United States Energy Association

A Fireside Chat on:
Challenges Ahead for Energy Supply: New Lessons from Large Volume Injection and Induced Seismicity

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March 30, 2023

Summary

As the horizontal well "explosion" has brought about oil and natural gas production increases, it has brought with it the management of very large volumes of produced water and their disposal. This growth has already been associated with induced seismicity from injection of produced water and, in some places, increases in the magnitude of that seismicity. And, as the analog of mega-scale CO_2 storage of captured CO_2 will begin to grow, it will similarly bring the inherent activities of reservoir loadings, pressure monitoring and fluid displacements.

Challenges Ahead for Energy Supply: New Lessons from Large Volume Injection and Induced Seismicity

Outline

I. Energy Transition Drivers and Incentives

II. CCS, Big Projects and Capital: Where to put the Captured CO_2?

III. What & Where are the Analogs?

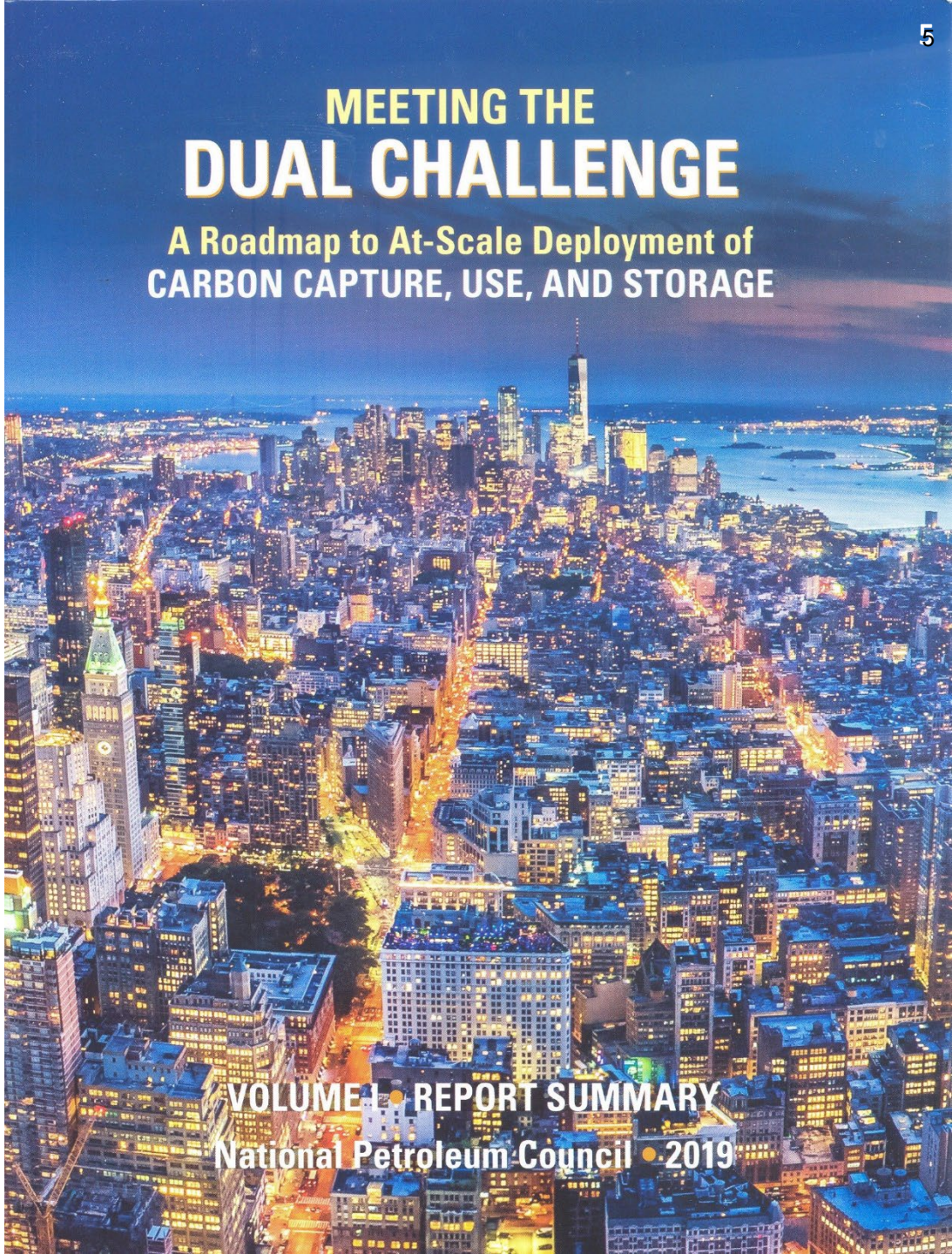
IV. Where not to put the CO_2

V. Are the Geomodels Incomplete?

VI. Who is Best to Judge Good and Secure sites?

I. Energy Transition Drivers and Incentives

Industry Taking on the Challenges (1)



Source: www.greenbiz.com/article/why-we-need-ccs-any-cost

- The acceleration of carbon capture storage (CCS) technology deployment is a critical factor within this agenda. CCS is a critical component of any sustainable energy and greenhouse gas policy. It is not the only one – we need energy efficiency solutions, renewable energy options and more nuclear. But we also need CCS because of our continuing reliance on fossil fuels.
- If there is no CCS, we will be in very dire straits. Because there are some very important economies for which we cannot expect a drop in the use of coal, for example: the United States, China, Russia, South Africa.

CLIMATE WEEK NYC

II. CCS*, Big Projects and Capital: Where to put the Captured CO_2?

* Many refer to CCS as to include CO_2 Storage while Producing a Product – I prefer to distinguish between “pure storage” aka sequestration) and add the U in CCUS when treating CO_2 as a commodity

CCS and CCUS

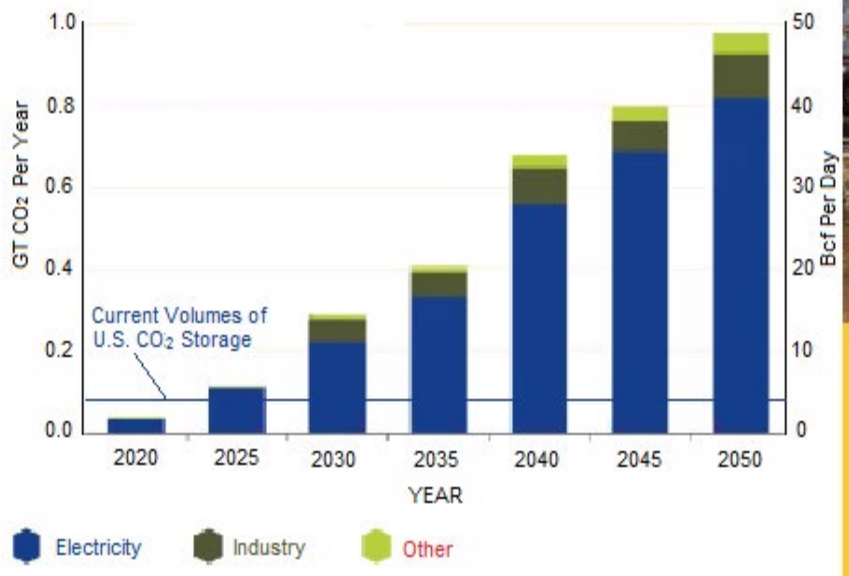
- CCS: Carbon Capture and Storage
  - Captured 'Waste' CO_2 Injection – where almost all projects to date are at small scale and injection without any producing wells
- CCUS: Carbon Capture Utilization and Storage
  - During Injection, produces a product as in oil during CO_2 EOR* or CO_2 Nat'l Gas Enhanced Recovery
  - The CO_2 is an Expensive Commodity, Reservoir Pressures are Carefully Controlled and Regulated not to Exceed Pressure Limits Established by State Oil and Gas Regulatory Agencies
  - Historically CO_2 EOR has been an Active Process for Five Decades while Storing an Estimated Amount of new CO_2 Exceeding 20 trillion cubic feet (400 billion metric tons) and produced over 2 billion bbls of oil
  - Current rates of Purchased (aka "new" i.e., non-recycled) CO_2 injection approach 2.5 billion cubic feet per day (50 million tons per year)

* *In a Large EOR project we can assume >95% of 'new' (i.e., captured or purchased) CO_2 is permanently stored in the reservoir*

Shell's Forecast for US Carbon Capture Storage Rates

Deploy carbon capture, utilization and storage at scale

CO_2 Emissions Captured by CCS from all US Energy



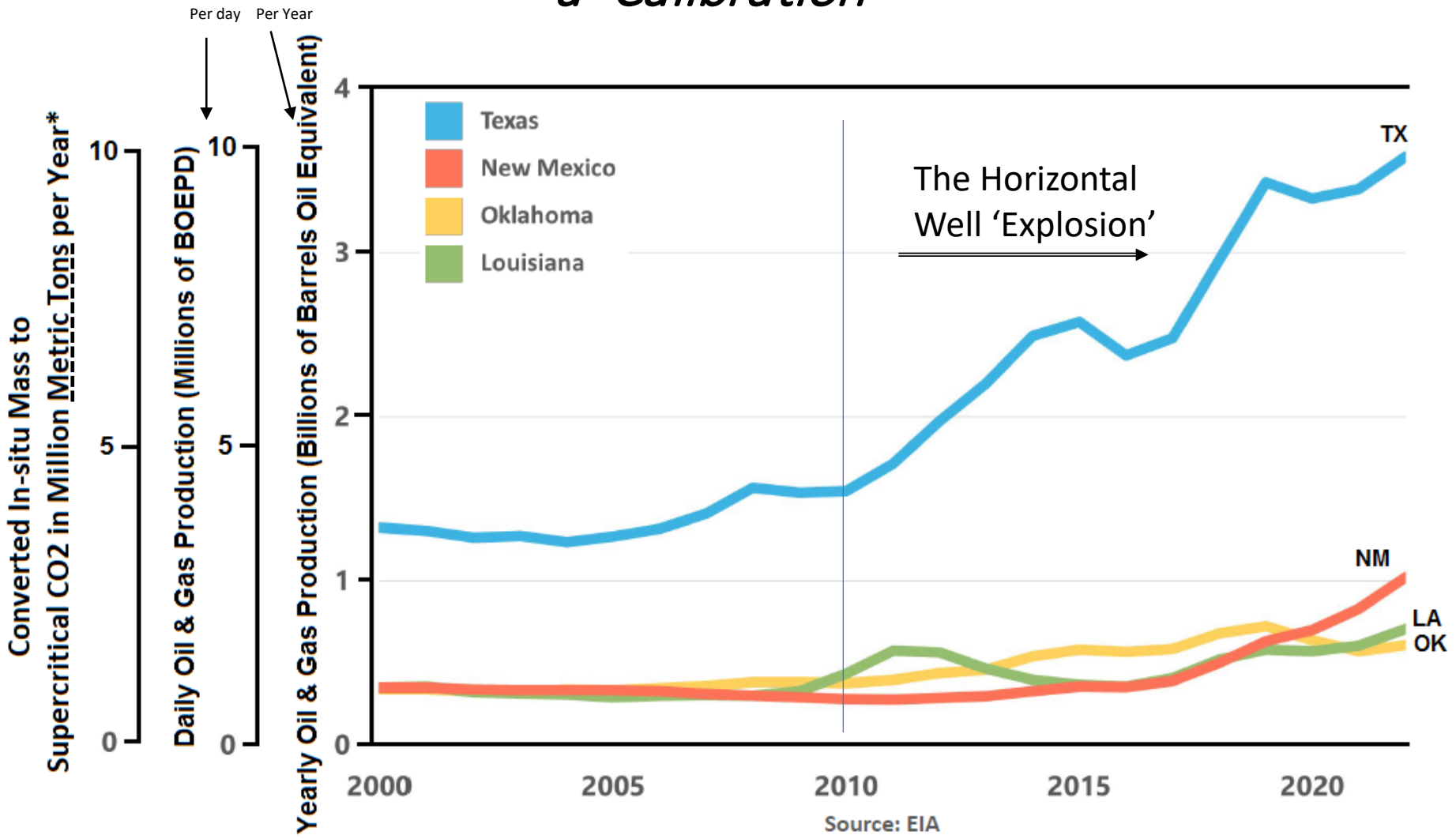
Adapted from Shell International Pesentation -2020

A US net-zero CO_2 energy system by 2050

- CCUS is essential, e.g. industrial processes, bio-energy power generation, gas-fired power generation and direct air capture
- Build one major US CCUS facility every 3 months until 2050 (each capturing more than 8 million metric tons per year)
- Utilization of captured CO_2 is important, but eventually restrict to permanent (or near-permanent) storage

December 2020

Recent Reservoir Extraction Growth to Huge Volumes
a 'Calibration'



* Using 2 mscf = 1 bbl in-situ and 19.25 mscf per metric ton

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III. What are the Storage Analogs?

Site Selection - Putting CO_2 in the Right Geologies

Mother Nature (MN) Shows us that Buoyant Fluids like Natural Gas and CO_2 can be Effectively Geologically Trapped

But we can also say that MN and New Experience is showing us that some Geological Sites face Issues with Buoyant Fluids Migrating in the Subsurface and Finding a Pathway to the Surface….

…or what we are now witnessing with Large Volume Water Disposal, a Pathway Down to the Crust where Earthquakes can be Triggered

So Where Do We See Higher Volume Secure Storage?

- Natural Gas Storage (Buoyant Fluid)
- National Oil Repositories (Strategic Petroleum Reserve)
- Water Floods (Density Neutral)
- CO_2 Floods (Buoyant Fluid)

✓ Intermittent (Some Failures)

✓ Salt Domes (Moderate Volumes – No Failures)

✓ Long History but a Density Neutral Injectant

✓ 50-year History and Large Volumes of Storage*

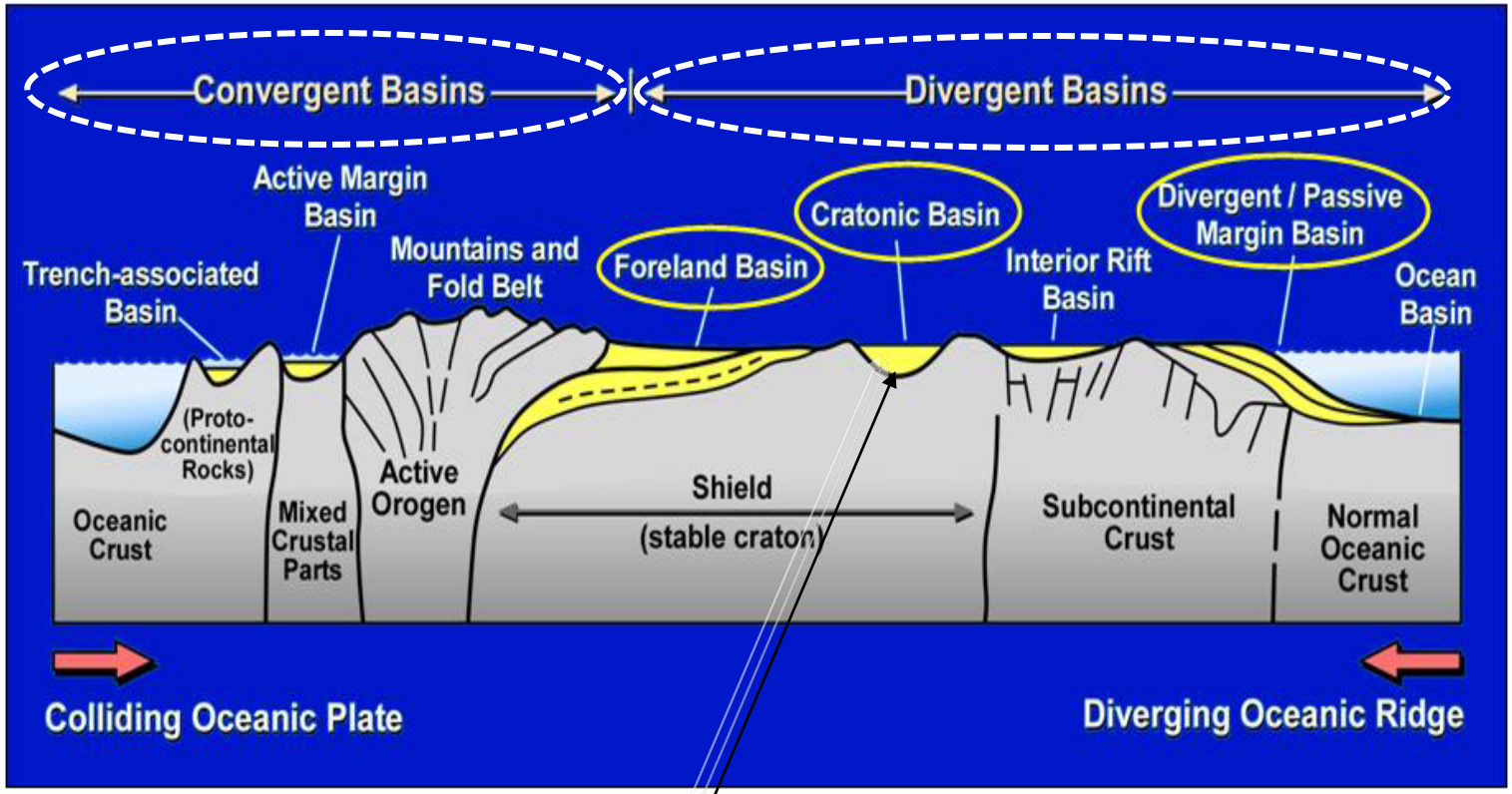
* Our Closest Thing to Secure Storage Sites with Buoyant Fluids, Large Volume Analog

Secure Sites for CCS are Not Ubiquitous

- Many folks have worried about leaky wellbores *(industry fixes these when encountered)* so we look elsewhere, often where subsurface data is sparse
- A few studies have tried to categorize leaky geologies

The Following Slides are from a Report Attempting to Rate Subsurface Basins for Suitable Storage Sites

Cross Sectional Representation of Various Types of Sedimentary Basins



Usually Evaporite Capped*

Source: Hitchon et al., 1999

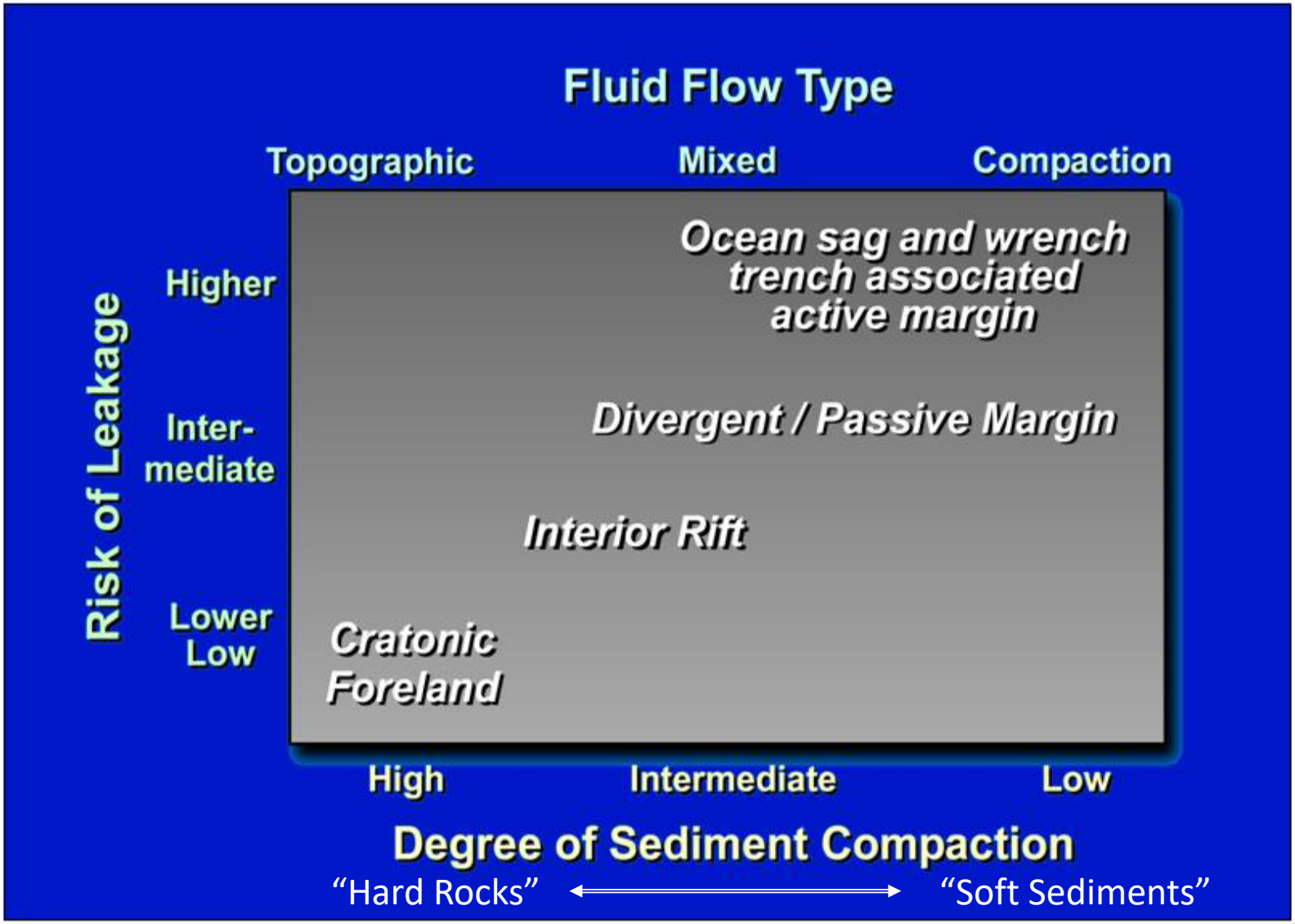
* Evaporites such as Salt (NaCl) and Anhydrites ($CaSO_4$) at >2500' Depth are Ductile and Provide Excellent Capping or Bottom Seals

Ref: Hitchon et al, Dynamic basin analysis: an integrated approach with large data bases, Geological Society, London, Special Publications 1987, 34:31-44;

Hitchon et al, The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide, Geological Society, London, Special Publications 2004, 233:129-145;

Hitchon B, Gunter WD, Gentzis T, Bailey RT (1999), "Sedimentary basins and greenhouse gases: a serendipitous association" Energy Convers Manage 40:825–843

Risk of Leakage in Sedimentary Basins



Source: Hitchon et al., 1999

Let's Pause here for a moment to chat

Questions/Thoughts before Moving on to the New Data?

What Has The Industry Learned About Site Risks?

"Macro" Site Risks for Storage

Critical Subsurface Storage Considerations to Evaluate, **Model** and Quantify

1. Pressure Management
2. Reservoir Seal Maintenance
3. Wellbore Integrity
4. Challenges in Determining Lateral Continuity of Reservoirs
5. Horizontal Drilling and Transmissive Natural Fracture Lessons
6. Today's Seismicity Lessons
7. Strike-Slip Faulting/Lineaments
8. "Formation Overload" *(Soft Sediments)*
9. Non-technical Factors Important for CO_2 Storage

It is Not all Study, Study, Study and Get Us Nowhere…

Fortunately, there is Good News…
and Some Flags to Pay Attention to

As shown earlier and augmented by large volume water disposal, we have some secure storage case histories to rely upon and emissions need to be captured so let's get moving

But…How Dangerous is it to Rely on Small Volume Injection Site Analogs?

- Lots of excellent USDOE research has evaluated small volume CCS sites in many parts of the country
- The fast moving and very recent horizontal well experience of the oil and gas industry is demonstrating that the large volumes of water production and injection without fluid removal are, in several subsurface conditions, creating seismicity and seal issues (more on this coming)
- The large and upfront expenses of CO_2 capture and processing for large volumes of CO_2 injection need more confidence than small volume injection pilots provide
- And a Question out of the'Blue': Where will the Insurance Companies Land on Deep Saline Formation CCS?

Demonstrated Secure Storage and Intra-cratonic Basins*
(North America Specific)

- Permian Basin
- Alberta Basin
- Rockies Intermontane Basins
- Williston Basin
- Michigan Basin

** But even these may be not perfect as we will show*

IV. What are our Warning Signs on Where not to put the CO_2?

Let's Look at Some Recent Case Histories

New Experience: Northern Alberta

MARCH 23, 2023

Stanford study finds wastewate oil production triggered major Canada

New research reveals wastewater injected underground by fossil fue earthquake in November 2022 in the Peace River area of Alberta's oi study to link seismicity in the area to human activity.

BY ADAM HADHAZY

A new study by Stanford University researchers has found that one of the most pow ever recorded in Alberta, Canada, was likely caused by oil and gas activity.

On November 30, 2022, a 5.6-magnitude earthquake shook the remote Peace River region in northwestern Alberta, a part of Canada's oil sands region. Although people felt shaking more than 400 miles away, residents and businesses have not reported injuries or damage.

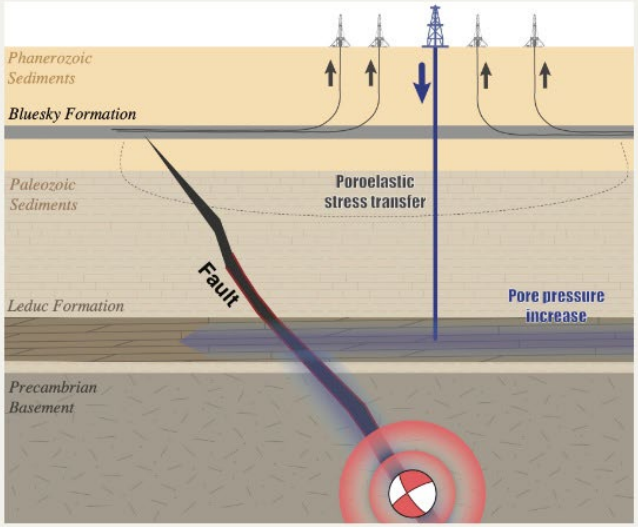
A view of the Peace River in northern Alberta, Canad

Energy regulators for the region described the earthquake as a natural tectonic event. A rigorous new analysis by Stanford geophysicists suggests, however, that oil industry activity – specifically, disposal of wastewater deep underground – most likely triggered the tremor. Three slightly smaller earthq same area again on March 16, less than a mile from last year's big quake.

https://news.stanford.edu/2023/03/23/oil-sand-wastewater-triggered-large-albert

Finding the culprit

Over recent decades, scientists have documented hundreds of earthquakes induced by oil and gas operations worldwide, especially in the United States. To assess the origins of the Peace River earthquake, the Stanford team and colleagues employed a well-proven approach that considers seismic events' details and context, including location, depth, timing, regional history of background earthquakes, and records of industrial activity.



The injection of fluids increases pore pressure within the underlying fault, destabilizing it. The induced reverse fault slip (beachball) heaves the overlying strata, creating the ground deformation observed in satellite images. *(Image credit: Schultz et al., 2023)*

Operations in the Peace River area center on extracting a thick, black, sticky form of oil known as bitumen. To mobilize the tar-like substance for easier pumping up to the surface, workers inject huge amounts of hot water or solvents underground, where it can mix with heavy metals, hydrocarbons, and harmful chemicals. The most economical way to dispose of this wastewater is by re-injecting it underground. Since bitumen recovery operations began in the Peace River study area in the 1980s, about 40,000 Olympic swimming pools (100 million cubic meters) of wastewater have been injected underground.

The researchers compared publicly available information about wastewater disposal activities in Peace River to ground deformation measured by satellite and regional seismic monitors. "The Alberta government deserves credit for its transparency for providing public access to production and disposal data," said Ellsworth. Overall, the results tied frequent, minor earthquakes to wastewater disposal from bitumen recovery going back almost a decade, strongly implicating the big November 2022 temblor as well.

https://news.stanford.edu/2023/03/23/oil-sand-wastewater-triggered-large-alberta-earthquake/

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Ref: Journal of Petroleum Technology: https://jpt.spe.org/stanford-study-finds-wastewater-disposal-from-oil-production-triggered-major-earthquake-in-canada

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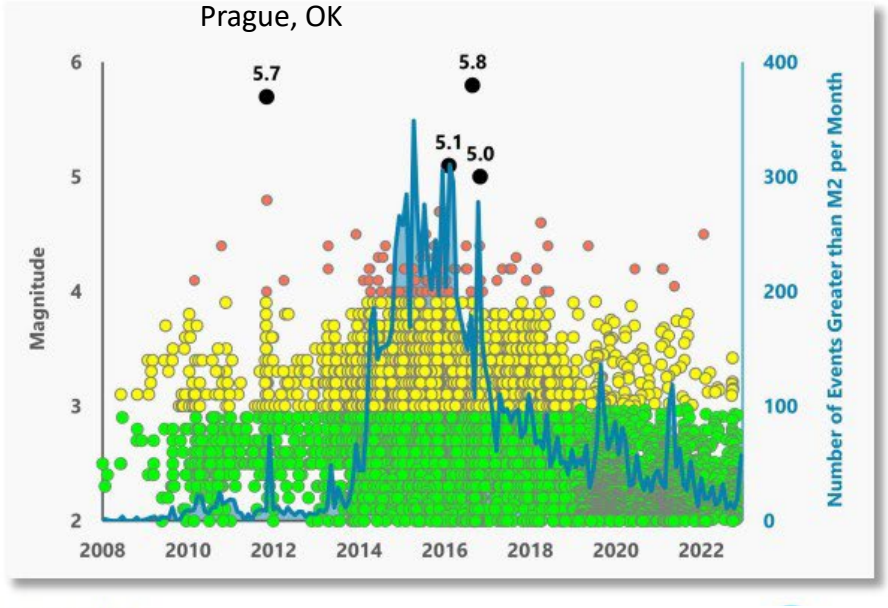
Oklahoma Induced Seismic Activity

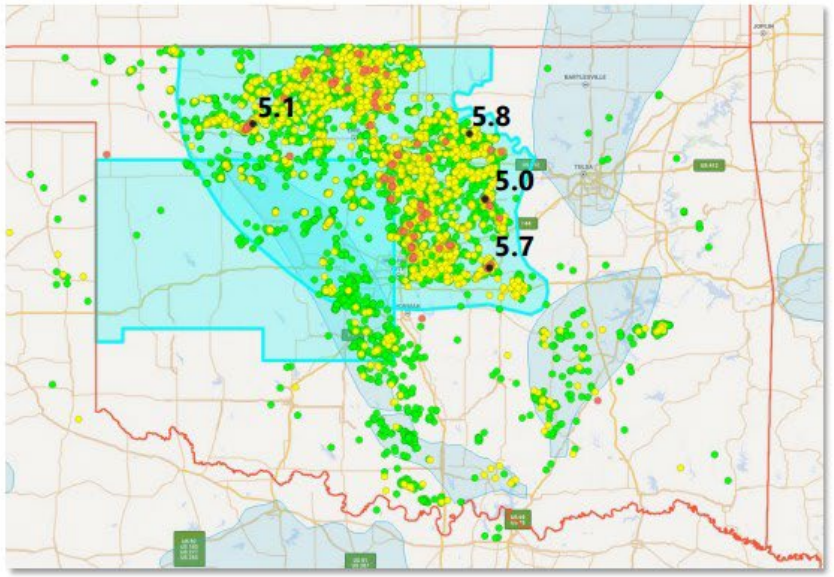
Central and Western Oklahoma Seismicity

Magnitude vs. Time



Source: USGS

Map of Epicenters



- *Compliments of B3 Insight*

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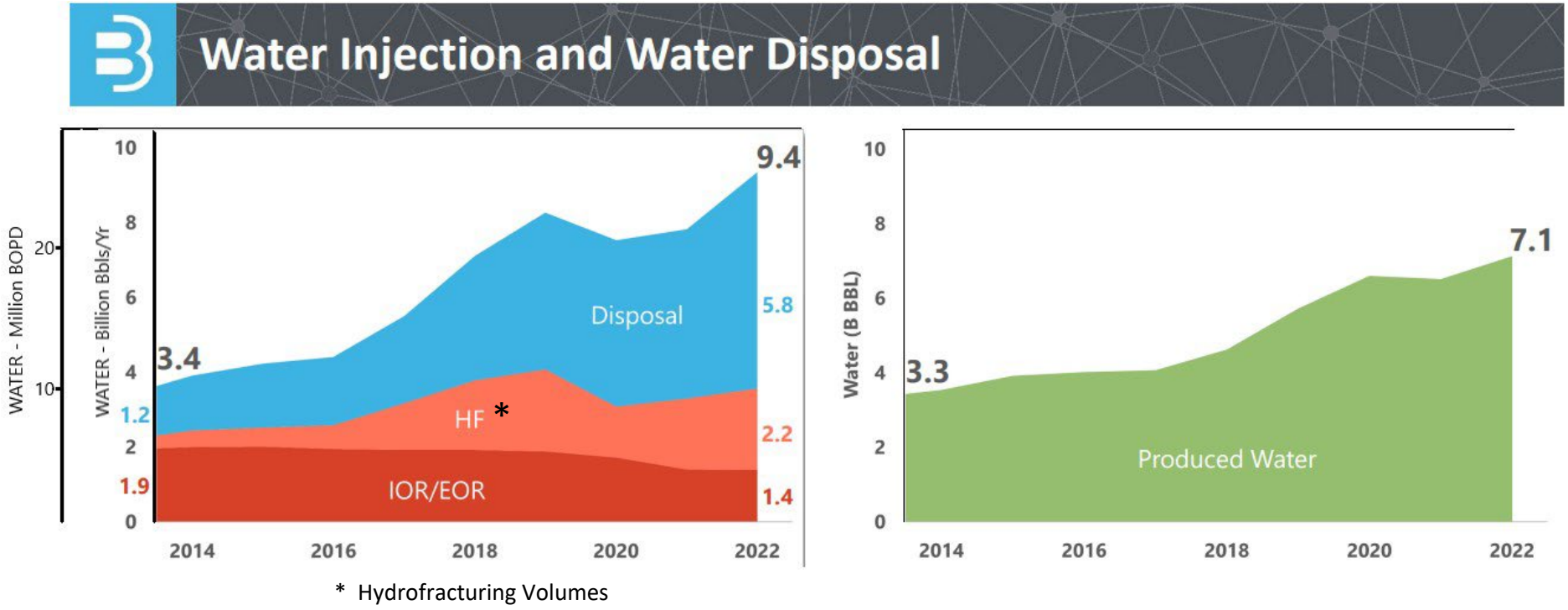
Now Jumping to the Permian Basin: Water Handling*



* Hydrofracturing Volumes

** Compliments of B3 Insight*

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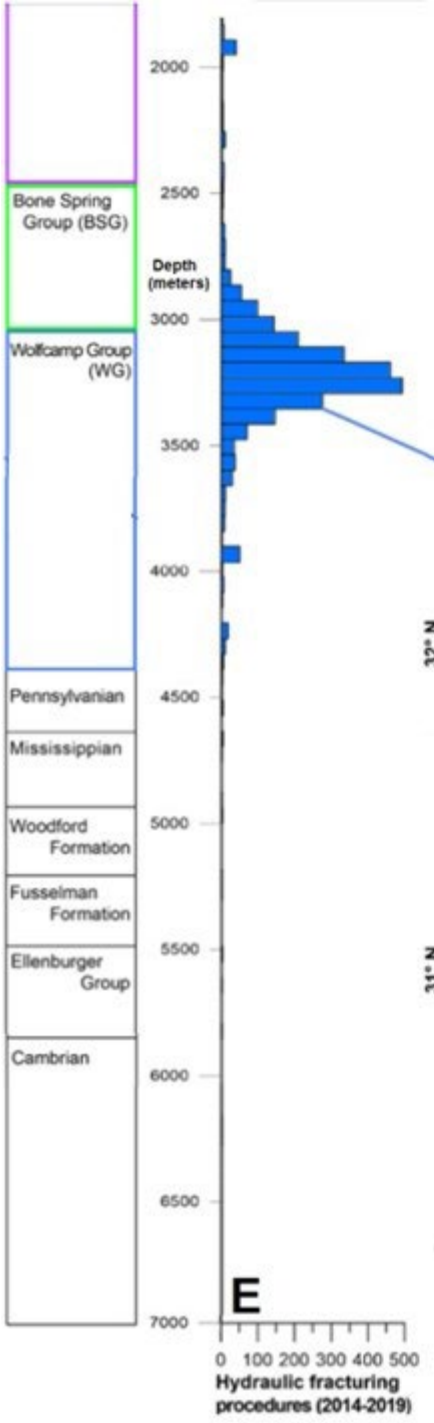
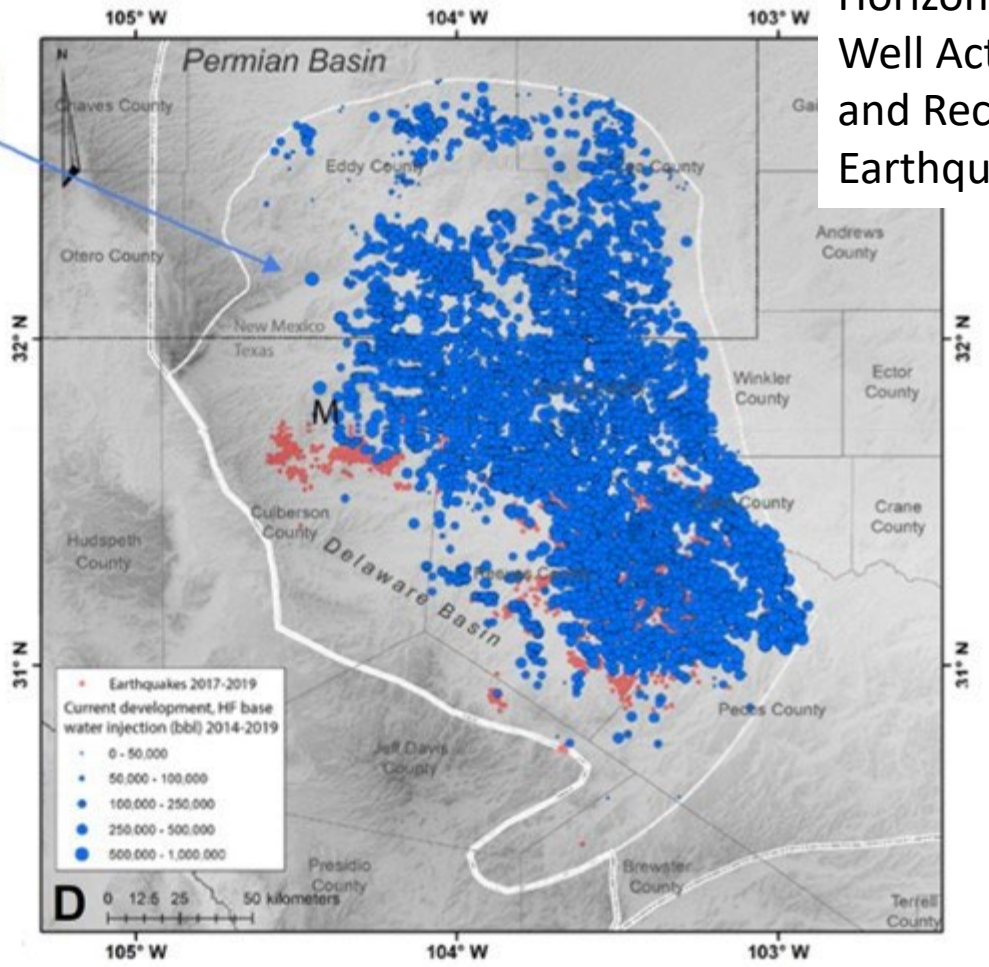
New Experience: PB Delaware Basin





Horizontal Well Activity and Recent Earthquakes

Dvory, N.Z. & Zoback, M.D (2021), "Prior oil and gas production can limit the occurrence of injection-induced seismicity: A case study in the Delaware Basin of western Texas and southeastern New Mexico, USA," Geology (2021) 49 (10): 1198–1203, https://doi.org/10.1130/G49015.1

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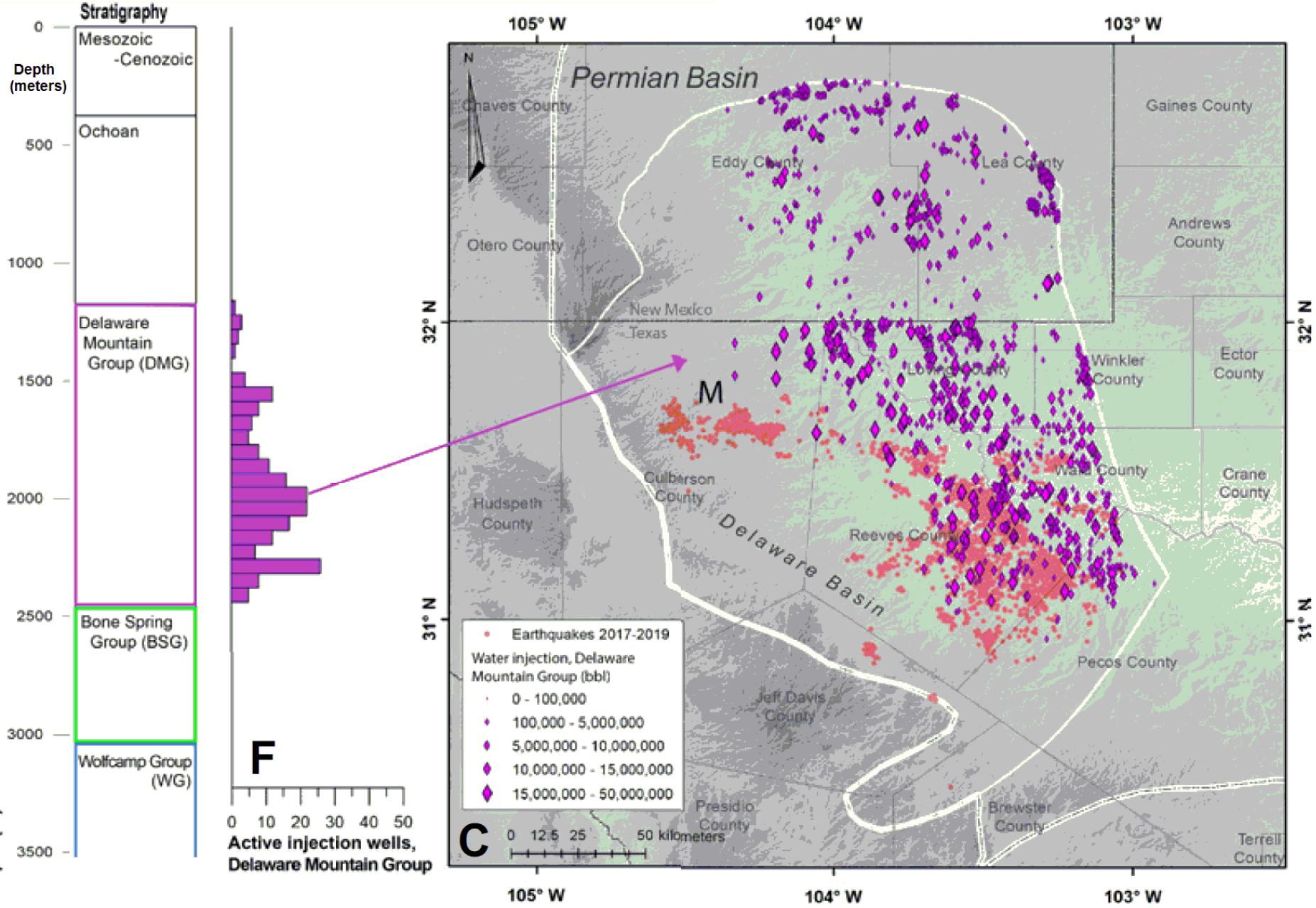
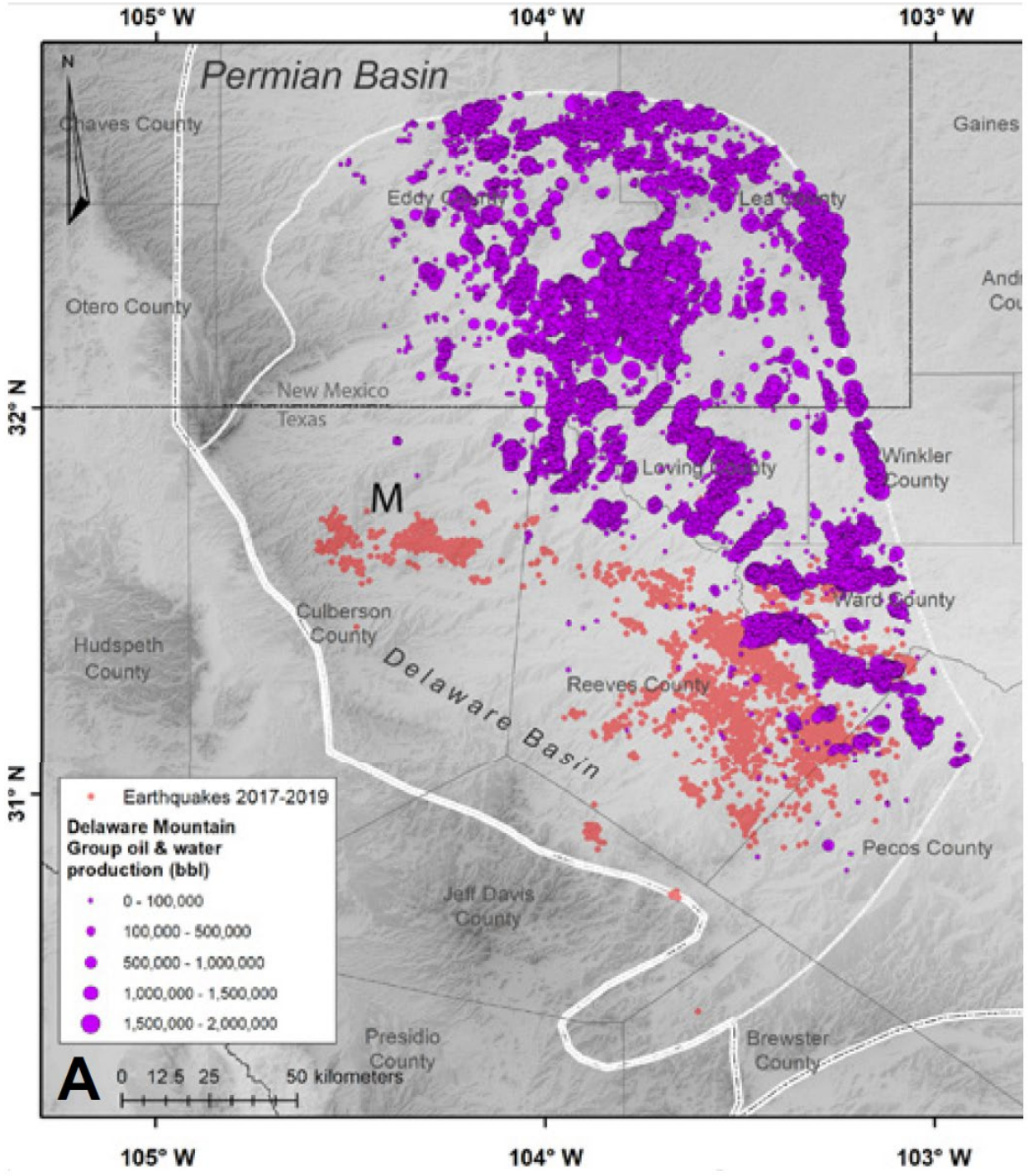
Delaware Basin "Shallow" Water Disposal and Earthquake Activity



Dvory, N.Z. & Zoback, M.D (2021), "Prior oil and gas production can limit the occurrence of injection-induced seismicity: A case study in the Delaware Basin of western Texas and southeastern New Mexico, USA," Geology (2021) 49 (10): 1198–1203, https://doi.org/10.1130/G49015.1

New Experience:

Induced Seismicity and Previous Fluid Removal



Dvory, N.Z. & Zoback, M.D (2021), "Prior oil and gas production can limit the occurrence of injection-induced seismicity: A case study in the Delaware Basin of western Texas and southeastern New Mexico, USA," Geology (2021) 49 (10): 1198–1203, https://doi.org/10.1130/G49015.1

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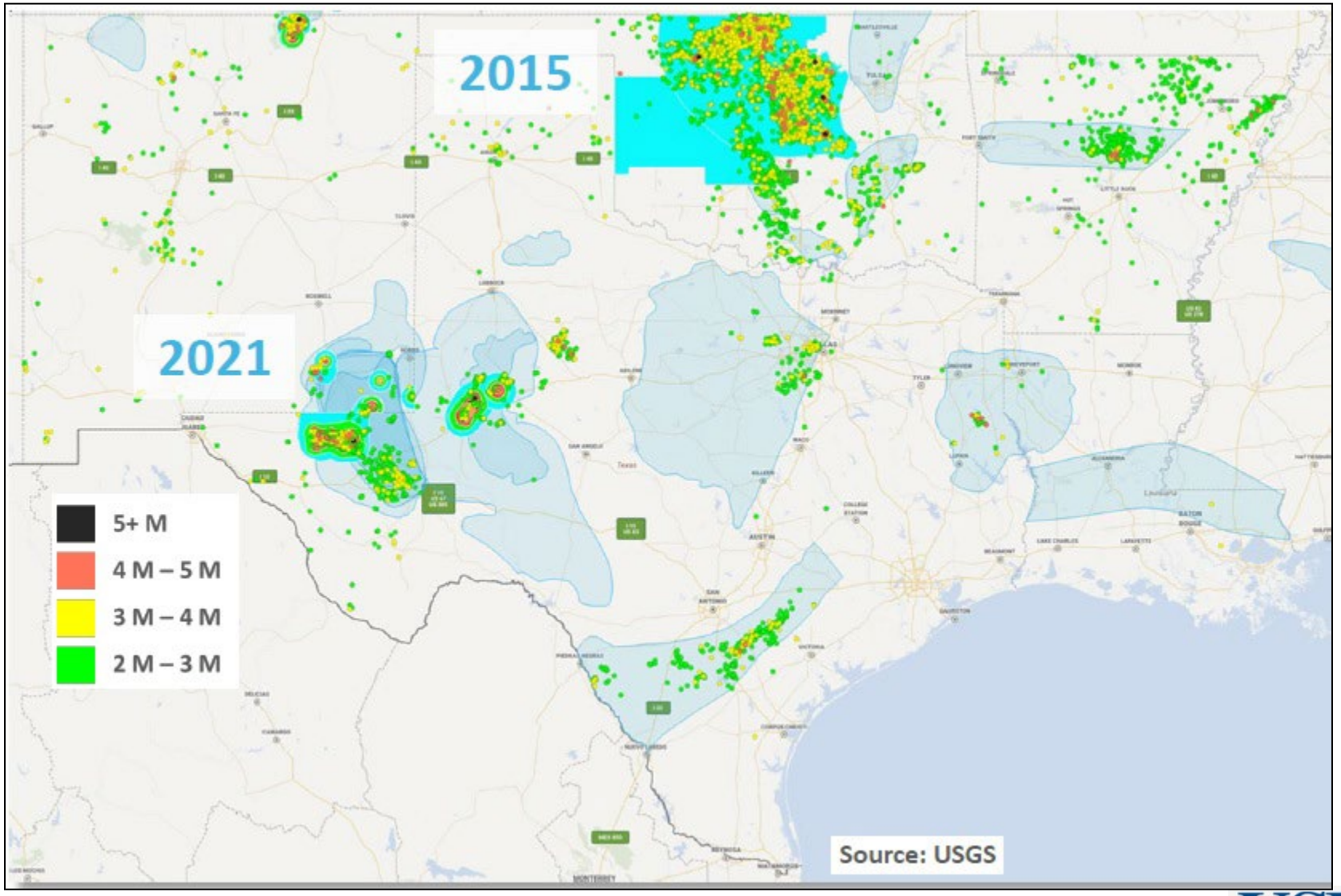
Large Volume Water Injection:
Regional Seismicity



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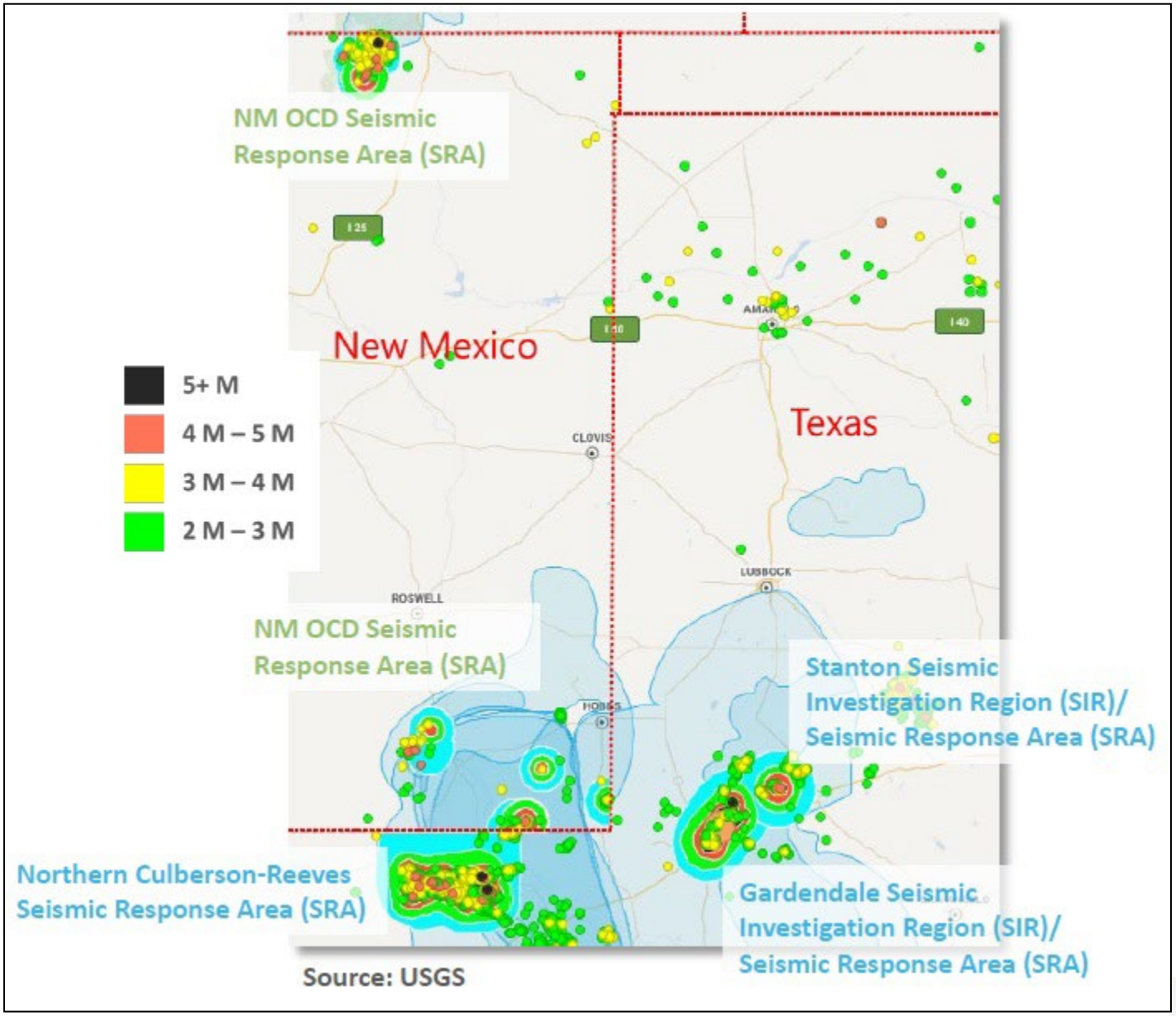
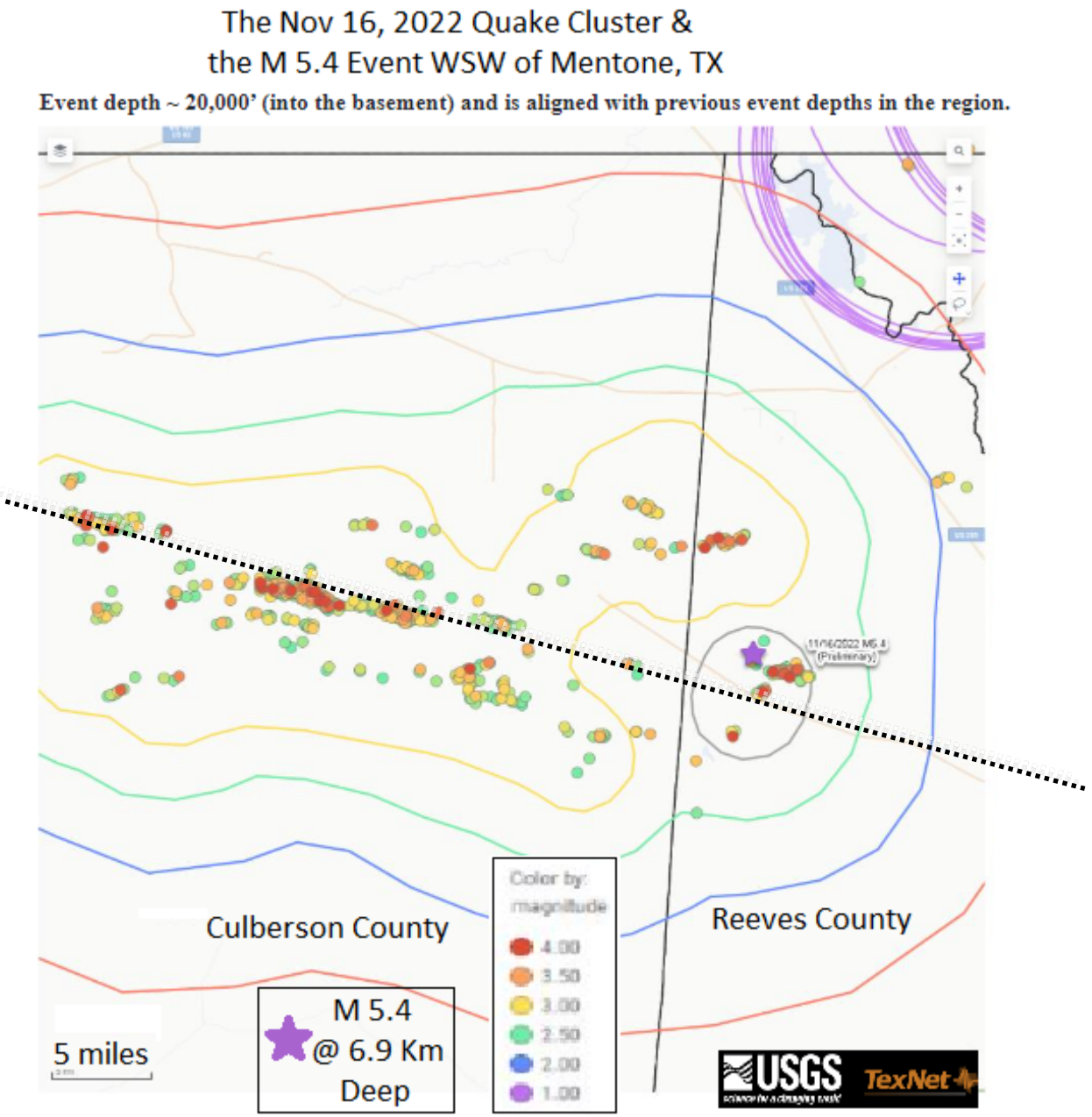
Managing the EQ Risks: SRAs and SRIs

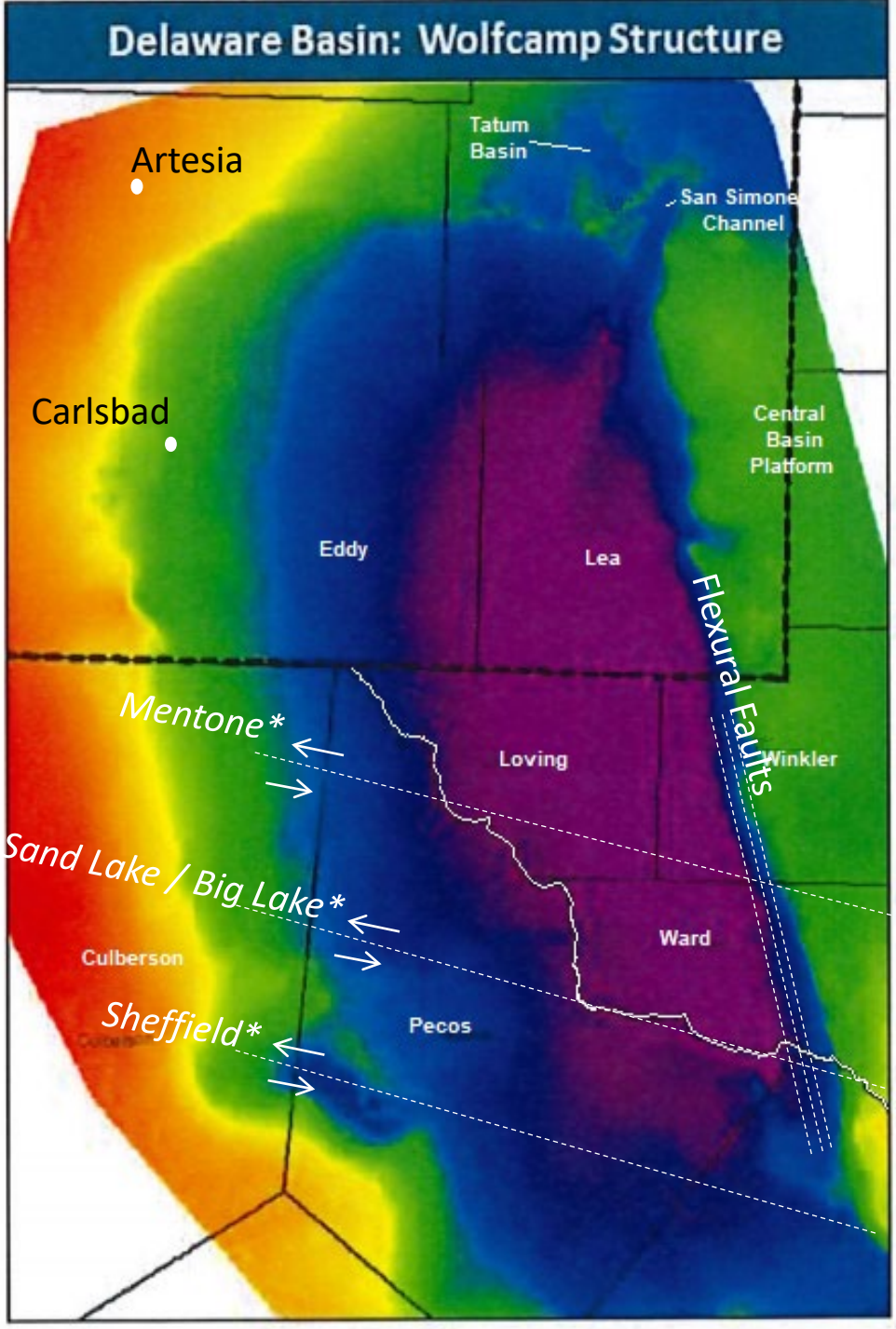


Lessons for Large Volume Water Disposal in the Permian Basin and the November 16, 2022 Quake Cluster



with Key Strike Slip Lineaments

(with West Side of CBP Flexural Faults Superimposed)



ESG and Social License to Operate

mrt★

NEWS // LOCAL

City protests injection wells at T-Bar Ranch

City of Midland and Pilot Water Gathering Delaware at odds over Pilot's plans to drill injection wells adjacent to the city's T-Bar Ranch Well Field.

Mella McEwen, MRT.com/Midland Reporter-Telegram

March 22, 2023

A dispute has broken out between the City of Midland and Pilot Water Gathering Delaware over Pilot's plans to drill saltwater injection wells adjacent to the city's T-Bar Ranch Well Field in Winkler County.

Last summer, Pilot applied to drill 18 disposal wells in Sections 15 and 16 in Winkler County, where the City of Midland owns the entire groundwater estate in and under the entirety of the two sections and both the surface and groundwater rights in approximately 20,229 acres adjacent to the two sections. Three wells have been drilled but are not in use, and three have received permits.

Midland officials in July had granted an easement for Pilot to construct a pipeline bringing produced water from New Mexico to the disposal wells. They learned in December that Pilot had earmarked five of the wells as "commercial" and protested, saying they had not received notice as an affected party who would surely be harmed as the T-Bar field supplies 30 to 35% of the city's water. They said they should have been notified as required under Statewide Rule 9. Pilot responded the designation as "commercial" was in error and thus the notification requirement did not apply.

Midland again protested, saying project would inject salt water and RCRA-exempt waste through the field, possibly endangering a major source of the city's water supply. Pilot's assertion is it will complete the wells with three strings of casing and the distance from the current water supply aquifer will protect groundwater.

The city filed a motion to consolidate the docket for amending the five wells into one, which was protested by Pilot. A preconference hearing on the motion by Pilot to dismiss the consolidation request was held March 7, and a ruling is expected this coming week. Depending on the ruling, either party can request a hearing before the three commissioners.

50 Years of Experience but there is Pushback on CO_2 EOR with Storage

- "It Just Makes More Oil!"

But…..

- Has Proven Long Term and Secure Storage
- Long Standing Regulatory Regime is in Place and now with EPA's Augmented SubPart RR*
- Unlike CCS Deep Saline Projects, EOR Balances Volumes In and Out of the Reservoir
- Insurance Companies Considerations – They Like Proven Track Records

* *For More Precise Documentation of CO_2 Volumes Injected, Produced, and Recycled*

Can We Reduce Emissions of CO_2 While Making EOR Oil?

- Data Base of Life Cycle Assessments (LCA) on CO_2 EOR
- *When Only Oil Revenues Drove Success of EOR, CO_2 Purchases (and Reservoir Retained CO_2) has to be Minimized*
  - *Value of Storing CO_2 can be a Game Changer*
- Can the Industry Design an EOR Project to Make a Carbon Neutral Barrel?

VI. Are the Geomodels Incomplete?

Challenges with Geomechanical Models

- Mother Nature is Quite Variable and Complex and we are Trending to Areas with Little Subsurface Data

<u>In Hard Rocks</u>

- Are we Able to Model the Bottom Seals to Avoid Crustal Injection and Possible Induced Seismicity?

<u>in Soft Sediments</u>

- Are we Considering Things like a Formation's Consolidation History?
- Are we Considering Formation Overload Displacements when Fluids in are not in Balance with Fluids out?

Where is the Business of Storage Today?

1. The Urgency of CO_2 Capture is Intense
2. The Incentives are in Place in the U.S.
3. Much Experience with Small Volume CO_2 Injection in a Variety of Geologies
4. Large Volume Injection Mostly Resides with Water Disposal

VI. Who is Best to Judge Fully the Secure Sites?

Put Yourself in the Regulator's Seat for a Moment

- You have Commercial Interests Seeing the Enhanced 45Q and with Big Project Ideas Coming into your Office – and maybe lots of projects
- You are Seeing their GeoModels of Site Response – some well Done, Some Leaving out Key Geomechanical Processes
- You have Pressures from the Companies and the Legislature to Approve the Permits to get the Projects Started
- You Feel Like you are on the "Hotseat"

Where to Get Geomodel Help?

Semi-random thoughts

- Industry
- National Risk Assessment Partnership (NRAP)
- US Geological Survey
- Others?

Closing (1)

- The developed, industrial world needs CCS (where energy reliability is fundamental to the economies)
- CCS can be done very successfully in appropriately screened sites
- The injection industry has learning invaluable recent lessons: Geomechanical models must Include analysis of the larger spectrum of site risks
- Storage risks are many and many sites will require exclusion – pressure will be on the regulators
- Upfront Investment $ are immense and confirmation of low risk, secure sites is a priority prior to project $ commitments
- Fortunately, proven secure sites are available but may require mass balancing fluid injection and withdrawals

Closing (2)

- Current US secure storage in CO_2 EOR is 50-60 million tons/yr but will require 15-20x scale-up
- Long distance, large diameter CO_2 pipelines will be required to access the additionally required secure storage locations
- Secure CO_2 storage is proven and expansion to the volumes needed is feasible
- Retraining large groups of geotechnical professionals for secure CO_2 storage is a necessity
- The existing oil industry professionals need to be central figures in the new CO_2 storage industry

Thank you

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432-682-7664 ofc

CO_2 Volumes Involved

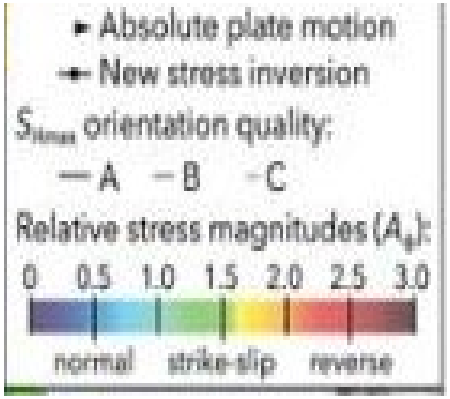
- April 19, 2021 (Reuters) - Exxon Mobil (XOM.N) recently floated a proposal for a public-private carbon storage project that would collect planet-warming carbon dioxide emissions from U.S. petrochemical plants and bury them in deep under the Gulf of Mexico.
- Exxon wants to sequester **up to 100 million metric tons of CO_2 per year*** under Gulf of Mexico waters
- The plan would require **"$100 billion or more"** from companies and government agencies to store 50 million metric tons** of CO_2 by 2030, with capacity potentially doubling by 2040, Joe Blommaert, president of Exxon's Low Carbon Solutions business, said in an interview.

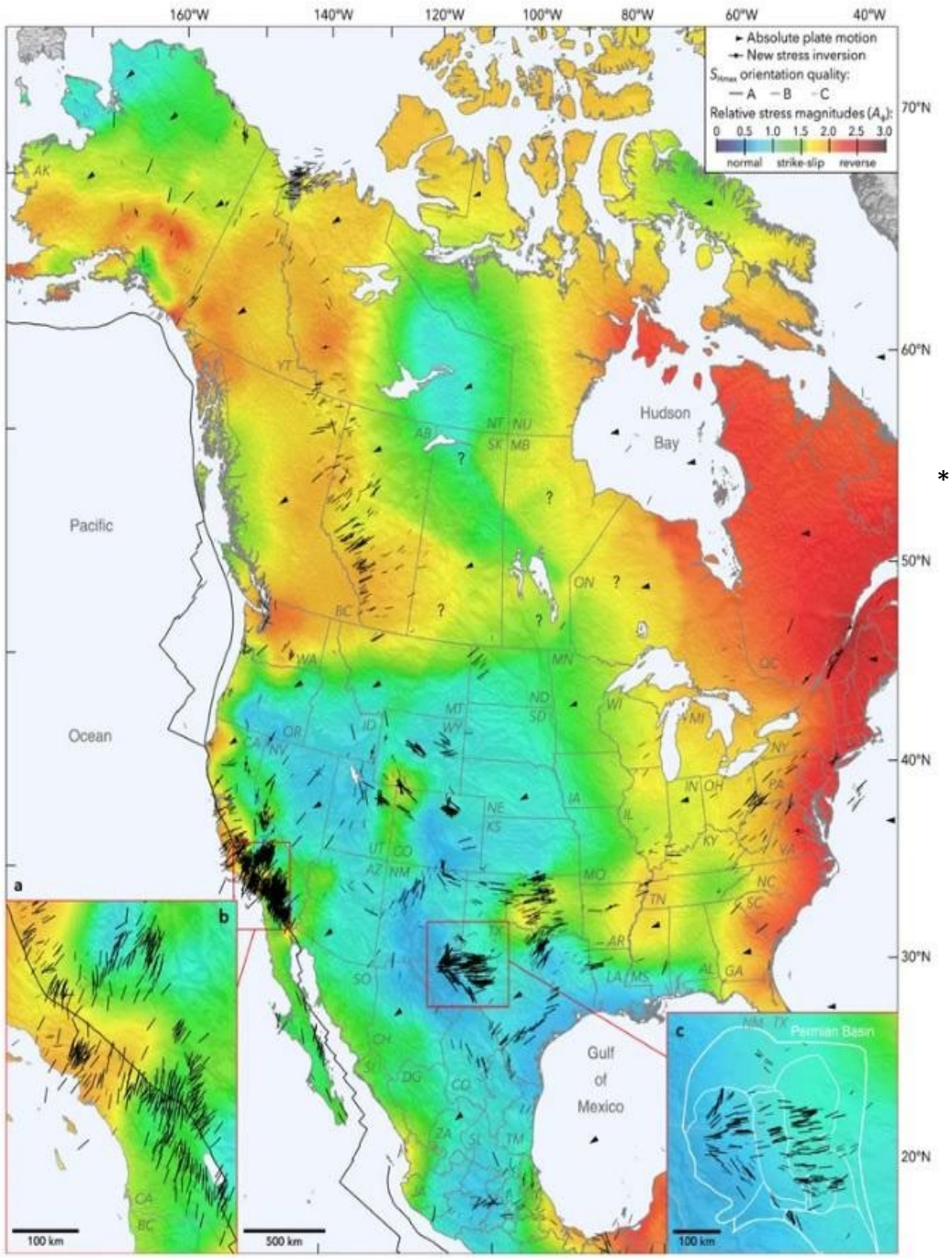
* Equivalent to ~5 bcfpd

** Equivalent to ~1 tcf (for comparison, McElmo Dome is 20 tcf)

Seismic Stress States and Fault Tendencies*

aided by the Proliferation of Unconventional O&G Well Development





* After Lund Snee, J-E. and Zoback, M.D. (2022), State of Stress in Areas of Active Unconventional Oil & Gas Development in North America, AAPG Bulletin, V. 106, No. 2, (Feb 2022). PP. 355-385

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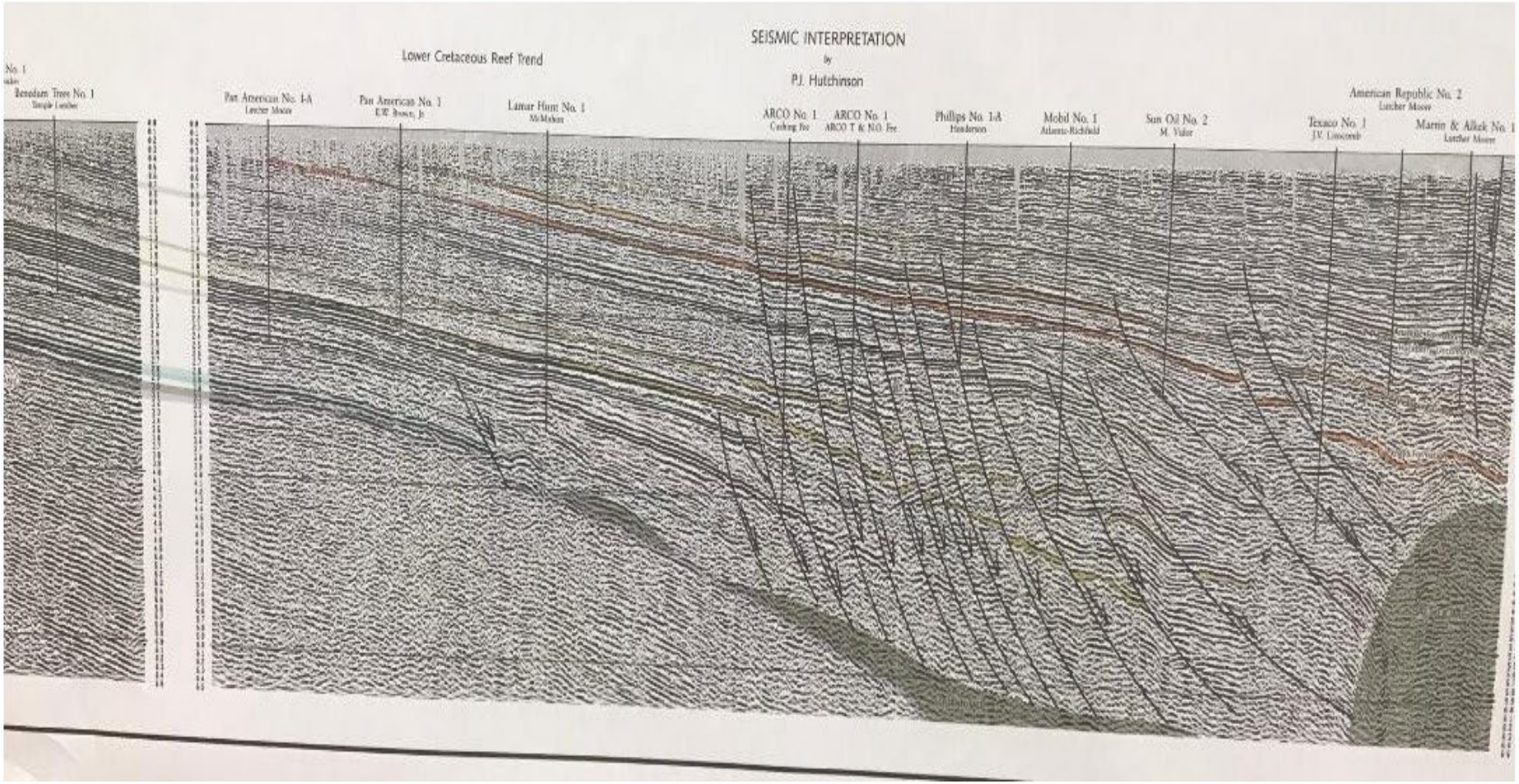
Geomechanical Modeling Example: Soft Sediments

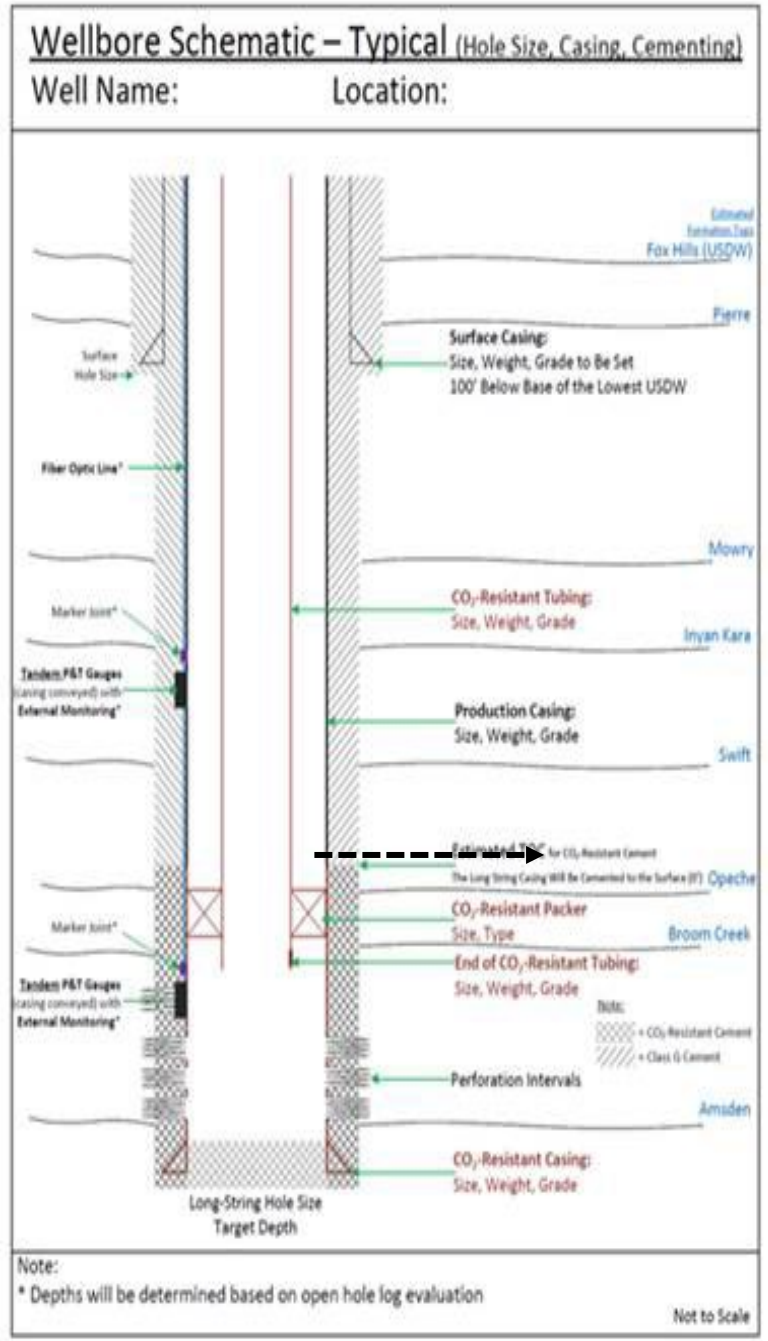
Example Gulf Coast Cross Section



Avoidance of ‘Down To Coast’ Fault Block Slippage from CO_2 Disposal and Formation Overload

Stiff Wellbore / Soft Sediment Displacement and Potential Leakage Path

Cement Sheath / Formation Interface



Example CCS Injection Well Diagram