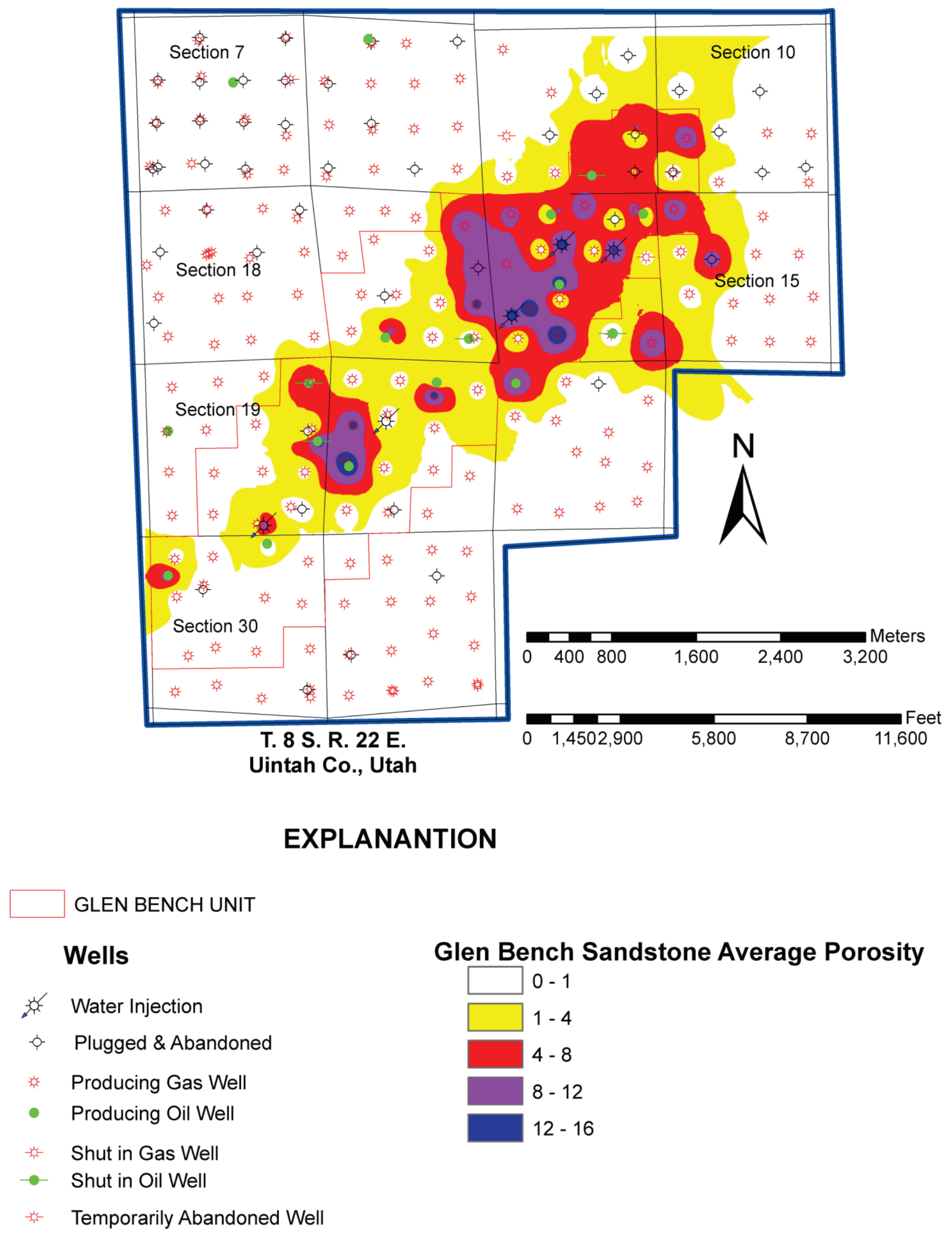

Figure 5. *Average porosity (in percent) distribution in the Glen Bench Sandstone.*

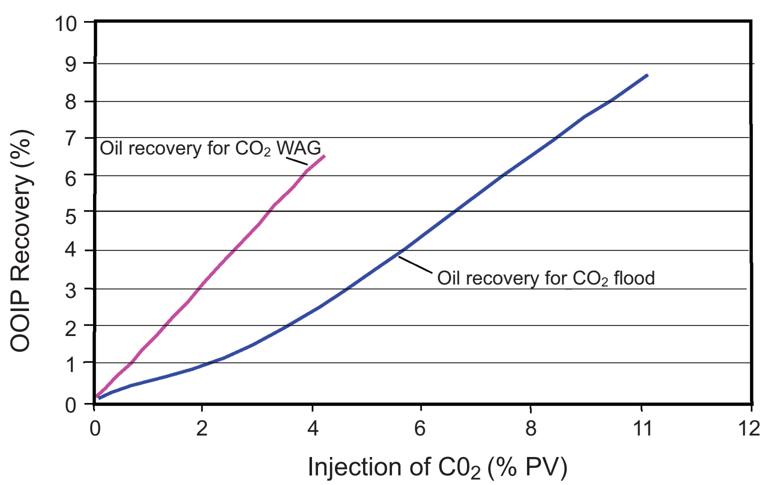

Figure 6. *OOIP recoveries in the Glen Bench field for a CO_2 flood and for WAG.*

The utilization factors of 6 mcf/stb for the CO_2 flood and about 3 mcf/stb for the WAG are still quite favorable. The distributions of CO_2 in the reservoir for the CO_2 flood, and for WAG are shown in figures 7 and 8. The well spacing impacts the spreading of CO_2 in the reservoir. The permeabilities employed in the field (5 md) do not allow for larger amounts of CO_2 injection, and as a result, very low volume (in terms of pore volumes of CO_2) is actually injected into the reservoir.

MONUMENT BUTTE NORTHEAST (MB-NE)

We obtained cross sections and digitized log files for the 16 MB-NE wells in section 25 T. 8 S., R. 16 E., Salt Lake Base Line and Meridian, from Newfield Exploration Company. The data, however, was incomplete and could not be processed in Petrel for direct input into the simulator. As a result, we combined this information with some of our previous results to create a reservoir simulation input file. By our calculations, section 25 had about 9 million barrels OOIP. An important aspect of the MB-NE field is the impact of hydraulic fractures, and all of the 16 wells in section 25 are hydraulically fractured. Hence, simulations were performed with and without hydraulic fractures to evaluate their impact on oil recovery. Primary production performance in section 25 is shown for the two cases in figure 9.

The recoveries without and with hydraulic fractures are about 7 and 8.5%, respectively, and are similar to the observed field performance. Oil saturations after primary recovery are shown in figure 10. There is significant oil saturation in section 25 of the MB-NE unit at all locations. Once the primary recovery was concluded, waterflood was undertaken. Waterflood recovery with and without the presence of hydraulic fractures is shown in figure 11. The incremental waterflood recovery with hydraulic fractures is less than without hydraulic fractures. This is due to some channeling of fluids through the hydraulic fractures, making the flood slightly less effective. The incremental recoveries of about 10% are also close to what are observed in the field. A three-dimensional depiction of oil saturation after the waterflood is shown in figure 12. Except for the areas around the injectors, the oil saturation target for CO_2 flooding is high (0.5 on the average).

After the waterflood, CO_2 flood or CO_2 WAG was modeled in MB-NE (section 25). CO_2 flood recoveries with and without hydraulic fractures are plotted in figure 13. Low waterflood recoveries provide a large target for oil recovery. As a result, recoveries as high as 50% OOIP are seen with CO_2 floods. Higher initial recoveries are observed with hydraulic fractures. However, CO_2 breaks through earlier leading to lower total recoveries. It should be noted that section 25 is modeled as a no-flow segment leading to complete displacement of the moveable oil in the model. The CO_2 utilization numbers are similar in the cases with and without hydraulic fractures—about 6 mcf/stb for both the cases.

The WAG recoveries for MB-NE (section 25) are shown in figure 14. Modeled recoveries of about 40% are attained. The case with hydraulic fractures yields slightly higher OOIP recoveries than without hydraulic fractures. The CO_2 utilization factors for CO_2 WAG would be about 4 mcf/stb.

CONCLUSIONS

This study demonstrates the significant potential of CO_2-EOR in the Uinta Basin, Utah. The final recoveries are dependent strongly on the oil viscosity as CO_2 dissolves in the oil and on relative permeability functions employed. Sensitivity studies conducted using generic simulations show that cutting the viscosity in half increases recovery by about 10% for equivalent pore volume CO_2 injected. Relative permeability end-points determine the ultimate recoveries, and hence have significant process impact. Post waterflood incremental recoveries from 10–30% can be expected in both modeled reservoirs. The most favorable cases have been discussed in this report. Since closed boundary simulations were performed, all injected CO_2 stayed within the boundaries and contacted oil was produced. In practice, all injected CO_2 may not stay within the target horizons. Presence of hydraulic fractures does not decrease the potential recovery from the use of CO_2-EOR. WAG recoveries were generally less than CO_2 flood recoveries, primarily because the reservoirs are thin and recoveries are limited by the ability to inject CO_2 and not by profile control. The CO_2 utlization factors are also extremely favorable, ranging from about 3 mcf/stb for WAG applications to 6 mcf/stb for straight CO_2 floods.

ACKNOWLEDGMENTS

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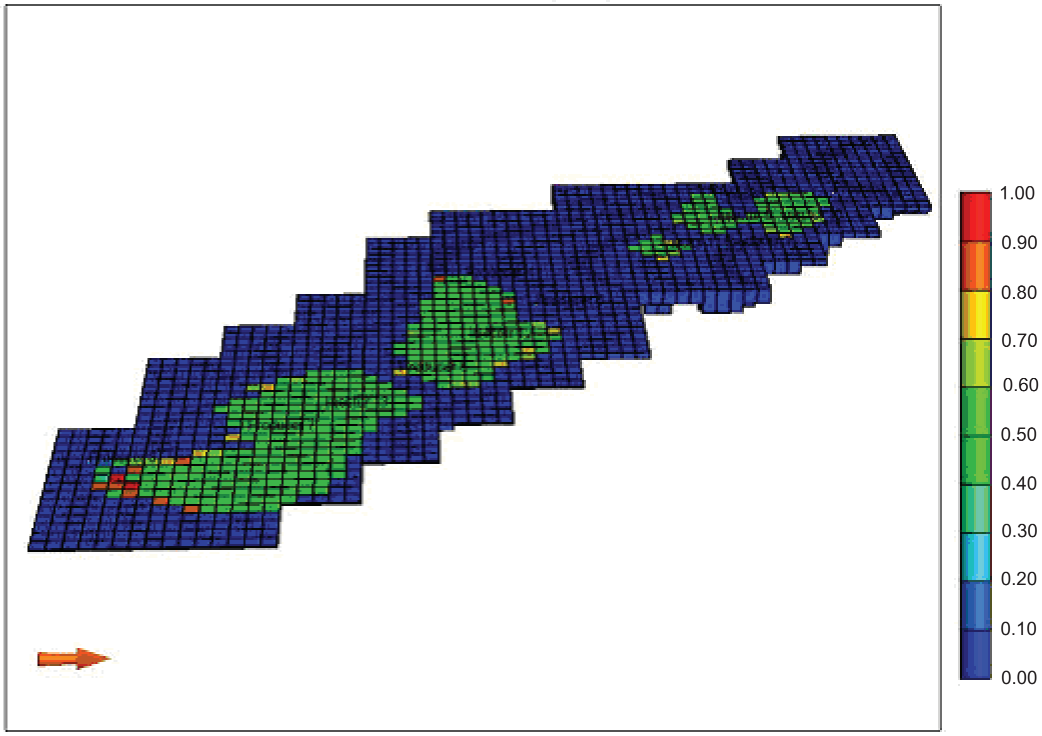

Figure 7. *CO_2 distribution in the Glen Bench field under a CO_2 flood. Arrow points eastward; The scale bar is for CO_2 mole fraction in the gas phase. The grid size is 264 ft by 264 ft.*

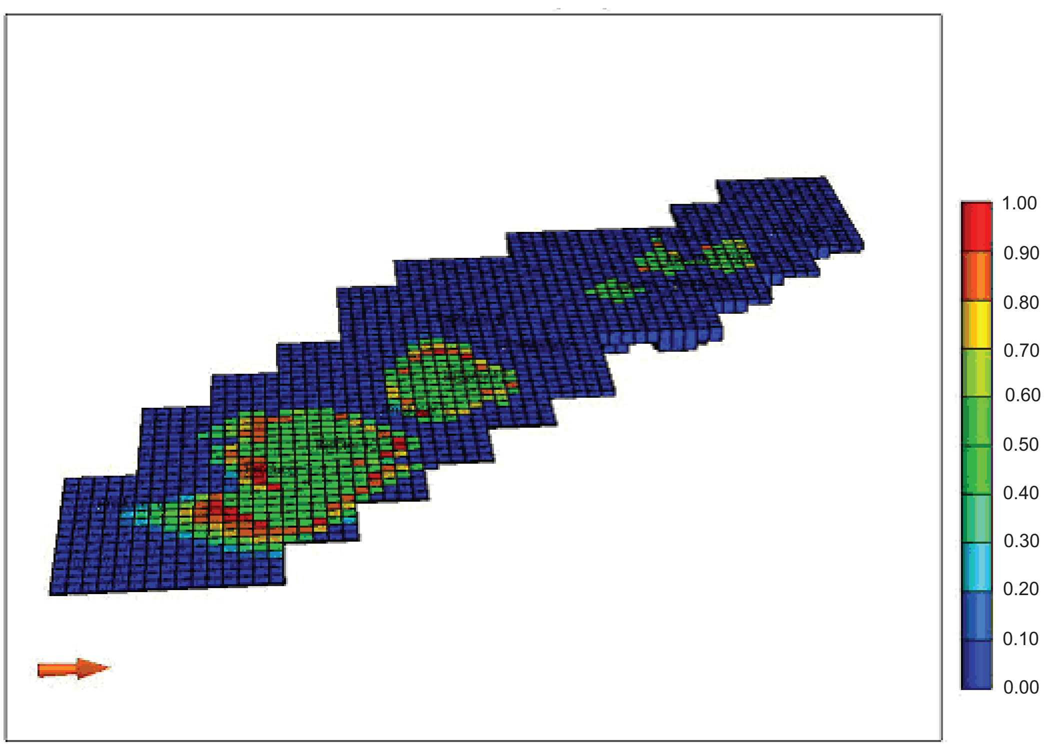

Figure 8. *CO_2 distribution in the Glen Bench field undergoing Water Alternating Gas(WAG) displacement. Sharp CO_2 fronts are formed in WAG. Arrow points eastward; The scale bar is for CO_2 mole fraction in the gas phase. The grid size is 264 ft by 264 ft.*

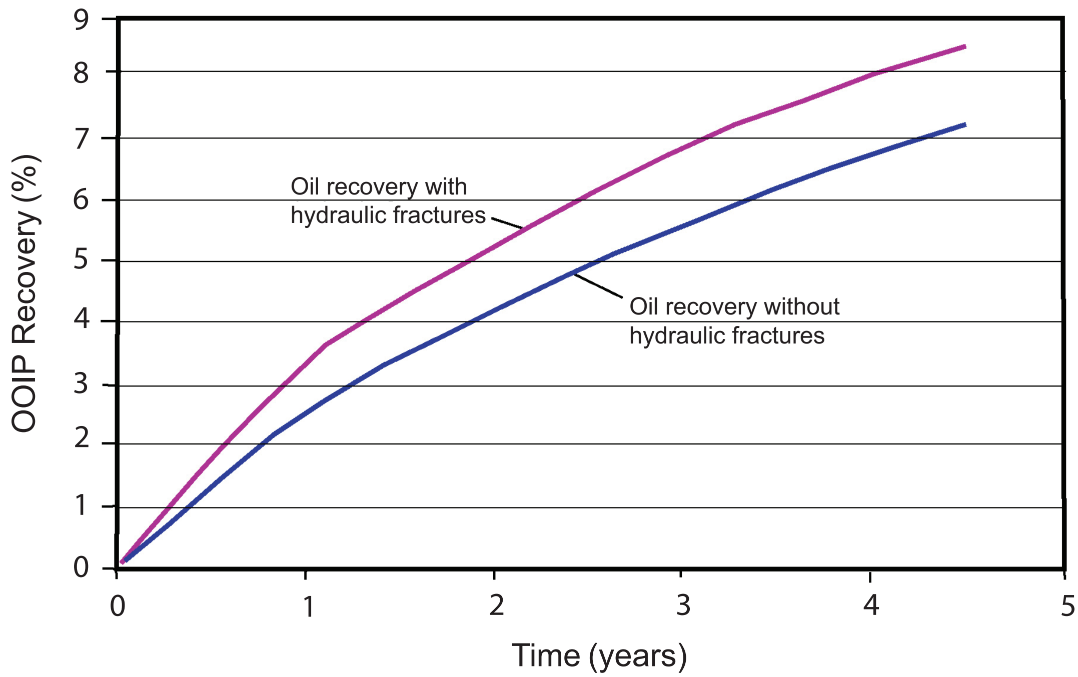

Figure 9. *Primary recovery from section 25, T. 8S., R. 16E., MB-NE, with and without hydraulic fractures (HF).*

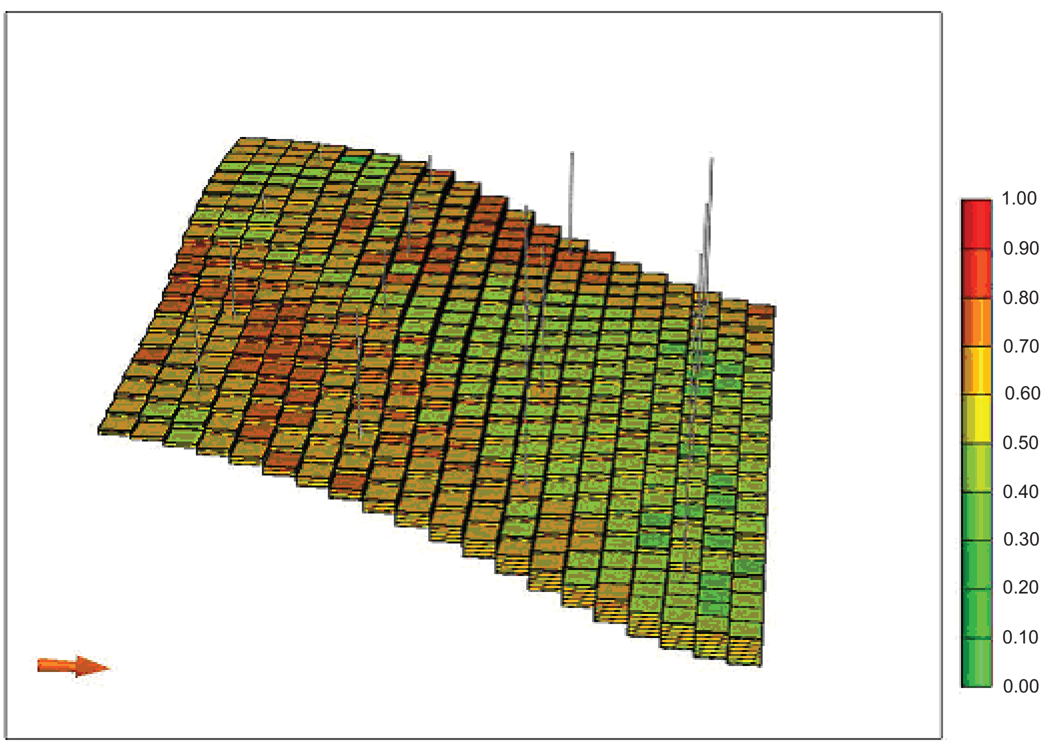

Figure 10. *Oil saturation in MB-NE (section 25) after the primary production. The scale bar shows oil saturation fraction; arrow shows which way is east, while north is upward; the plot is showing D-sands; lines are wells. The grid size is 264 ft by 264 ft.*

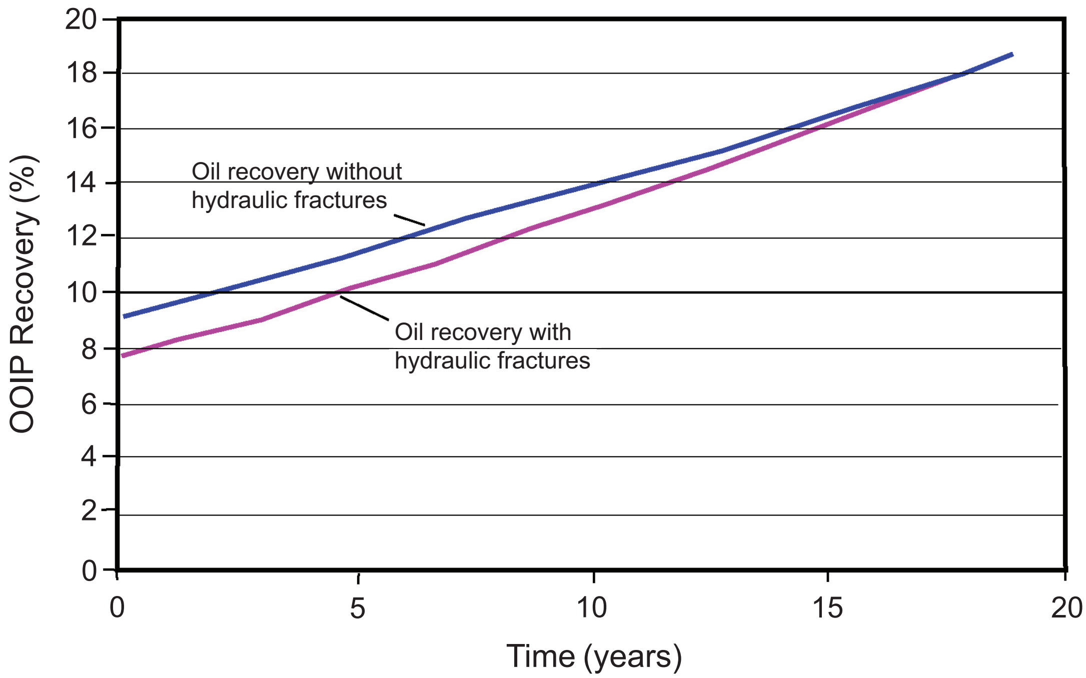

Figure 11. *Waterflood recovery in MB-NE (section 25), with and without hydraulic fractures. The incremental waterflood recovery with hydraulic fractures is less than without hydraulic fractures.*

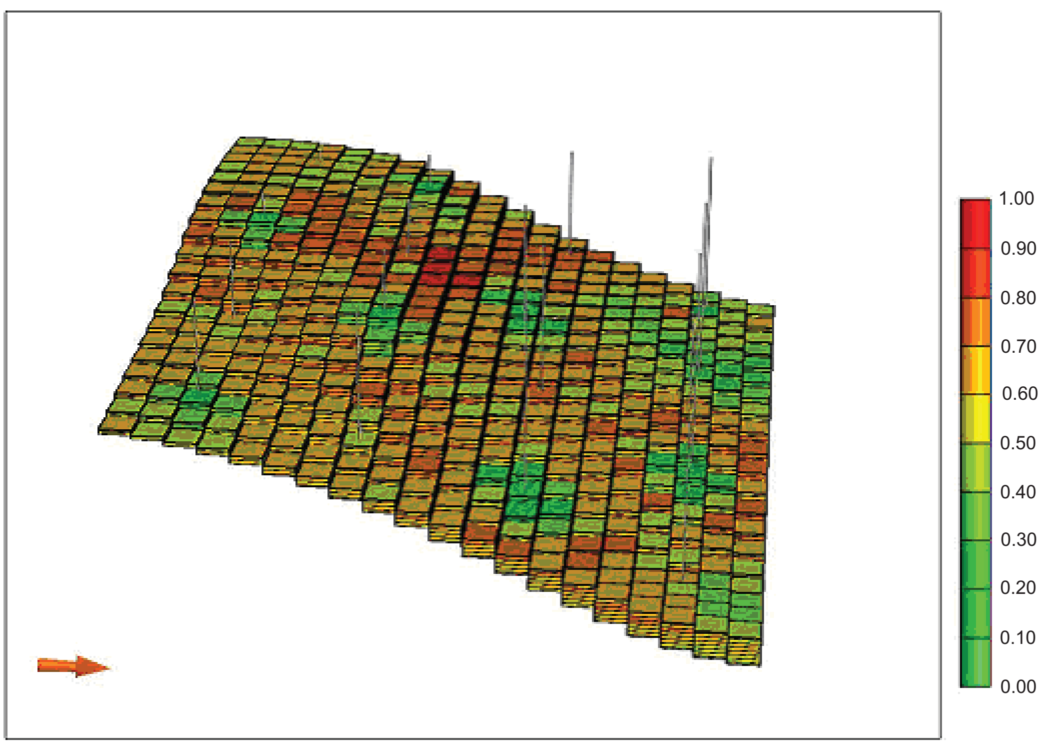

Figure 12. *Post waterflood oil saturation in MB-NE (section 25). The scale bar shows oil saturation fraction; arrow shows which way is east, while north is upward; the plot is showing D-sands; lines are wells. The grid size is 264 ft by 264 ft. Oil saturation targets of 0.5 on the average are observed except near injectors.*

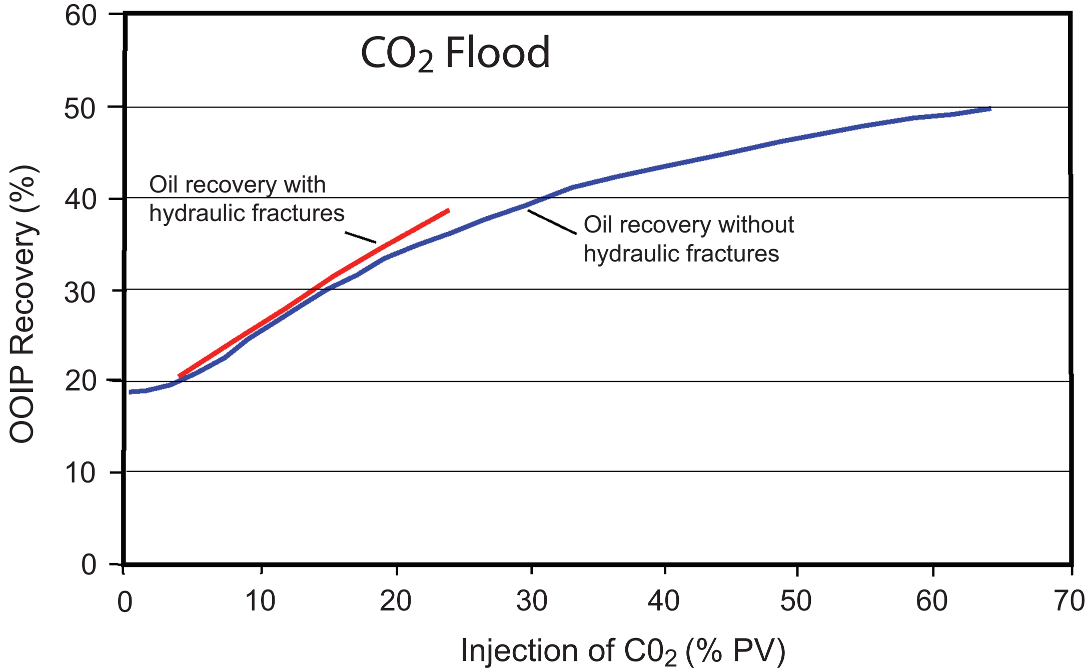

Figure 13. *CO_2 flood recoveries in MB-NE (section 25) with and without hydraulic fractures. Higher initial recoveries are observed with hydraulic fractures, however, CO_2 breaks through earlier leading to lower total recoveries.*

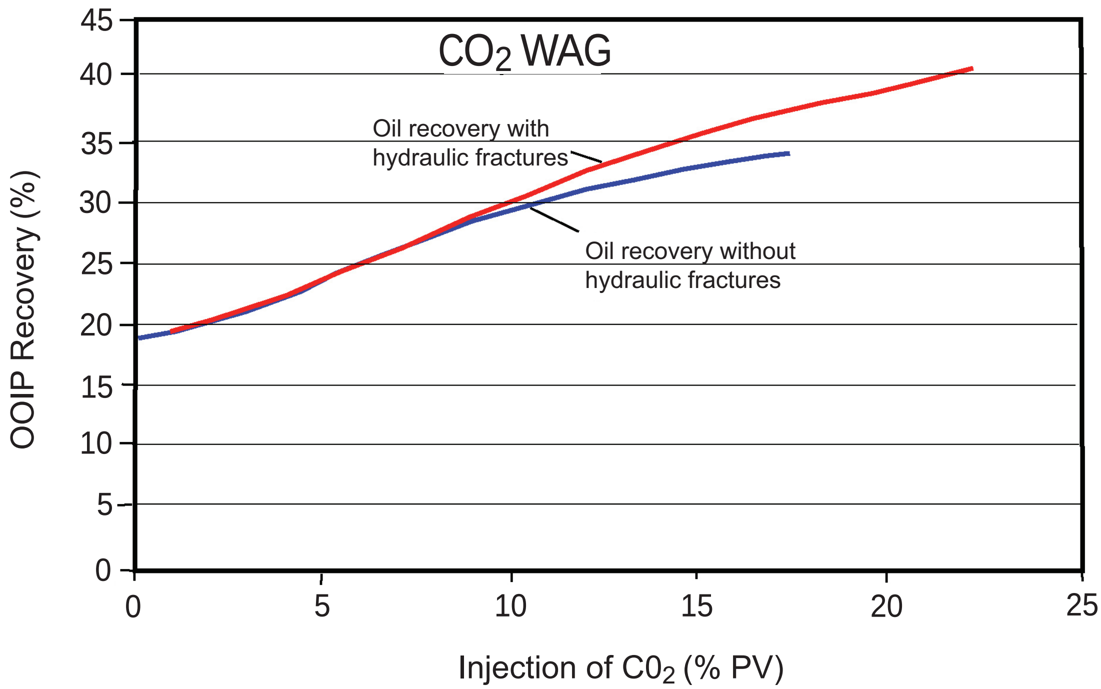

Figure 14. *CO_2 WAG recoveries in MB-NE (section 25) with and without hydraulic fractures.*

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