

A Brief History of CO₂ EOR, New Developments and Reservoir Technologies for CO₂ EOR in Conjunction with Carbon Capture, Utilization and Storage (CCUS)

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Carbon dioxide flooding (CO₂ Enhanced Oil Recovery or CO₂ EOR) was developed 40 years ago as a method to produce higher percentages of the oil that resides in a reservoir. It has grown into a sub-industry producing almost 300,000 barrels a day from over 180 enhanced oil recovery (EOR) projects around the world. During the life of a project, almost the entire amount of CO₂ purchased for the project remains stored in the reservoir while an amount roughly equal to that purchased volume of CO₂ project remains stored in the reservoir while an amount roughly equal to that purchased volume of CO₂ is recycled and reinjected in what is commonly called a “closed loop system.” Given some form of incentives for CO₂ storage like the 45Q tax credit in the U.S., the economics of CO₂ EOR change and can greatly expand CO₂ capture projects and CO₂ EOR deployment. With the concurrent CO₂ storage (often referred to as Carbon Capture Utilization and Storage or CCUS), the EOR projects produce a lower carbon oil than other oil utilized today and will open up new targets called residual oil zones (ROZs) which can be thought of as hybrid deep saline reservoirs with the capability to produce some lower carbon oil to offset costs of industrial CO₂ capture projects.

Research related to the ROZs along with the explosive growth of horizontal drilling are beginning to be seen as adding greatly to reservoir understanding. All horizontal drilling requires depressuring of the producing formations while producing small amounts of the oil in place. The depressured pore space can be followed by CO₂ injection to further enable CO₂ EOR and CCUS while producing a greater portion of the stranded oil resource. It also can offset the expense and accelerate the capture of surface-sourced carbon dioxide and permanently storing the CO₂ in large volumes in reservoirs and out of the atmosphere.

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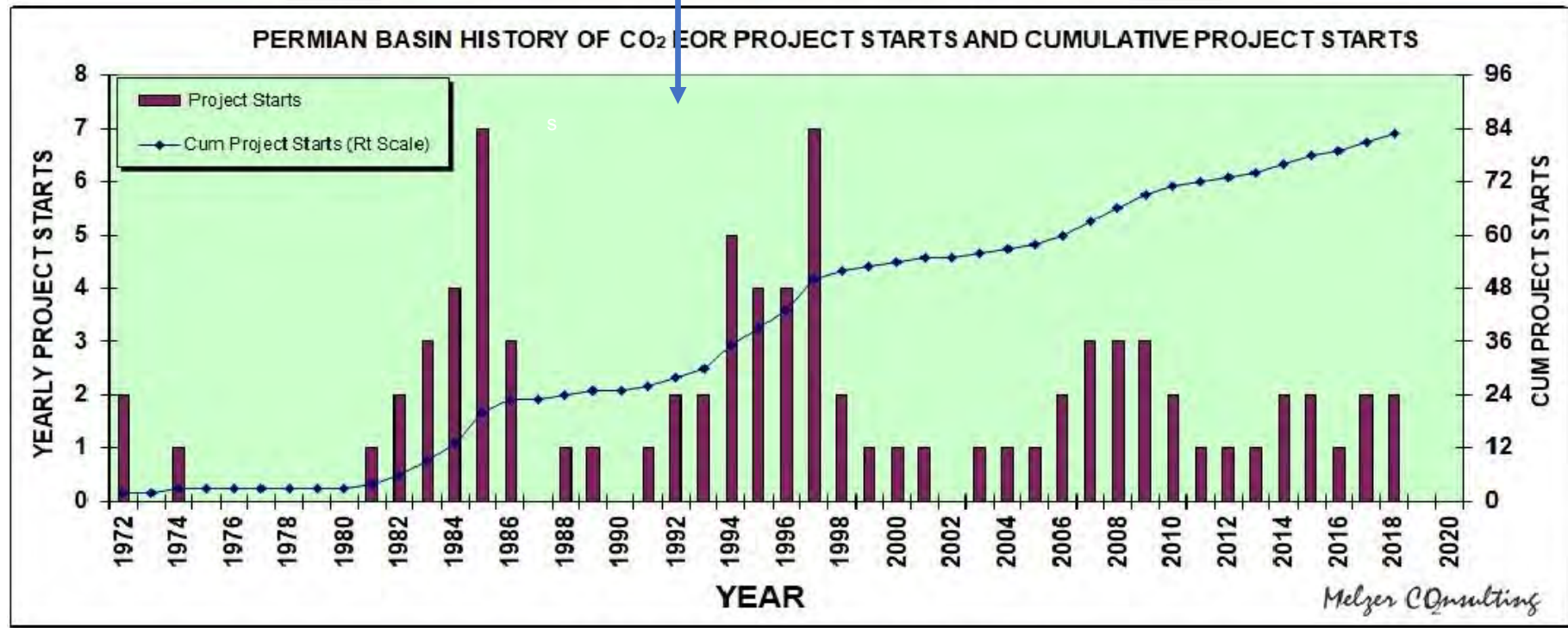
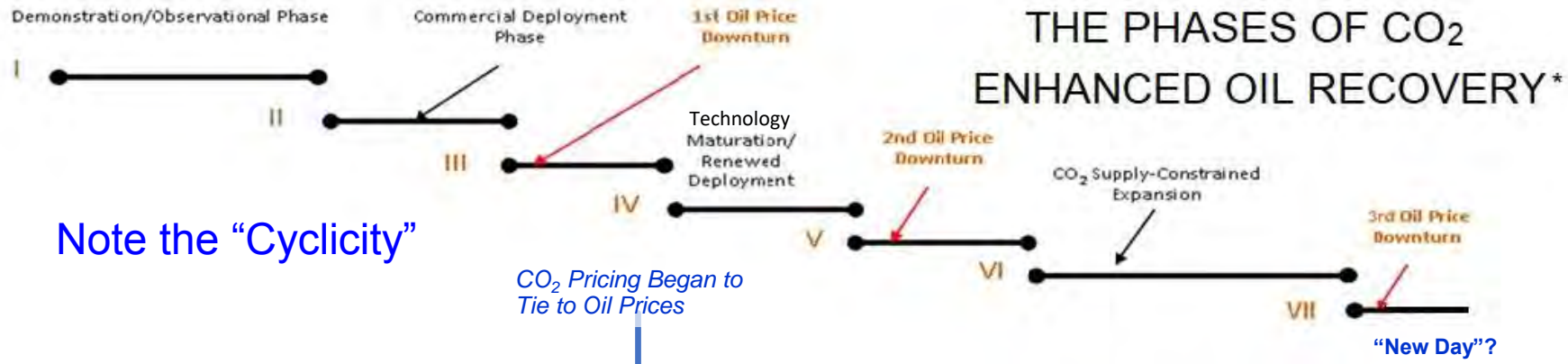
Outline of Presentation

- I. A Brief History of CO₂ Enhanced Oil Recovery
- II. The Mounting Competition to Advanced Recovery
- III. New Developments
 - A. Well Drilling and Completion
 - B. Reservoir Understandings
- IV. CO₂ Emissions Capture and Storage

The History of CO₂ EOR

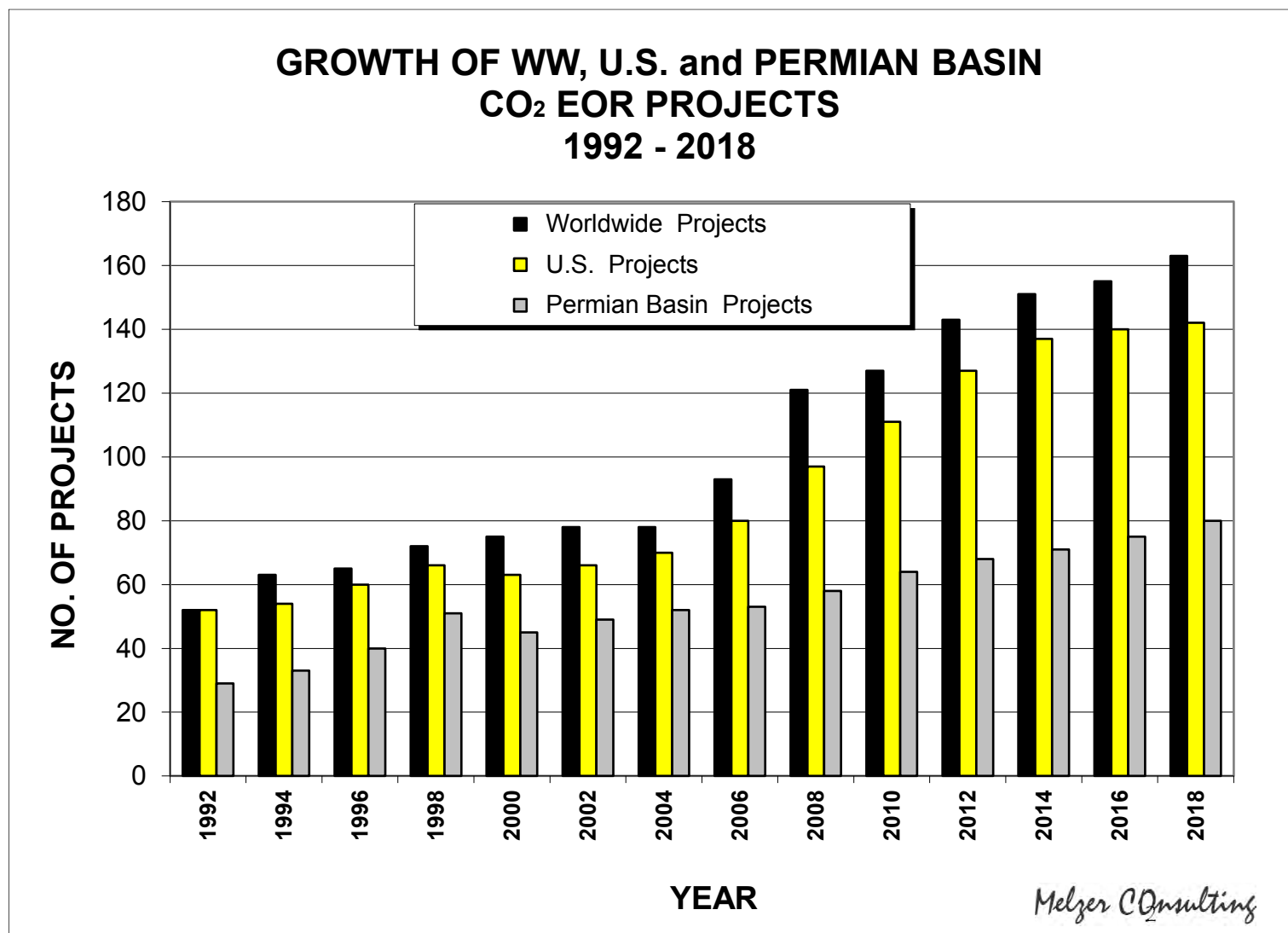
- 1960's** A Couple of Small Scale Pilot CO₂ Injection Projects Were Implemented
- 1972** CO₂ Capture & Compression was Installed in the Southern Permian Basin at Val Verde Nat'l Gas Plants, PLs Built to McCamey and Snyder for the SACROC and North Cross Fields, First Large Scale CO₂ EOR Projects Begun
- 1978-79** Cortez, Bravo Dome and Sheep Mtn PLs Planned and ROW Acquired
- 1982** Pipelines Completed and Large San Andres Oilfields Began Injecting
- 1980s** CO₂ PLs and EOR Projects Started in Rockies, Gulf Coast, Michigan, Canada, Hungary, Turkey, Romania and Trinidad
- Late 70s to 2014** Continued Growth in the Permian Basin, Mississippi, and Rockies
- 2000's** CO₂ Supply Limitations in the U.S. – Slowing of New Projects & Project Expansions
- 2018** New Projects on Hold Due to Low Oil Prices

Graphical History of CO₂ EOR*

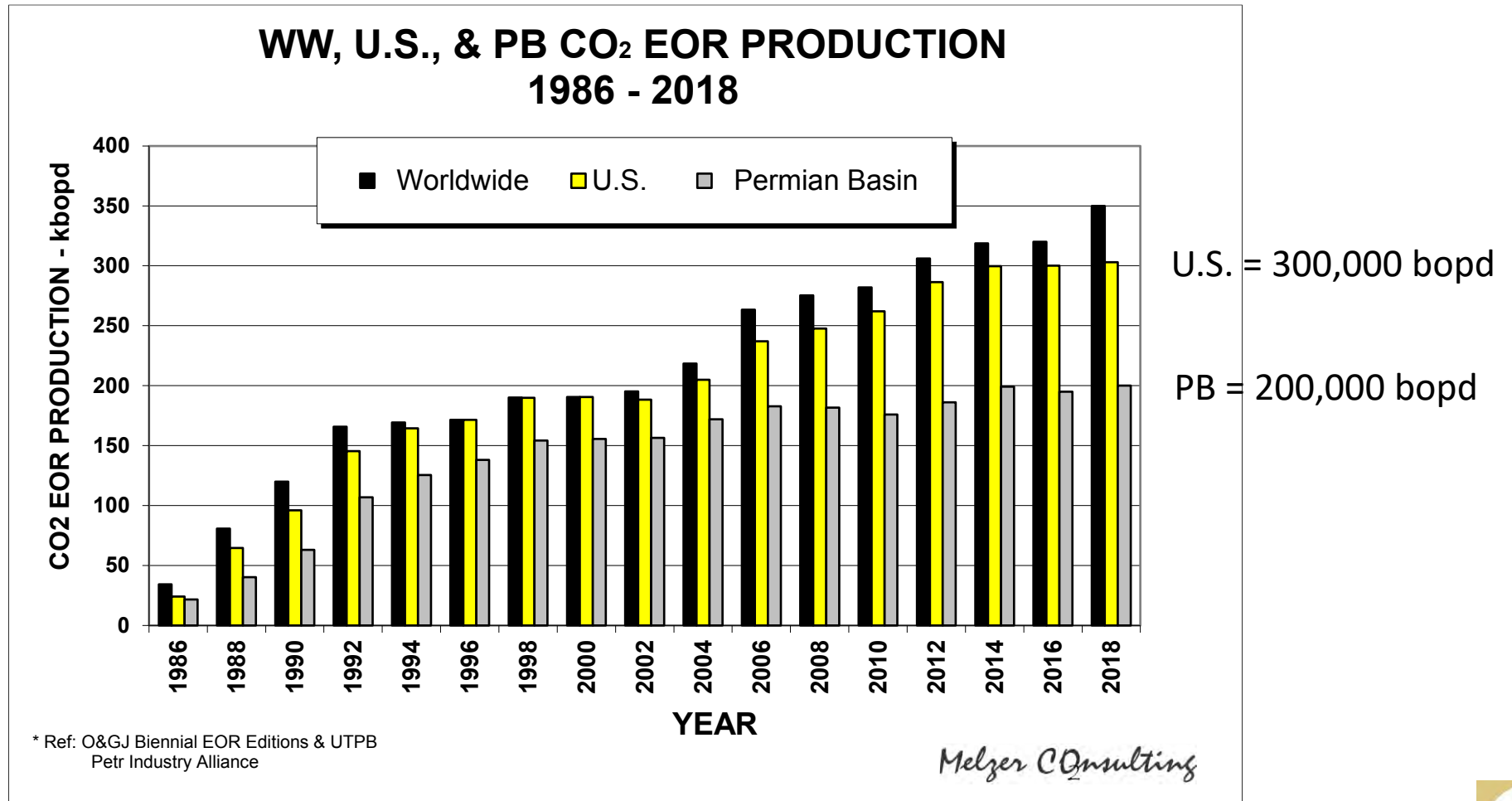


* as Benchmarked to the Permian Basin Region of the SW U.S.

The Permian Basin and Worldwide Project History



The Permian Basin and Worldwide Production History



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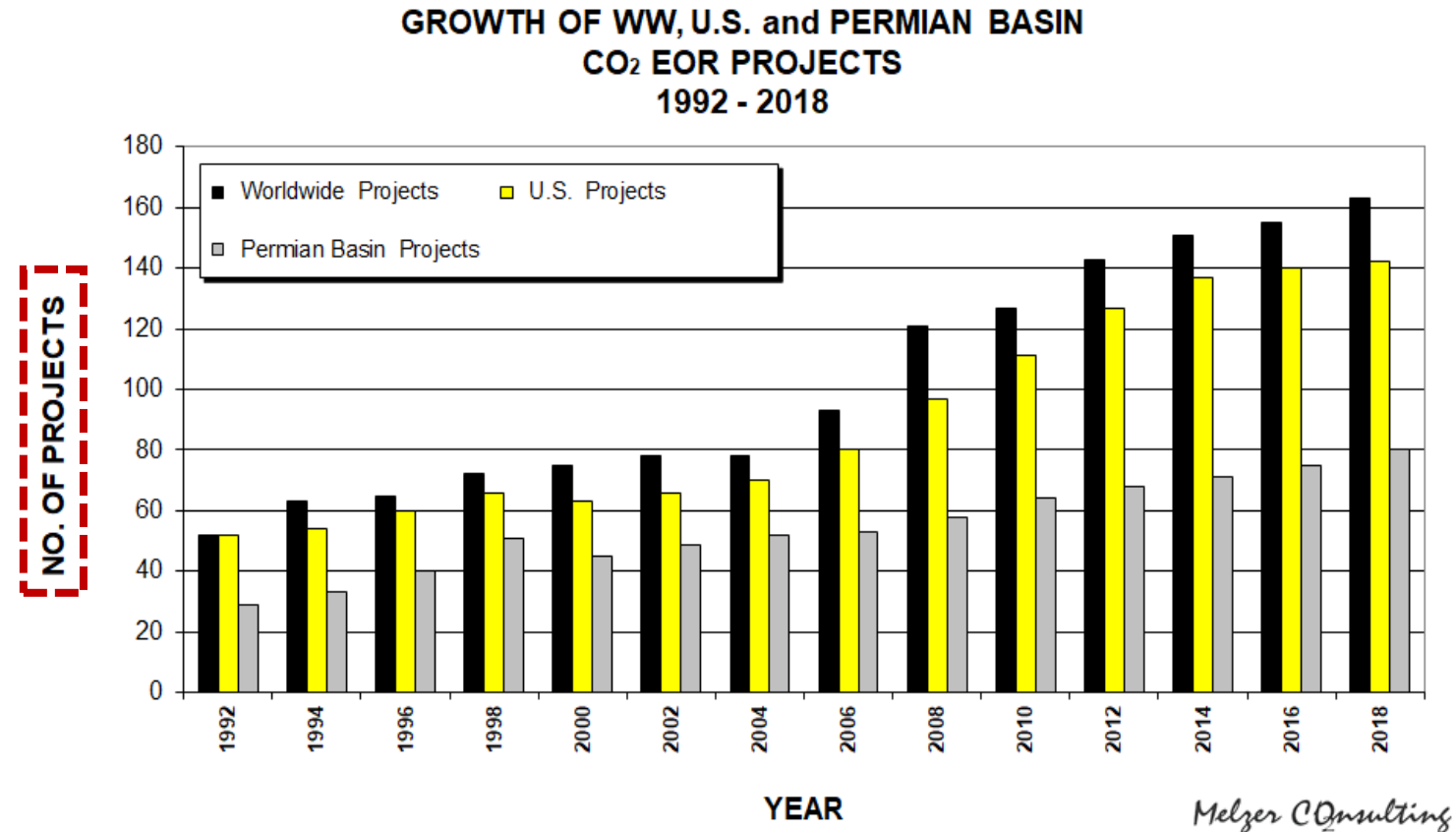
Despite the “2020 Double Whammy*”, Much of Our Oil & Gas Industry is Still Feeling *the Excitement*

- Producing Unconventional Reservoirs
- Producing Unconventional Oil (More on this Later)
- The Explosion of Innovative Tools for Horizontal Completions
- Better Drilling Rigs and Bits for Faster Drilling

* The Saudi ‘Flotilla’ of Tankers (Feb 2020) and Covid-19 Oil Demand Destruction

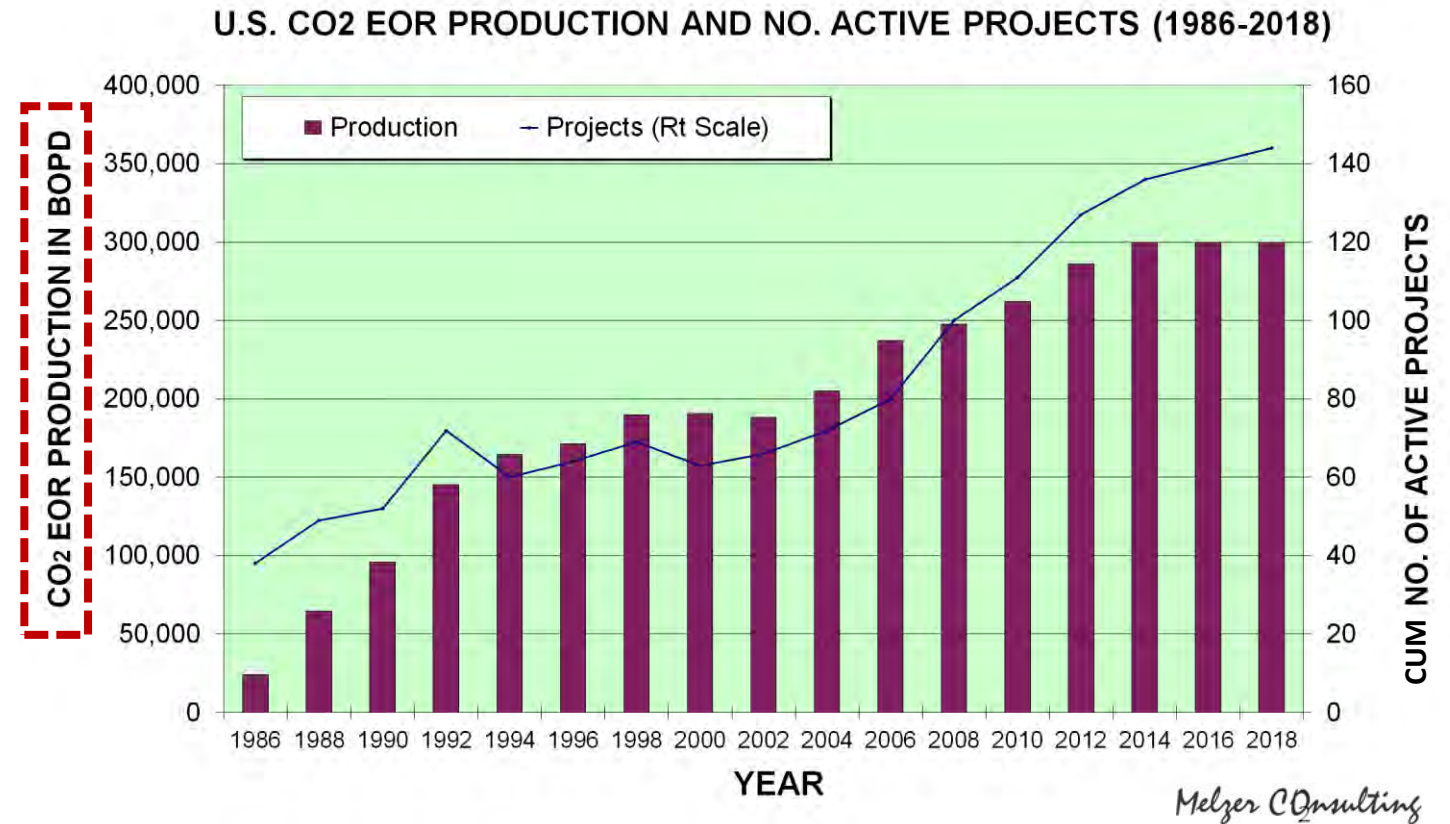
Where is CO₂ EOR in all this **New Excitement?** (1)

- The 'Turtle and the Hare'
 - CO₂ EOR is the Turtle
 - Steady but Slow Growth



Where is CO₂ EOR in all this **New Excitement?** (2)

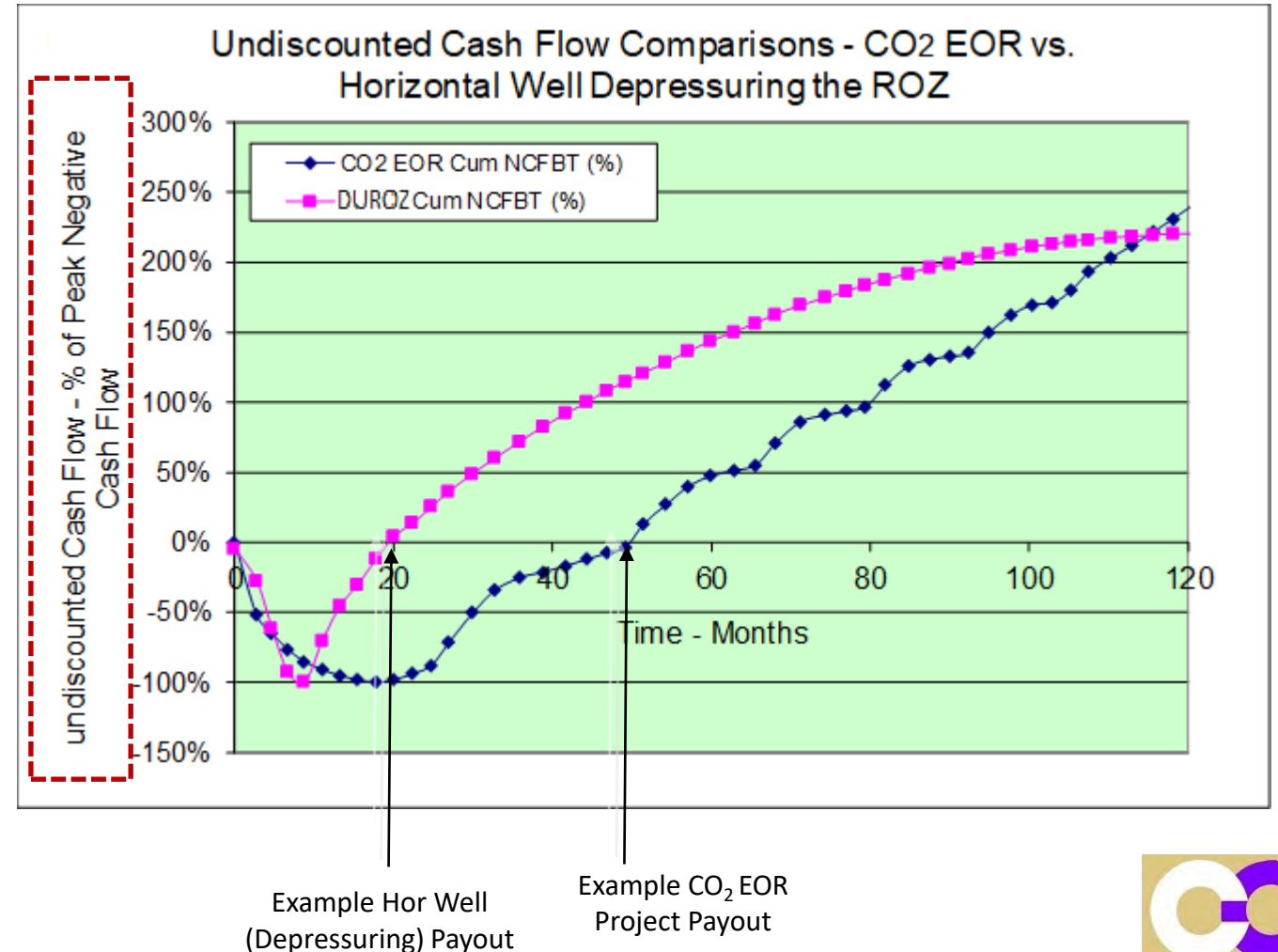
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Where is CO₂ EOR in all this New Excitement? (3)

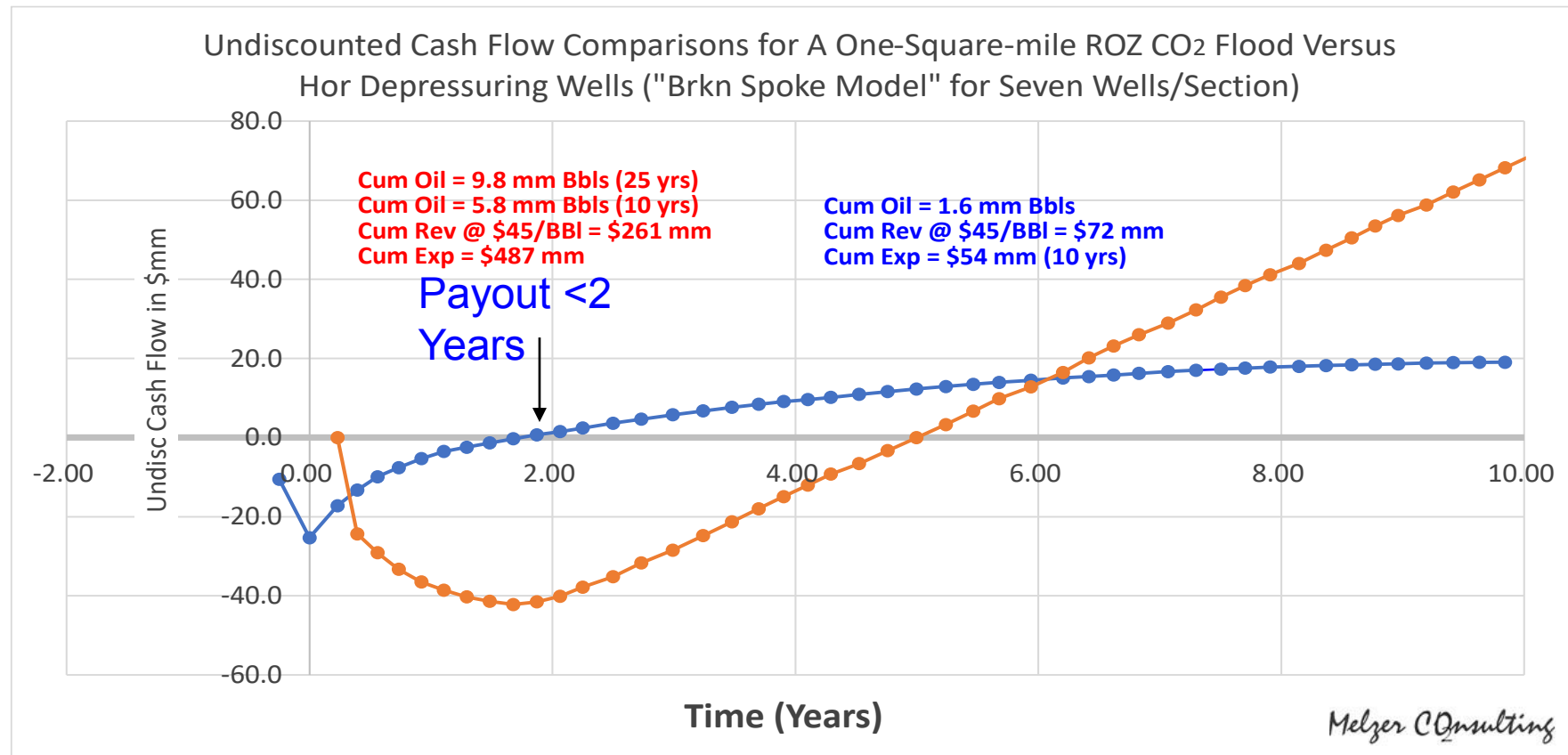
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- IRR vs. Booking Reserves
 - Short Term Payouts vs.
 - Long Term Perspective?



Then Compare Undisc Cash Flow of the Reservoir Depressuring Wells to the CO₂ EOR Project

- Horizontal Drilling Project Setup is Easier, Can Start Earlier



Conclusion: Less 'Out-of-Pocket' Cash and Faster Payout but Makes Less Oil, Lasts only 10 Yrs

So Where is CO₂ EOR in all this **New Excitement?** (4)

- The ‘Turtle and the Hare’
 - CO₂ EOR is the Turtle
 - Steady but Slow Growth
- IRR vs. Booking Reserves
 - Short Term Payouts vs.
 - Long Term Perspective?
- Looking at a “Second Life?”
 - CCUS (Concurrent Oil Production and CO₂ Storage)

45Q – Value of Credit

Two different values are available:

1. EOR TYPE

- Must be used as a tertiary injectant in enhanced oil recovery (EOR) or natural gas recovery project (or “utilized”)
- Must be disposed of in “secure geological storage” (or “utilized”)
- Old value per metric ton: \$10 (2009), adjusted for inflation annually
- New value per metric ton: \$12.83 (2017) up to \$35 (2026)

= \$2.00/Mcf

2. NON-EOR TYPE

- Cannot be used as a tertiary injectant or “utilized”
- Must be disposed of in “secure geological storage”
- Old value per metric ton: \$20 (2009), adjusted for inflation annually
- New value per metric ton: \$22.66 (2017) up to \$50 (2026)

= \$2.60/Mcf

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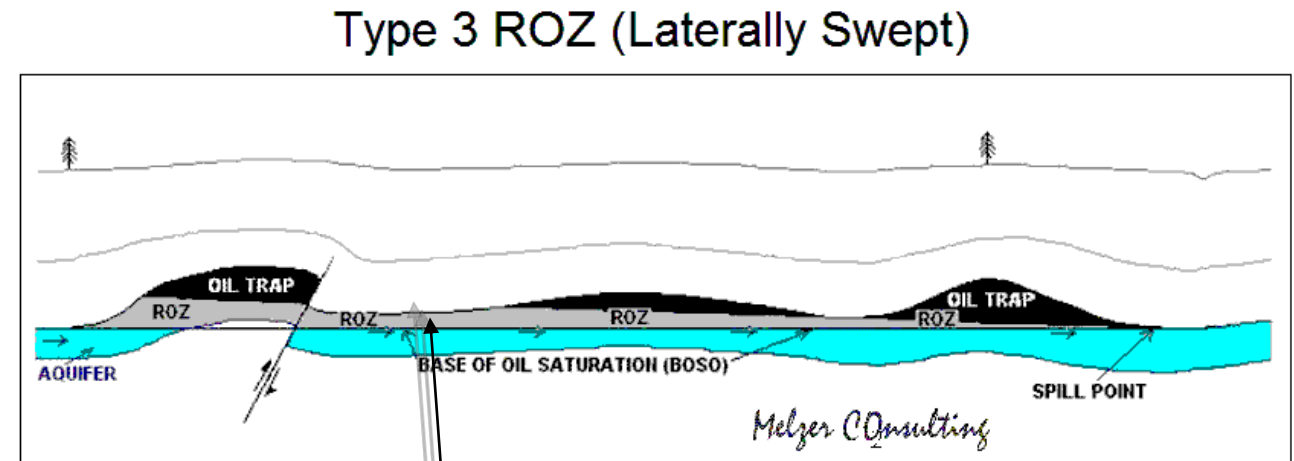
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Let's Look Closer at the New Learnings that have Come from the Horizontal Revolution and CO₂ EOR

Several, Incidentally, come from the San Andres ROZ Studies
(Originally Motivated by our CO₂ EOR Interests)

Very Quickly: What is a Residual Oil Zone?

- It is an Interval in a Formation with Immobile Oil but the Moveable Fluid is Water
- It can be Formed by Man's Waterfloods or by Nature
- In the Geological Past it was a Paleo Oil Entrapment and Subsequently Invaded by Water
- There are Three General Types of Natural ROZs based upon how the Water Invaded the Paleo Trap
- The One Most Common and Extensive is a Laterally Swept ROZ



ROZs can underlie an oil field and can also be present with no main payzone above ("Greenfield")

Summary of Recent (Key) New Learnings (1)

1. We already Mentioned the Faster Drilling and Completion Tool Innovations (....and there are many!)
2. Horizontal Wells are Demonstrating Vertical Transmissive Fractures are More Common than Believed in the Age of Vertical Wells
3. Flowfields in Transmissive Fractures are Often Present and Generally Analogous to ROZ Flowfields Causing Sour Oil and Gases Even in Normally Sweet Oil Environments
4. Intrinsic Microbes Alter the Oils, Gasses, and Even the Rocks But Their Effects are Relatively Minor without Flowfields to Disseminate the Normally Inhibiting H₂S (More on this later)

Summary of Recent (Key) New Learnings (2)

5. Residual Oil Zones (ROZs) are Common in Many Basins and Should be Recognized as Different from Transition Zones
6. ROZs can be Found Beneath the OWCs and in 'Greenfields'
7. ROZs can be Commercially Exploited with (CO₂) EOR
8. Gassy ROZs can be Commercially Exploited with Horizontal Well Primary Recovery (Reservoir Depressuring)
9. Limited Natural Waterflood Sweep Leaves Gassy ROZs
10. Unlimited Natural Waterflood Sweep Leaves a 'Heavy' Oil

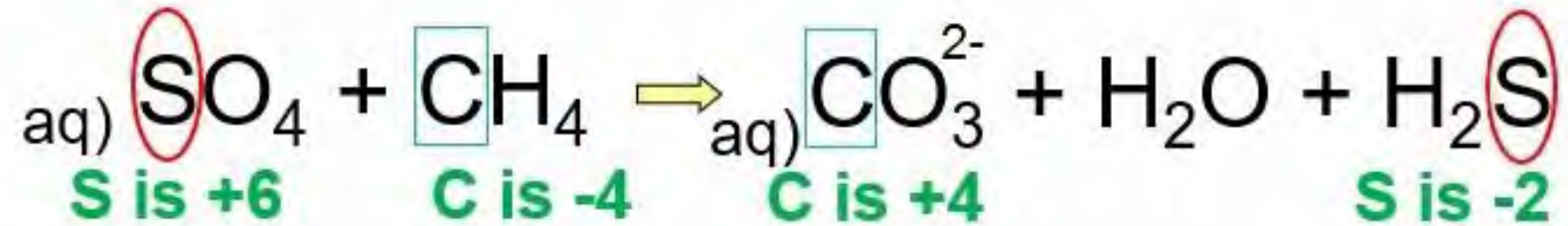
Summary of Recent (Key) New Learnings (3)

11. New Studies are Suggesting Oil- and Mixed-Wettability in a Formation are Often Functions of the Oil & Water 'Swap' Process and Related Microbial Activity in a Reservoir

All But that Last New Learning Have Been Addressed in Past Annual CO₂ Conferences ([see CO2Conference.net](http://CO2Conference.net))

- Most of those Learnings had Their Origins from Enhanced Recovery Studies and Observations Related to ROZs
- Many Apply to the Horizontal Revolution
- Many Relate Directly to CO₂ Geological Storage and Relate to GhG Emission Reductions (Segues to the Last Section)

Let's Examine that Aforementioned H₂S Generation



Microbes remove 8 Electrons from the Carbon and transfer them to the Sulfur

the Source Sulfate is Reduced and is Released as H₂S to Sour the Oil and Gas

Re: Vance, David (2012), RPSEA II Project Chapter 4 (adapted)

Note: This Process is Active When H₂S Concentrations Remain Low, i.e., < 200 ppm)

Now Taking the ROZ Biogeochemistry Insights One Level Further

- First, Why Hasn't the Industry Noted this Before?
 - Accumulations of H₂S from the Aforementioned Process Inhibits Continued Microbial Activity: Minimizing the Microbial Effects
 - The Lateral Sweep ROZ and its Flow Field Disseminates the H₂S: Amplifies the Process and Effects Such that Observational Enigmas* Emerge

* In the San Andres Fm of the PB, we see 300' Thick Oil Shows Below the Oil/Water Contacts, 300' Thick Oil Shows without an Overlying Main Payzone, Nearly Uniform 30-40% Residual Oil Saturations for 300' Distances Below the OWC, etc. In most other formations and in other basin, those shows are thinner and we dismissed as transition zones

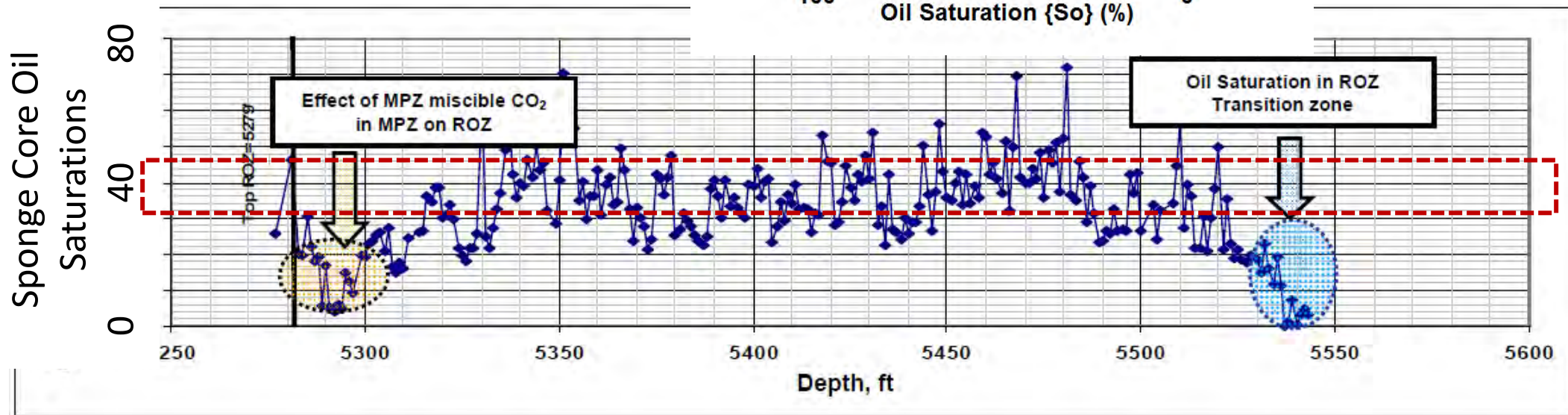
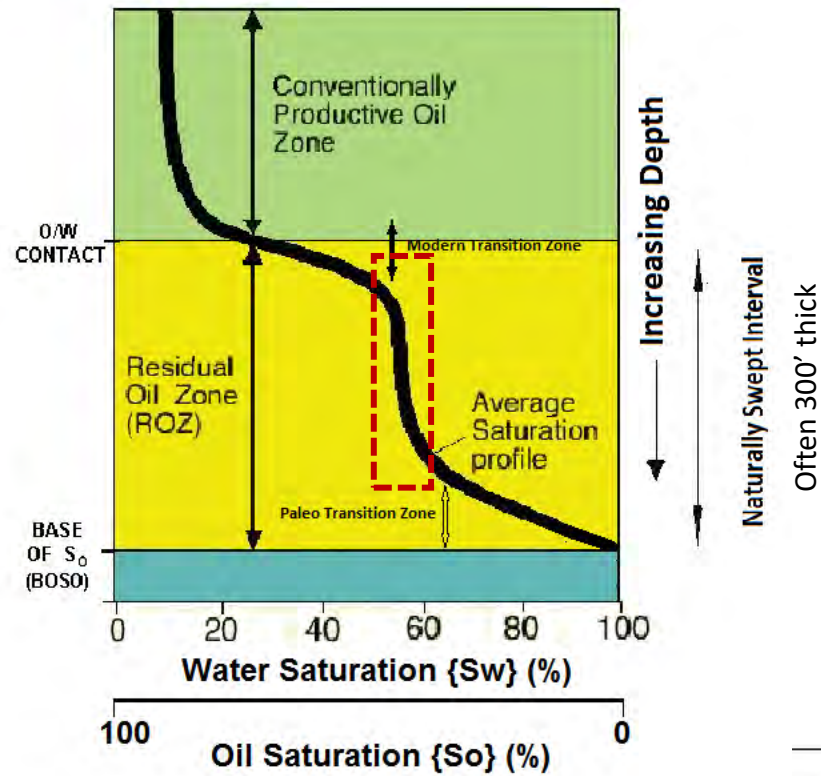
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- Second, What About the Shorter-lived Flow Field In the Original Oil Entrapment?

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This also leads Us to Talk About Wettability

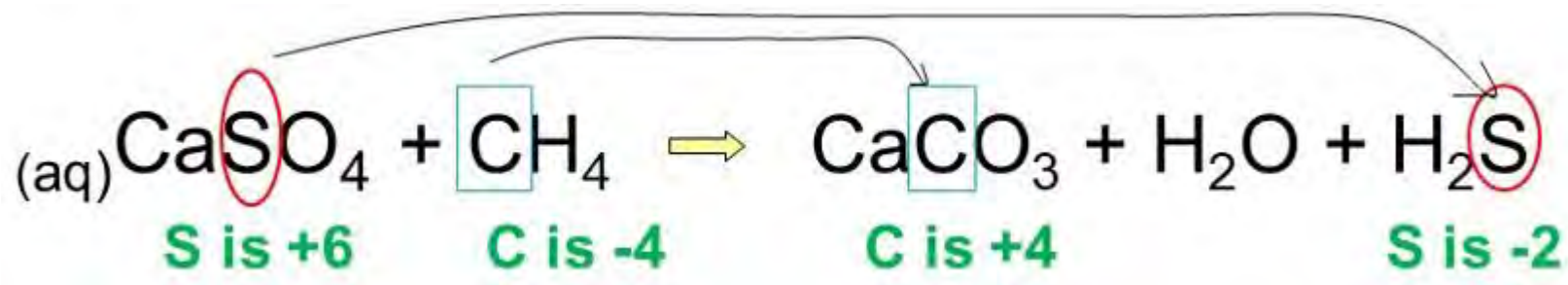


Honapour, M et al (2012), SPE 133089 – Fig 14

The Dominant Dolomization Process

(At Least for the San Andres Formation)

Key Biogenic (Redox) Reaction



Will also Create Saturated SO_4 Conditions in the Water

We are showing Methane here as the source of carbon but.....it may be other hydrocarbons molecules also

- **Microbes remove 8 Electrons from the Carbon and transfer them to the Sulfur**
- **H_2S is Created and Can Inhibit Future Activity (But...A Flowfield Can Disperse)**
- **Dolomitization Typically Follows as Well**

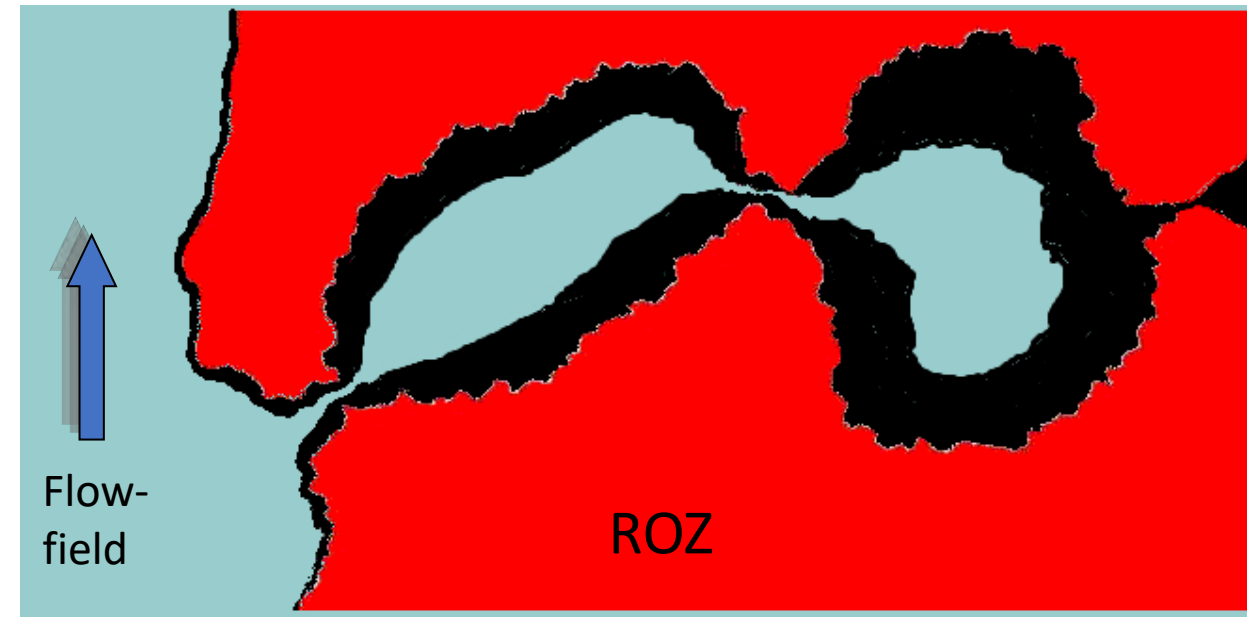
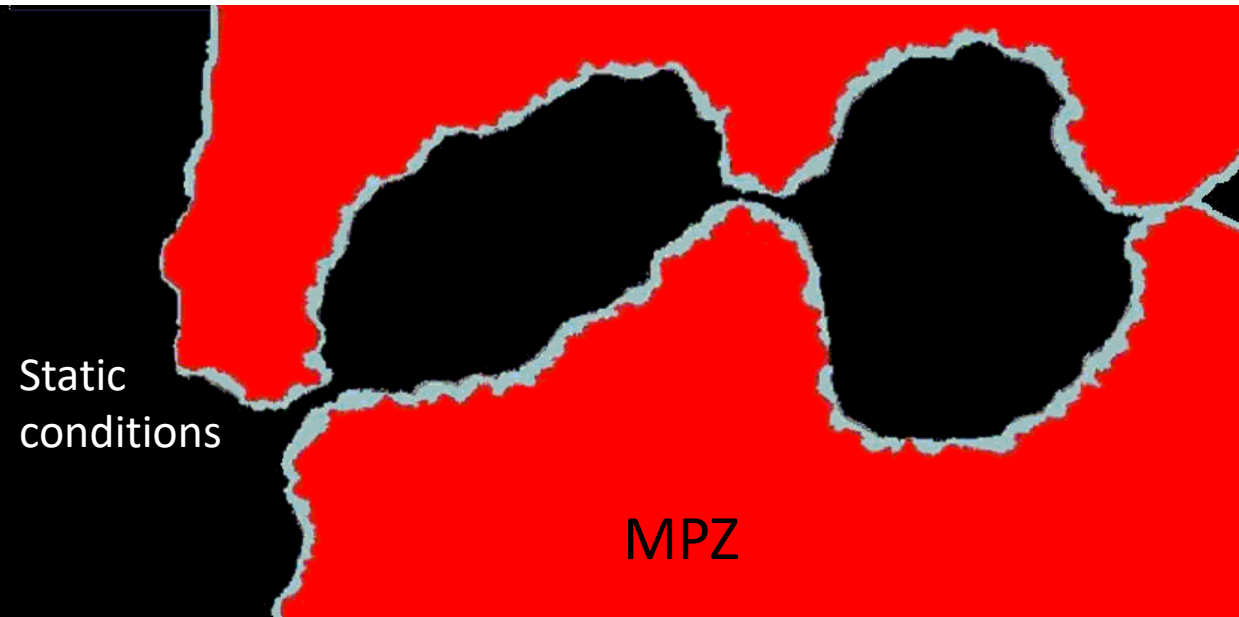
$$\text{CaCO}_3 + \text{Mg} \longrightarrow \text{MgCa}(\text{CO}_3)_2$$

Souring the Oil and Gas

New Dolomite Surfaces Attract Oil over Water, Re: Oil Wettability

Re: Vance, David (2012), RPSEA II Project Chapter 4

Water- and Oil-Wet



If the matrix, clastic particles, or cement is carbonate or arkosic, the rock will have a preference to oil over water and, (our theory) when during the original oil entrapment and water/oil exchange occurs, some mixed wettability will result

I Need to Stop Here for a Minute and Give Due Credit to Two Persons on our ROZ Team

- Dr. Robert Trentham at UTPB (Trentham_r@utpb.edu); For his insights on the Permian Basin tectonic history and his wealth of general geological expertise
- David Vance at Arcadis (David.Vance@arcadis.com): for his invaluable scientific understanding of biogeochemistry, intrinsic microbes present in the earth, and the biological processes often at work in anaerobic environments

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Greenhouse Gas (GhG) Emissions Capture

- The Clean Air Act (CAA) of 1970 gave EPA the Authority to Establish National Ambient Air Quality Standards (NAAQS) to Control Emissions – Particulates, S_{ox} , NO_x , and others
- In 2007 the US Supreme Court Classified Heat Trapping Emissions (including Both Methane and CO_2) as “Air Pollutants” and (under the CAA) the U.S. EPA was Given Authority to Pass Regulations to Curb GhG Emissions
 - They became Included in New Source Performance Standards (NSPS) and Required Emissions to be Reportable at Plants/Projects Exceeding Certain Threshold Emissions
 - The New Classification also placed GhGs into Regulatory Control under EPA’s Federal Safe Drinking Water Act (SDWA {1974})

* The “U” Representing Utilization Like in CO_2 EOR where the CO_2 is Injected for Producing Oil but also Storing CO_2 in the Reservoir

No Other Utilization Scheme has Yet to Show it can Abate CO₂ Emission Streams to the Levels that CO₂ EOR can Handle

- The Permian Basin Alone has Already Securely Stored over 20 Trillion Cubic feet (1 billion metric tons)
- There is Pore Space in Many Basins Around the World also that are Available if Given Capacity to Deliver the CO₂ There can be Implemented
- The Formation Depressuring Occurring with the Shale Plays is Greatly Adding to the Pore Space that is Available
- The CCUS Technology is Proven and Ready to Go to Work on CO₂ Emission Reductions

Thank you