A Database and Probabilistic Assessment Methodology for Carbon Dioxide Enhanced Oil Recovery and Associated Carbon Dioxide Retention in the United States

Peter D. Warwick, Mahendra K. Verma, Emil Attanasi, Ricardo A. Olea, Madalyn S. Blondes, Philip A. Freeman, Sean T. Brennan, Matthew D. Merrill, Hossein Jahediesfanjani, Jacqueline Roueche, and Celeste D. Lohr

March 17, 2015, Reston, VA

U.S. Geological Survey

Department of the Interior

Outline for Presentation

- Energy Independence and Security Act
- Background on the U.S. Geological Survey (USGS) Geologic Carbon Sequestration Project
- Review of USGS Comprehensive Resource Database
- Review of USGS probabilistic assessment methodology for carbon dioxide enhanced oil recovery (CO_2-EOR) and associated CO_2 retention
- Summary and discussion

Energy Independence and Security Act 2007
Public Law 110–140 (U.S. Congress, 2007)

TITLE VII—CARBON CAPTURE AND SEQUESTRATION

Subtitle B—Carbon Capture and Sequestration Assessment and Framework

SEC. 711. CARBON DIOXIDE SEQUESTRATION CAPACITY ASSESSMENT.

(b) METHODOLOGY— …shall develop a methodology for conducting an assessment under subsection (f), taking into consideration—

(1) the geographical extent of all potential sequestration formations in all States;

(2) the capacity of the potential sequestration formations;

(3) the injectivity of the potential sequestration formations;

(4) <u>an estimate of potential volumes of oil and gas recoverable by injection and sequestration of industrial carbon dioxide in potential sequestration formations</u>

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USGS Methodology for a National Assessment of Geologic Carbon Dioxide Storage Resources (Brennan et al., 2010; Blondes et al., 2013)

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A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage

By Sean T. Brennan, Robert C. Burruss, Matthew D. Merrill, Philip A. Freeman, and Leslie F. Ruppert

Open-File Report 2010–1127

U.S. Department of the Interior
U.S. Geological Survey

http://pubs.usgs.gov/of/2010/1127

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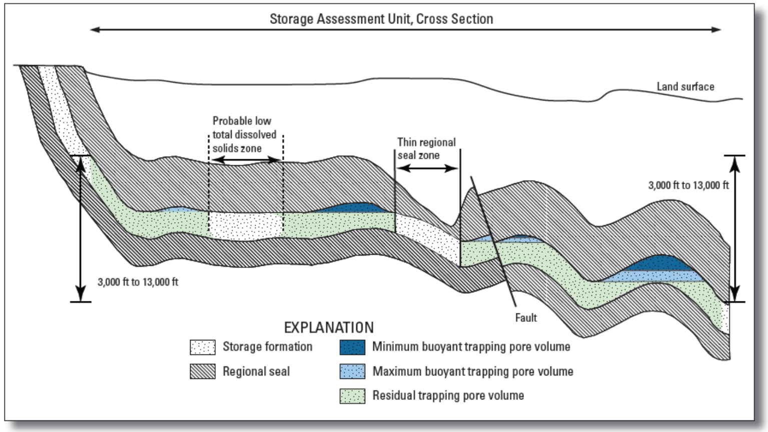
National Assessment of Geologic Carbon Dioxide Storage Resources—Methodology Implementation

By Madalyn S. Blondes, Sean T. Brennan, Matthew D. Merrill, Marc L. Buursink, Peter D. Warwick, Steven M. Cahan, Troy A. Cook, Margo D. Corum, William H. Craddock, Christina A. DeVera, Ronald M. Drake II, Lawrence J. Drew, Philip A. Freeman, Celeste D. Lohr, Ricardo A. Olea, Tina L. Roberts-Ashby, Ernie R. Slucher, and Brian A. Varela



Open-File Report 2013–1055

U.S. Department of the Interior
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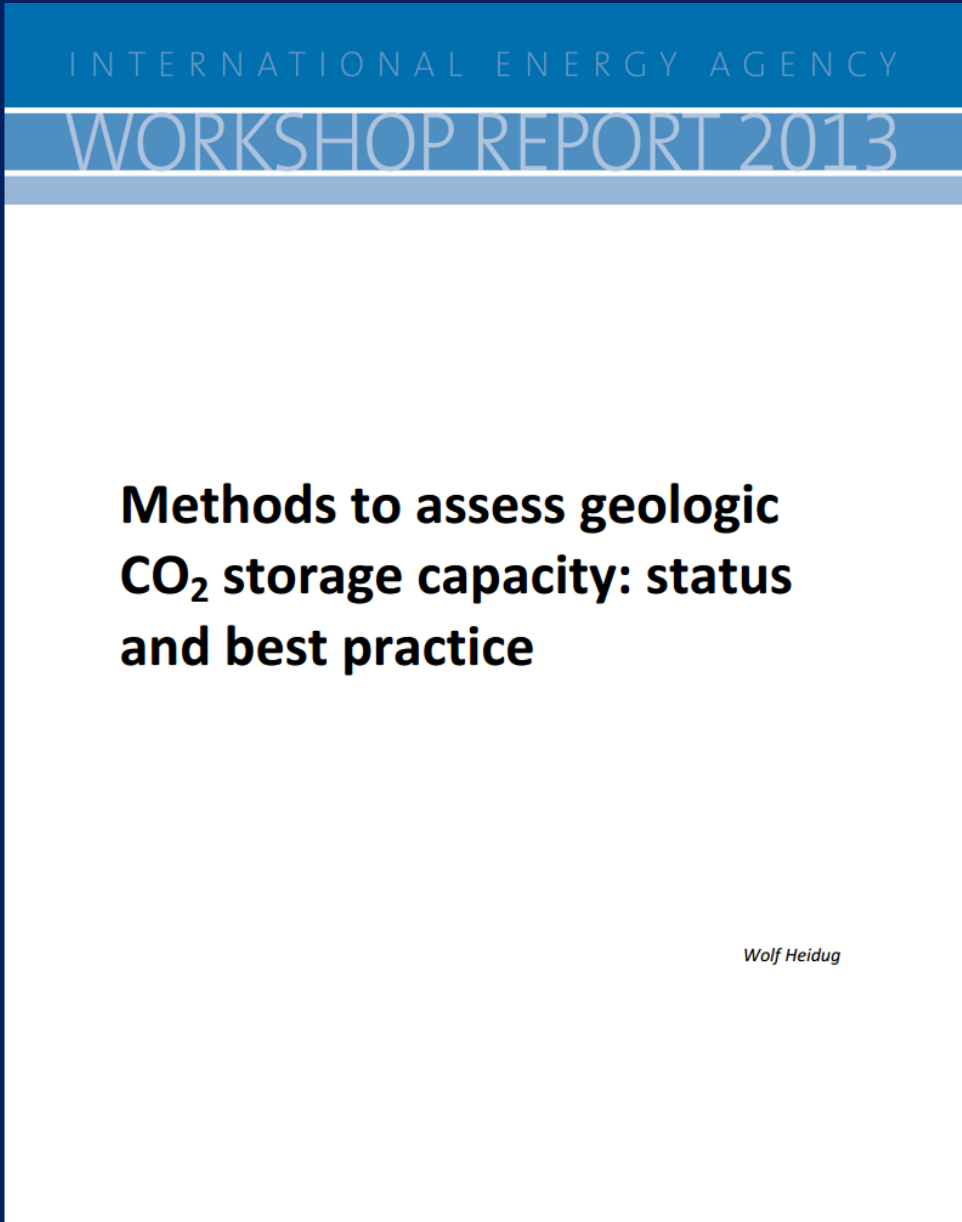
http://pubs.usgs.gov/of/2013/1055


INTERNATIONAL ENERGY AGENCY

WORKSHOP REPORT 2013

Methods to assess geologic CO_2 storage capacity: status and best practice

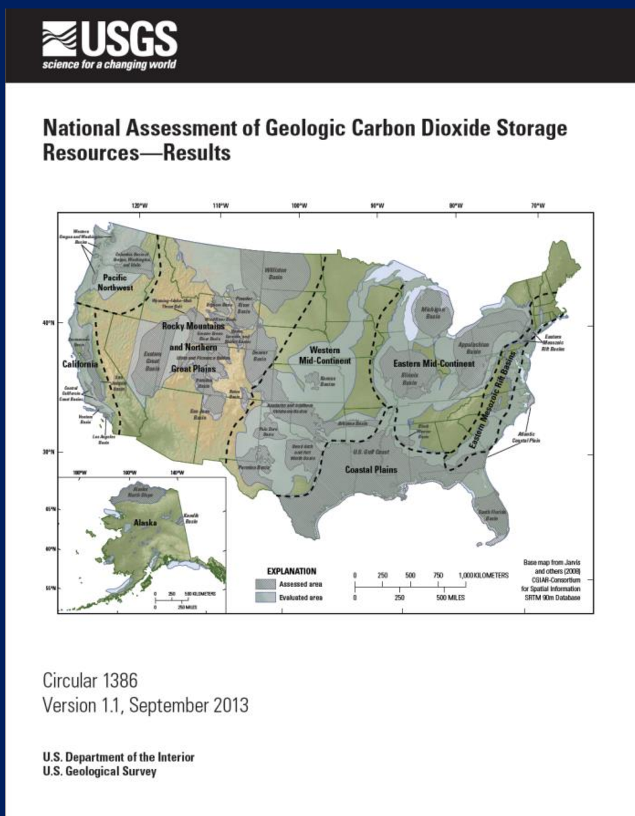
Wolf Heidug

The USGS methodology for assessing carbon dioxide (CO_2) storage potential for geologic carbon sequestration was endorsed as a best practice for a country-wide storage potential assessment by the International Energy Agency (IEA).

https://www.iea.org/publications/freepublications/publication/methods-to-assess-geological-co2-storage-capacity-status-and-best-practice.html

USGS National Assessment of Geologic Carbon Dioxide Storage Resources

by U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013a,b,c



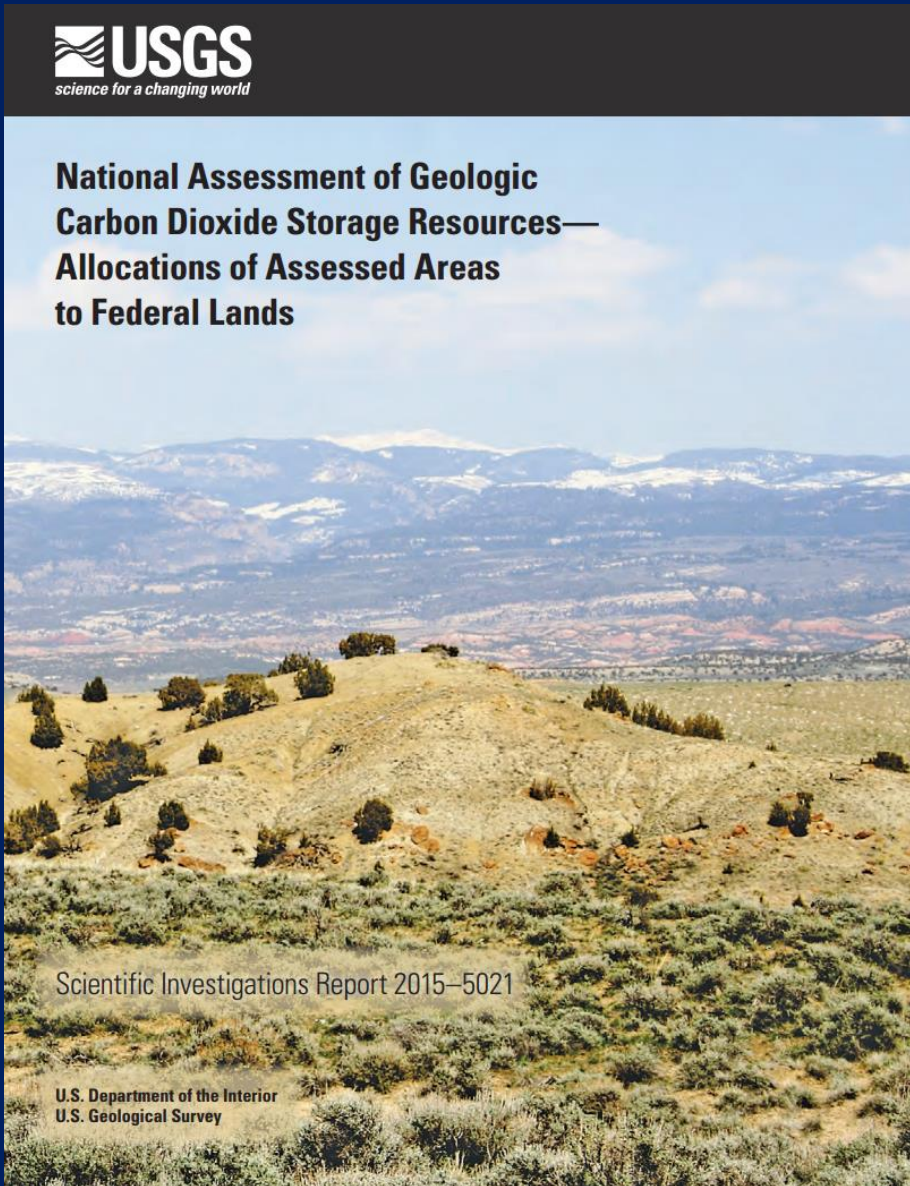
Three companion assessment reports:

a. Data - USGS Data Series 774:
http://pubs.usgs.gov/ds/774/

b. Results - USGS Circular 1386:
http://pubs.usgs.gov/circ/1386/

c. Summary - Fact Sheet 2013–3020:
http://pubs.usgs.gov/fs/2013/3020/

USGS



National Assessment of Geologic Carbon Dioxide Storage Resources—Allocations of Assessed Areas to Federal Lands

By Marc L. Buursink, Steven M. Cahan, and Peter D. Warwick

Basin report series:
http://dx.doi.org/10.3133/ofr20121024

http://co2public.er.usgs.gov/viewer/

U.S. Geological Survey Scientific Investigations Report 2015–5021, http://dx.doi.org/10.3133/sir20155021

USGS

Carbon Sequestration – Geologic Research and Assessments

Task 1: Methodology development and assessment of national CO_2 enhanced oil recovery (EOR) and associated CO_2 storage potential

Objective: requested by legislation; complete methodology and conduct an assessment

Task 2: Geological studies of reservoirs and seals in selected basins with high potential for CO_2 storage

Objective: conduct focused, detailed geological studies of reservoirs and seals in selected basins

Task 3: Natural CO_2 and helium - resources and analogues for anthropogenic CO_2 storage

Objective: study natural CO_2 reservoirs as analogues for CO_2 storage; assess the availability of recoverable natural CO_2 for use in EOR; requested by legislation to assess helium resources

Task 4: Economics of CO_2 storage and enhanced oil recovery

Objective: evaluate economics of CO_2 storage in saline reservoirs and EOR projects

Task 5: Storage of CO_2 in unconventional geologic reservoirs

Objective: produce national maps of potential coal and shale reservoirs for CO_2 storage

Task 6: Induced seismicity associated with CO_2 geologic storage

Objective: seismic monitoring at CO_2 injection sites

Task 7: Outreach

http://go.usa.gov/8X8

USGS

Methodology Development and Assessment of National CO_2 Enhanced Oil Recovery and Associated CO_2 Storage Potential

- Requested by Energy Independence and Security Act
- Goal is to develop a probabilistic assessment methodology and then estimate the technically recoverable (pre-economic) hydrocarbon potential using CO_2-EOR within the United States
- The recoverable hydrocarbon volume occupies potential pore space that may be available for sequestration of anthropogenically produced CO_2 in subsurface hydrocarbon reservoirs

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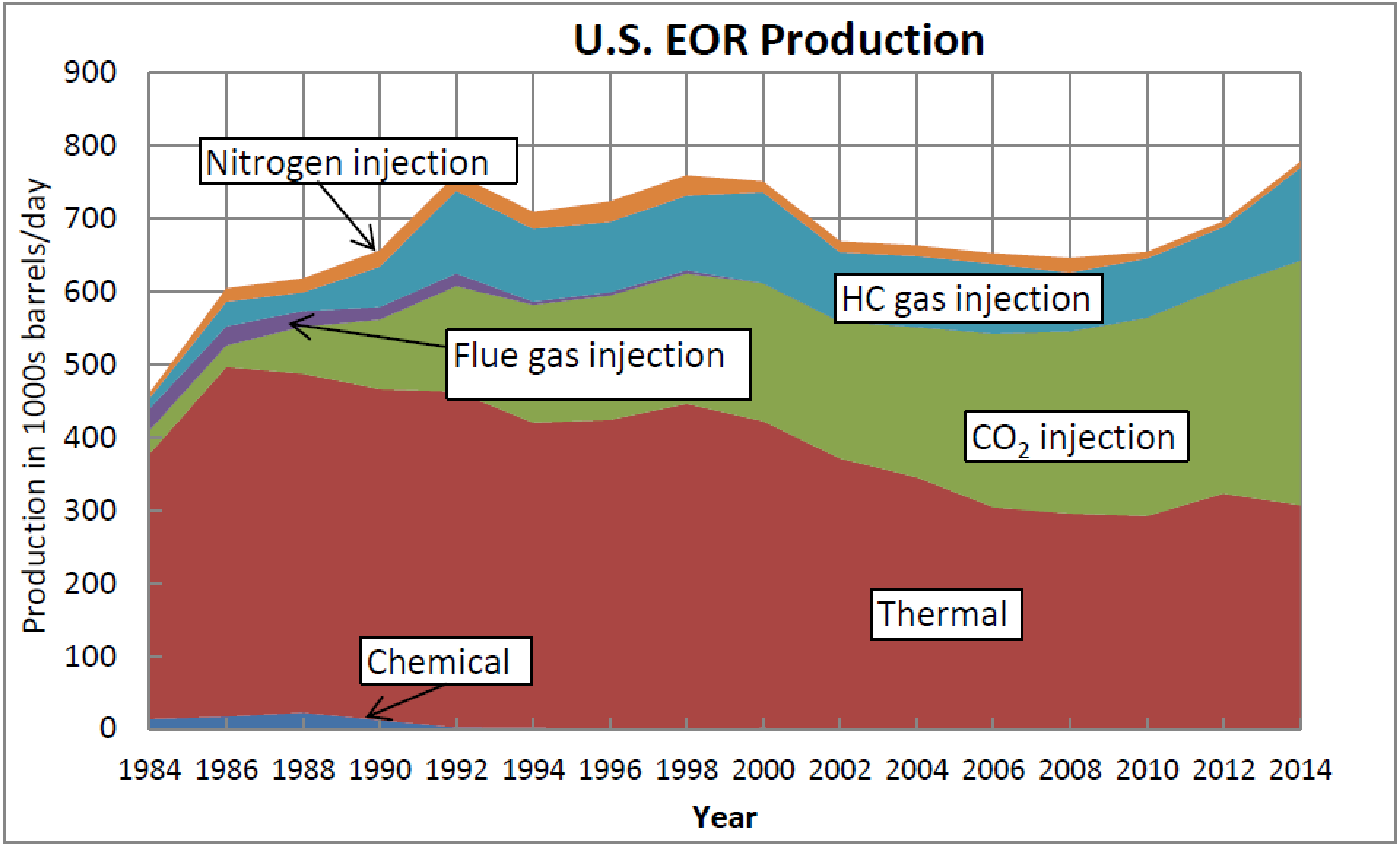
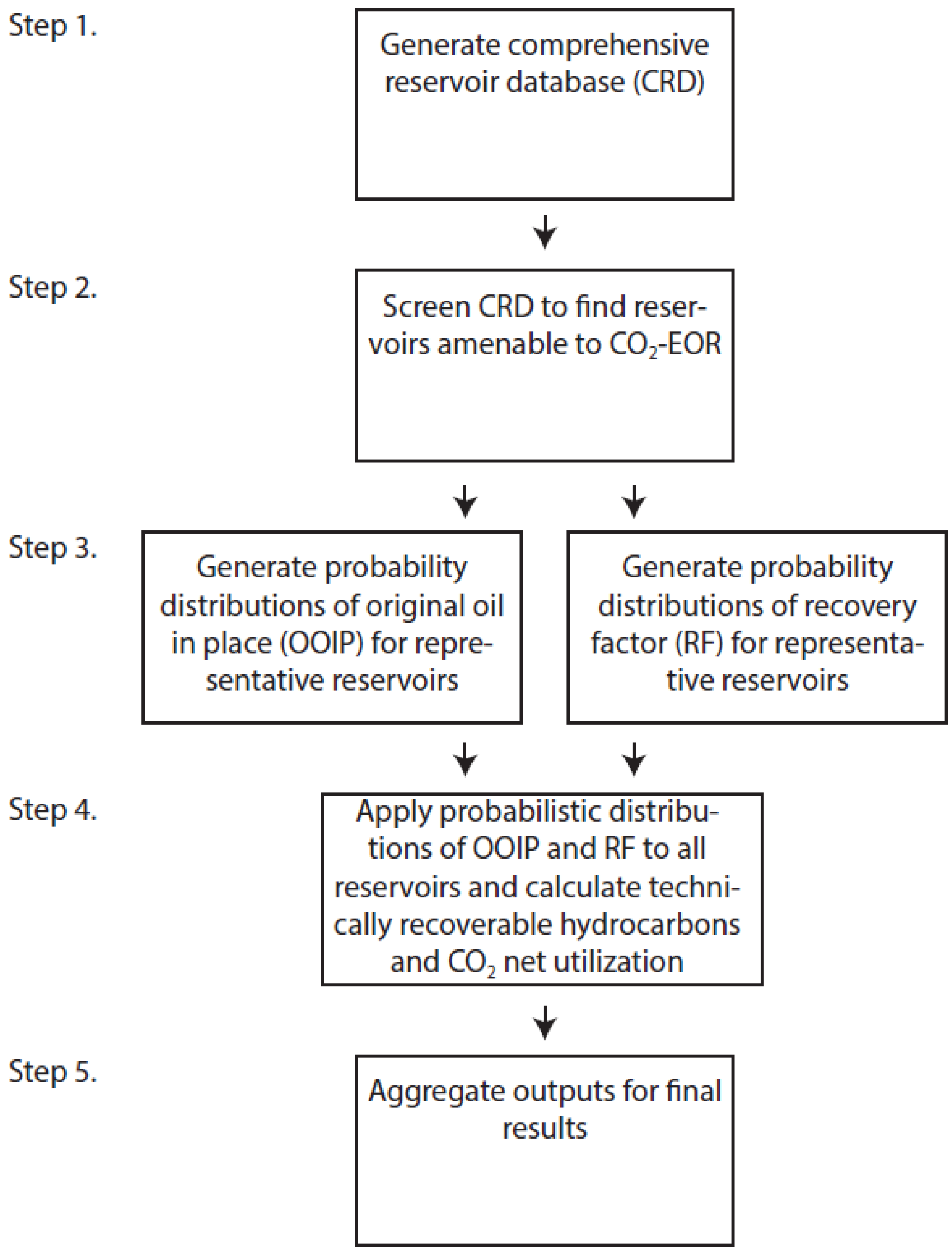


Plot showing oil production in barrels per day associated with various enhanced oil recovery (EOR) methods. The recovery associated with the CO2-EOR process has increased over time. (Source: Koottungal, 2014; Kuuskraa and Wallace, 2014; Verma, 2015) Note: HC, hydrocarbon.

Framework of the USGS probabilistic assessment method for oil recovery potential using CO_2 and associated CO_2 retention



USGS Methodology: Volumetric Approach

Step 1: Build a comprehensive resource database (CRD) for reservoirs within U.S. sedimentary basins:

Overview of a Comprehensive Resource Database for the Assessment of Recoverable Hydrocarbons Produced by Carbon Dioxide Enhanced Oil Recovery

By Marshall Carolus, Khosrow Biglarbigi, and Peter D. Warwick
Edited by Emil D. Attanasi, Philip A. Freeman, and Celeste D. Lohr

(Report with USGS editors)

Step 1. Comprehensive Resource Database (cont.)

- Primary data sources: IHS Energy Group (2011); IHS Inc. (2012), and Nehring Associates Inc. (2012)

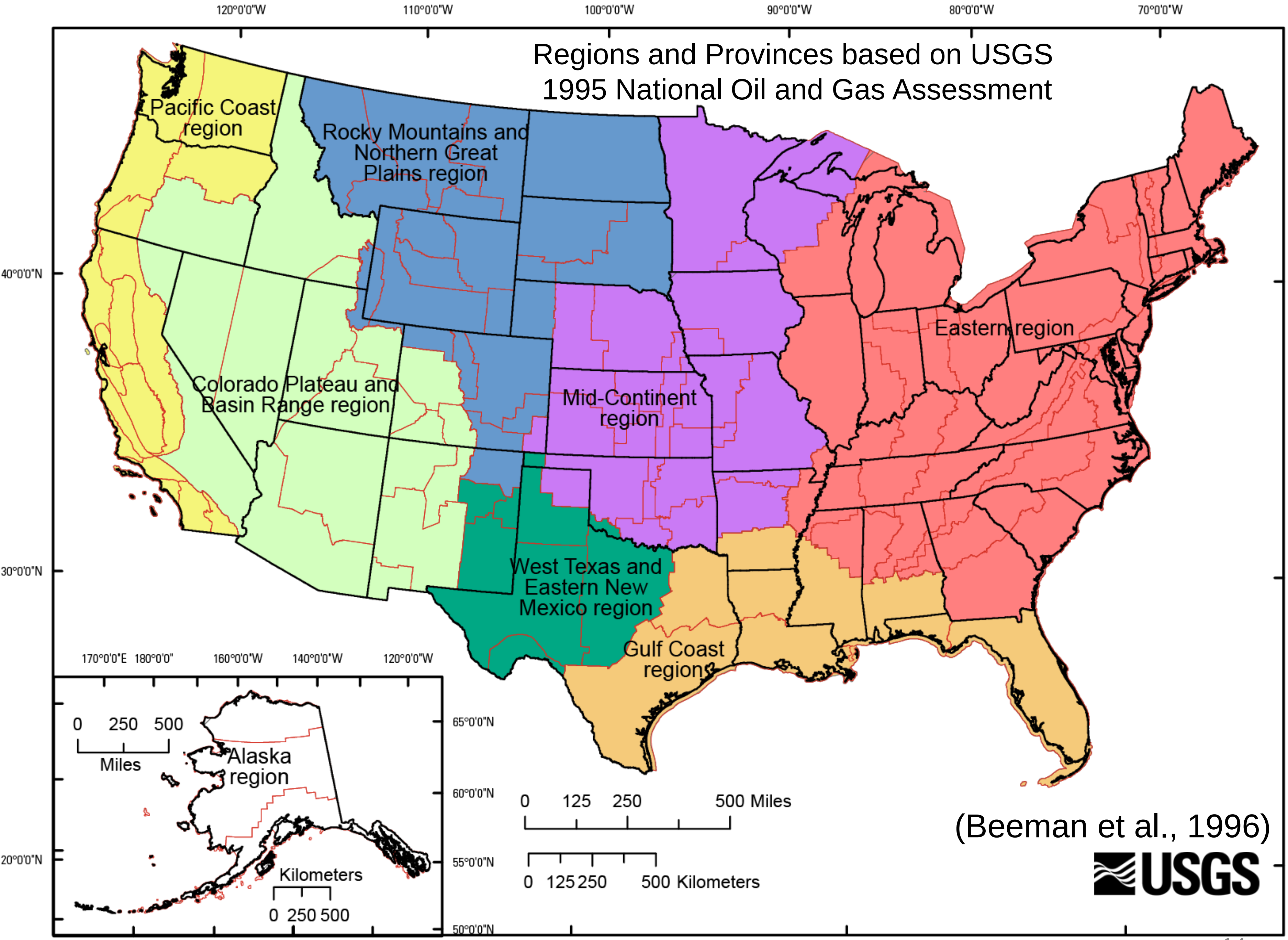
- Other publicly available or donated proprietary data sets

Populate database for missing data using:

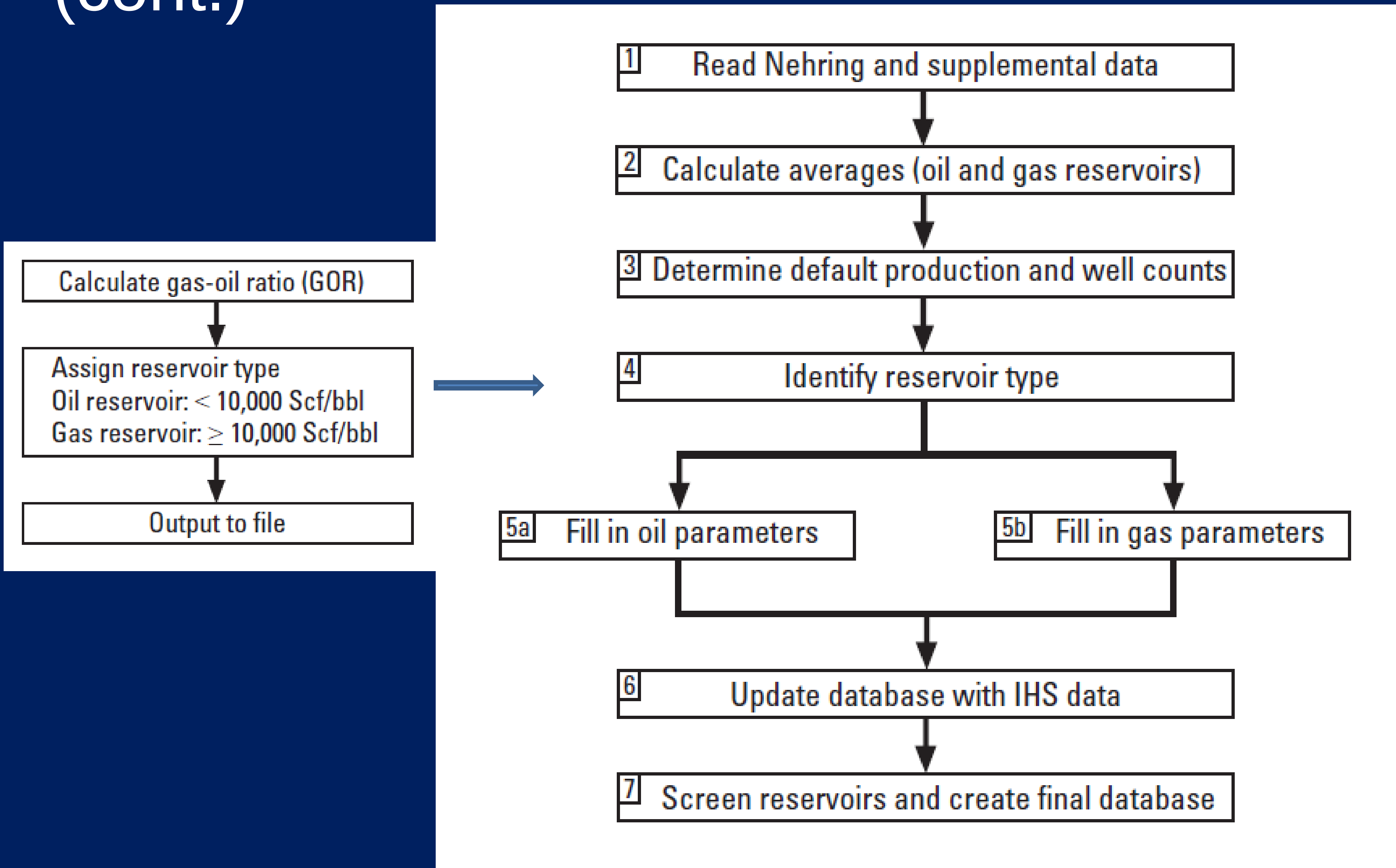
- Analogs
- Algorithms
- Simulations

The CRD entries are by reservoir and are divided into regions, provinces and plays defined by the USGS 1995 National Oil and Gas Assessment (Beeman et al., 1996)

USGS


Regions and Provinces based on USGS
1995 National Oil and Gas Assessment
Pacific Coast region
Rocky Mountains and Northern Great Plains region
Colorado Plateau and Basin Range region
Mid-Continent region
Eastern region
West Texas and Eastern New Mexico region
Gulf Coast region
Alaska region
120°0'0"W
110°0'0"W
100°0'0"W
90°0'0"W
80°0'0"W
70°0'0"W
40°0'0"N
30°0'0"N
20°0'0"N
170°0'0"E 180°0'0"
160°0'0"W
140°0'0"W
120°0'0"W
65°0'0"N
60°0'0"N
55°0'0"N
50°0'0"N
0 250 500
Miles
Kilometers
0 250 500
0 125 250 500 Miles
0 125 250 500 Kilometers
(Beeman et al., 1996)
USGS

Step 1. Comprehensive Resource Database (cont.)



Scf/bbl = standard cubic feet per barrel

Step 1. Comprehensive Resource Database (cont.)

Calculated oil and gas values of reservoir properties in the CRD. The averaged variables are indicated by "‡".

Oil Properties	Gas Properties
Net pay (thickness)‡	Net pay (thickness) ‡
Depth‡	Depth‡
Temperature gradient‡	Temperature gradient‡
Pressure gradient‡	Pressure gradient‡
Porosity‡	Porosity‡
Permeability‡	Permeability‡
Initial oil saturation‡	Initial gas saturation‡
Initial water saturation‡	Initial water saturation‡
Initial formation volume factor‡	CO_2 concentration‡
API gravity‡	N_2 concentration‡
Gas gravity‡	H_2S concentration‡
Well spacing‡	Gas gravity‡
Sulfur content‡	Heat content‡
Initial formation volume factor‡	Sulfur content‡
Reservoir area	Initial gas formation volume factor
Active wells	Lithology type
Original oil in place*	Well spacing
Recovery factor	Producing area
Current pressure	Gas compressibility
Current formation volume factor	Gas-in-place volume
Current oil saturation	Recovery factor
Current water saturation	Original gas in place
Current gas saturation	Current gas formation volume factor
Gas-to-oil ratio	Current temperature
Swept zone oil saturation	Current oil saturation
Viscosity	Current water saturation
Dykstra Parsons Coefficient	Current gas saturation
Size class	Current Z factor
Lithology	Water influx
Minimum miscibility pressure	NGL-to-gas ratio
Fracture pressure	Condensate-to-gas ratio
	Viscosity
	Size class

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Step 2: Screening Criteria for Reservoirs in the CRD where CO_2 is either Miscible, Miscible Transitional, or Immiscible in the oil

Screening criteria (units)	Miscible	Miscible Transitional	Immiscible
API gravity (API)	>25*	22 ≥ API ≤ 25	**13 ≤ API ≤ 22****
Viscosity (cP)			**>10+**
Depth (ft)			**1,400++**
Reservoir Pressure (psi)	**Minimum miscibility pressure ≤ fracture pressure - 400**	**Minimum miscibility pressure ≤ fracture pressure - 400**	

* National Petroleum Council (1984)
** Hite (2006)
\+ Taber et al. (1997)
\++ Henline et al. (1985)

API = American petroleum Institute
cP = centipoise
ft = feet
psi = pounds per square inch

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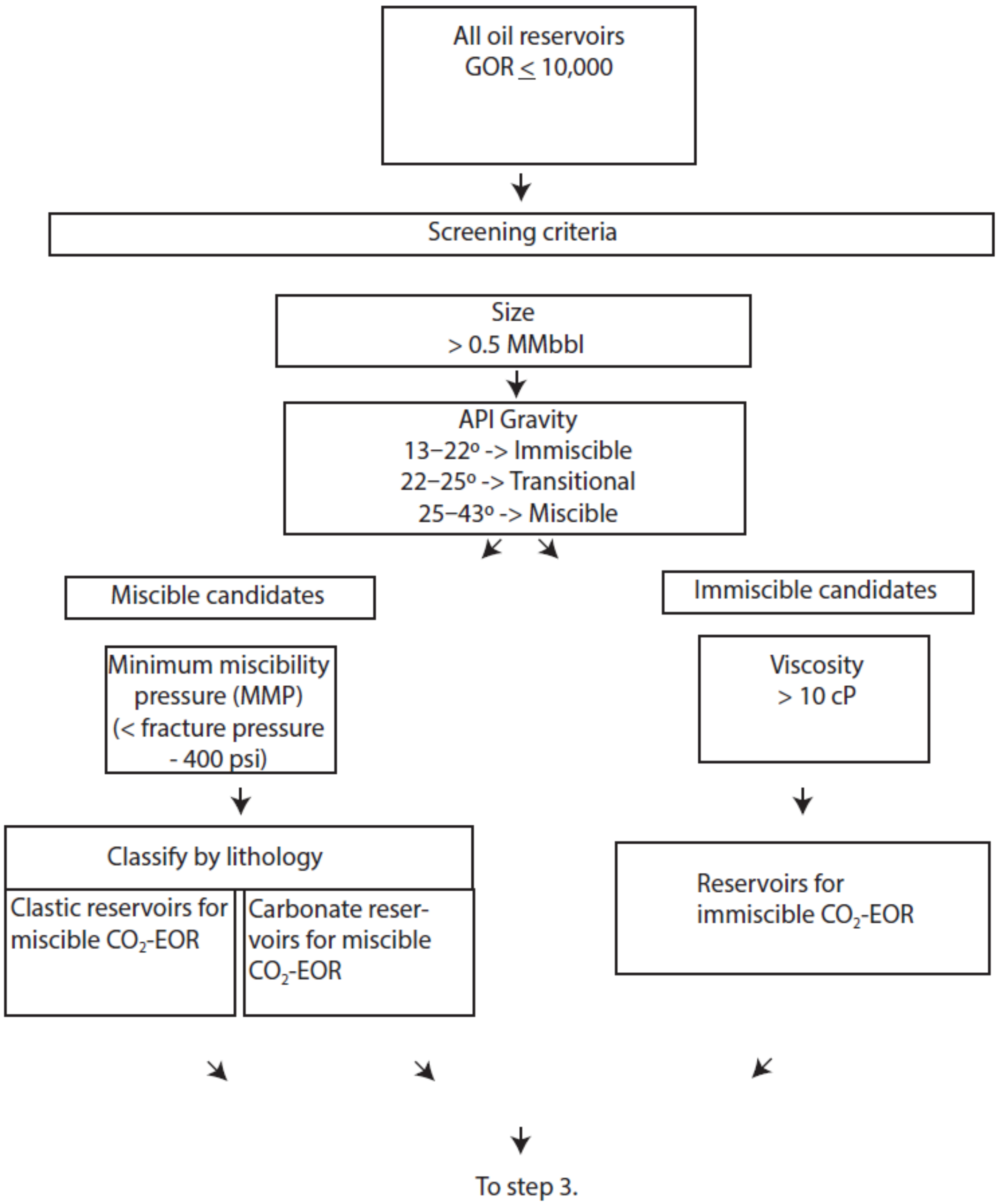
Step 2. Screen CRD to identify reservoirs amenable to CO_2-EOR



USGS Methodology: Volumetric Approach (cont.)

Step 3: The CO_2-EOR volume for each reservoir is modeled by the original oil-in-place (*OOIP*) multiplied by a recovery factor (*RF*):

$$EOR = OOIP * RF$$

Step 3.1: The largest uncertainty of the OOIP depends on the uncertainties of two basic values: rock volume and richness of OOIP per acre foot.

$$OOIP\ per\ acre\text{-}foot = 7{,}758((Ø)(S_{oi}))/FVF_o$$

where OOIP is expressed in terms of barrels per acre-foot, Ø is porosity in fraction, S_{oi} is initial oil saturation in fraction, and FVF_o is the oil formation volume factor in barrels per stock tank barrel (STB).

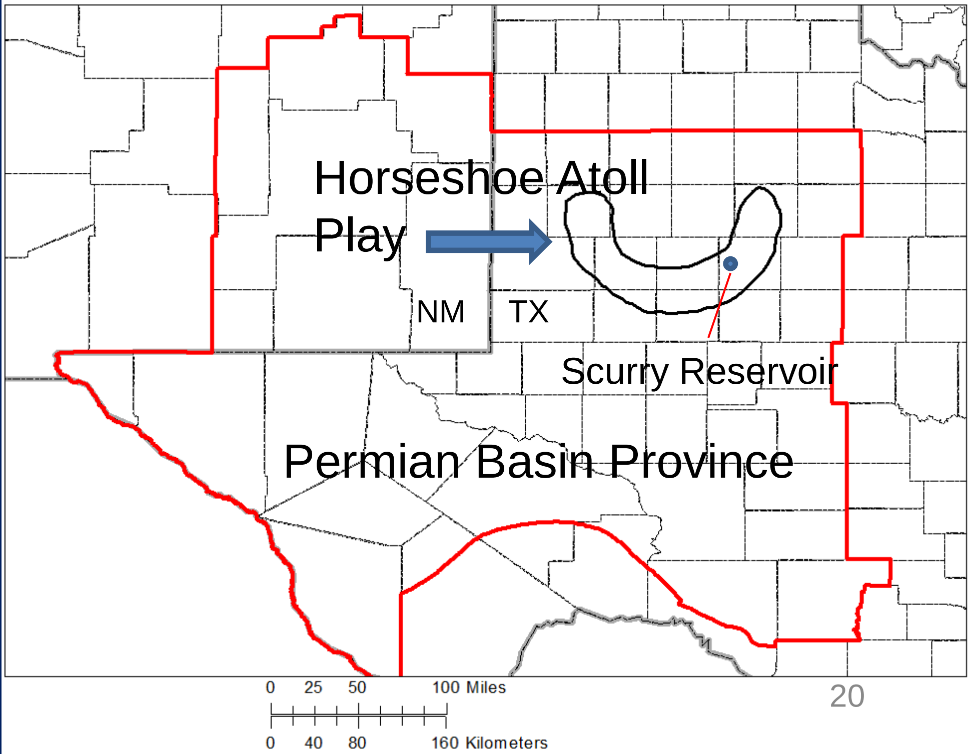
USGS

USGS Methodology: Volumetric Approach (cont.)

Step 3.2: Estimate the variability of the OOIP

- A representative reservoir in each play, usually with the largest OOIP, will be evaluated by the assessment geologist to determine the minimum and maximum average values for Ø and S_{oi}. The most likely values will be from the CRD.
- The range of values for the representative reservoirs in the play will be scaled and used to model the probability distribution of the OOIPs for the other reservoirs in the play.

For example, in the Horseshoe Atoll Play in the Permian Basin of Texas, the Scurry Reservoir (SACROC) was used as the representative Reservoir to model OOIP distributions for the other reservoirs in the play.



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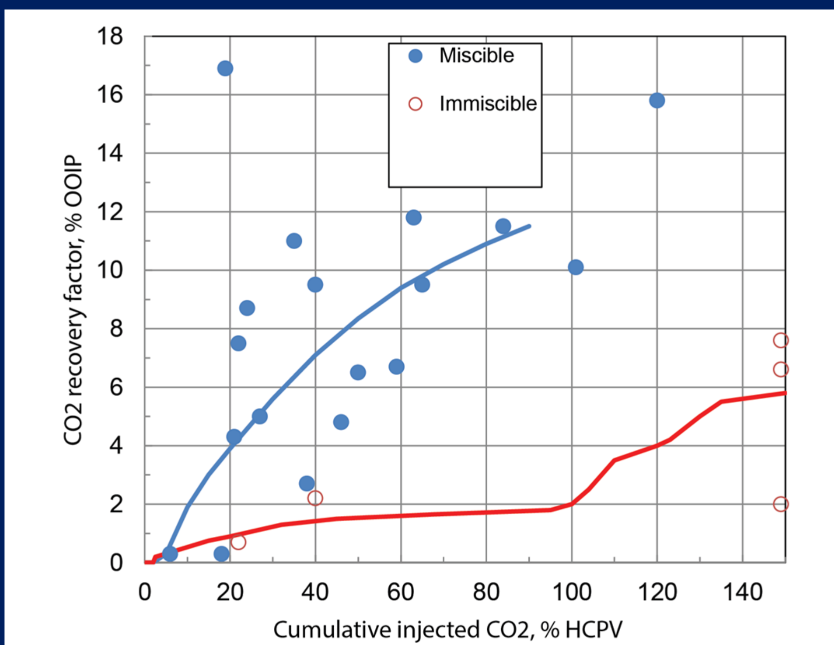
USGS Methodology: Volumetric Approach (cont.)

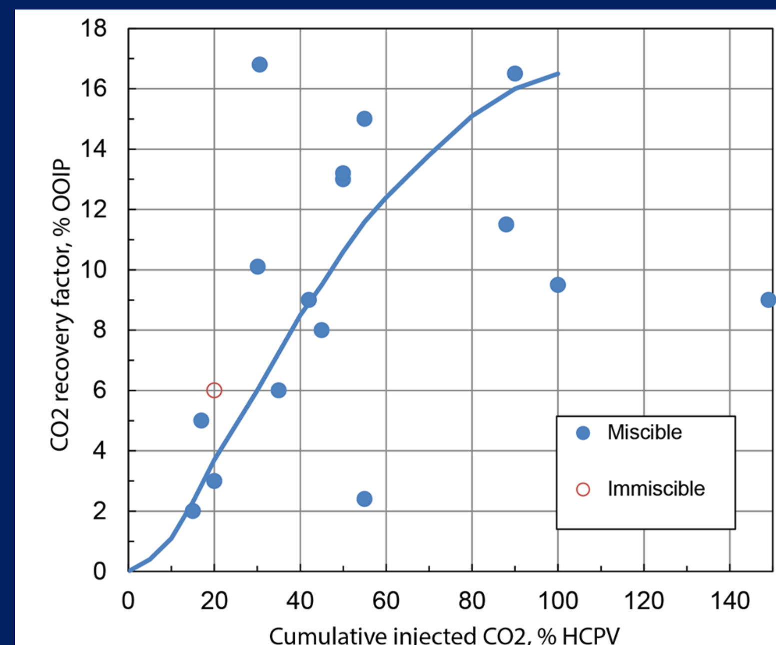
*EOR = OOIP * RF*

Step 3.3: The uncertainty of *RF* will be based on:

- Reservoir simulations using CO_2-Prophet (publicly available CO_2-EOR modeling software)
- Decline curve analysis and recoverable hydrocarbon volume
- Recovery factors reported in the literature (as below, from Olea, written commun., 2015)



Recovery factors for sandstones; Dots denote reported point values and the continuous curves are regarded as representative summaries of the general trends. CO_2-EOR, carbon dioxide-enhanced oil recovery; HCPV, hydrocarbon pore volume; OOIP, original oil-in-place.



Recovery factors for carbonates. Dots denote reported point values and the continuous curve is regarded as a representative summary of the general trend. CO_2-EOR, carbon dioxide-enhanced oil recovery; HCPV, hydrocarbon pore volume; OOIP, original oil-in-place.

Recovery factors for carbonates

USGS Methodology: Volumetric Approach (cont.)

Step 3.4 Variability of RF

- Sensitivity analysis using reservoir models by CO_2-Prophet, show the Dykstra Parsons coefficient (VDP), HCPV CO_2 injected, and residual oil saturation after water flooding (S_{orw}) has the most impact on RFs.

- The assessment geologist will determine the minimum and maximum average values for VDP, HCPV, and S_{orw}. The most likely values will be from the CRD.

Step 3.5: Associated CO_2 storage resulting from CO_2-EOR will be based on:

- Reservoir simulations using CO_2-Prophet

- CO_2 storage (loss) reported in the literature (Olea, 2015)

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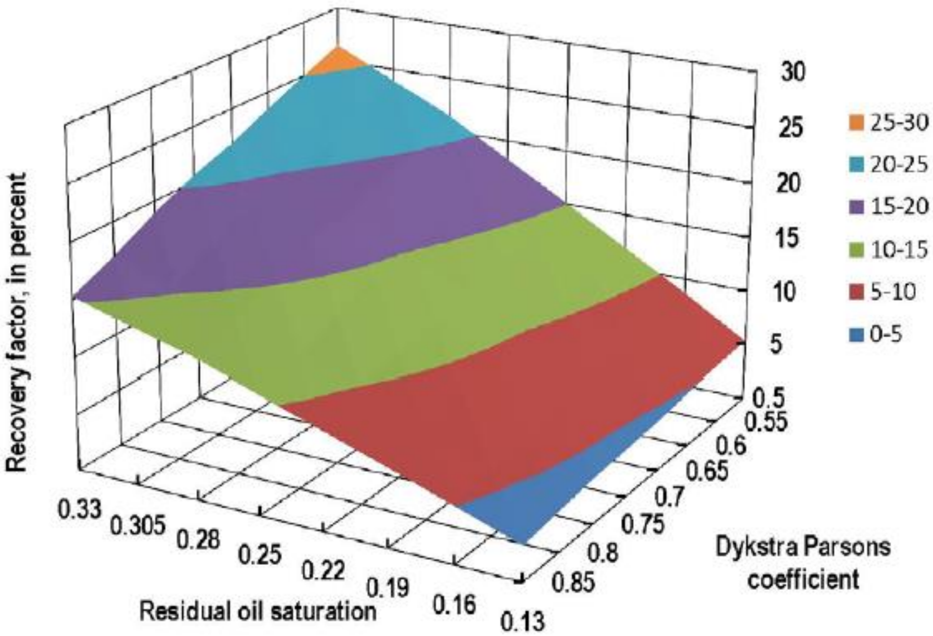
HCPV = hydrocarbon pore volume
VDP = measure of reservoir heterogeneity of the vertical permeability



Graph of carbon dioxide (CO_2) enhanced oil recovery (EOR) recovery factors, in percent of the original oil-in-place, shown as a function of reservoir heterogeneity as measured by the Dykstra Parsons coefficient and the residual oil saturation at the start of the EOR program. The CO_2 Prophet reservoir model was used to compute recovery factors for a representative reservoir (Attanasi, written commun., 2015).

Graph of carbon dioxide (CO_2) enhanced oil recovery (EOR) net CO_2 utilization factors, in thousands of cubic feet per barrel (both measured at standard surface conditions), shown as a function of reservoir heterogeneity as measured by the Dykstra Parsons coefficient and the residual oil saturation at the start of the EOR program. The CO_2 Prophet reservoir model was used to compute net CO_2 utilization factors for a representative reservoir (Attanasi, written commun., 2015).

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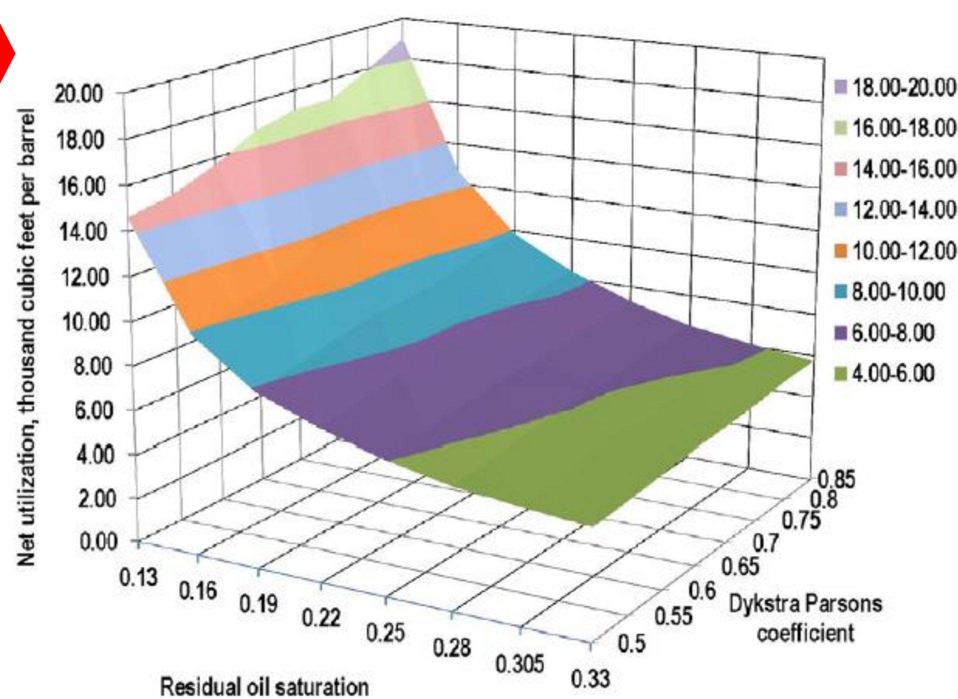
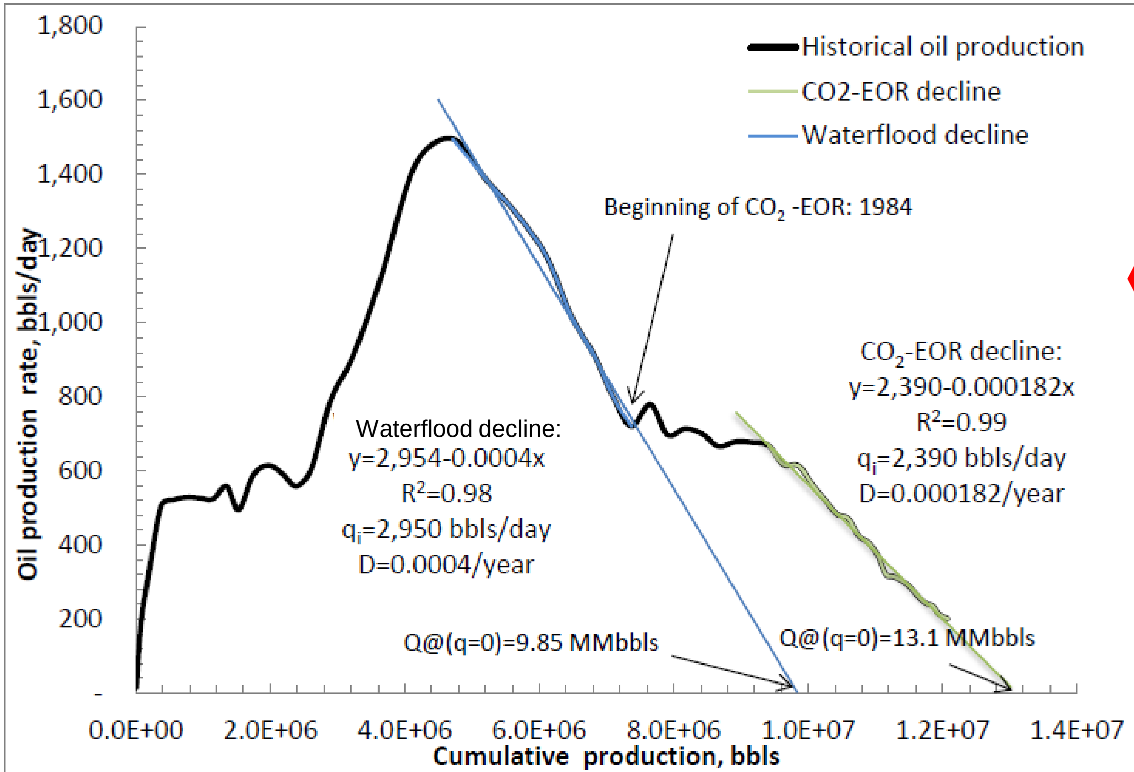
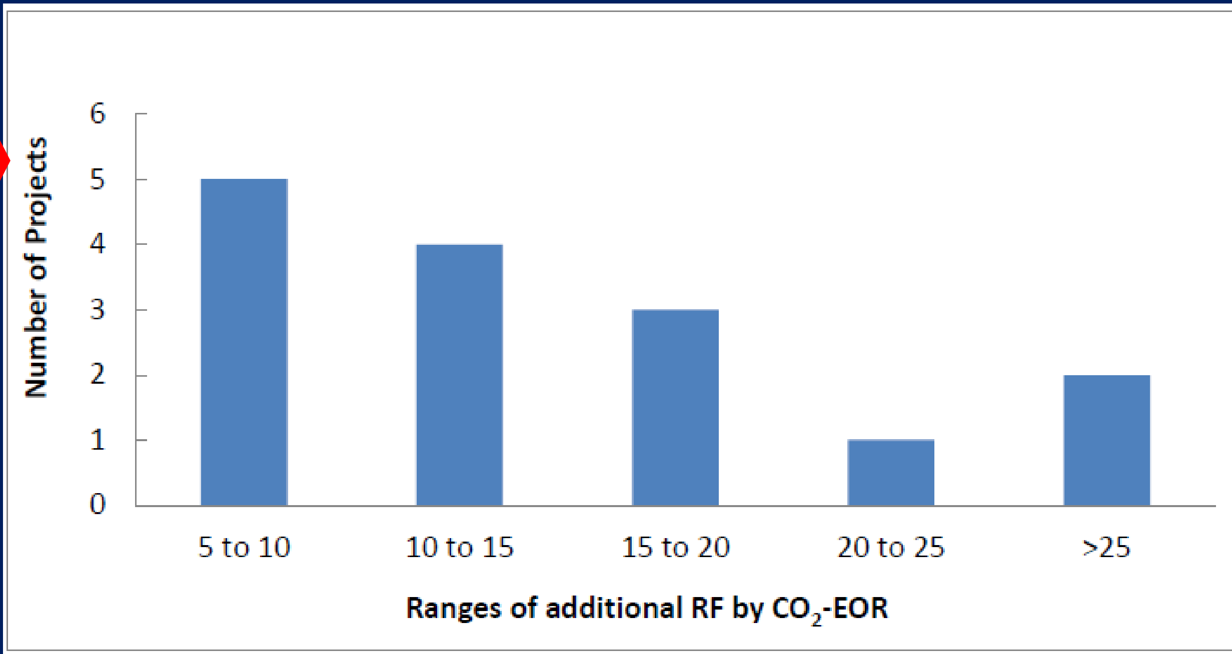




Oil production rate versus cumulative oil production for San Andres Limestone, Sable oil field. Data from IHS Inc. (2012). Black line = oil producton; blue lines = waterflood decline; green lines = CO_2-EOR decline (Jahediesfanjani, written commun., 2015).

R^2 = goodness of fit; qi = is initial oil production rate; D = decline rate per year; Q = cumulative production (x); q = oil production rate (y).

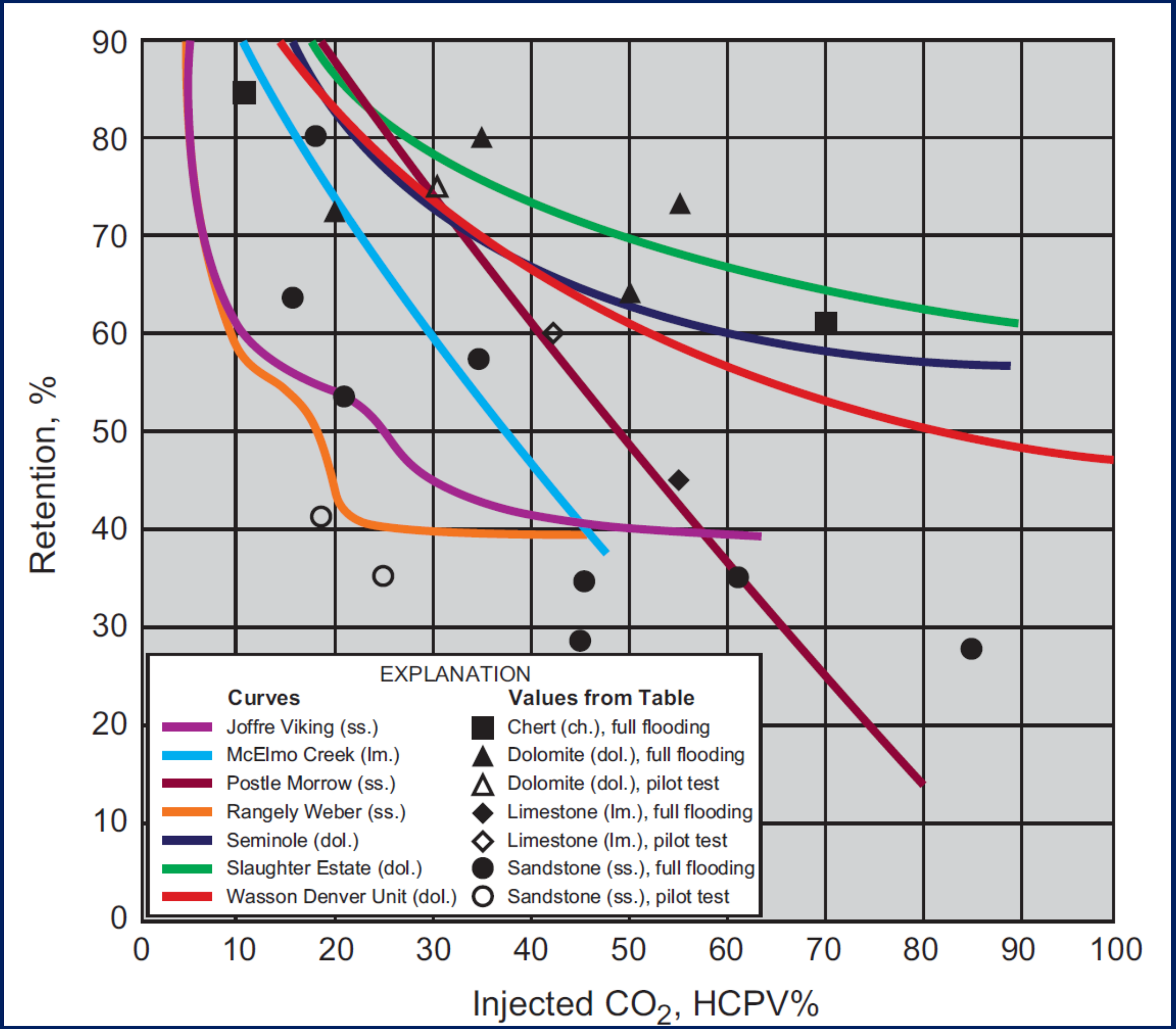
Number of studied projects falling within various ranges of additional oil recovery factors due to CO_2-EOR (Jahediesfanjani, written commun., 2015)..



Bbls/day = barrels per day; MMbbls = million barrels; RF = recovery factor

USGS

Combined display of values found in the literature for miscible CO_2 flooding (Olea, 2015)



Retention in CO_2-EOR

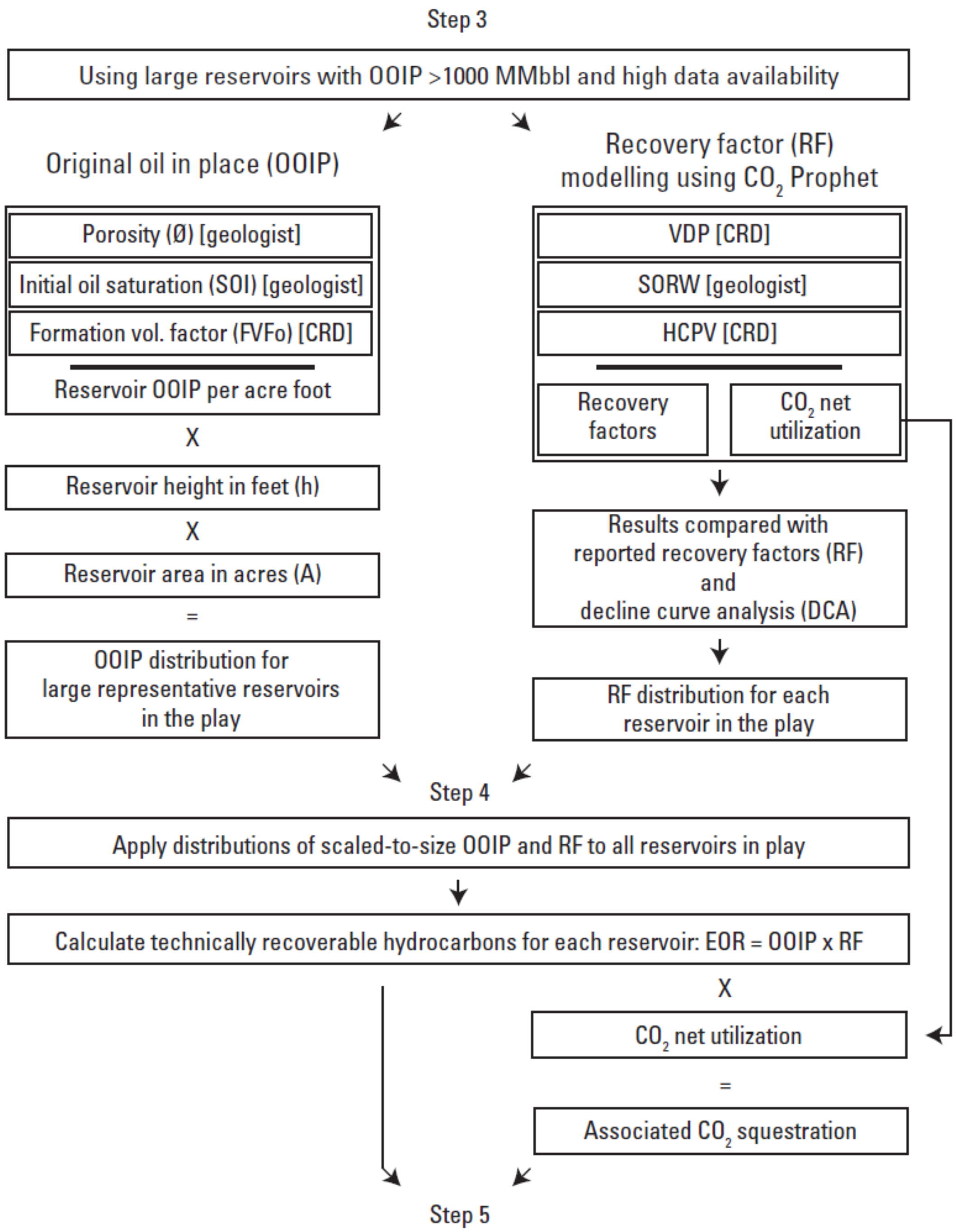
- Dissolution into non-productive oil
- Dissolution into the formation waters
- Chemical reaction with reservoir minerals
- Accumulation in the pore space vacated by the produced oil
- Leakage and dissolution into the subjacent aquifer
- Loss into a thief zone

Retention in carbonate > siliciclastic reservoirs

USGS

USGS Methodology: Volumetric Approach (cont.)

Step 4: The assessment procedure will generate a numerical probability distribution for each reservoir within a play.


Step 3
Using large reservoirs with OOIP >1000 MMbbl and high data availability
Original oil in place (OOIP)
Recovery factor (RF) modelling using CO_2 Prophet
Porosity (Ø) [geologist]
Initial oil saturation (SOI) [geologist]
Formation vol. factor (FVFo) [CRD]
Reservoir OOIP per acre foot
X
Reservoir height in feet (h)
X
Reservoir area in acres (A)
=
OOIP distribution for large representative reservoirs in the play
VDP [CRD]
SORW [geologist]
HCPV [CRD]
Recovery factors
CO_2 net utilization
Results compared with reported recovery factors (RF) and decline curve analysis (DCA)
RF distribution for each reservoir in the play
Step 4
Apply distributions of scaled-to-size OOIP and RF to all reservoirs in play
Calculate technically recoverable hydrocarbons for each reservoir: EOR = OOIP x RF
X
CO_2 net utilization
=
Associated CO_2 squestration
Step 5

USGS Methodology: Volumetric Approach (cont.)

Step 5.1: The numerical distributions will be aggregated at the play, basin, region, and national levels by a process that closely follows that of the USGS national CO_2 storage assessment (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013b) as it is described in Blondes and others (2013).

Step 5.2. Final probability distributions can be used to extract information about uncertainty in the results, such as means, 5^{th} percentiles, medians or 95^{th} percentiles.

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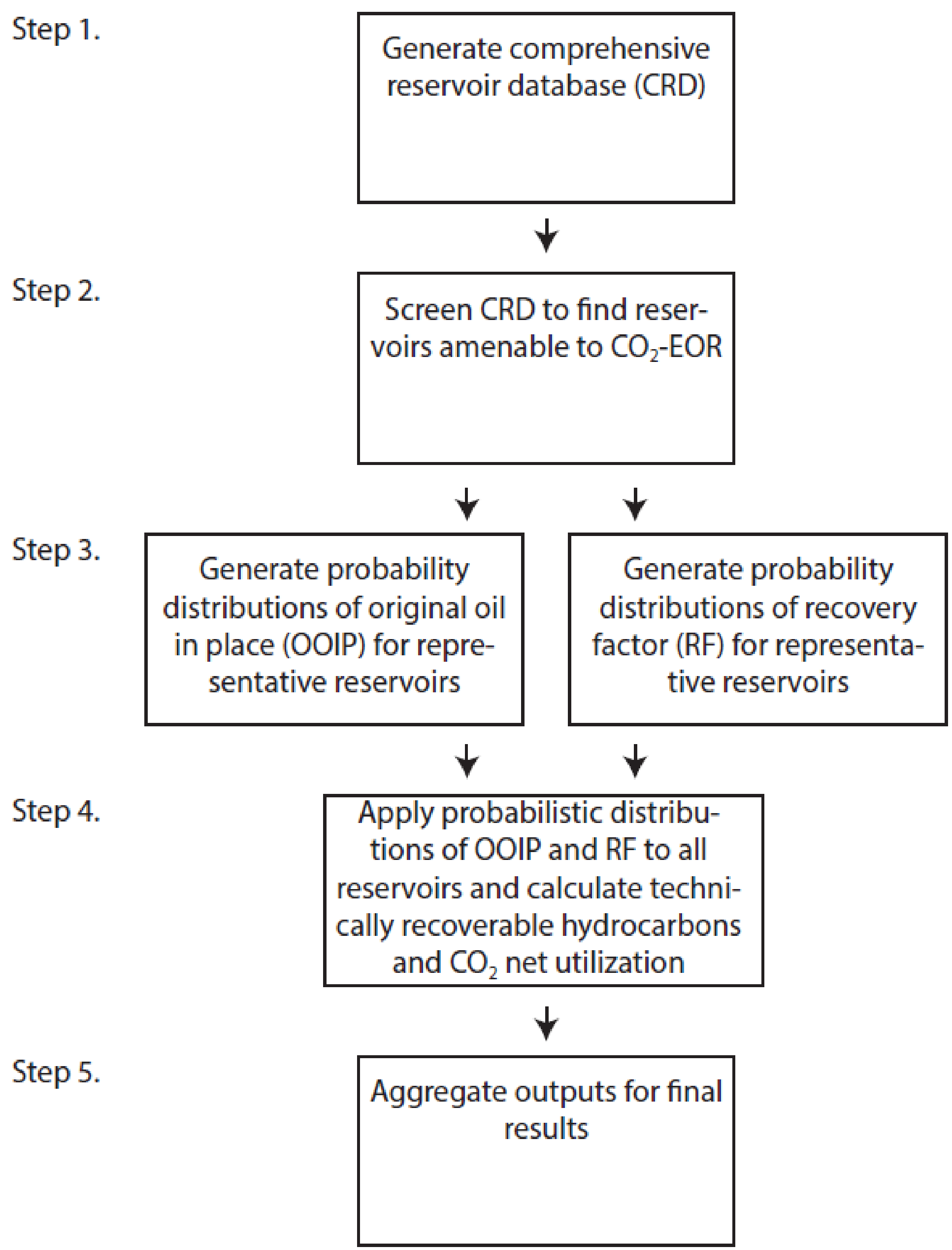
Step 1.
Generate comprehensive reservoir database (CRD)
Step 2.
Screen CRD to find reservoirs amenable to CO_2-EOR
Step 3.
Generate probability distributions of original oil in place (OOIP) for representative reservoirs
Generate probability distributions of recovery factor (RF) for representative reservoirs
Step 4.
Apply probabilistic distributions of OOIP and RF to all reservoirs and calculate technically recoverable hydrocarbons and CO_2 net utilization
Step 5.
Aggregate outputs for final results

USGS

Recent USGS published reports on CO_2-EOR

Attanasi, E.D., and Freeman, P.A., 2016, Play-level distributions of estimates of recovery factors for a miscible carbon dioxide enhanced oil recovery method used in oil reservoirs in the conterminous United States: U.S. Geological Survey Open-File Report 2015–1239, 36 p., http://dx.doi.org/10.3133/ofr20151239.

Freeman, P.A., and Attanasi, E.D., 2016, Profiles of reservoir properties of oil-bearing plays for selected petroleum provinces in the United States (ver. 1.1, February 2016): U.S. Geological Survey Open-File Report 2015–1195, 68 p., http://dx.doi.org/10.3133/ofr20151195.

Olea, R.A., 2015, CO_2 retention values in enhanced oil recovery: Journal of Petroleum Science and Engineering, v. 129, p. 23–28.

Verma, M.K., 2015, Fundamentals of carbon dioxide-enhanced oil recovery (CO2–EOR)—A supporting document of the assessment methodology for hydrocarbon recovery using CO_2–EOR associated with carbon sequestration: U.S. Geological Survey Open-File Report 2015–1071, 19 p., http://dx.doi.org/10.3133/ofr20151071.

Summary

- The USGS has developed a comprehensive resource database (CRD) and a probabilistic assessment methodology to estimate the technically recoverable hydrocarbon potential using CO_2-EOR within all qualifying reservoirs in the United States.
- The assessment results will include pre-economic estimates of the technically recoverable oil potential and resulting CO_2 retention by using CO_2-EOR.
- The methodology has been peer-reviewed and is in final stages of the USGS approval process. Subsequent reviews will include a review by the American Association of Petroleum Geologists Committee on Resource Evaluation (CORE).
- The assessment is planned for completion by 2018.

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http://energy.usgs.gov

http://go.usa.gov/8X8 (USGS geologic CO_2 project website)

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Brennan, S.T., Hughes, V.A., Friedman, S.J., and Burruss, R.C., 2005, Natural gas reservoirs with high CO_2 concentrations as natural analogs for CO_2: Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver, 6 p.

Buursink, M.L., Cahan, S.M., and Warwick, P.D., 2015, National assessment of geologic carbon dioxide storage resources—Allocations of assessed areas to Federal lands: U.S. Geological Survey Scientific Investigations Report 2015–5021, 21 p., *http://dx.doi.org/10.3133/sir20155021.*

Heidug, Wolf, 2013, Methods to assess geologic CO_2 storage capacity – status and best practice: International Energy Agency Workshop Report 2013, 44 p., *https://www.iea.org/publications/freepublications/publication/methods-to-assess-geological-co2-storage-capacity-status-and-best-practice.html.*

Henline, W.D., Young, M.A., and Nguyen, J.T., 1985, Feasibility study to modify the DOE steamflood and CO_2 (miscible) flood predictive models respectively to include light oil steamflooding and immiscible gas drive: U.S. Department of Energy National Institute for Petroleum and Energy Research Topical Report NIPER-54, Cooperative Agreement DE-FC01-83FE60149, 13 p., accessed at: *http://www.netl.doe.gov/KMD/cds/disk22/G-CO2%20&%20Gas%20Injection/NIPER54.pdf*.

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