ROSE
SUBSURFACE ASSESSMENT

SPE • AAPG • SEG
CCUS
CARBON CAPTURE, UTILIZATION, AND STORAGE
3–5 MARCH 2025 • HOUSTON
George R. Brown Convention Center

Quantifying Low Frequency, High Impact Events in Carbon Storage Projects

Peter Carragher

March 5, 2025

Creties Jenkins, Pieter Pestman, Rosalie Constable

Introduction

- For low frequency events, a forecast that nothing will happen is likely to be correct most of the time, *except when it is not.*

- Ignoring such low frequency events means that early indicators might be misinterpreted or dismissed, with no preparations or mitigations put in place.

    - *'Yet quality in a forecast is not about being correct most of the time. This is because for rare events, one can be correct most of the time with a simple null forecast - never saying an event will happen.'*

      (Gordon Woo, author of "Calculating Catastrophe" (Woo 2011, p.197)

Outline

- Definitions
- Generate lists of Adverse Events
- Methods to Assign Low Probabilities of Occurrence
- Assign the Range of possible monetary impacts
- MonteCarlo Sampling to illuminate Low Frequency, High Impact Events
- Establish MMV programs to detect and mitigate High Impact Events

Definitions

- Adverse Event
  - An occurrence that is either not predicted, or occurs outside of the limits of a model or prediction
    - *Features, Events & Processes (FEP) Methodology*
    - *Fault leakage, non-conformance of plume, well leakage etc*.

- Probability of Occurrence
  - The annual chance an adverse event will occur
    - *A shift from the usual focus on the chance of success.*

- Monetary Impact
  - A range of possible dollar costs, if an adverse event occurs
    - *Truncations are not applied to the range*

- Risk
  - The potential for loss, expressed in monetary terms but also extends to loss of reputation, licence to operate, and legal peril such as negligence, or gross negligence

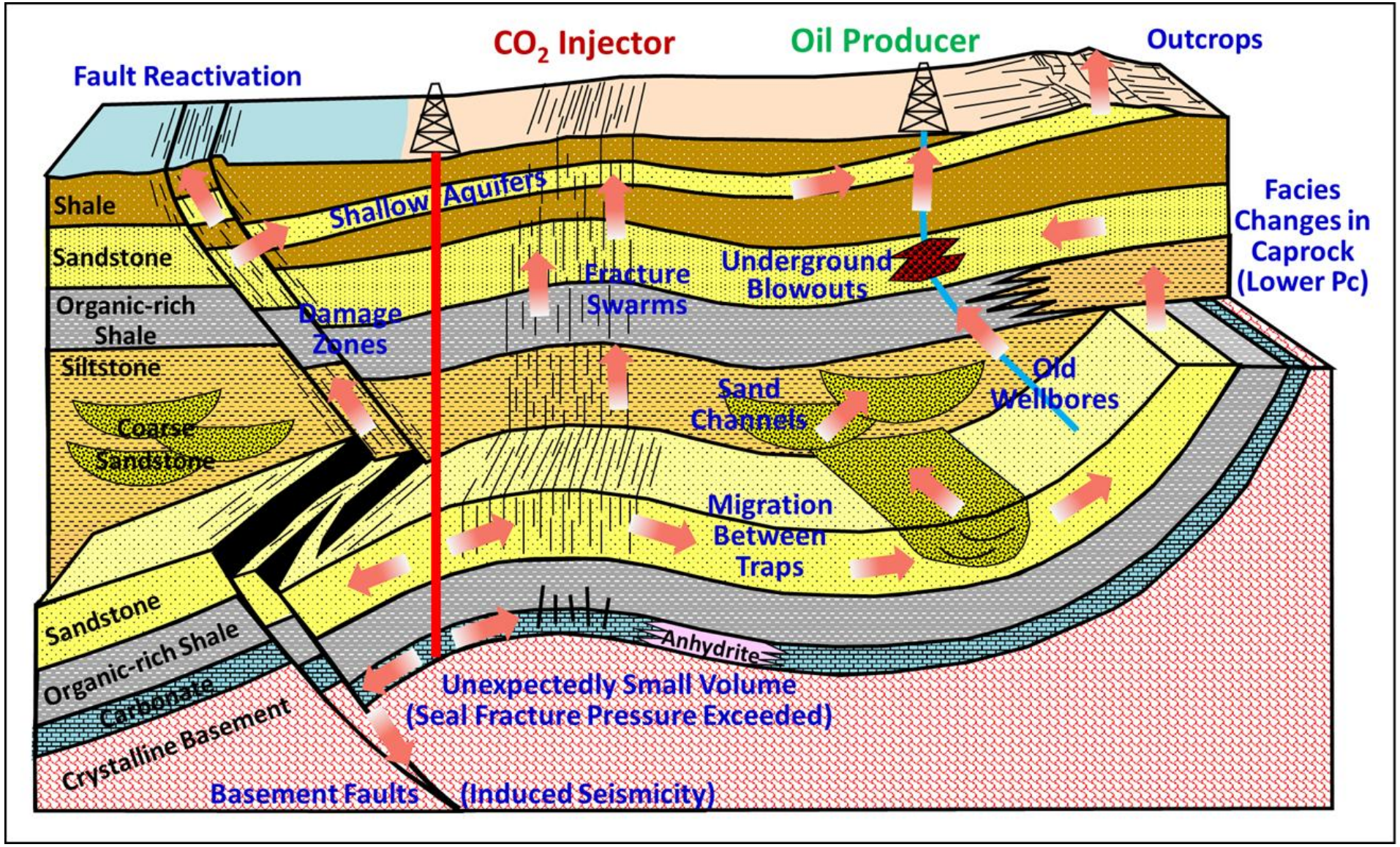
The Quintessa FEP Methodology

Key Source - the Quintessa CCUS Database with 144 questions in 8 Categories:

1. ***Assessment Basis***
2. ***External Factors***
3. ***CO_2 Storage***
4. ***CO_2 Properties, Interactions and Transport***.
5. ***Geosphere***
6. ***Boreholes***
7. ***Near-Surface Environment***
8. ***Impacts***

https://www.quintessa.org/co2fepdb/v2.0.0/

Subsurface FEPs



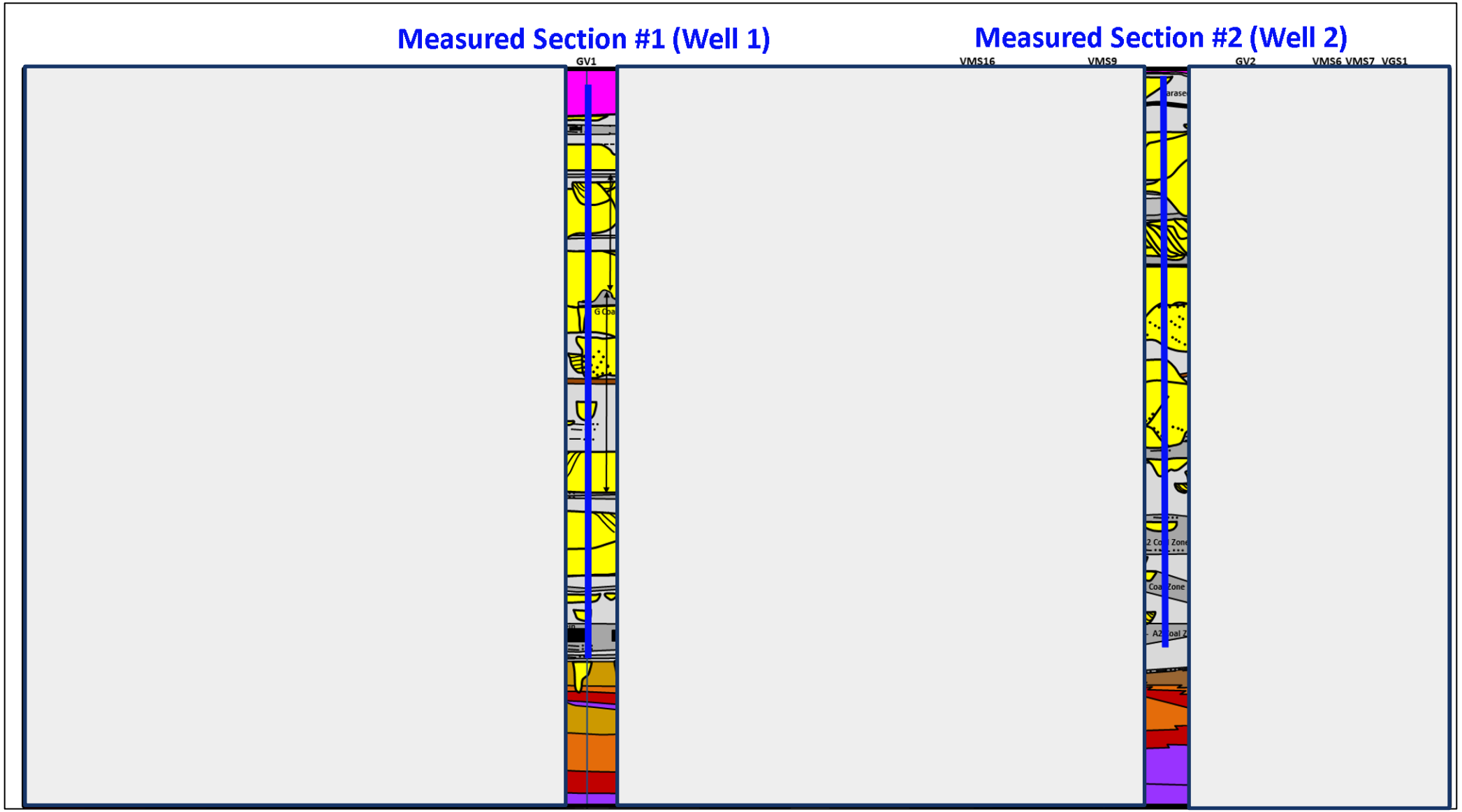
Modified after (Torabi, Gabrielsen et al. 2015)

Rose Scoping Evaluation

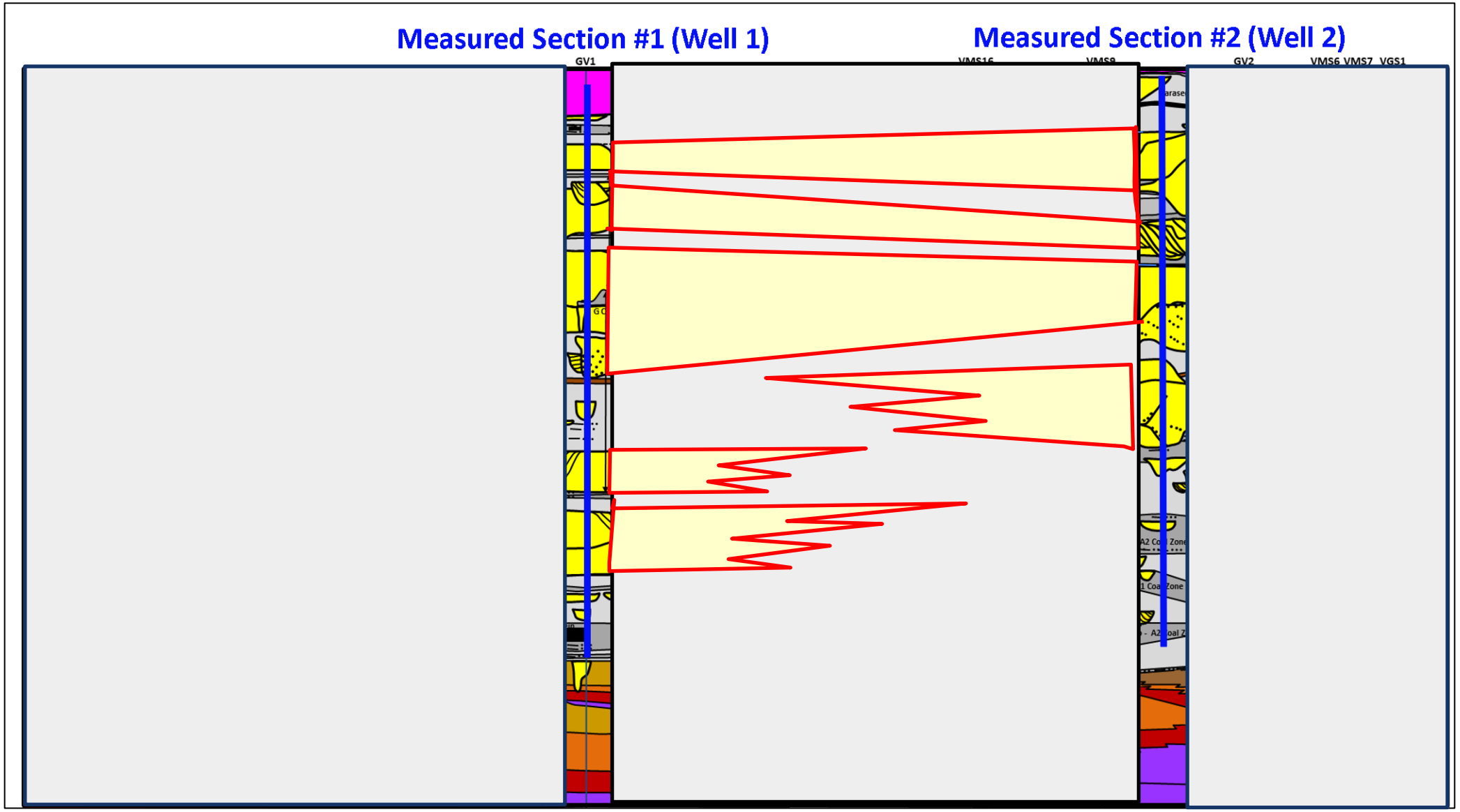
- Developed a set of 36 Questions in 3 Project Phases
  - Pre-Injection 13
  - Injection 18
  - Post-Injection 5
- Asking a set of two-part questions
  - What is the chance that an adverse event will occur?
  - If so, what is the possible impact?
- Example questions and impacts relating to reservoir description include the following: -

Question	Impact
What is the chance that there ARE more stratigraphic compartments in the trap than included in the estimate of sufficient quantity of CO2?	Increased Stratigraphic Compartmentalization reduces storage efficiency and can increase well count and Capex.
What is the chance that the observed plume extent DOES NOT CONFORM with the reservoir model?	Lack of conformance could indicate movement of CO2 outside of storage complex.
What is the chance that there are NOT ENOUGH options such as alternate reservoirs and well locations to maintain injection rates?	Inability to maintain injection rates through operational challenges would affect project economics

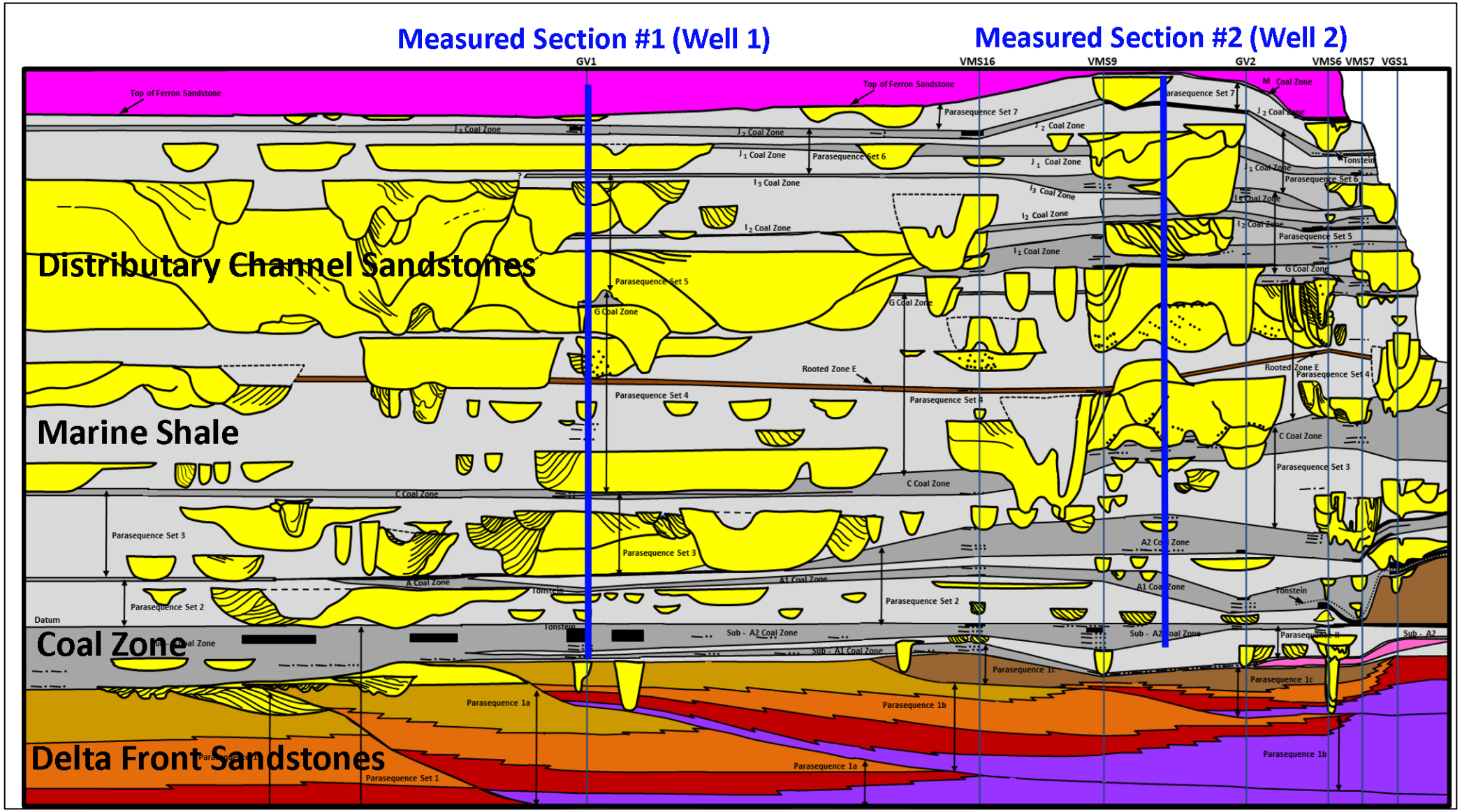
Reservoir Description



Reservoir Description

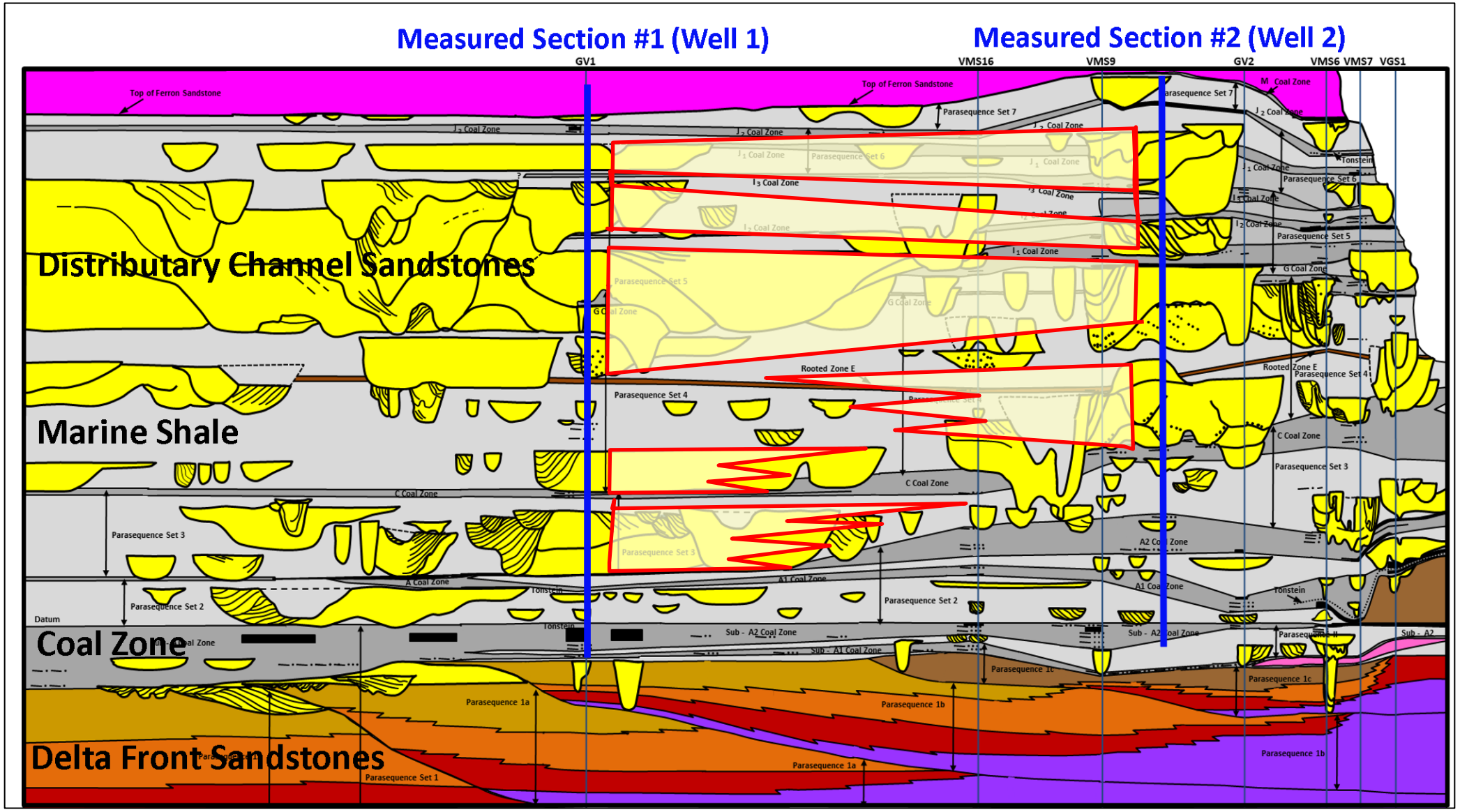


Reservoir Heterogeneity



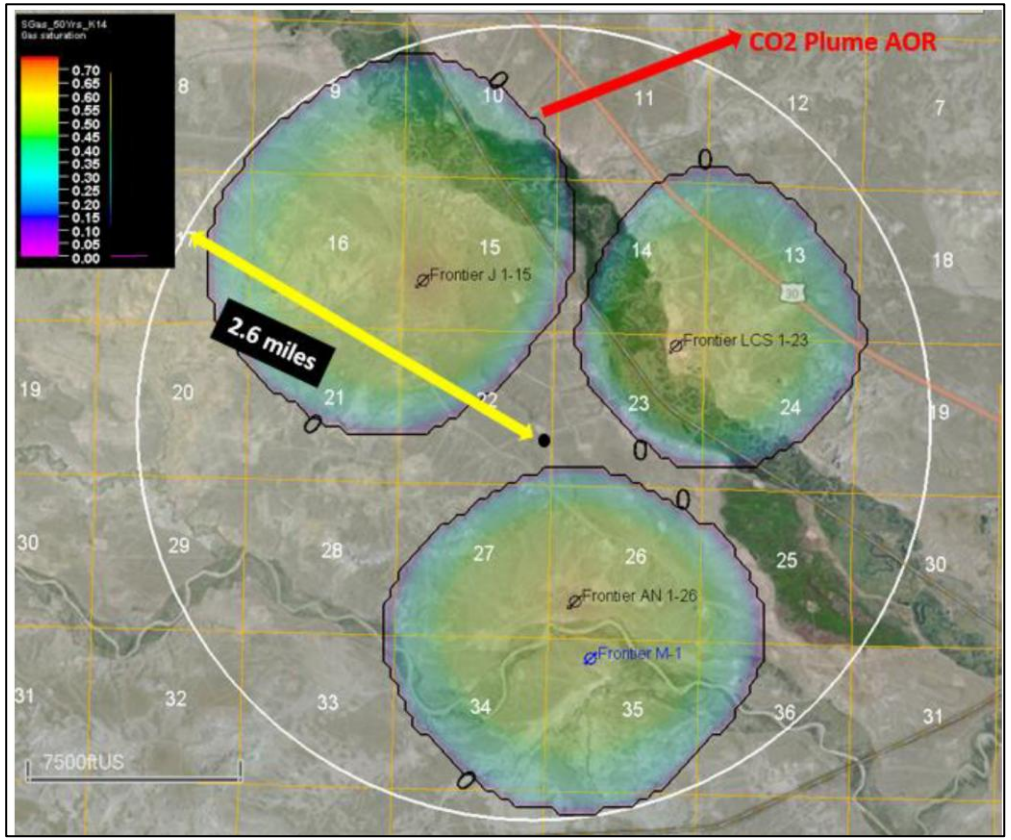
Geology by (Garrison, Bergh et al. 2004)

Reservoir Heterogeneity

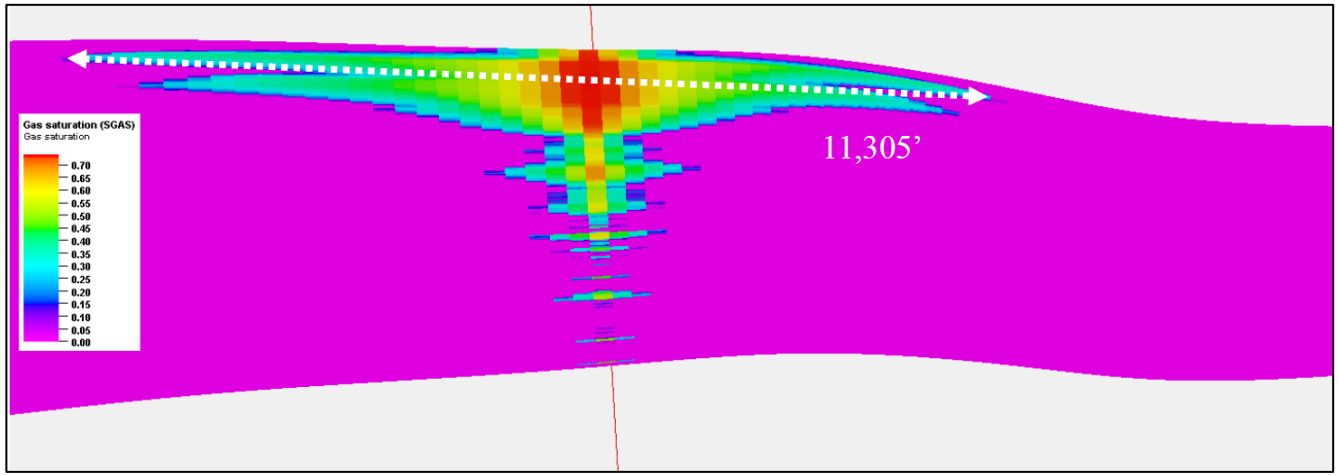


Geology by (Garrison, Bergh et al. 2004)

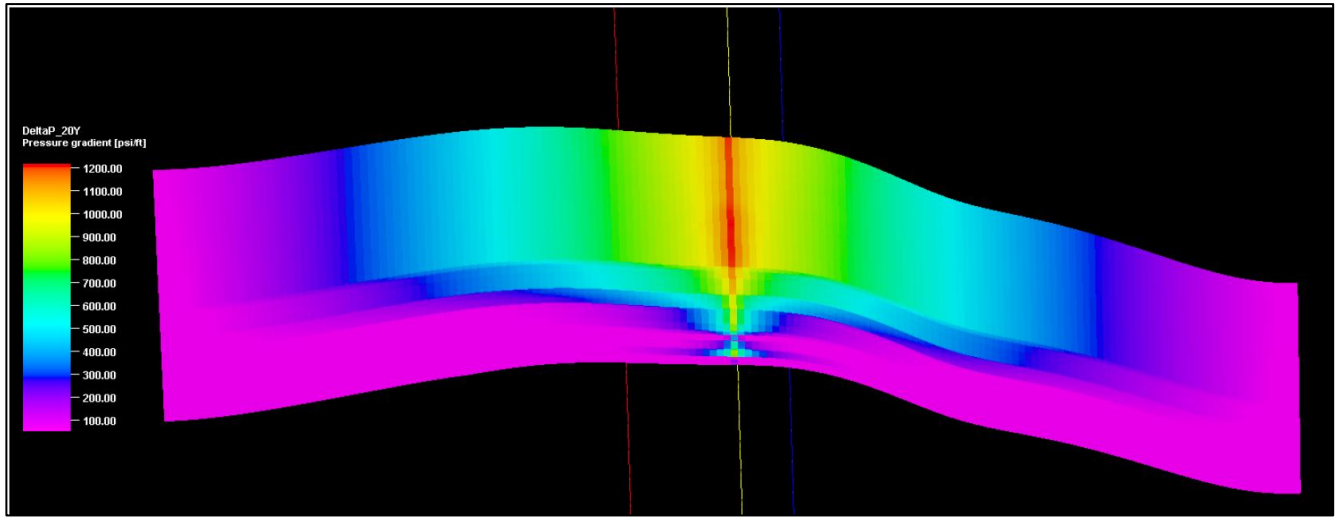
Published Class VI Plume and Pressure Model



Plume Extent after 20 years



Plume Extent after 20 years



Pressure Buildup after 20 years

Future Insights – Annual Frequency Data

e.g. 3 Injection wells in an area with 25 abandoned wells:

Base Frequency Rate = 0.084% per year.

Select 0.1% as the Annual Adverse Event Rate

Operation	Category	Frequency, Average Well	Frequency, Gas Well	Frequency, Oil Well	Unit
Producing Wells (Excluding External Causes)	Blowout	3.7×10^{-5}	7.2×10^{-5}	2.1×10^{-5}	per well year
	Well Release	4.5×10^{-5}	8.8×10^{-5}	2.6×10^{-5}	per well year
Producing Wells (External Causes)	Blowout	2.7×10^{-5}	2.7×10^{-5}	2.7×10^{-5}	per well year
	Well Release	-	-	-	per well year
Gas Injection Wells	Blowout	7.2×10^{-5}	7.2×10^{-5}	-	per well year
	Well Release	8.8×10^{-5}	8.8×10^{-5}	-	per well year
Water Injection Wells	Blowout	9.2×10^{-6}	-	-	per well year
	Well Release	1.1×10^{-5}	-	-	per well year
Abandoned Wells	Blowout/Well Release	2.3×10^{-5}	-	-	per well year

Zero	1:100,000	1:10,000	1:1,000	1:100	1:50	1:20	1:10	1:6.67
0%	0.001%	0.01%	0.1%	1%	2%	5%	10%	15%
0	$1x10^{-5}$	$1x10^{-4}$	$1x10^{-3}$	$1x10^{-2}$	$2x10^{-2}$	$5x10^{-2}$	$1x10^{-1}$	$1.5x10^{-1}$
Absolutely Impossible	Rare Frequency Events	Very Low Frequency Events	Low Frequency Events	Extremely Rare	Very Rarely	Rarely	Very Unlikely	Seldom

Source: IOGP (International Association of Oil & Gas Producers) Risk Assessment Data Directory Blowout Frequencies, Sept 2019

Constant Annual Event Rates

KEY
>9%
1% - 5%
<1%

Increasing Annual Event Rate →

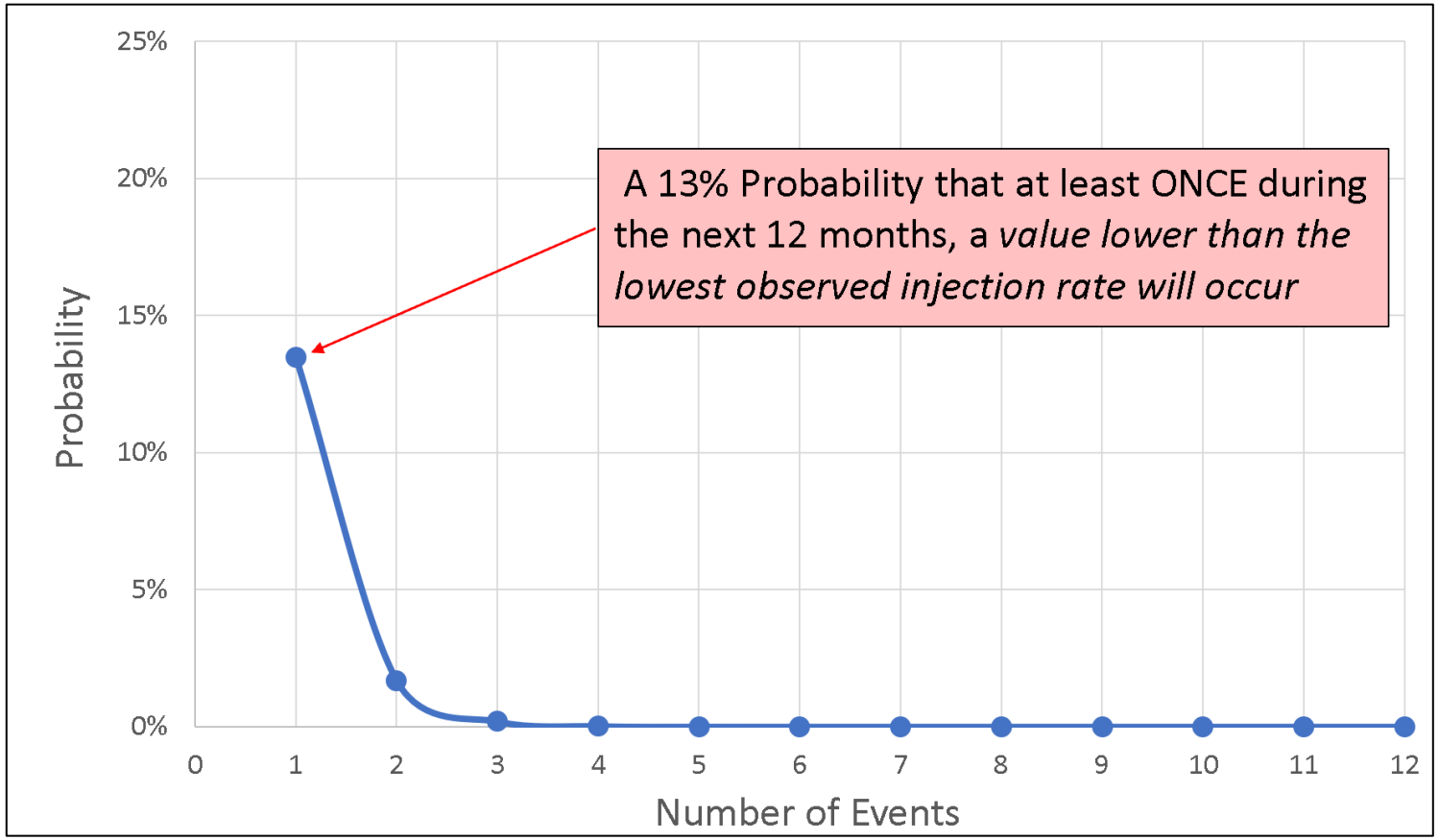
Increasing Time ↓

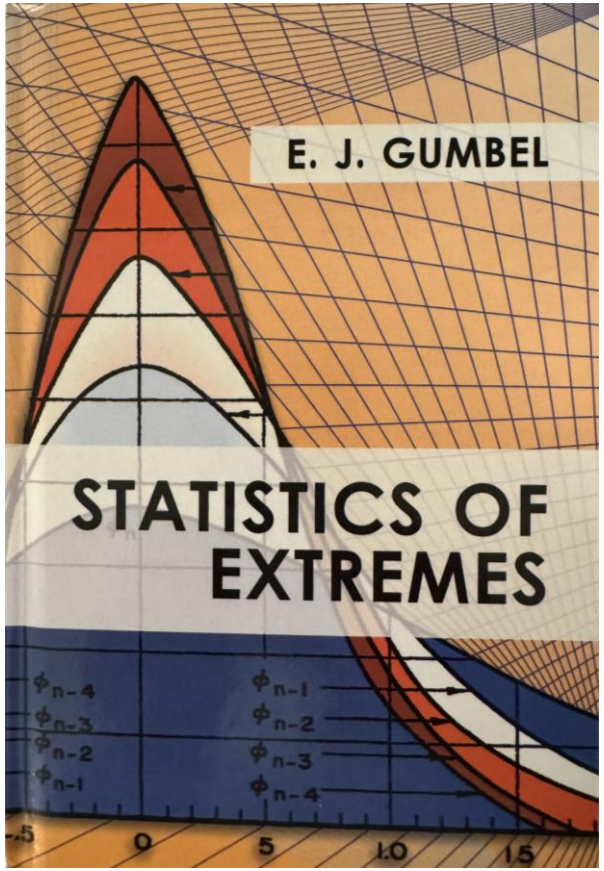
Labels	Case 4	Case 3	Case 2	Case 1
Verbal Risk Description - Annual Chances	*Rare Frequency Events*	*Very Low Frequency Events*	*Low Frequency Events*	*Extremely Rare*
Chance of An Adverse Event Per Year	0.001%	0.010%	0.100%	1.000%
Chance of No Adverse Event Per Year	*99.999%*	*99.990%*	*99.900%*	*99.000%*
Chance of One or More Adverse Events				
in 5 Years	0.01%	0.05%	0.56%	4.86%
in 10 Years	0.02%	0.11%	1.04%	9.63%
in 25 Years	0.03%	0.26%	2.45%	22.19%
in 50 Years	0.06%	0.50%	4.77%	39.64%
in 100 Years	0.11%	1.02%	9.54%	63.61%
in 250 Years	0.25%	2.53%	22.18%	91.82%
in 500 Years	0.49%	4.94%	39.35%	99.32%
in 1000 Years	0.96%	9.56%	63.20%	100.00%
Verbal Risk Description, 1000 Year Outcome	*Extremely Rare*	*Very Unlikely*	*Likely*	*Absolutely Certain*

Modified from (Jenkins, Pestman et al. 2024)

Future Insights - Mathematical

- Gumbel's Method of Exceedances addresses questions including
- What is the Chance that *Future Observations* will be less than past records?





Future Insights – Delphi Methods / Expert Judgement

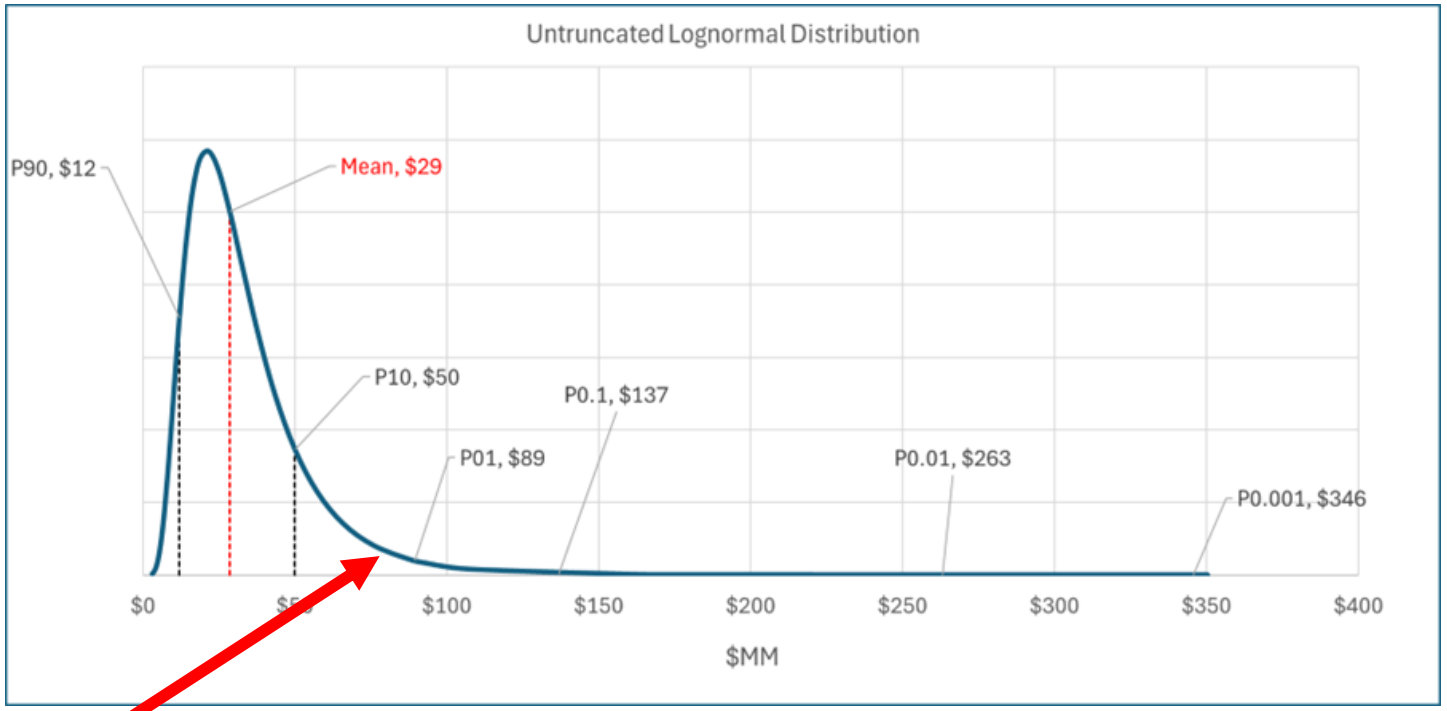
- Superforecasters* performance was consistently impressive. They consistently beat everything from financial markets to trained intelligence analysts with access to top secret information.
- Superforecasters are clever, on average, but by no means geniuses.
- People were classified into two categories:
  - **Hedgehogs**, whose understanding of the world depends on one or two big ideas, and
  - **Foxes**, who think the world is too complicated to boil down into a single slogan.
    - Superforecasters are drawn exclusively from the ranks of the ***foxes***…..
- Superforecasters have a “growth mindset”: a mix of determination, self reflection and willingness to learn from one’s mistakes.
  - The best forecasters were less interested in whether they were right or wrong than in why they were right or wrong. They were always looking for ways to improve their performance.
  - In other words, *prediction is not only possible, it is teachable*.

***Superforecasting: The Art and Science of Prediction** (Philip Tetlock and Dan Gardner.)

*Schoemaker, P. J. and P. E. Tetlock (2016). "Superforecasting: How to upgrade your company’s judgment." Harvard Business Review **94**(5): 73-78.

Monetary Impact

- Wide range of monetary values from Incidental to Catastrophic
- Model assumption – Untruncated Lognormal Distribution
- Includes extreme values
- The 1 in 100,000 impact may occur in the simulation



Scale of Monetary Impact	P90 - P10 $MM
Zero	0.0 - 0.0
Incidental	0.6 - 4.0
Minor	6.0 - 12.0
Moderate	12.0 - 50.0
Major	60.0 - 100.0
Severe	150.0 - 600.0
Catastrophic	600.0 - 2,000.0

Impact Categories and P90 – P10 ranges are user-defined

Computational

For each Question:

- Randomly sample Chance of an adverse event for each year 1 to 1,000
- If an adverse event occurs, randomly sample the Impact Distribution for that event

Then

- Aggregate all occurrences and impacts for each year in a single trial
- Repeat for sufficient trials to sample rare & very low frequency events
  - 1,000 to 40,000 trials
    - Data Arrays for further analysis (1,000 years x 5,000 rows = 5,000,000 data points)
  - Annual and Cumulative Risk charts
  - Undiscounted and Discounted values
    - Discount rate can be used to help estimate the bond amount needed to fund a selected probability level

Annual Risk $MM Undiscounted

In Year 30, during the Peak Risk period there are a range of possible outcomes: -

Mean outcome of ~$5MM

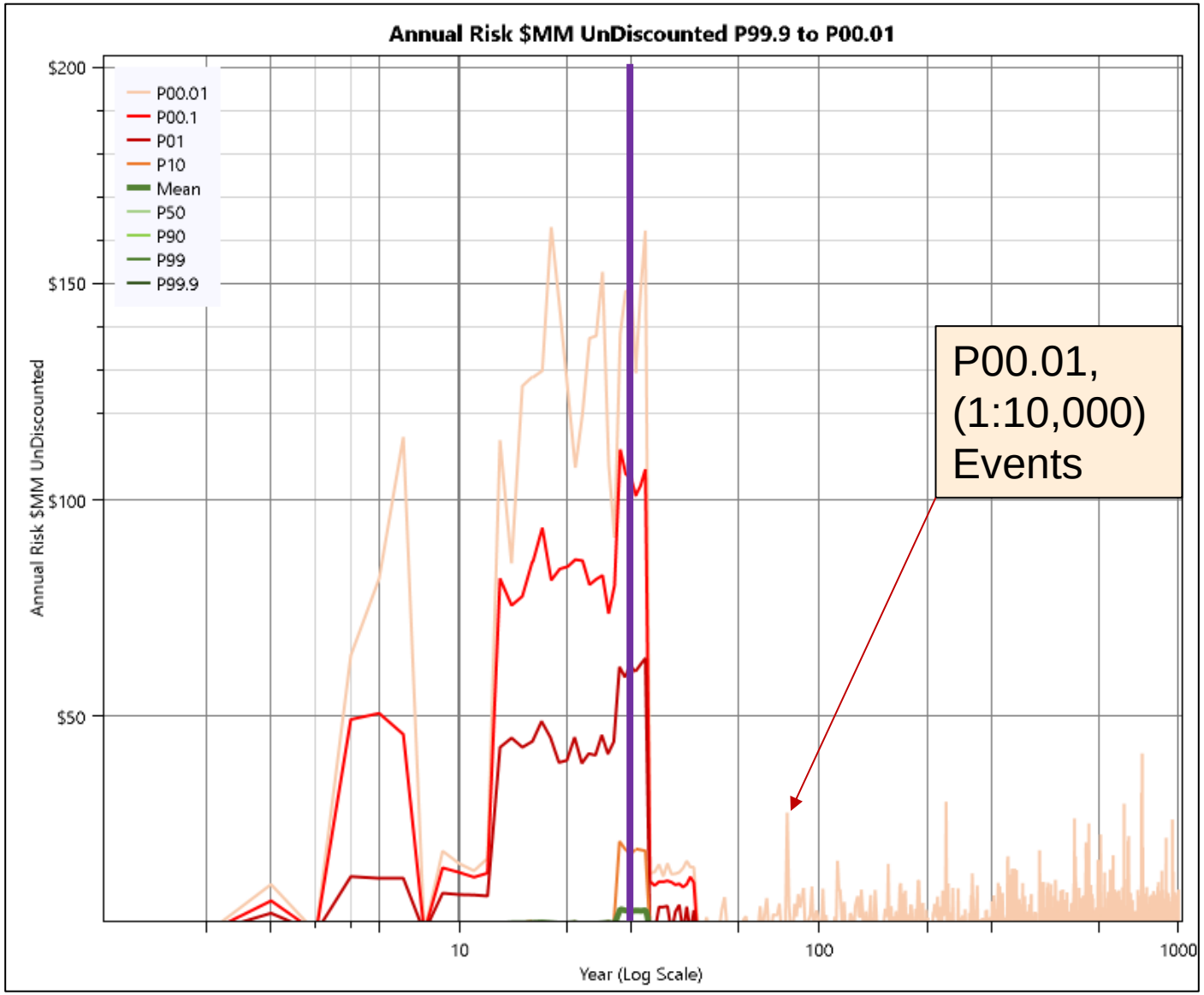
P10 outcome of ~$18MM

P01 outcome of ~$62MM

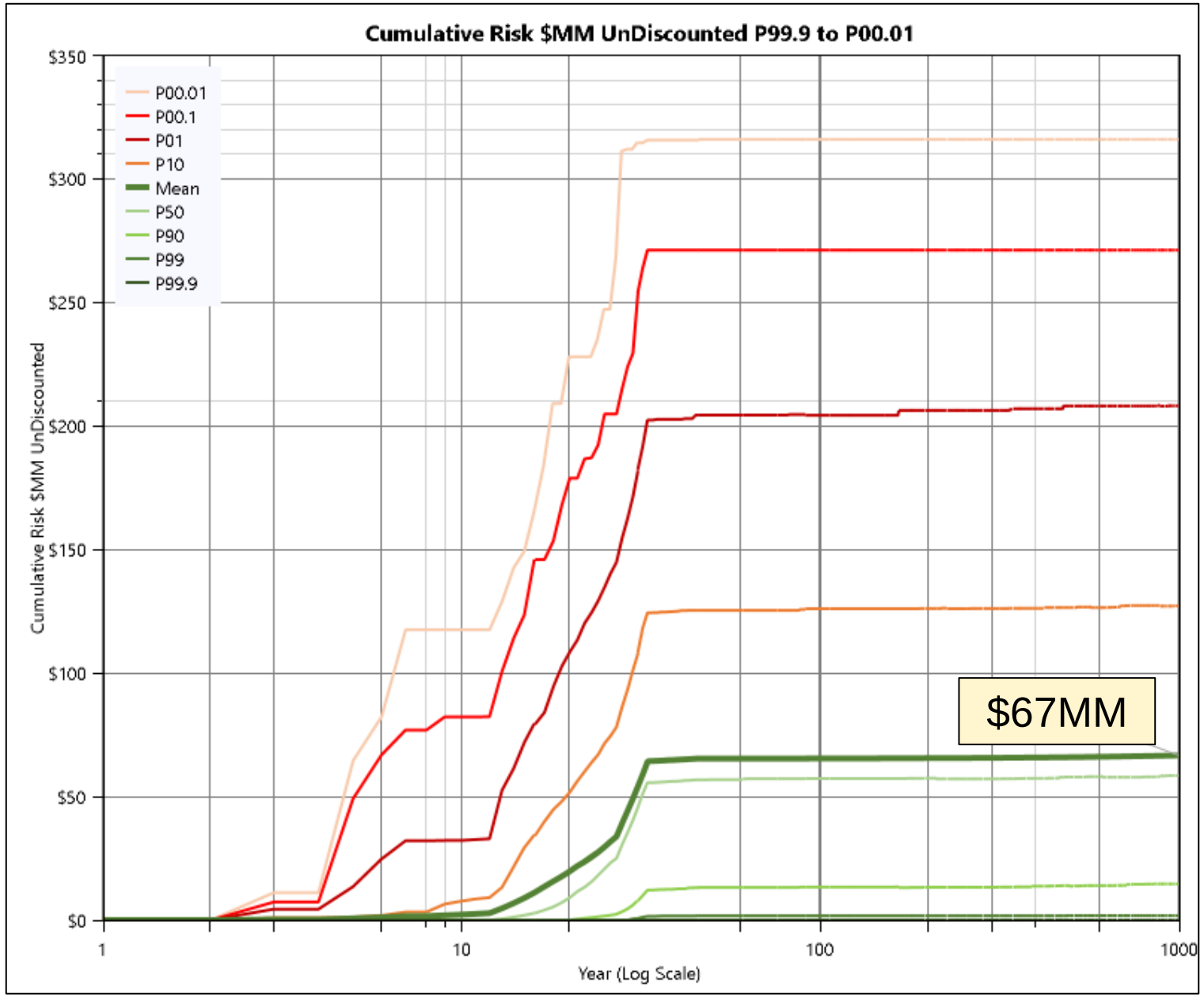
P00.1 outcome of ~ $105 MM

P00.01 outcome of ~$148MM

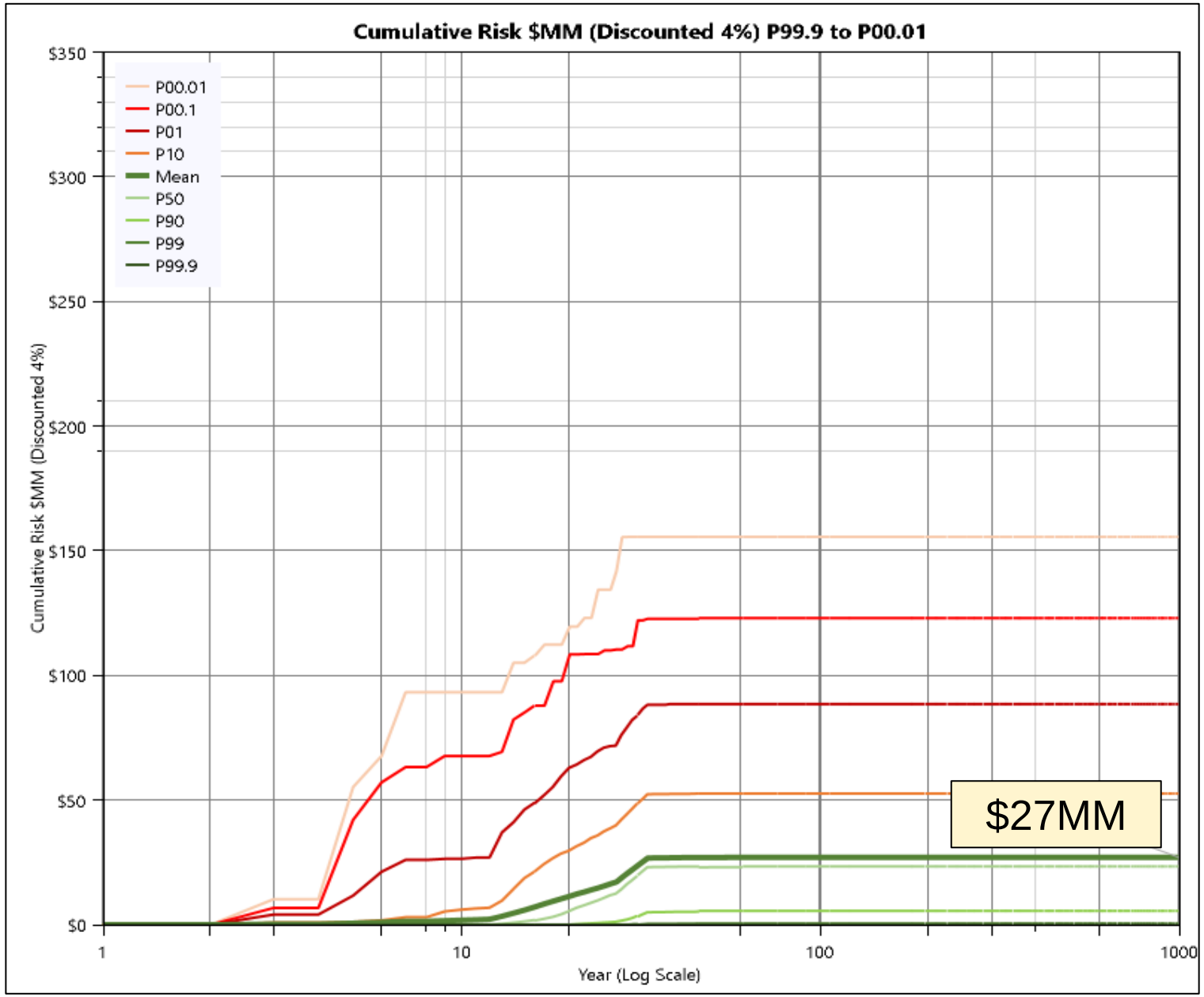
Mean project risk is low, but the chance of extreme events can't be ignored.



Cumulative Risk $MM, Undiscounted



Cumulative Risk $MM, Discounted at 4%



Designing the MMV program

Measurement, Monitoring and Verification

Traffic light scheme to help communication

Focus on the risk items with the highest exposure

Are there mitigations in place to prevent occurrence?

What are the early signals that could lead to an adverse event?

Can the MMV plan detect those signals?

What is the contingency plan if the adverse event occurs?

					Chance-weighted Mean Impact Exposure ($MM)		Chance of one or more events in 1000 Years		Mean Impact Exposure ($MM)	
Index	Project Phase	Topic	Sub-Topic	Question	Value	Rank	Value	Rank	Value	Rank
16	Injection	Reservoir (Dynamic)	Storage Effectiveness	What is the chance that there are NOT ENOUGH options such as alternate reservoirs and well locations...	17.532	1	0.649	2	27.014	5
17	Injection	Injection	Reservoir	What is the chance that the target injection rates to meet Contracted Volumes are NOT achieved?	12.203	2	0.447	3	27.276	4
19	Injection	Injection	Sustained Rate	What is the chance that the injection rate will NOT meet the goals set to store a sufficient quantity of CO2 in th...	8.472	3	0.317	5	26.691	6
20	Injection	Injection	Displaced Fluids	What is the chance that displaced fluids MOVE BEYOND the storage complex DURING Injection?	5.512	4	2.680	1	2.057	21
27	Injection	Infrastructure	Transport Facilities	What is the chance the CO2 Transport system NOT will deliver CO2 at the contracted minimum rate?	4.646	5	0.208	7	22.316	10
21	Injection	Injection	Plume / Pressure Front	What is the chance that the plume and associated pressure front EXTEND OUTSIDE of the storage compl...	3.356	6	0.119	10	28.106	3
26	Injection	Infrastructure	Capture Facilities	What is the chance the Capture facilities will NOT deliver CO2 at the contracted minimum rate?	2.361	7	0.276	6	8.541	14
22	Injection	Injection	Wellsite Facilities	What is chance that the existing and future wells WILL leak DURING Injection?	2.281	8	0.078	11	29.164	1
15	Injection	Reservoir (Dynamic)	Storage Effectiveness	What is the chance that the observed plume extent DOES NOT CONFORM with the reservoir model?	1.906	9	0.077	12	24.626	8
14	Injection	Reservoir (Dynamic)	Storage Effectiveness	What is the chance that the connected reservoir pore volume is NOT sufficient to store the Contracted Mass?	1.808	10	0.076	13	23.911	9
29	Injection	Infrastructure	MMV	What is the chance the MMV infrastructure will NOT be in place and robust enough to last until hand-over?	1.707	11	0.437	4	3.909	19
31	Post-Injection	Retainment	Plume / Pressure Front	What is the chance that the plume and associated pressure front EXTEND OUTSIDE of the storage compl...	1.600	12	0.184	9	8.688	13
12	Pre-Injection	Plan	Technical Maturity	What is the chance that the project will NOT be technically mature, executable, and will meet the start...	0.876	13	0.030	18	28.816	2
25	Injection	Injection	Social Acceptance	What is the chance that HSE breaches WILL ERODE OR BREAK social acceptance DURING Injection?	0.811	14	0.201	8	4.040	18
13	Pre-Injection	Plan	Regulatory	What is the chance that all regulatory and environmental approvals are NOT in place and will DE...	0.509	15	0.057	14	8.968	12

Record Keeping

“If it happened, you have to admit it was possible.” R. Megill

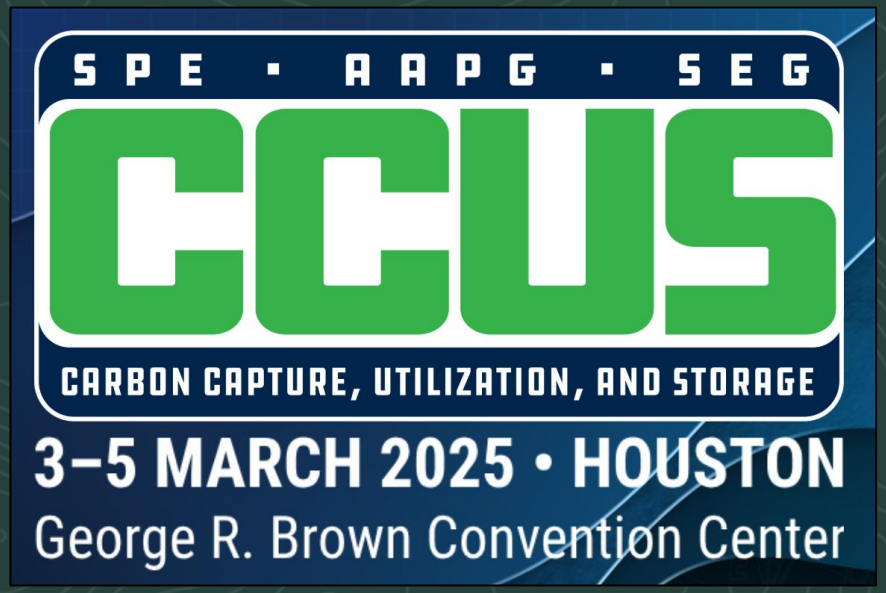
- Calibrating chance assessments and impacts requires consistent and thorough post-appraisal
- A prerequisite of post-appraisal is record keeping
  - What was the data used and the thinking about this possible event?
  - Was it recognized as a possibility?
- Do you have a robust record-keeping strategy including?
  - Authors
  - Date-Stamped Charts
  - Database
  - Print copies

Summary

- The annual rates of Low Frequency Events can be estimated by:-
  - Applied Frequency Data
  - Mathematical Models
  - Expert Judgement
- Monetary Impact is uncertain and can be expressed as a range
  - Distributions should not be bounded on the upside
- Robust MonteCarlo simulation is needed to illuminate Low Frequency, High Impact Events
  - Aggregation of annual results years 1-1,000
  - Thousands of trials
- Focus Measurement, Monitoring, and Verification on highest risk issues
  - Can early signals be detected and mitigated?
  - Contingency plans
- Record Keeping
  - Needed to calibrate the annual rates

References

- Jenkins, C., et al. (2024). "Long-term risk assessment of subsurface carbon storage: analogues, workflows and quantification." Geoenergy **2**(1): geoenergy2024-2014.
- Garrison, J. R., Jr., et al. (2004). High-Resolution Depositional Sequence Stratigraphy of the Upper Ferron Sandstone Last Chance Delta: An Application of Coal-Zone Stratigraphy. Regional to Wellbore Analog for Fluvial-Deltaic Reservoir Modeling: The Ferron Sandstone of Utah, American Association of Petroleum Geologists. **50:** DOI 10.1306/St50983
- Quintessa (2020). The Generic CO_2 Geological Storage FEP Database v2.0.0, Quintessa https://www.quintessa.org/co2fepdb/v2.0.0/.
- Schoemaker, P. J. and P. E. Tetlock (2016). "Superforecasting: How to upgrade your company's judgment." Harvard Business Review **94**(5): 73-78.
- Tetlock and Gardener, (2016) Superforecasting: The Art and Science of Prediction Crown Publishing
- Torabi, A., et al. (2015). "Strain localization in sandstone and its implications for CO2 storage." First Break **33**(7).
- Woo, G. (2011). Calculating catastrophe, World Scientific.



ROSE
SUBSURFACE ASSESSMENT

ROSE
SUBSURFACE ASSESSMENT

petercarragher@roseassoc.com