ROSE SUBSURFACE ASSESSMENT

FORCE

Quantitative Risking of CCS Projects with Legacy Wells

FORCE CCS Legacy Wells Seminar, 20 November 2025

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Talk Outline

- **Introduction** & **definitions**
- A structured **methodology** for quantitative analysis - CarbonSureRA
- **Case Study 1** – Full subsurface assessment of CCS project (UK North Sea)
    - Project set-up, methodology, question definition
    - Results snapshot
- **Case Study 2** – Focused assessment of legacy and injection wells (based on real project)
    - Project set-up, methodology, question definition, examples of events and impacts
    - Results snapshot & mitigation considerations
- **Conclusions**

Introduction

- CCS projects require containment that extends far beyond operational phase of projects
- Future adverse events may significantly affect project timing and costs
- Qualitative methods fail to capture impact of timing and magnitude, e.g.:
  - Risk Registers
  - Bow-tie diagrams
  - Risk Matrices
- Quantitative Risk Assessment - Objectives:
  - To identify and characterize adverse events and their associated risk profile
  - To facilitate monitoring, mitigation and contingency planning
  - To enhance management of risk and capital exposure and successful project outcomes
  - To illuminate low-frequency / high impact adverse events that may occur in the near to long-term future – beyond the range of normal contingencies
- But first some definitions and things to consider……

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Definitions for a Quantitative Risk Analysis

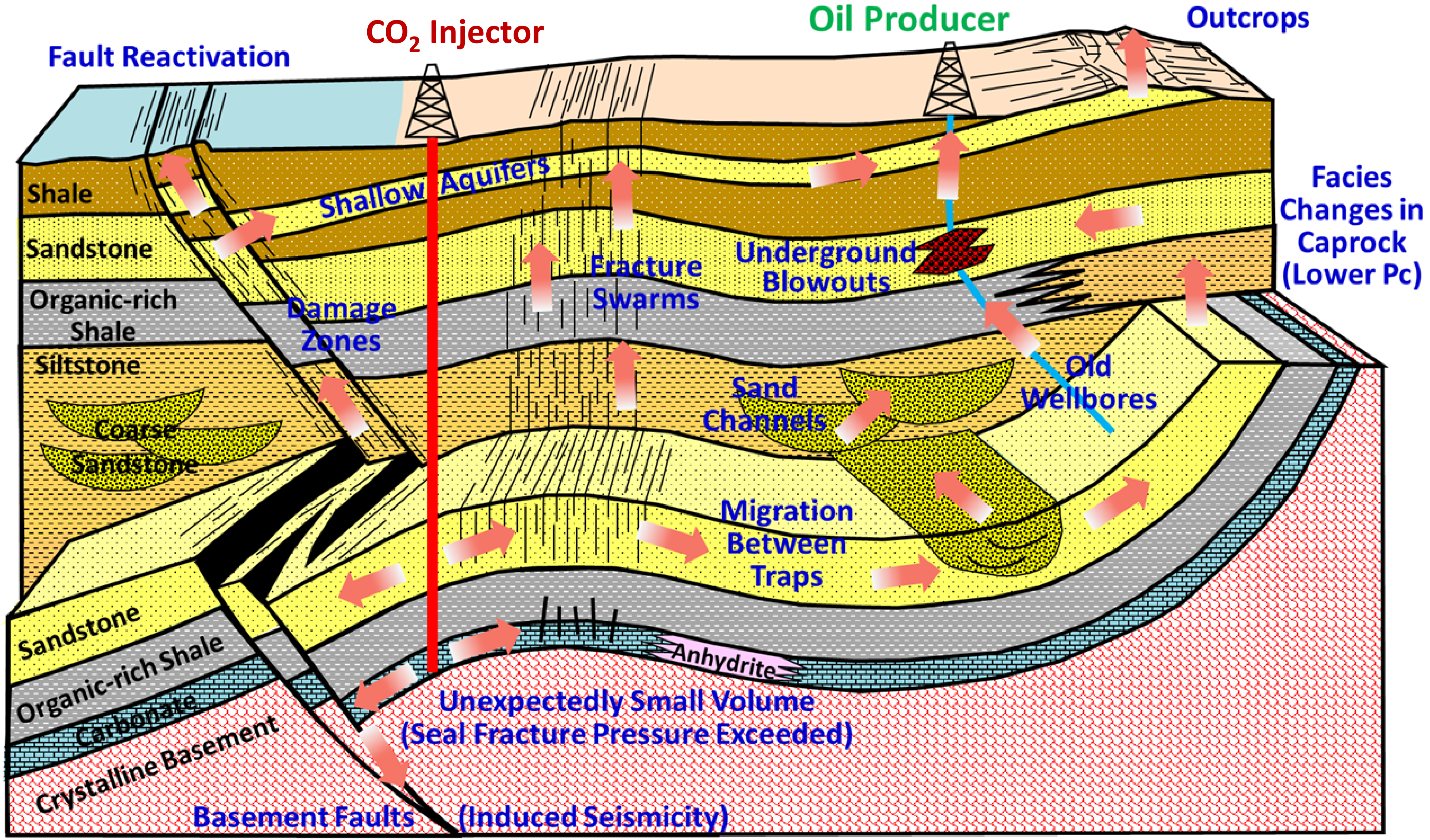
- **Adverse Event**
  - An unfavourable occurrence negatively impacting the project
  - *Features, Events & Processes (FEP) Methodology*

- **Probability of Occurrence**
  - The annual chance that an adverse event will occur
    - *Note – this is not chance of failure*

- **Monetary Impact**
  - A range of possible dollar costs, if an adverse event occurs

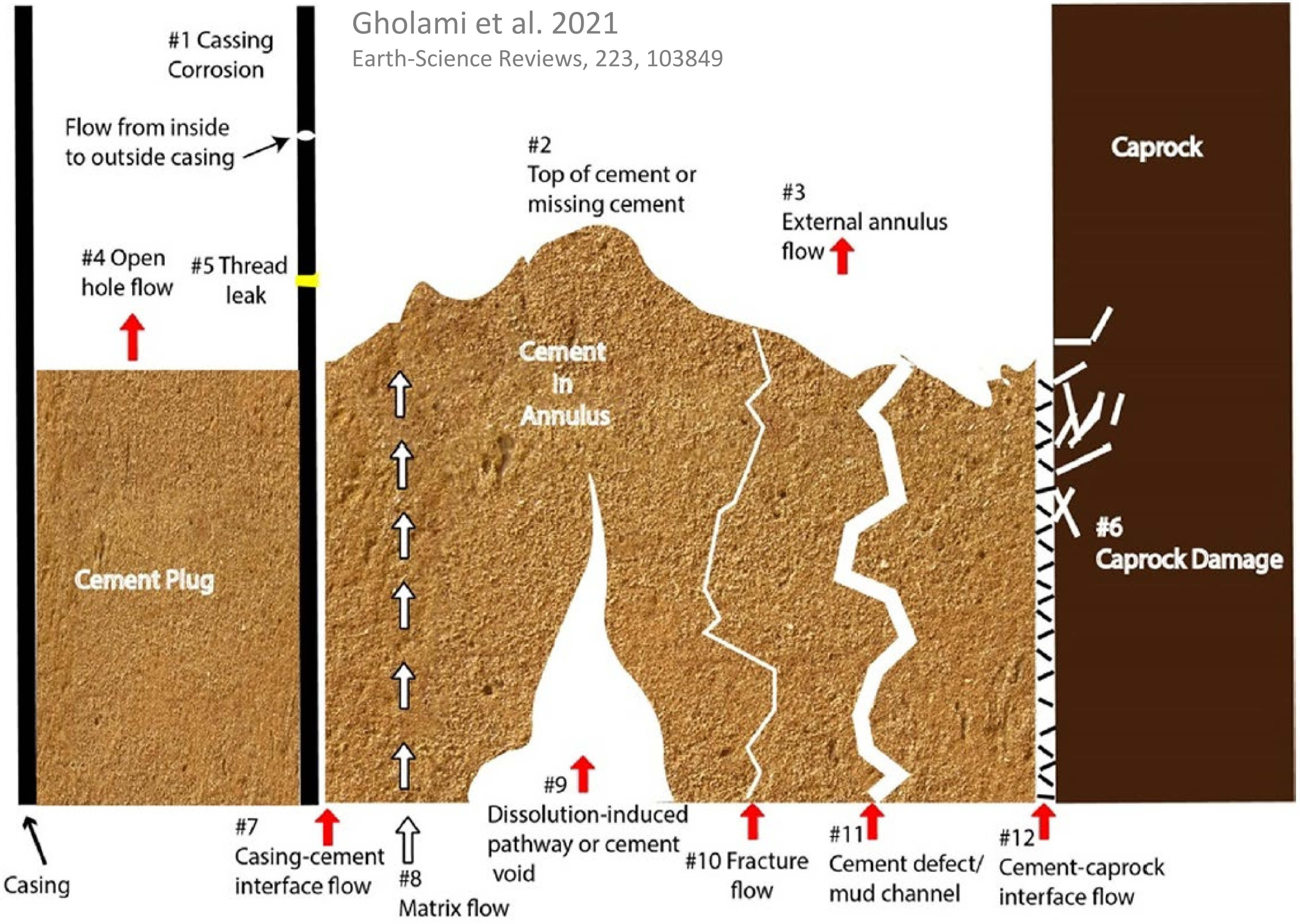
- **Risk**
  - The potential for loss, expressed in monetary terms but also extends to loss of life, loss of reputation, loss of license to operate and legal peril (e.g. negligence)

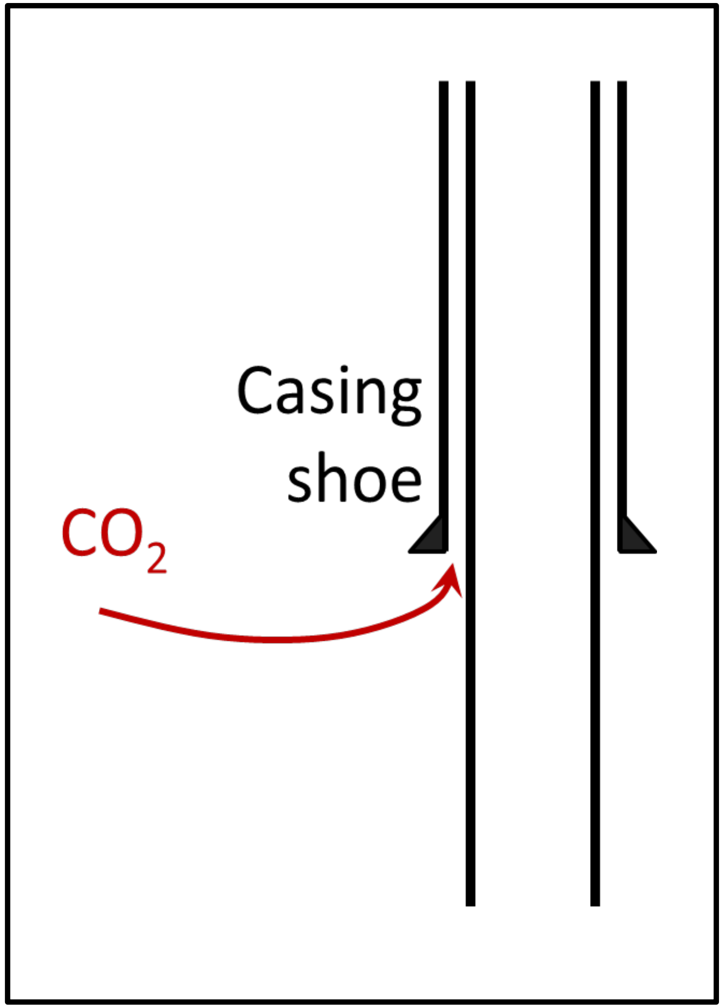
Subsurface Features, Events & Processes (FEPs)



Modified after (Torabi, Gabrielsen et al. 2015)

Wells Features, Events & Processes (FEPs)



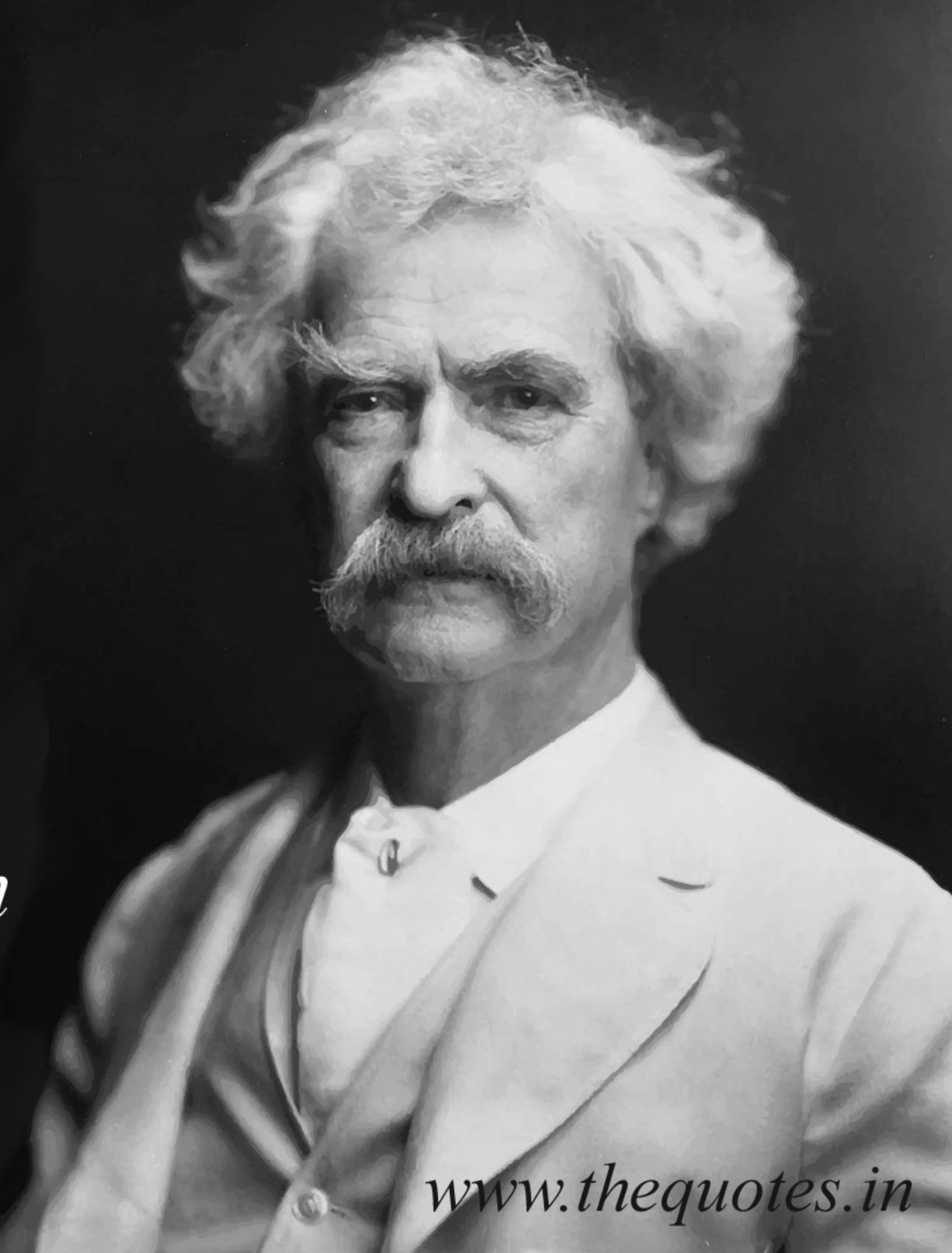


Two Dimensions of Risk & Uncertainty

- Epistemic Risk & Uncertainty:
    - Can increase knowledge of the system with additional data & analysis
    - E.g. reservoir property estimations can be improved by careful analysis of additional wells
- Aleatory Risk & Uncertainty:
    - Inherently random, cannot be reduced by technical work. Can only be observed and estimated
    - E.g. natural seismicity prediction, or well failure rates
    - Frequency data from relevant analogs can inform estimates
- Both types need to be considered – deterministic models are insufficient

It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so.

Mark Twain



We need to keep our apertures wide and consider all the impactful risks over a project’s life!

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Low Frequency, High Impact Events

- 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)

Combining the Components in a Quantitative Risk Analysis

For each Question:

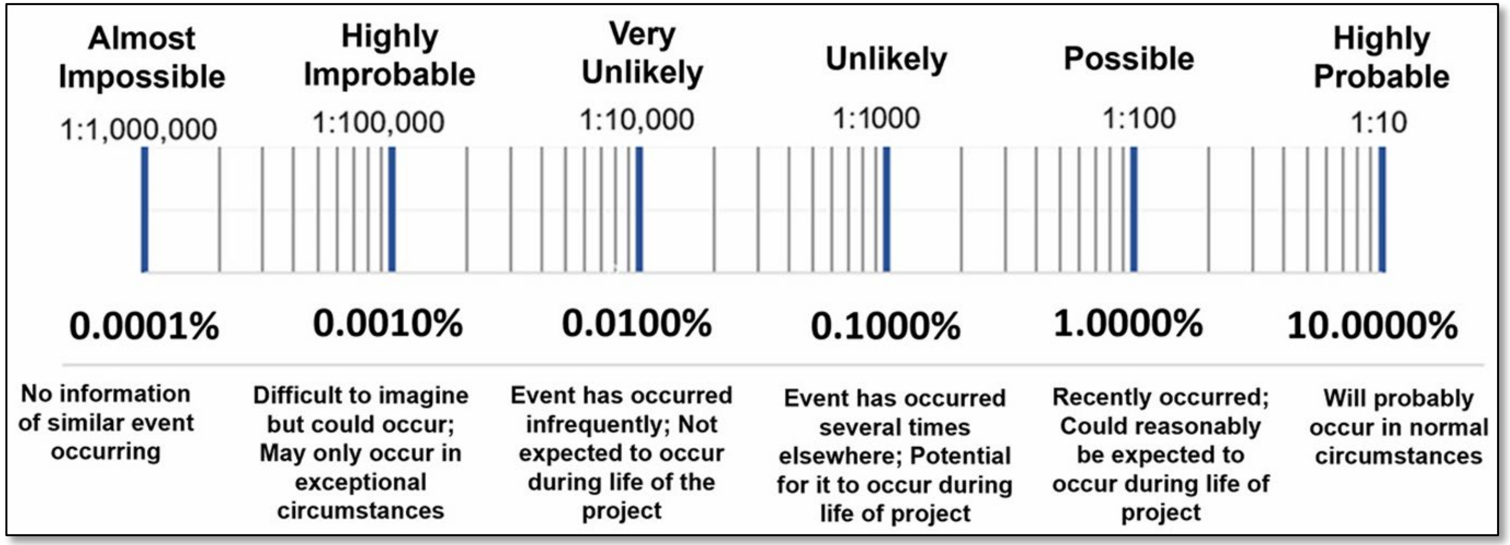
- Randomly sample chance of each adverse event occurring in each year (1 to 1,000)
- If an adverse event occurs, randomly sample the Monetary Impact Distribution for that event

Then:

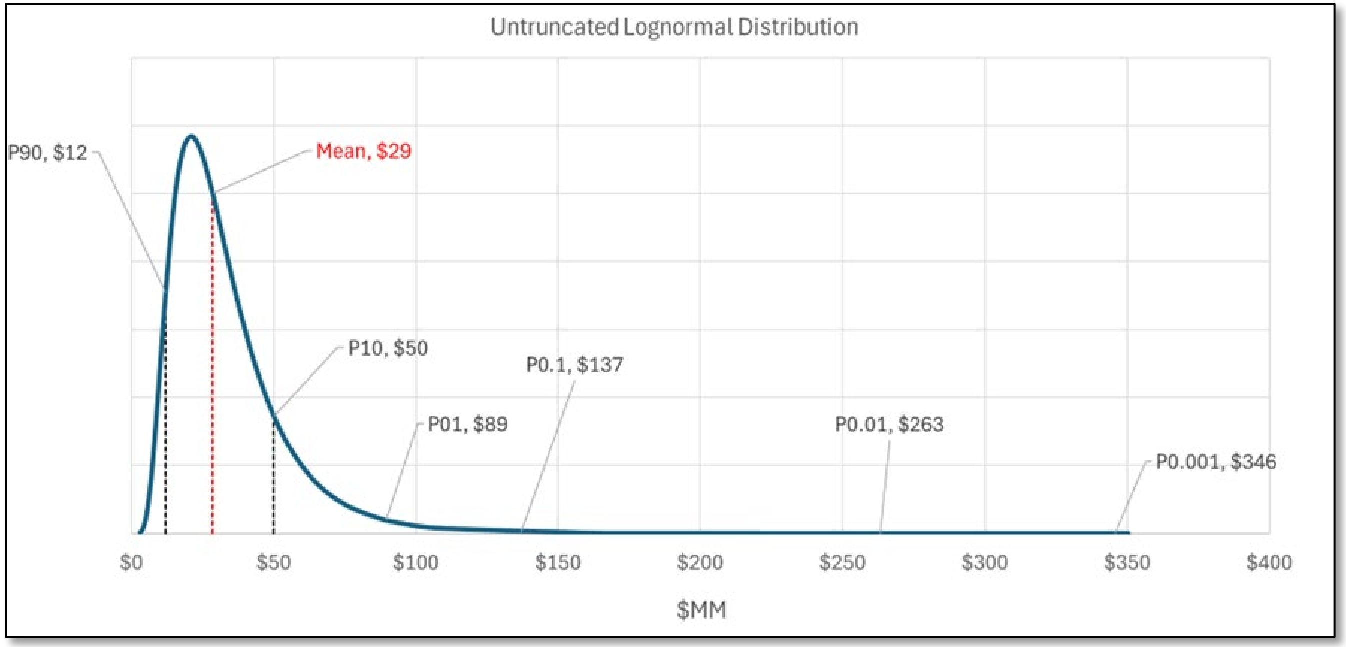
- Aggregate all occurrences and impacts for each year in a single trial
- Conduct sufficient trials to sample rare & very low frequency events
  - 1,000 - 40,000 trials
  - Determine mean risk and associated percentiles
  - Annual and Cumulative Risk charts
  - Undiscounted and Discounted values

Mean Risk = Frequency of Occurrence x Mean Impact

- For low annual frequency events and long timeframes
- The scale shown here links numerical values to descriptive risk terms



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



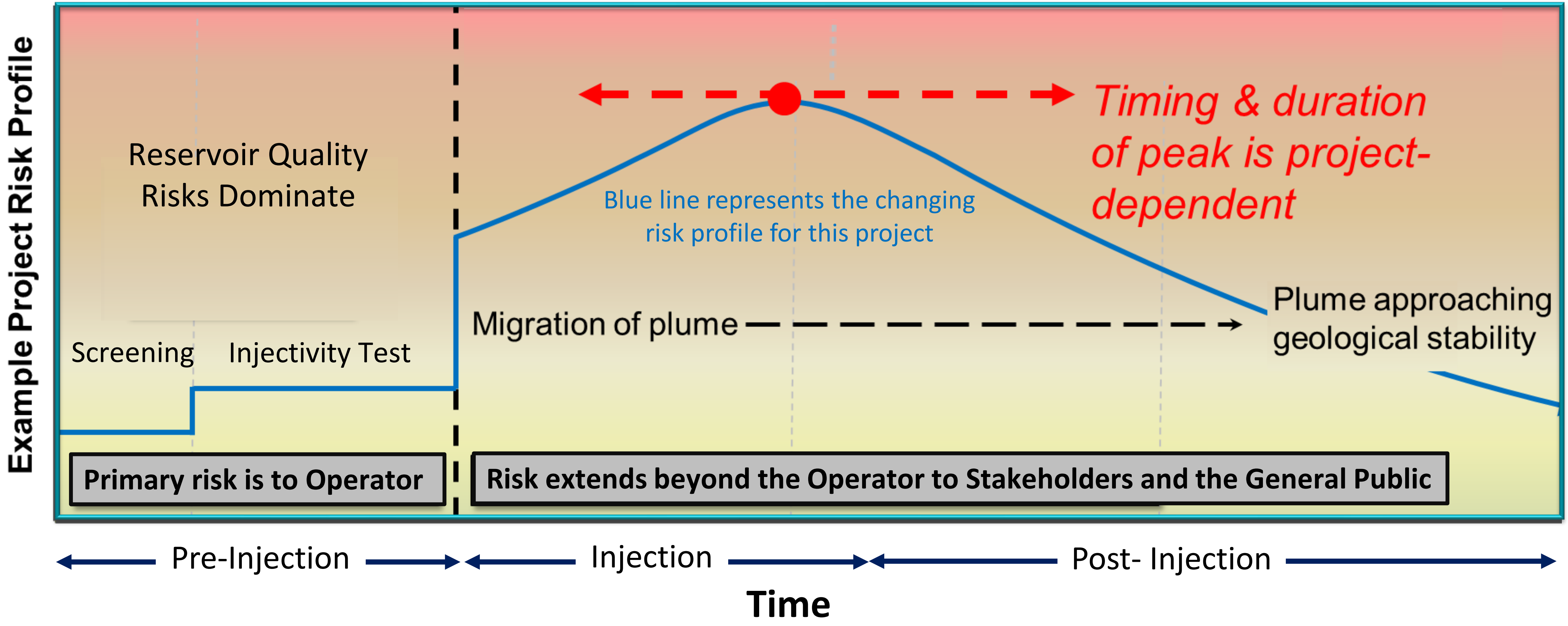
Where do we get Frequency Data from?

1. Statistical data from injection projects
2. Analog data from CCS projects
3. Reservoir model: make it fail (evaluate uncertainties within the model)
4. Expert judgment

Operation	Category	Frequency, Average Well	Frequency, Gas Well	Frequency, Oil Well	Unit
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

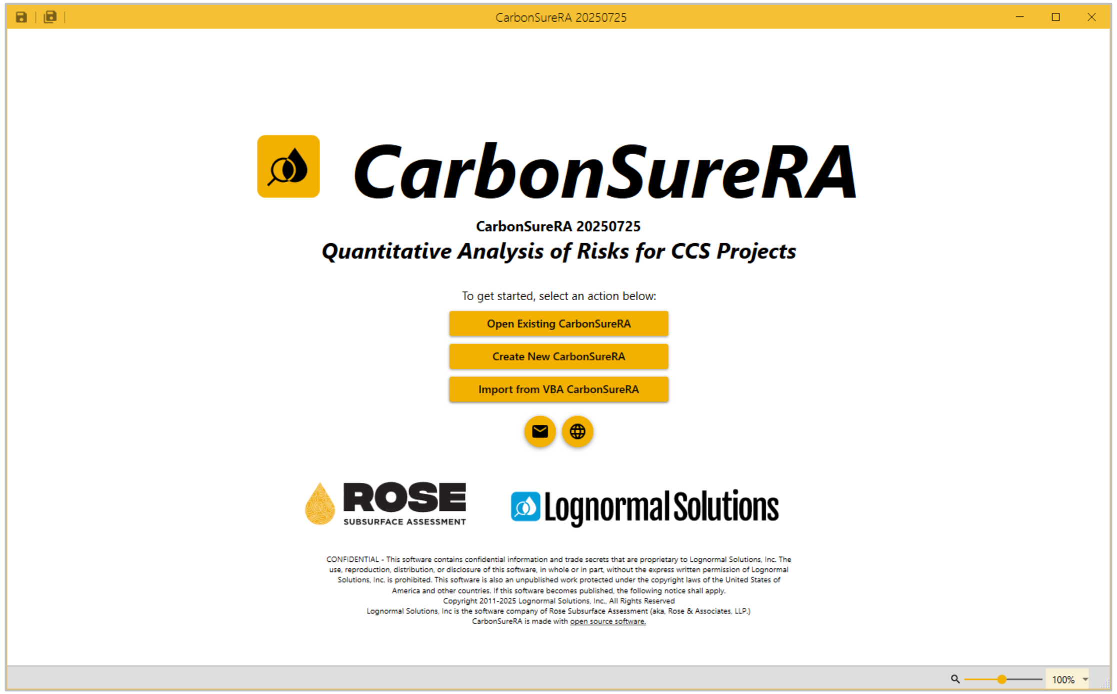
Source: IOGP (International Association of Oil & Gas Producers) Risk Assessment Data Directory Blowout Frequencies, Sept 2019

Peak Risk Relative to Project Life



What are some of the ways we can identify and mitigate these risks?

Quantitative Analysis - CarbonSureRA



- Risk Register to identify “adverse events” with potential to cause losses or project cessation
- CarbonSureRA converts a qualitative risk register to a quantitative assessment of project risks, using:
  - Chance of Occurrence
  - Monetary Impact
- Calculates the magnitude and timing of risk for the project

- **Two case studies analysed:**
  1. Risk assessment of CCS project – focus on subsurface, plus high-level capture & transport risks
  2. Detailed focus study on legacy and injection well containment risks

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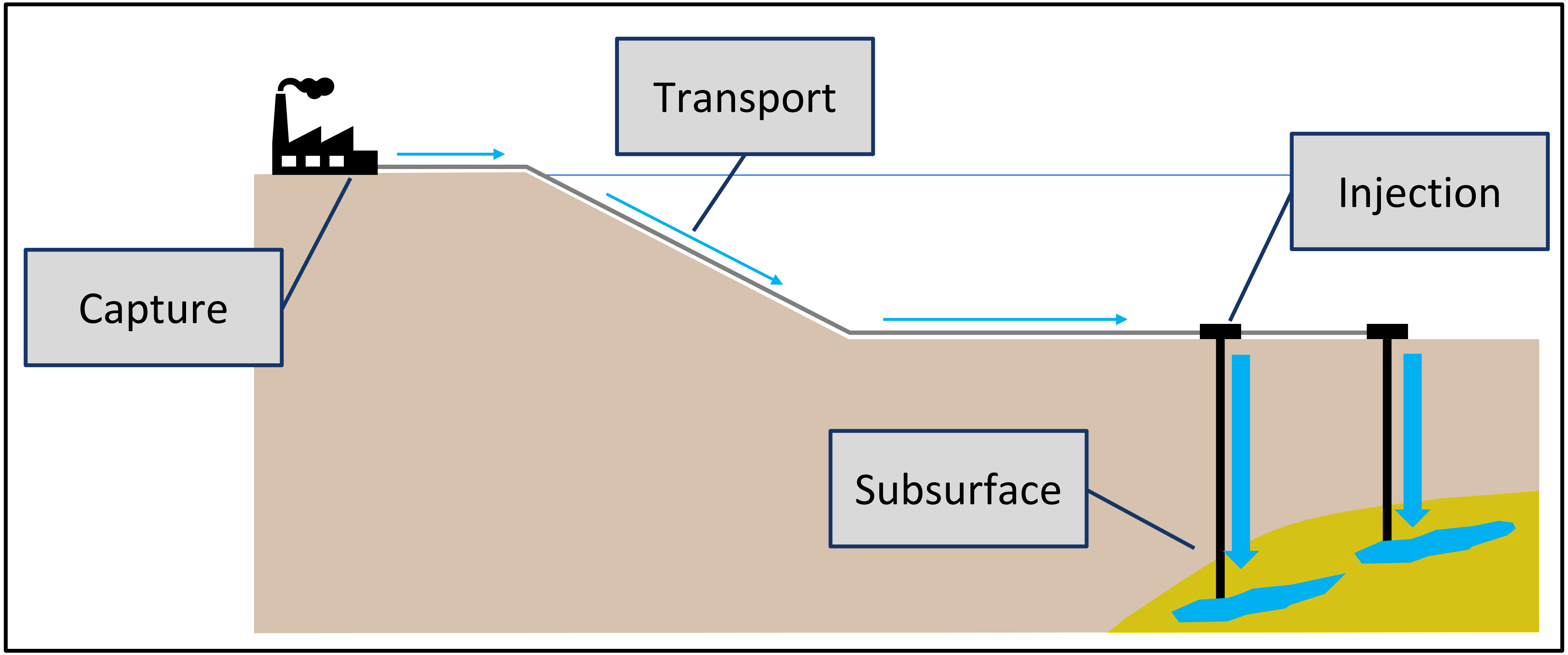
Case Study 1: Full Project Screening



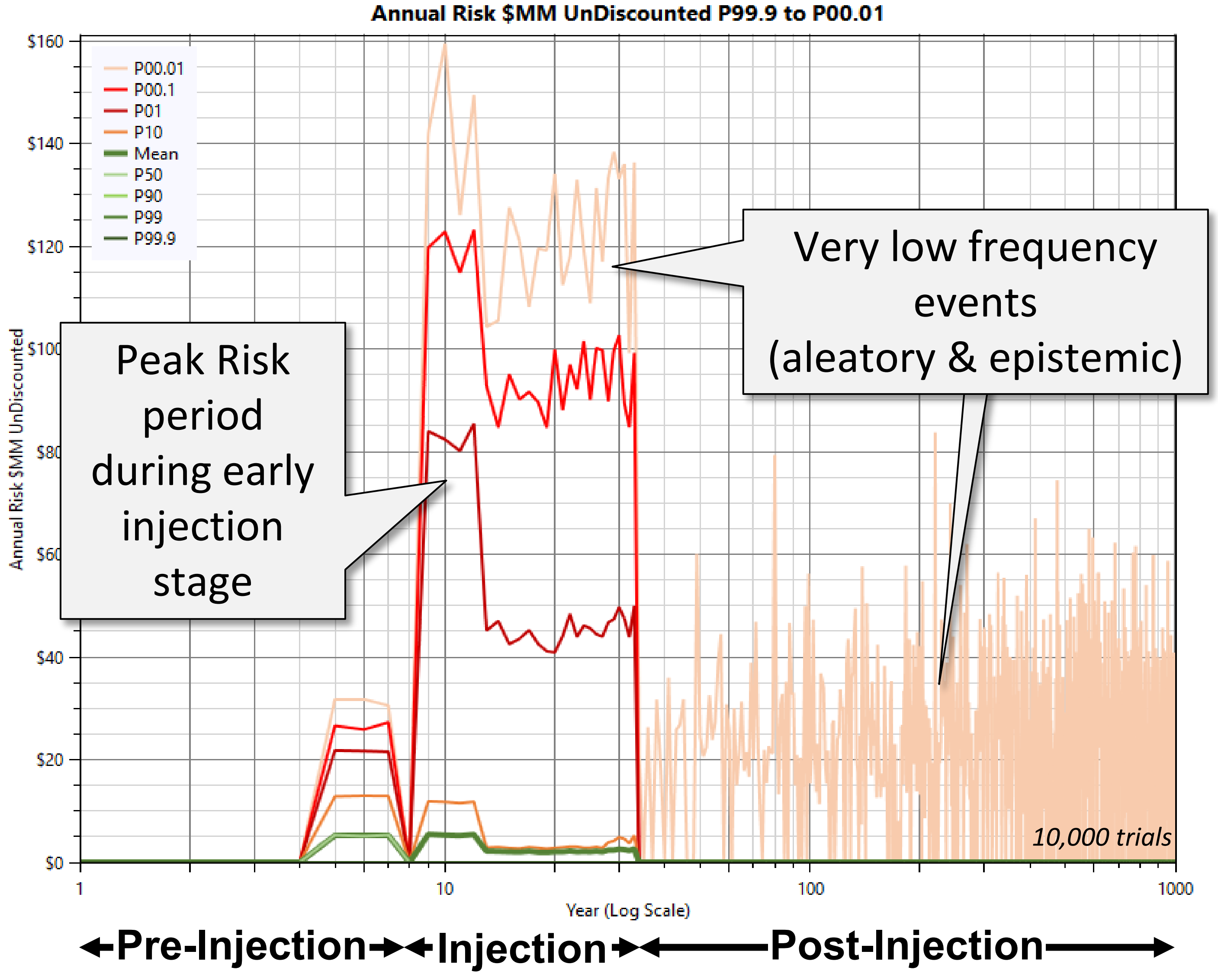
Case Study 1: Full Project Screening

- North Sea Project – risk register of 36 questions defined using publicly available data and reports
  - Range of events assessed for pre-injection, injection and post-injection stages (1,000 years)
  - Range of risk types covering full project: reservoir, trap, containment, long-term well integrity, injectivity, infrastructure, project and supply chain risks
- For each event, we ask:
  - What is the chance this adverse event will occur?
  - If so, what is the possible monetary impact?
- Example questions relating to reservoir description include the following:

Question (Event Assessed)	Impact If Event Occurs
What is the chance that there are more stratigraphic compartments in the trap than are included in the estimate of storage volume?	Increased stratigraphic compartmentalisation 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.

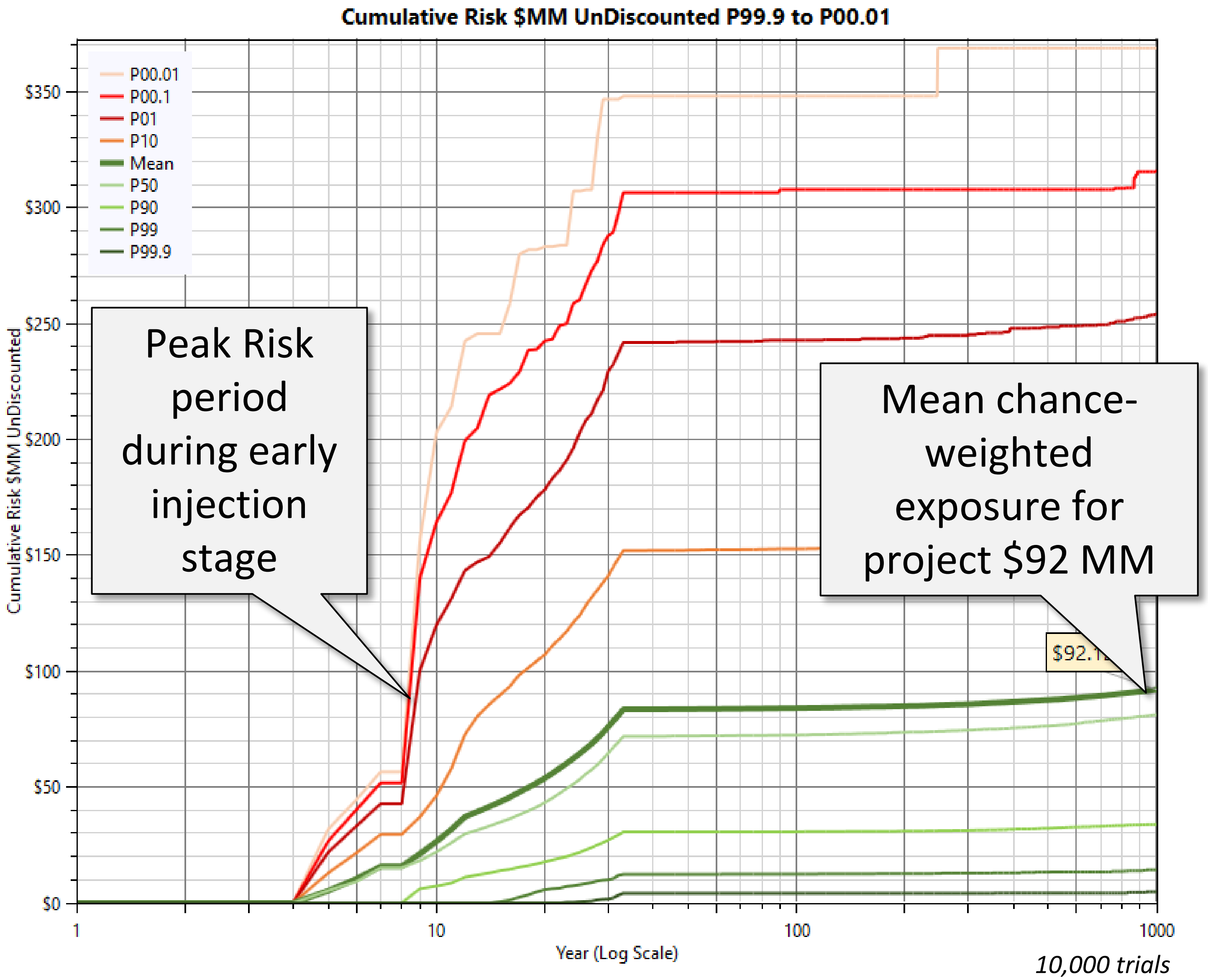
Case Study 1: Full Project Screening

- Undiscounted Annual Risk vs Time (impact in US$)
- Mean annual exposure up to ca. $5MM in any one year
- Peak risk period in early injection stage
- Potential for low frequency, high impact events – P0.01 case (1:10,000 chance)
- Note that this is a snapshot in time. As more data becomes available, the model can/should be updated.



Case Study 1: Full Project Screening

- Undiscounted cumulative Risk vs Time (impact in US$)
- Peak risk period in early injection stage
- Mean chance-weighted exposure for project ca. $92 MM
- Need to understand risk tolerance and retained vs insured risk for the project



Case Study 1: Full Project Screening

- Drill down into the results to identify the events with the largest:
  - Chance-weighted mean impact exposure
  - Chance of one or more events occurring over the 1,000 year modelled period
  - Mean impact exposure in $MM

Summary Statistics

					Chance-weighted Mean Impact E...		Chance of one or more events in 1000 Years		Mean Impact Exposure ($MM)	
Index	Project Phase	Topic	Sub-Topic	Question	Value	Ra	Value	Rank	Value	Rank
22	Injection	Injection	Plume / Pressure Front	What is the chance that the plume, associated pressure front, and/or displaced fluids will MOVE BEYOND the...	13.426	1	0.466	6	28.831	8
12	Pre-Injection	Plan	Technical Maturity	What is the chance that the project will NOT be technically mature and executable, with all componen...	10.511	2	1.194	3	8.800	18
27	Injection	Infrastructure	Capture Facilities	What is the chance the Capture facilities will NOT deliver CO2 at the contracted minimum rate/volume o...	9.063	3	1.825	1	4.967	19
20	Injection	Injection	Pressure Interference	What is the chance that cross-well pressure interference (including interference with other injection projects) w...	8.758	4	0.305	9	28.725	10
31	Injection	Infrastructure	Commercial Viability	What is the chance that changes in tax credits and other incentives could negatively impact the project?	7.840	5	0.244	12	32.197	5
19	Injection	Injection	Completion Effectiveness	What is the chance that the injection zone CANNOT be completely isolated allowing CO2 to enter units above...	6.998	6	0.250	11	28.026	12
28	Injection	Infrastructure	Transport Facilities	What is the chance the CO2 Transport system will NOT deliver CO2 at the contracted minimum rate/volume o...	5.620	7	1.454	2	3.866	20
13	Pre-Injection	Plan	Regulatory	What is the chance that all regulatory, health, safety and environmental approvals are NOT in place and wil...	5.264	8	0.595	4	8.849	16
18	Injection	Injection	Reservoir	What is the chance that the target injection rates, required to store the contracted volumes of CO2 in th...	4.888	9	0.062	17	78.963	3
16	Injection	Reservoir (Dynamic)	Storage Effectiveness	What is the chance that there are NOT ENOUGH options, such as alternative reservoirs and well locatio...	3.990	10	0.453	8	8.812	17
36	Post-Injection	Retainment	Social Acceptance	What is the chance that HSE and/or regulatory breaches WILL ERODE OR BREAK social acceptance D...	2.896	11	0.101	13	28.733	9
33	Post-Injection	Retainment	Wellsite Facilities	What is chance that legacy wells, injectors and future wells WILL leak DURING Post-Injection?	2.722	12	0.096	15	28.322	11

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Case Study 1: Full Project Screening

- Summary statistics can be used for checking inputs
- Example below: is the CO_2 plume more likely to extend beyond the license boundaries *during* injection (driven by pressure) or *after* injection (driven by buoyancy)?

Summary Statistics

					Chance-weighted Mean Impact E...		Chance of one or more events in 1000 Years		Mean Impact Exposure ($MM)	
Index	Project Phase	Topic	[illegible]	[illegible]	Value	Rank	Value	Ra…	Value	Rank
2	Injection	Containment	CO2 Plume	What is the chance that the CO2 plume EXTENDS OUTSIDE of the license DURING Injection?	53.711	2	0.195	2	275.721	13
3	Injection	Containment	Pre… Front	What is the chance that the pressure front EXTENDS …	10.469	6	0.178	3	58.684	16
36	Post-Injection	Retainment	C…	…TENDS …	1.711	15	0.034	4	50.019	17

Chance of CO_2 plume extending outside of license during injection period: 19.5 %

Chance of CO_2 plume extending outside of license after injection period: 3.4 %

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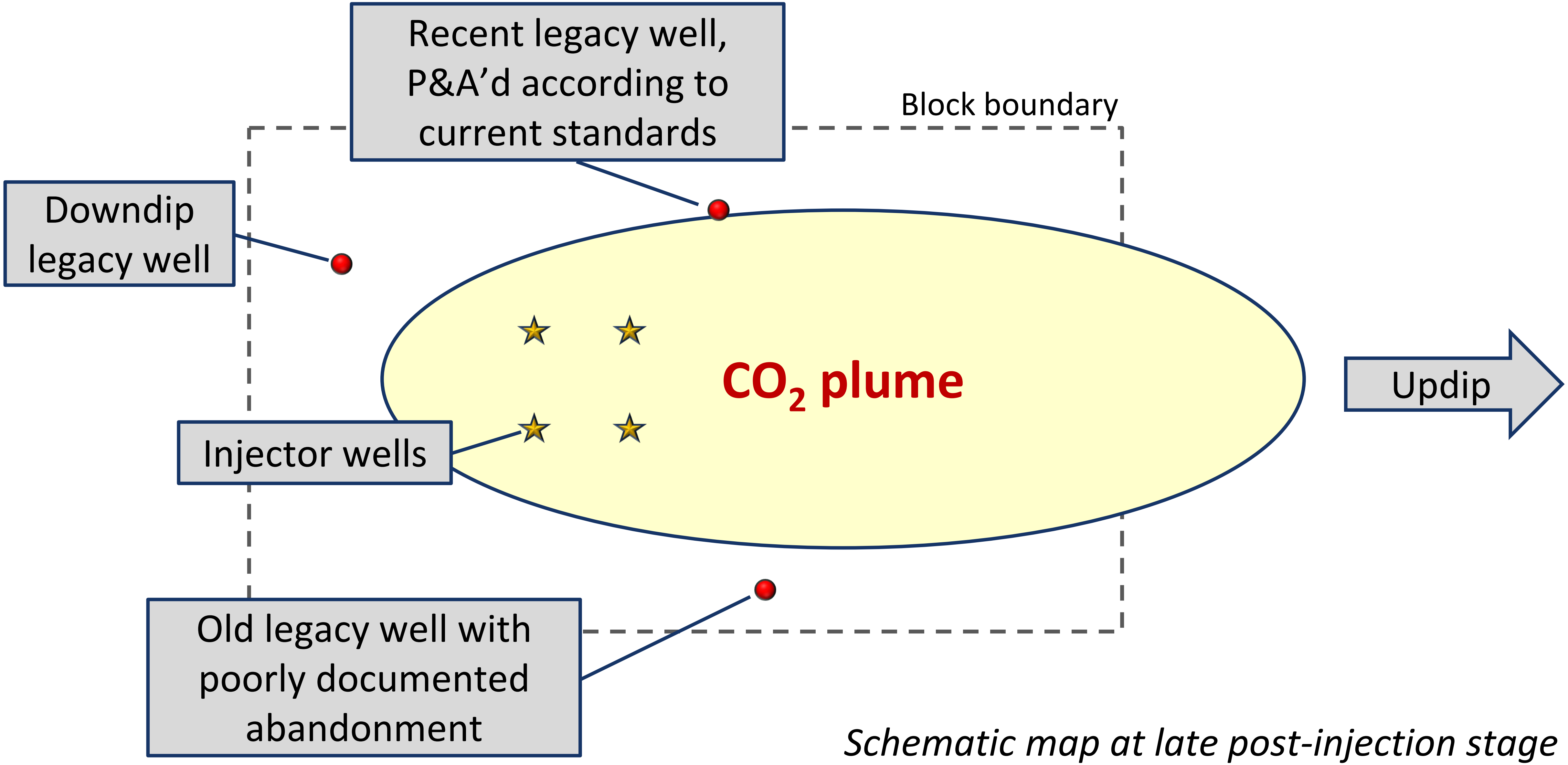
Outputs to Address Specific Business Questions

Specific business questions can be addressed with data interrogation workflows using the output charts and tables.

For example:

- What is the total potential cost exposure for the project, including low probability / high impact events?
- When is the highest cost exposure encountered during the project, including low probability / high impact events?
- What is the Chance of Success for this project?
- Which Project Phase / Time Intervals carry the highest risks?
- Which Adverse Events / Questions are the biggest impact items?
- What is driving Chance-Weighted Impact – Chance / Cost / Time Interval duration?
- Which Adverse Events Can be Mitigated?

Case Study 2: Well Containment Focus



Schematic map at late post-injection stage

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Case Study 2: Well Containment Focus

- An actual CCS project was assessed for the well containment focus
- Worked with Operator subject experts to define risk register of 68 questions specifically relating to legacy and injection well containment risks
- Events assessed for injection and post-injection phases only – total of 993 years modelled
- Each legacy well was assessed individually for the likelihood the plume could reach the well AND the likelihood of leakage (based on condition and P&A data for the well)
  - ✓ Likelihoods estimated assessing robustness of simulation model/uncertainties within the model
  - ✓ If CO_2 plume reaches a legacy well, minor leakage is highly probable, but probably not detectable using current monitoring methods
  - ✓ Detectable leakage is probable, depending on quality of abandonment
- This likelihood was assessed for each of the project stages, per year
  - ✓ Thus, peak risk could be identified
- Long-term integrity of injection wells: preliminary assessment made
- Financial impacts were estimated for all assessed risks, per well, and per project stage

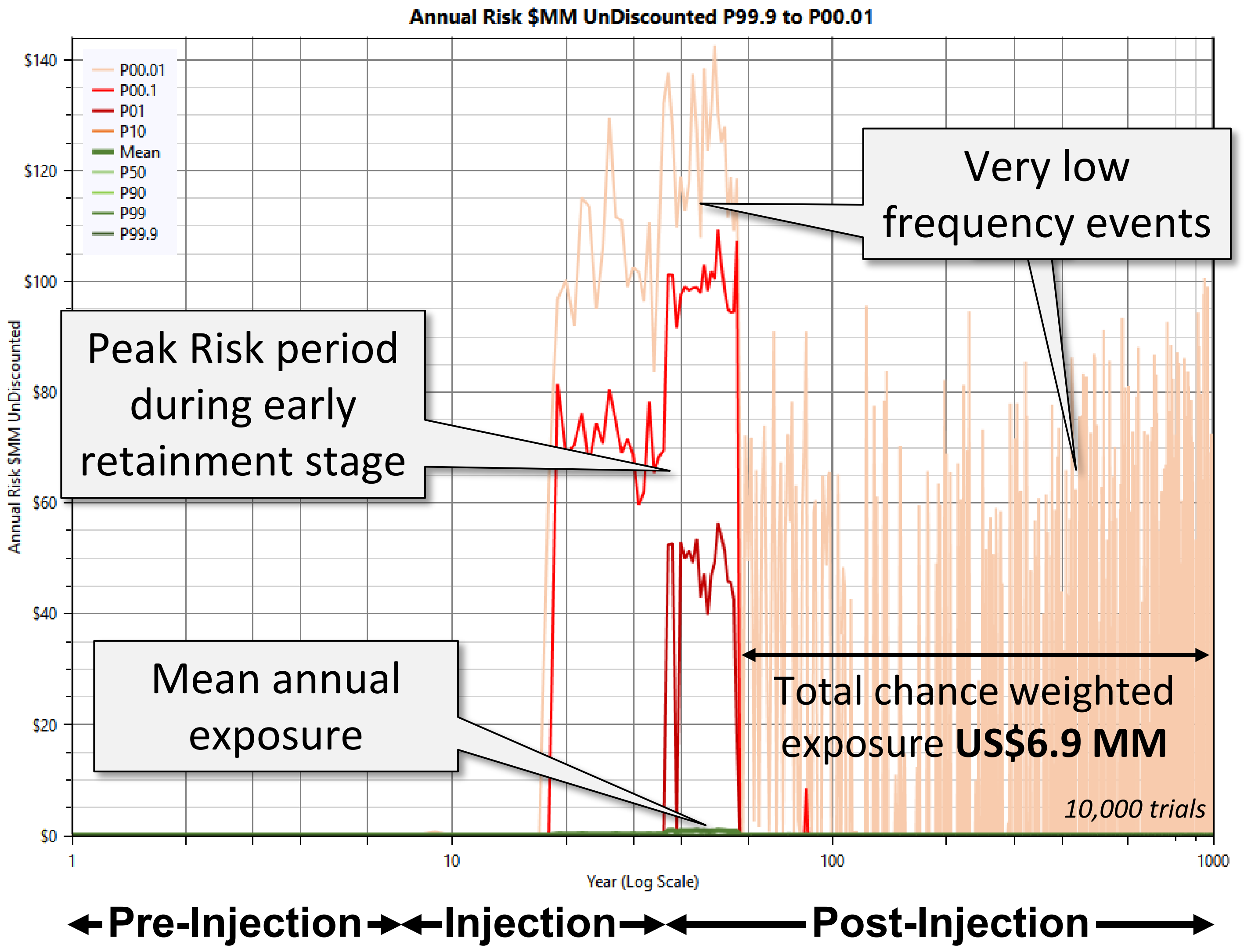
Case Study 2: Well Containment Focus

Example questions relating to legacy well retainment include the following:

Question (Event Assessed)	Impact If Event Occurs
What is the chance that CO_2 will reach legacy well #1, and in doing so, detectable amounts of CO_2 will flow to the sea floor through the casing and/or annular cement during injection?	CO_2 leakage outside of storage complex can result in fines or penalties and may require changing injection strategy (possibly reducing injection rate).
What is the chance that CO_2 will flow into a shallow formation through the casing and/or annular cement of a CO_2 injection well during or after abandonment?	CO_2 leakage outside of storage complex can result in fines or penalties.

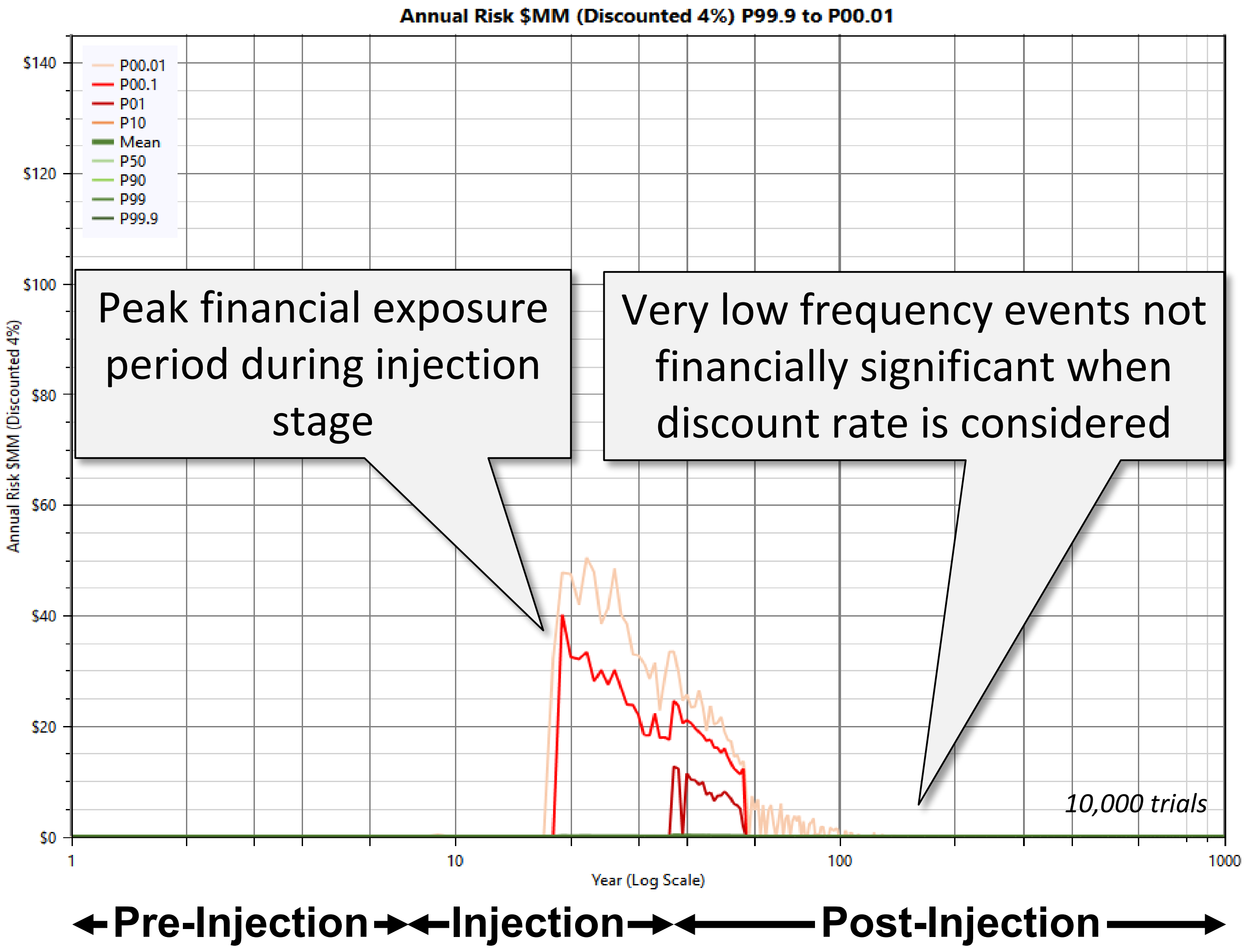
Case Study 2: Well Containment Focus

- **Undiscounted** Annual Risk vs Time
- Low mean exposure in relation to well risks
- Peak risk period in early retainment (post-injection) stage
- Potential for low frequency, high impact events in the P0.01 case (1:10,000 chance)
  - Total chance weighted exposure over retainment stage of 943 years (Project Year 57-1,000) is **US$6.9 MM**



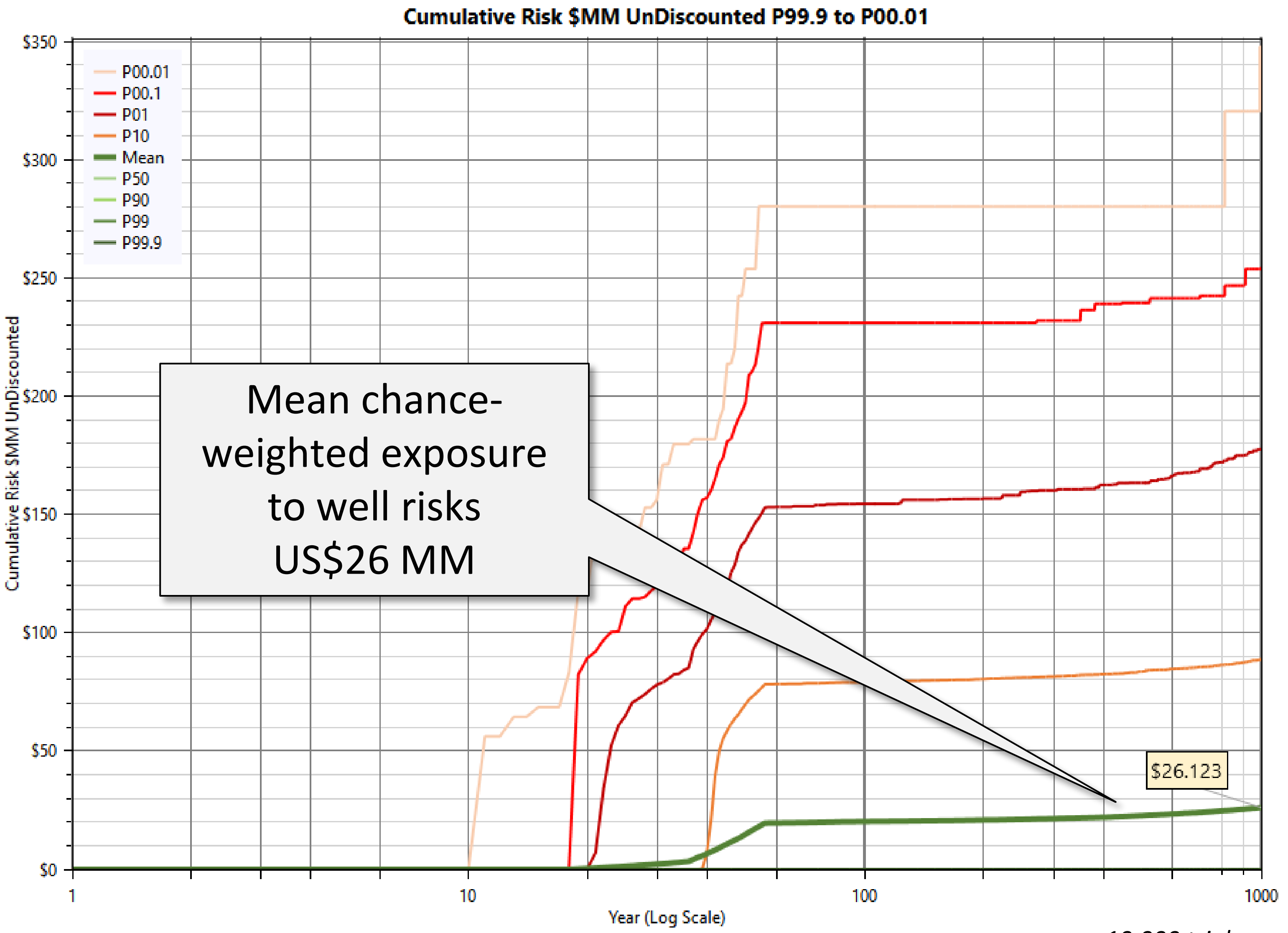
Case Study 2: Well Containment Focus

- **Discounted** Annual Risk vs Time
- Low mean exposure in relation to well risks
- Peak financial exposure period in injection stage
- Financial impact in the long-term future of low-frequency events drops significantly



Case Study 2: Well Containment Focus

- **Undiscounted** Cumulative Risk vs Time
- Mean exposure in relation to well risks ~US$26 MM (undiscounted)
- Risk exposure based on point-in-time looking far into the future
- Risk analysis helps to clarify MMV programmes and manage risks



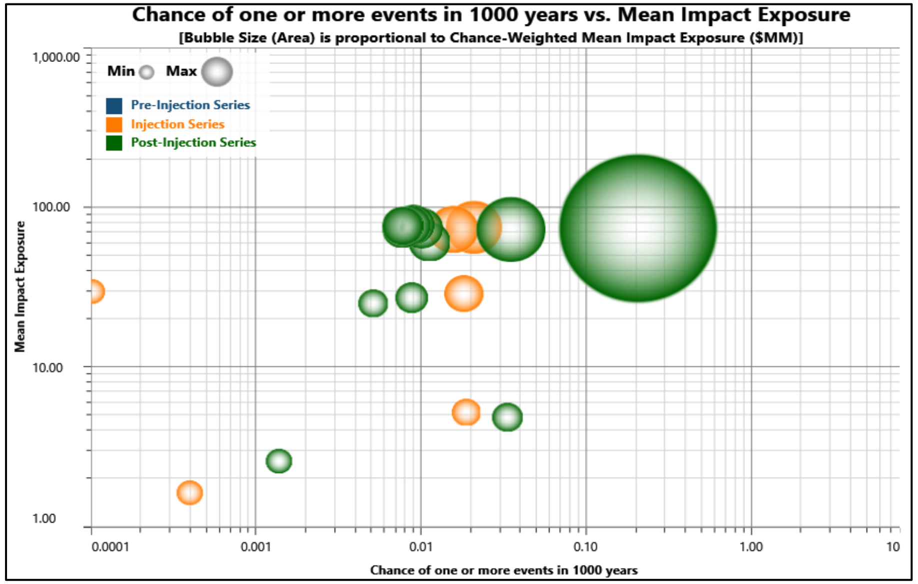
10,000 trials

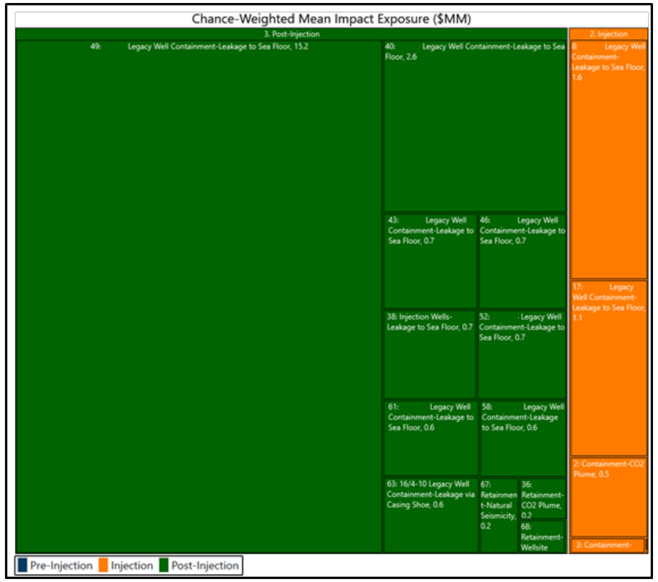
Case Study 2: Well Containment Focus

- Analysis of events that have the greatest impact helps design the MMV program (Measurement, Monitoring, & Verification).
- Focus on risk items with the highest exposure.
- Are mitigations in place to identify precursors to events and then prevent their 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 event occurs?

Summary Statistics

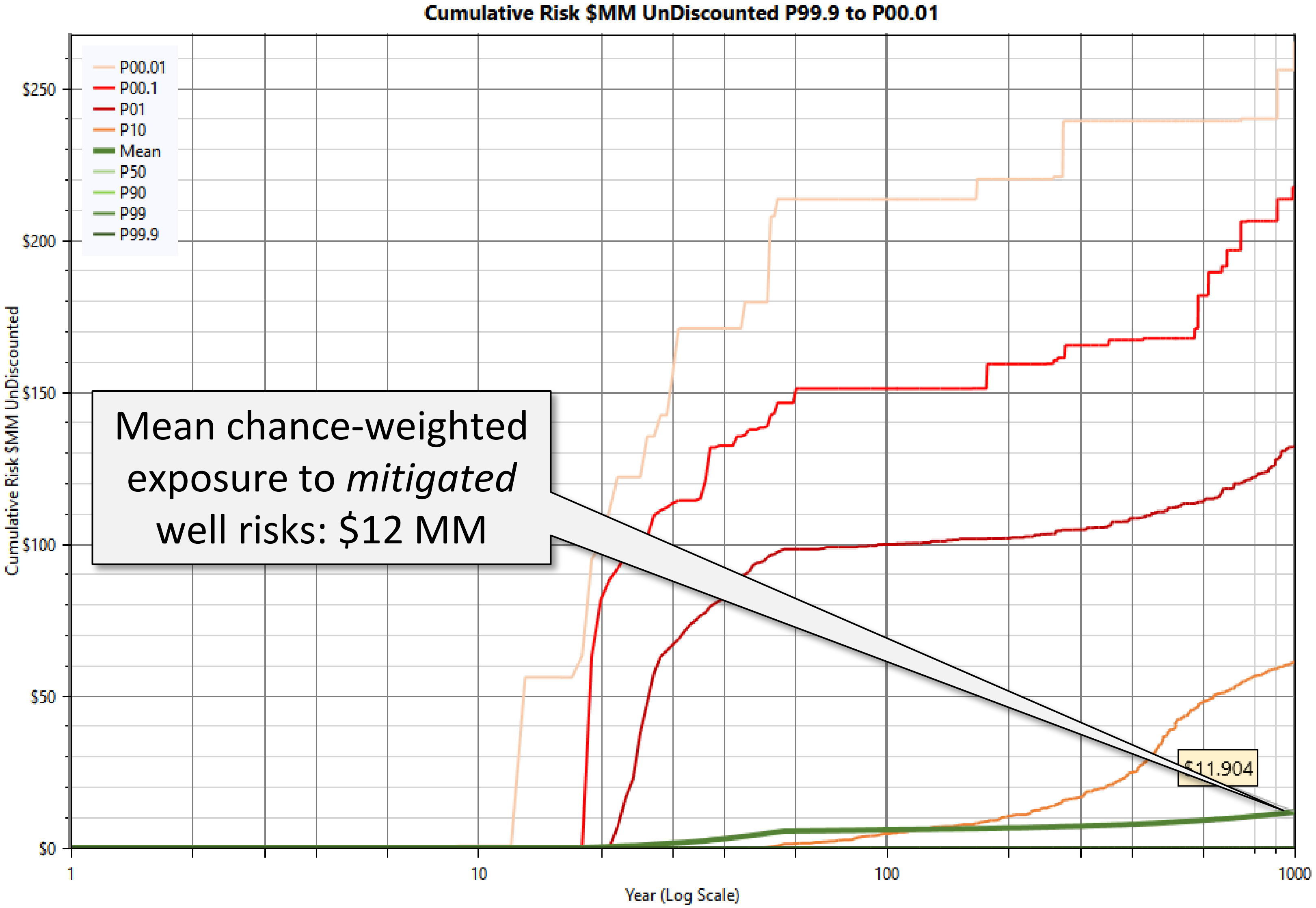
					Chance-weighted Mean Impact E...		Chance of one or more events in 1000 Years		Mean Impact Exposure ($MM)	
Index	Project Phase	Topic	Sub-Topic	Question	Value	Ra	Value	Rank	Value	Rank
49	Post-Injection	Legacy Well Containment	Leakage to Sea Floor	What is the chance that CO2 will reach the legacy well, and in doing so a detectable volume of C...	15.199	1	0.209	1	72.862	7
40	Post-Injection	Legacy Well Containment	Leakage to Sea Floor	What is the chance that CO2 will reach the legacy well, and in doing so a detectable volume of C...	2.567	2	0.035	2	72.507	8
8	Injection	Legacy Well Containment	Leakage to Sea Floor	What is the chance that CO2 will reach the legacy well, and in doing so a detectable volume of C...	1.555	3	0.021	4	74.398	5
17	Injection	Legacy Well Containment	Leakage to Sea Floor	What is the chance that CO2 will reach the legacy well, and in doing so a detectable volume of C...	1.144	4	0.016	7	72.425	9
43	Post-Injection	Legacy Well Containment	Leakage to Sea Floor	What is the chance that CO2 will reach the legacy well, and in doing so a detectable volume of C...	0.738	5	0.010	9	73.033	6





Case Study 2: Undiscounted, Mitigated

- Scenario assessing impact of mitigation action:
  - Move injection well location to reduce likelihood of plume intersecting a key legacy well
- Mean chance-weighted exposure for the project reduces from $26 MM to $12 MM
- Demonstrates risk reduction and impact of mitigation action



10,000 trials

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Conclusions

- CO_2 transport and storage are susceptible to multiple risks. A quantitative risking tool can be used to assess the chance that adverse events will occur over project life and estimate their aggregate financial impact.
- In quantifying risk, adverse events can be foreseen and addressed via monitoring and mitigation, reducing financial exposure and increasing the chance of project success.
- Analysis of the likelihood of the CO_2 plume reaching legacy wells, and of CO_2 leakage along legacy and injection wells, provides information that can guide mitigation and monitoring priorities:
  - Peak risk: periods of highest exposure.
  - Ranking of wells that have highest likelihood of leakage, with the highest impact.
- Quantitative risking is also useful for communicating threats to stakeholders and determining the amount of coverage needed from a bond or insurance policy.
  - Are currently working to understand *Why, When and How Should You Insure Your CCS Project?*

Acknowledgments & References

Acknowledgements: Rose Subsurface Assessment - Peter Carragher, Creties Jenkins, Pieter Pestman, David Cook, Juliet Irvin. Rosalie Constable - Constable Energy Consulting.

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Thank you! Questions?

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