Bringing Stochastic Methods to the Assessment of Mechanical Top Seal Strength at Potential CO_2 Storage Sites

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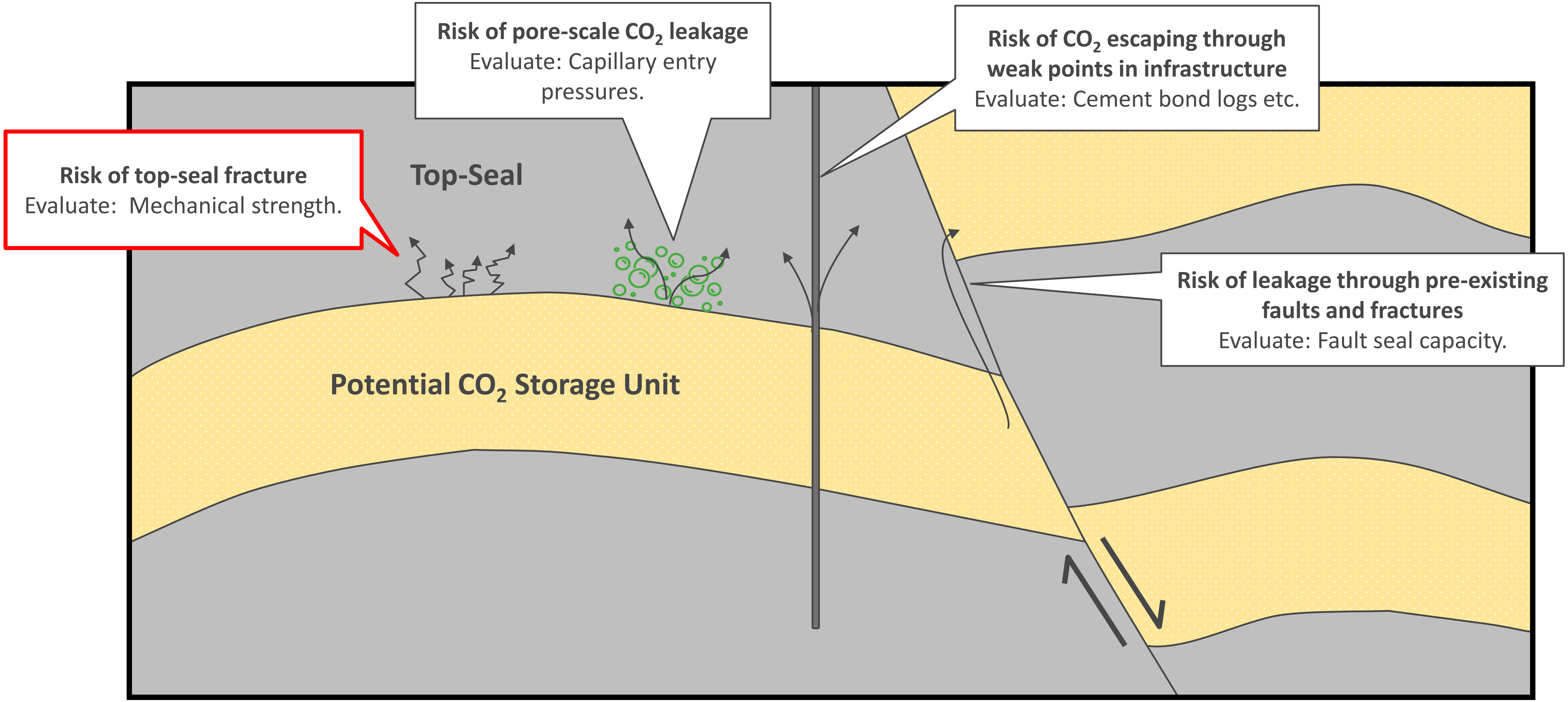
Outline

- Background
- Modifying the deterministic evaluation of mechanical top-seal strength
- Case Studies
  - In Salah, Algeria
  - Aurora, Norway
  - Smeaheia, Norway
- Conclusions

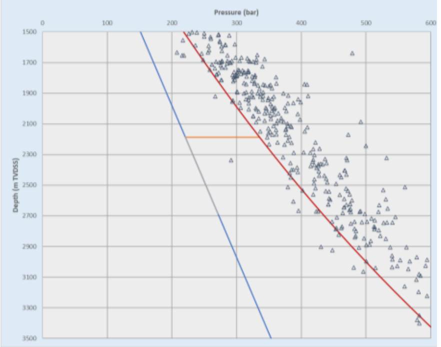
Containment Risk

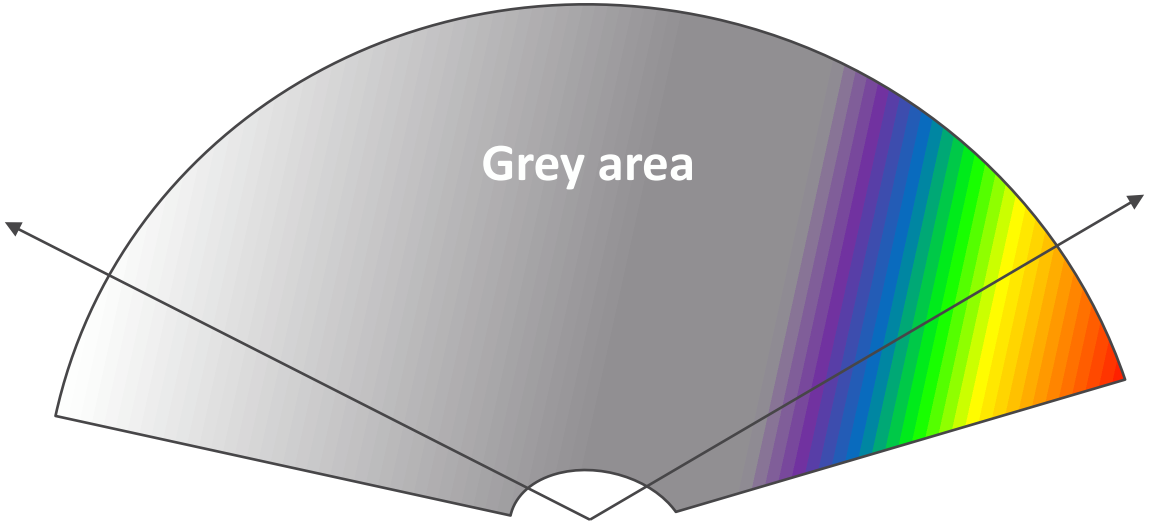


Methods of Assessing Mechanical Top-Seal Strength

Stochastic Analysis

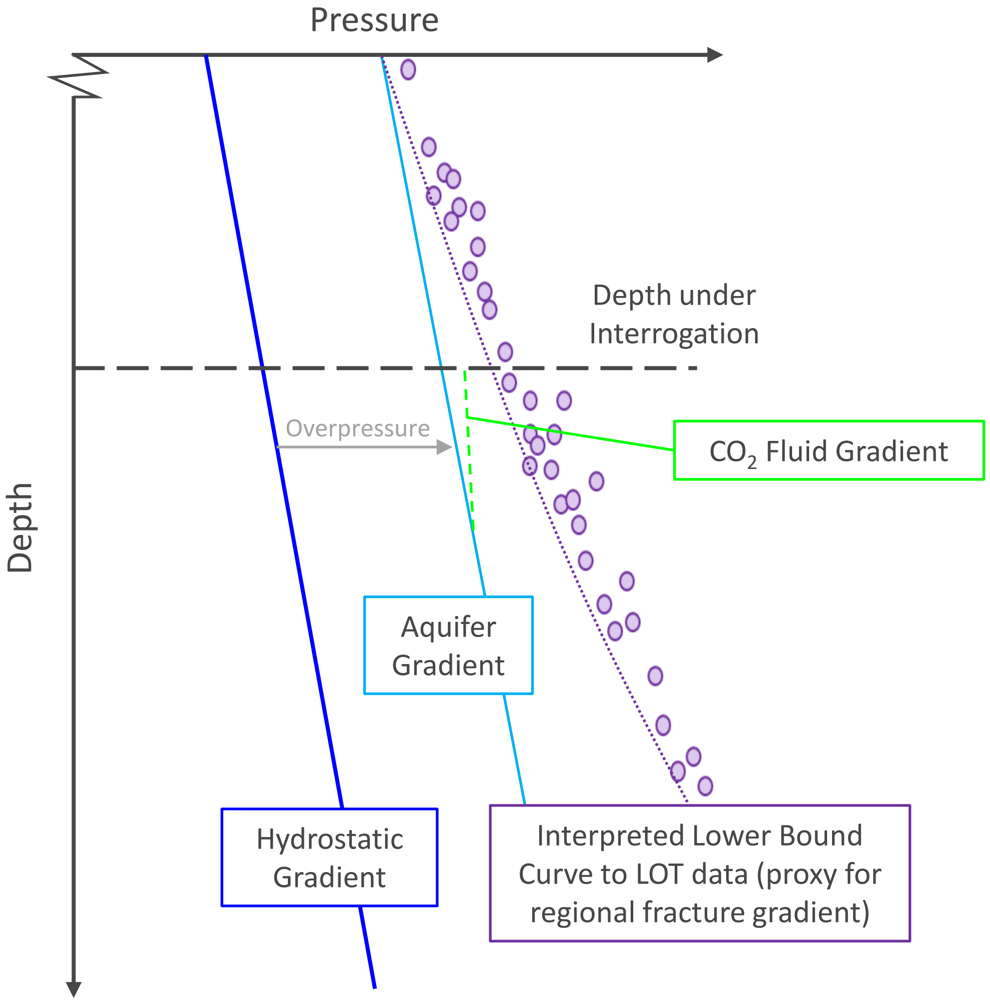
Deterministic
Pressure-depth plot





3D modelling and
simulation

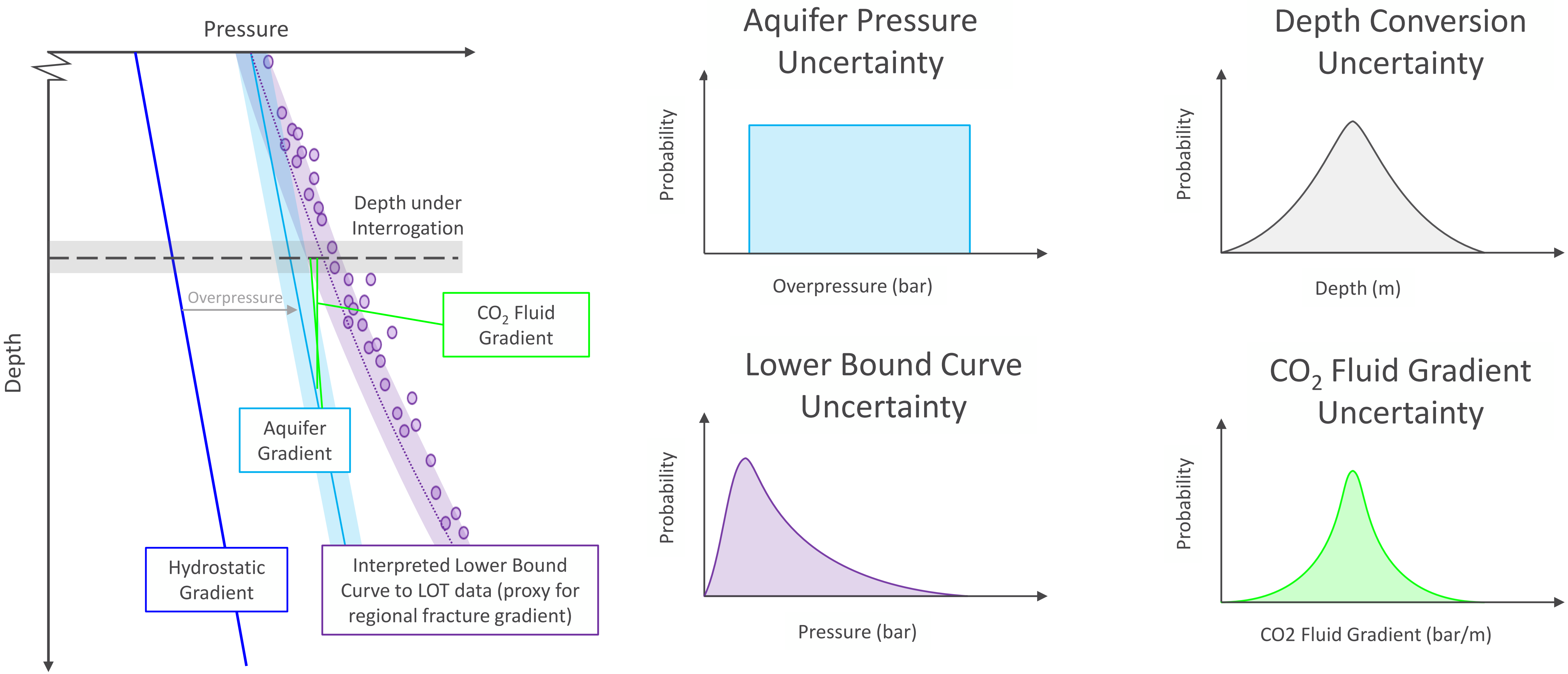
Deterministic Approach to Top-Seal Strength



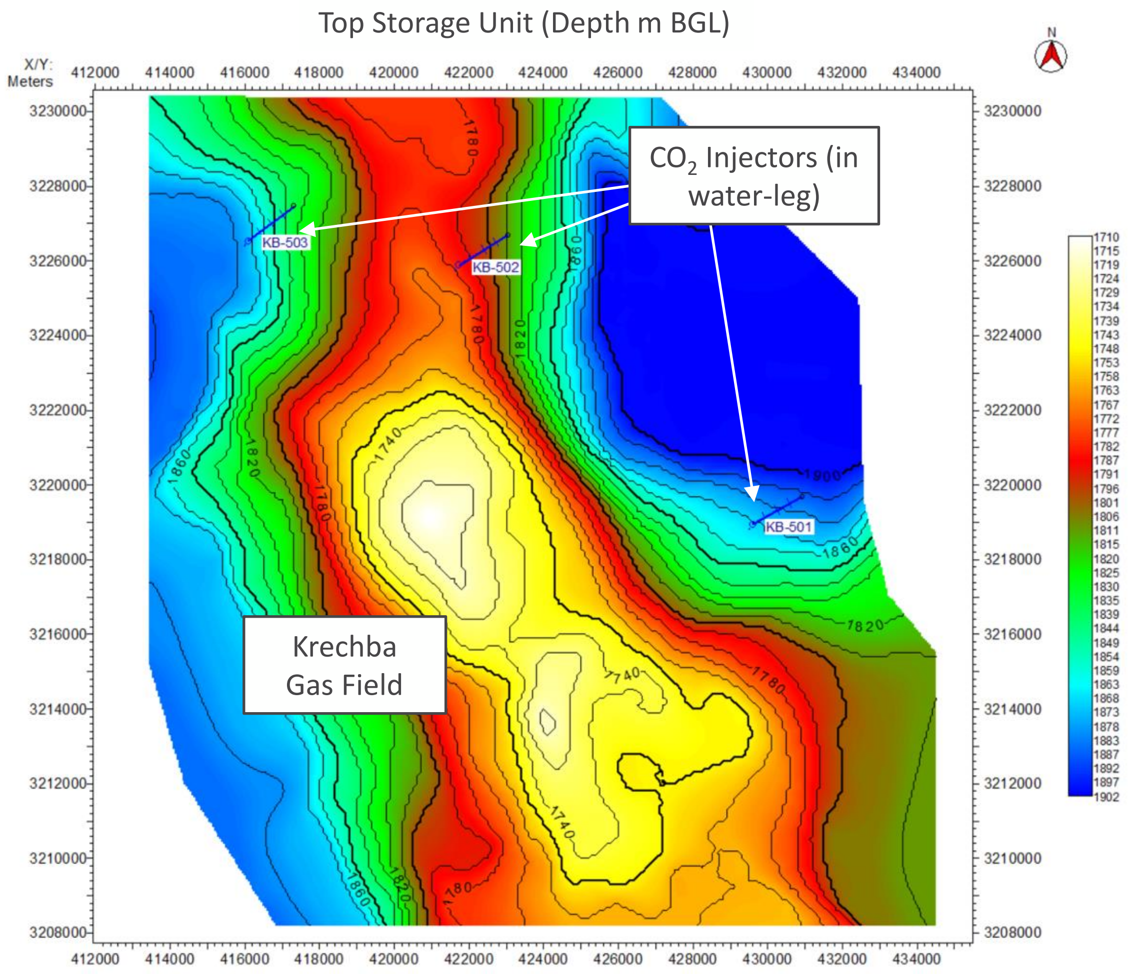
Approach published by Gaarenstroom et al., 1993

- A pressure-depth plot can be created to understand the top-seal strength at a depth of interest. This requires knowledge of:
  - Expected aquifer gradient and pressure in the storage unit.
  - Fracture gradient.
  - Depth structure.
  - Pressure and temperature conditions.
- There is usually considerable uncertainty on all of these parameters.
- We need to be able to evaluate the significance of these uncertainties and how they relate to containment risk, as well as project economics.
- How many deterministic models would it take to fully capture all of the uncertainties?

Stochastic Modification



In Salah, Algeria

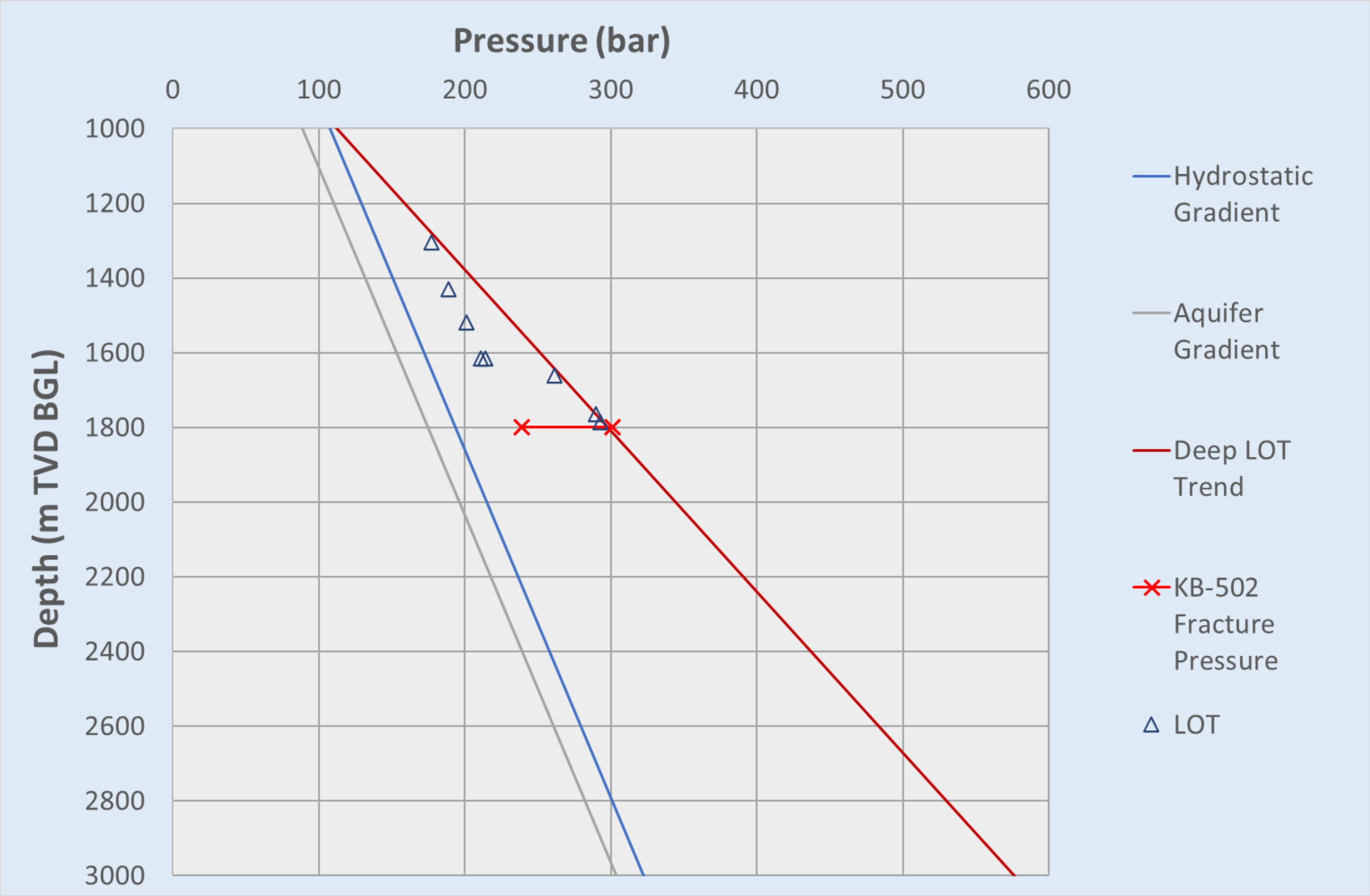


After Vasco et al., (2018)

- In Salah provides a case example where the answers are known.
- The learnings can be applied for modelling mechanical top-seal risk when we don't have the answers.
- The storage unit is Carboniferous Tournaisian sandstones, down-dip from the producing Krechba gas field.
- This storage unit has relatively low permeability, resulting in a significant rise in pore pressure during injection.
- Top-seal is provided by Carboniferous Visean shales. The lower-most portion of the caprock is a silty shale with pre-existing fractures.
- 3.8 Mt CO_2 were injected into In Salah between 2004 and 2011.
- Injection was stopped in 2011 because monitoring suggested CO_2 had migrated vertically into the lower part of the top-seal.

References: Bjornara et al., (2018), Shi et al., (2019), Vasco et al., (2018) & White et al., (2014)

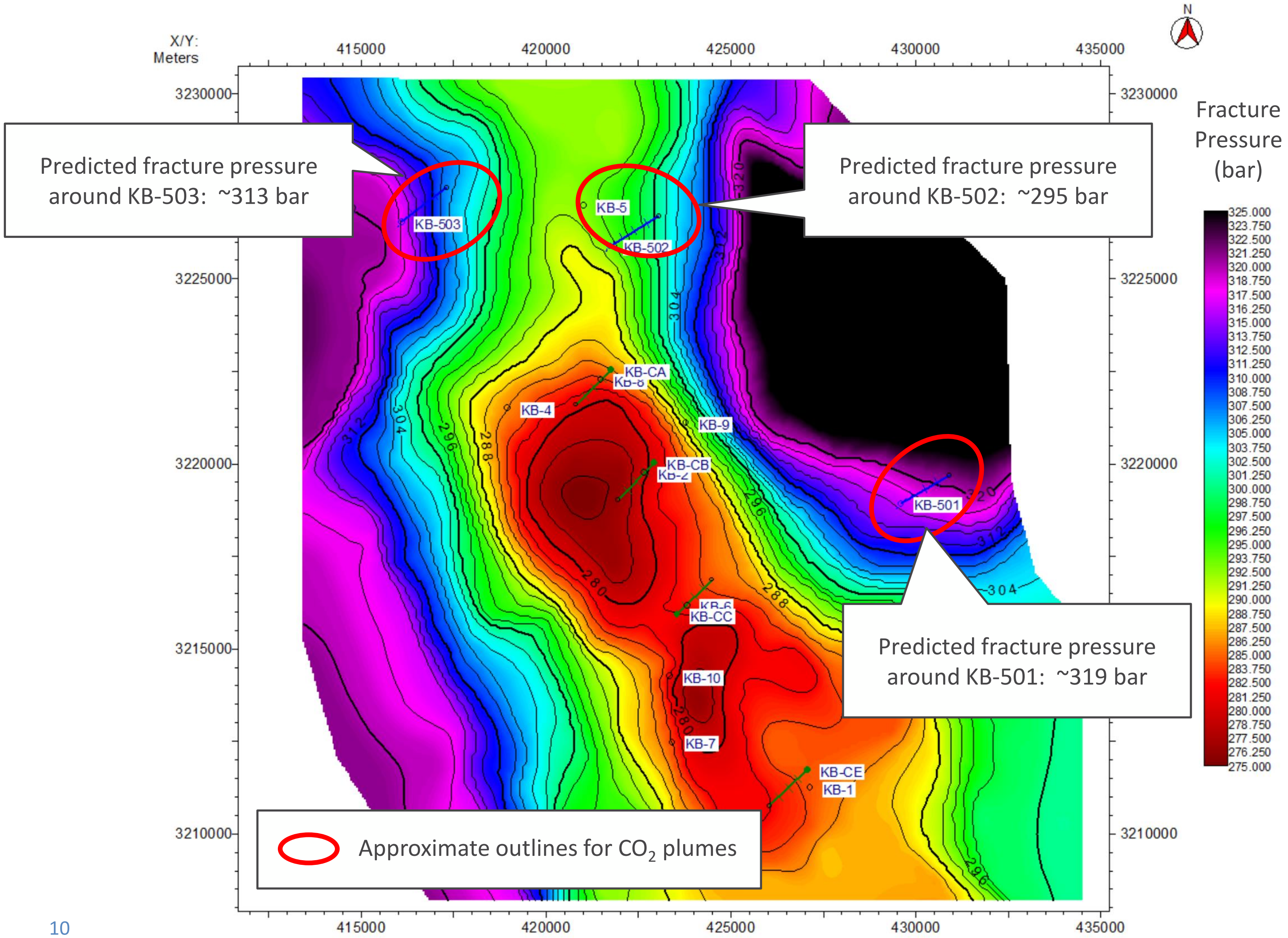
In Salah Pressure Context



LOT data from Vasco et al., (2018)
Fracture pressure data at KB-502 from White et al., (2014)

- LOT data from the cap-rock shows two distinct trends.
- Due to infrastructure limitations, no downhole pressure gauges were installed in the In Salah injector wells.
- During injection, downhole pressure had to be estimated from well-head pressure gauges, leading to significant uncertainty on pressures within the storage unit.
- Because of this uncertainty, a range of fracture pressures has been published for KB-502, the shallowest injector (red line).
- These fracture pressures have all been calculated using various methodologies. The stronger end of this range is consistent with LOT data from the lower portion of the caprock.

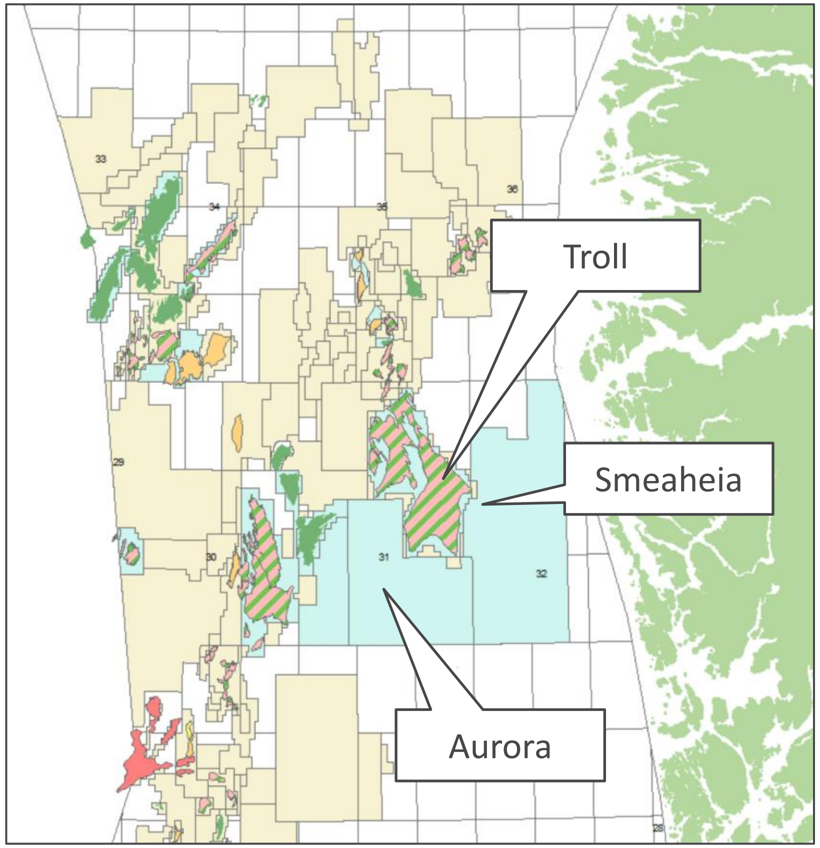
Fracture Pressure Map (Deeper LOT Trend)



Created from depth map in Vasco et al., (2018)

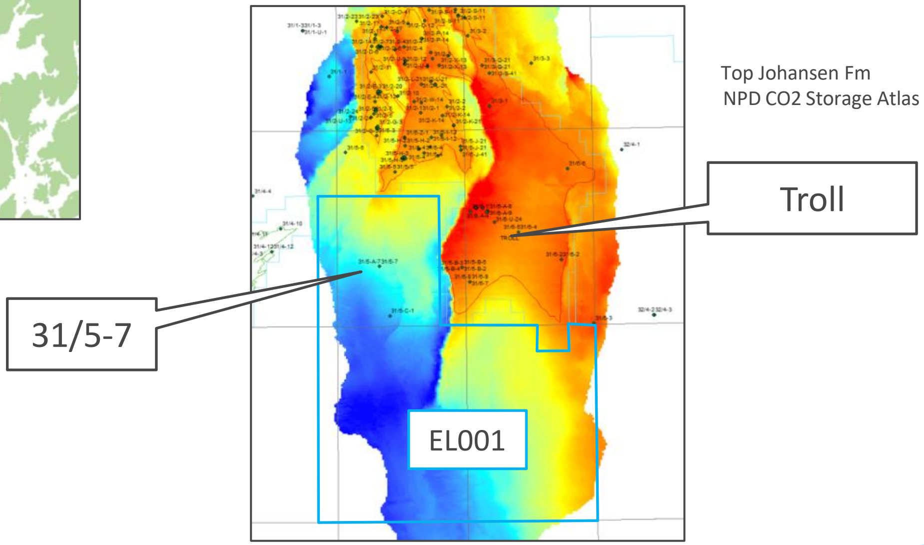
- Due to its shallower depth, KB-502 has the weakest fracture pressure of all the injector wells (~295 bar).
- Injection pressures in KB-502 reached an estimated 330 bar, and the immediate caprock is believed to have fractured.
- This highlights the importance of understanding what the fracture pressure is, as well as the ability to monitor when this limit is being approached, so that action can be taken.
- The top-seals above KB-501 and KB-503 are not believed to have fractured during injection.
- These wells are deeper so their predicted fracture pressures are greater
- Other factors (such as lithological variations in the cap-rock) can also influence fracture pressure at any given location.

Aurora (Northern Lights), Norway



Shapefiles from NPD

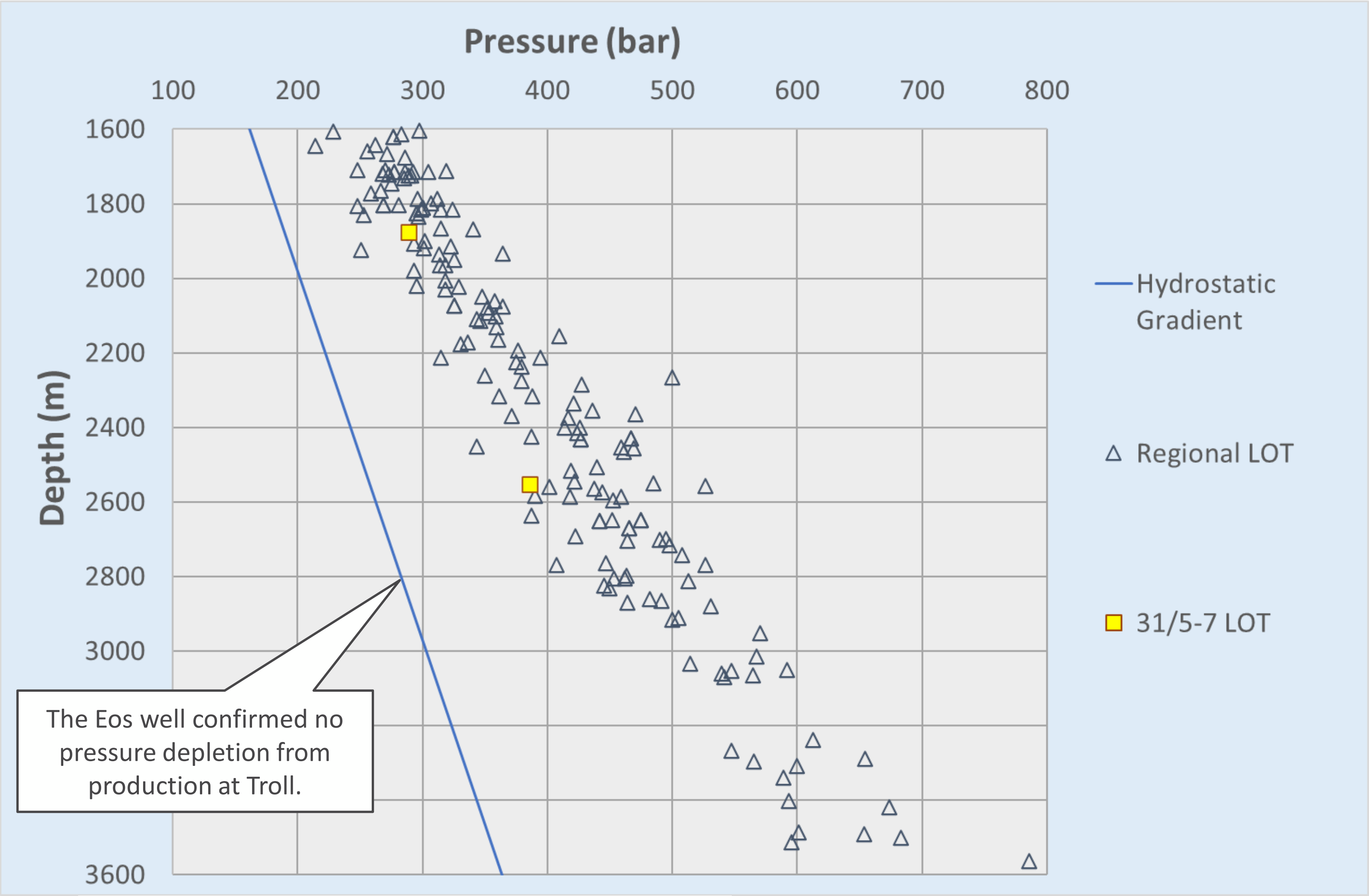
- The storage complex at Aurora is the Lower Jurassic Dunlin Group.
- Injection will be into the gently sloping aquifers of the Johansen and Cook Formations.
- Shales of the Drake Formation provide the primary seal.
- Up to 1.5 Mt CO_2 is planned to be injected per year for the first 10 years of the project.
- The Eos well (31/5-7) was drilled in 2019/20 to gather information for de-risking the Aurora site for CO_2 storage.



Top Johansen Fm
NPD CO2 Storage Atlas

References: Equinor (2020) & Meneguolo et al., (2020)

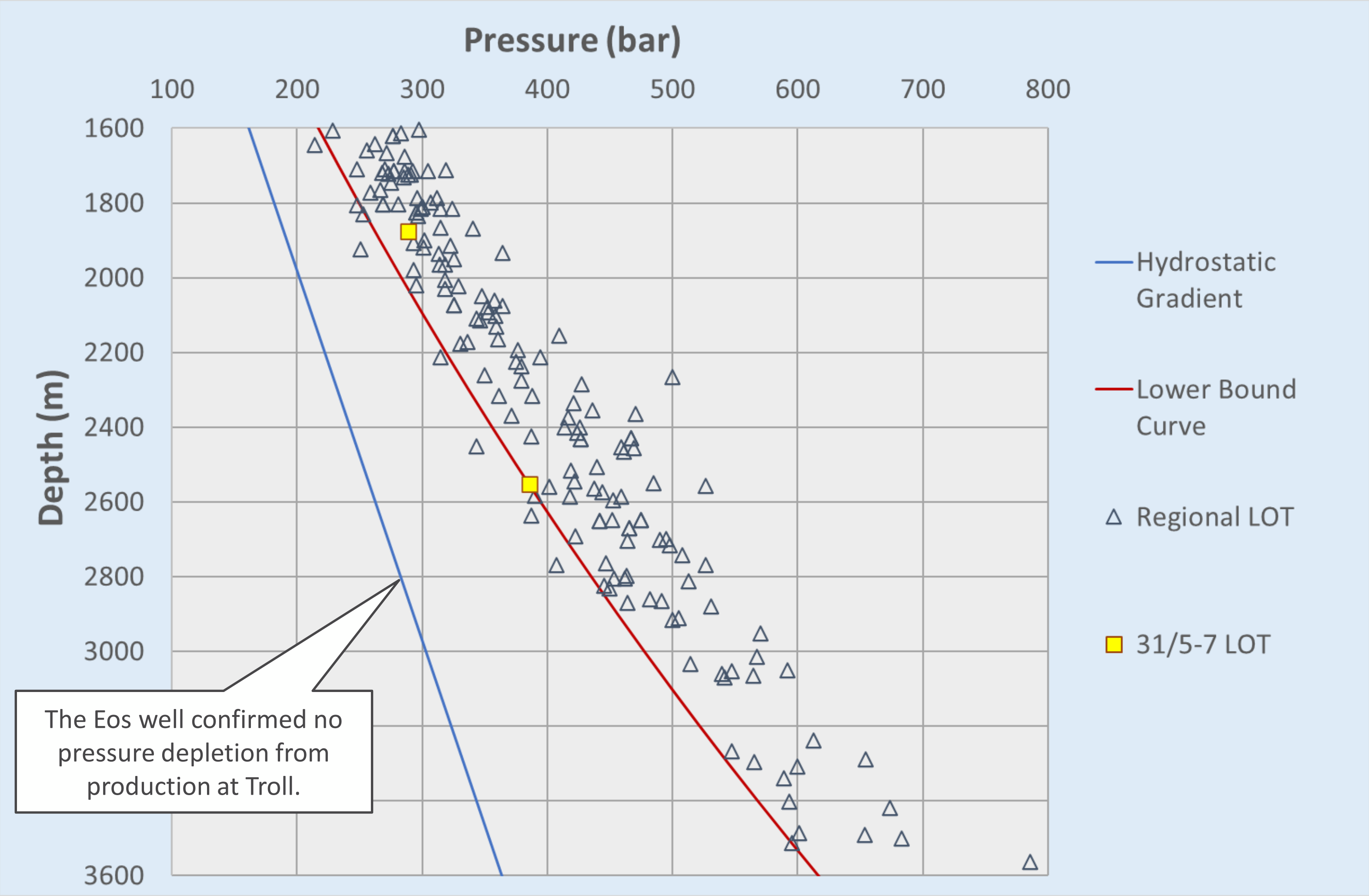
Aurora Pressure Context



LOT from: https://factpages.npd.no/en/wellbore/TableView/With/CasongAndLot

- The Eos well confirmed production at Troll has not caused pressure depletion.
- LOTs were carried out in the Eos well to test the top-seal strength (yellow squares).
- Each LOT is only able to sample a pin-point location in the caprock and, as such, is unable to capture geological variability or measurement uncertainty.
- Regional LOT data from surrounding blocks is also shown (from the NPD database).
- The scatter from the regional LOT data can be used to model uncertainty around the fracture gradient, rather than pinning a deterministic analysis to the LOT from Eos alone.

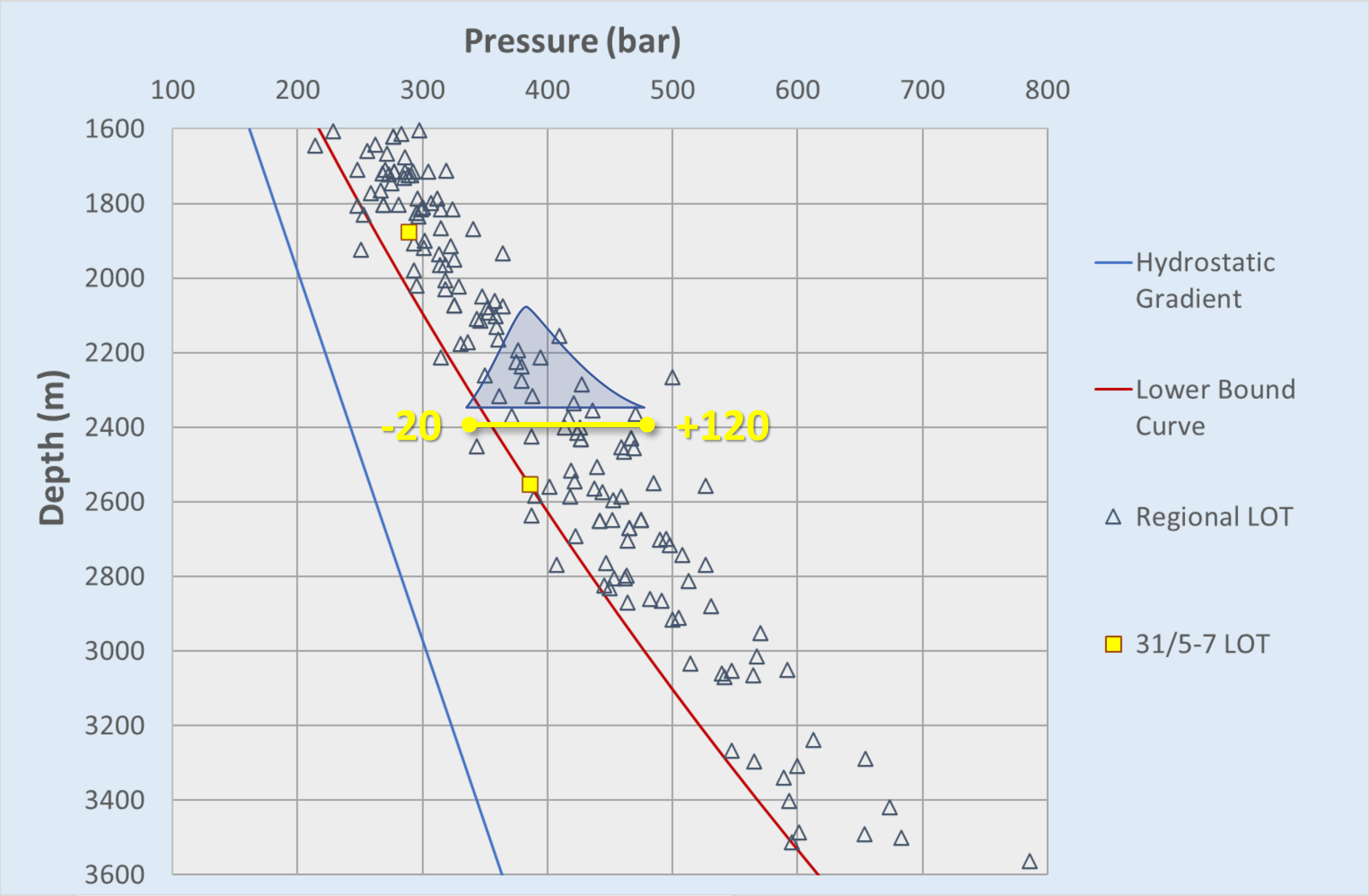
Aurora Pressure Context



LOT from: https://factpages.npd.no/en/wellbore/TableView/With/CasongAndLot

- Here, a Lower bound curve has been interpreted from the regional LOT data (maroon).
- This curve is consistent with the LOT measured in the Drake in the Eos well.
- To capture the uncertainty on this curve (and thus the fracture gradient) we can look at the amount of scatter on the regional LOT data.

Defining an Uncertainty Range on the LBC



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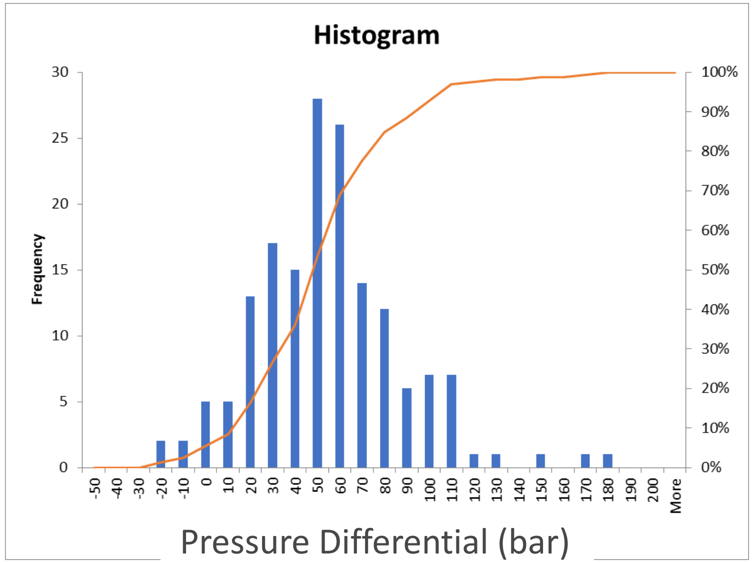
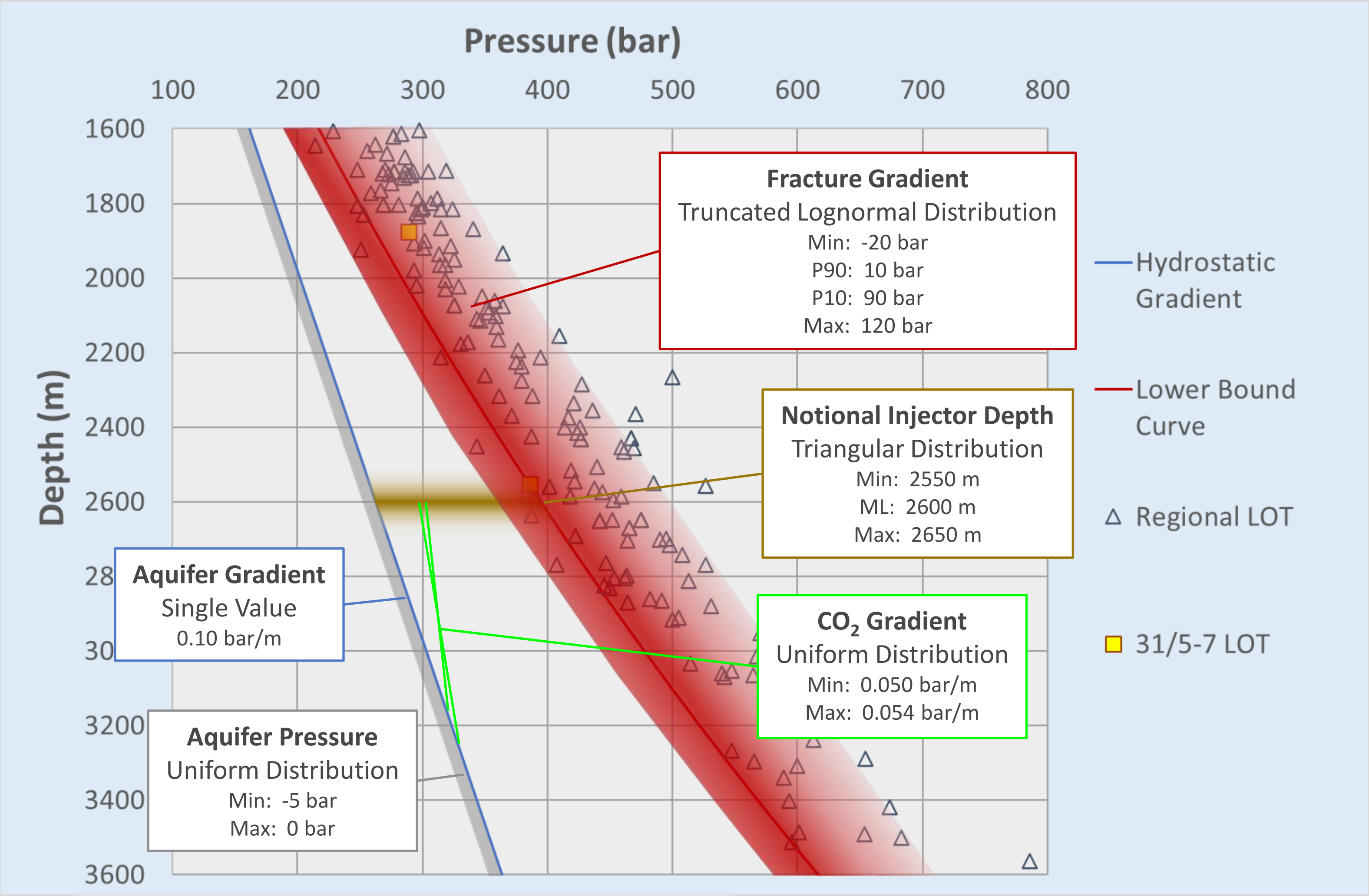


Histogram of the pressure differential between measured LOT and the LBC.

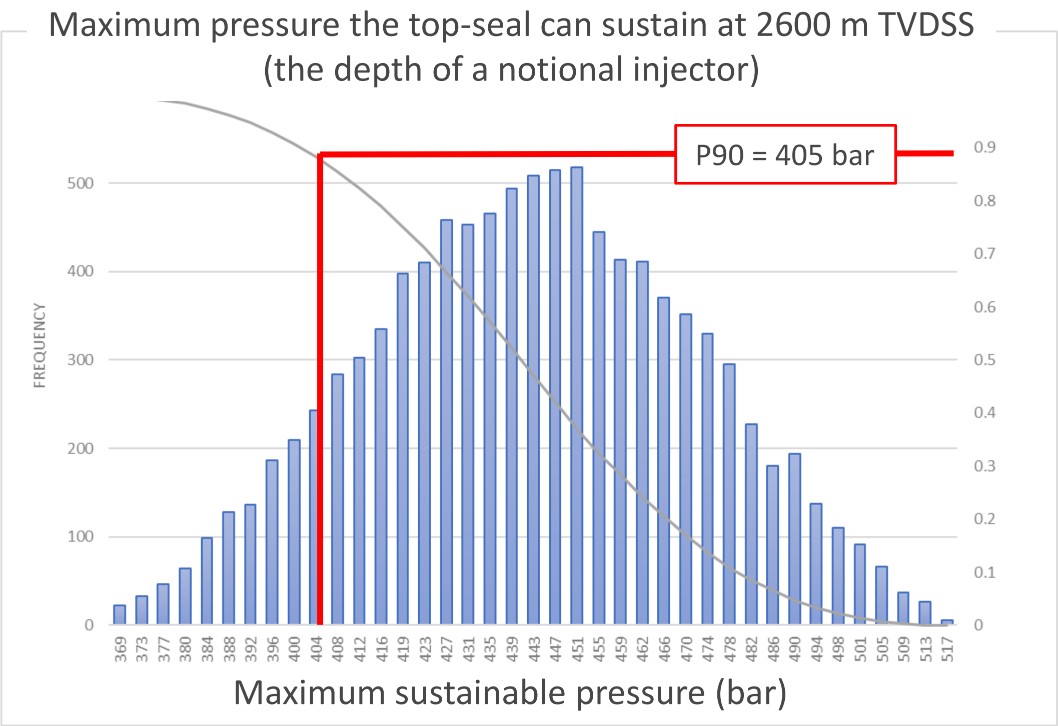
By examining the shape of the histogram, a bespoke distribution can be designed for modelling the pressure uncertainty on the LBC (which is a proxy for fracture gradient).

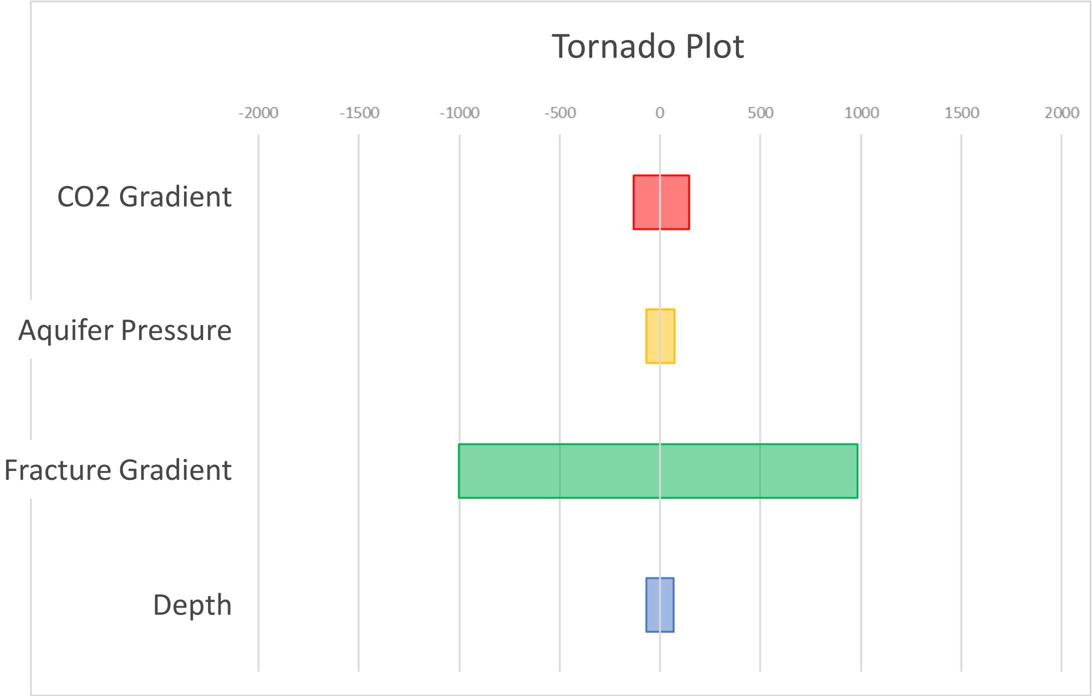
Model Inputs (Aurora)



LOT from: https://factpages.npd.no/en/wellbore/TableView/With/CasongAndLot

Stochastic Results





405 bar is the P90 pressure the top-seal is able to able to sustain for a notional injector penetrating the Cook at 2600 m.

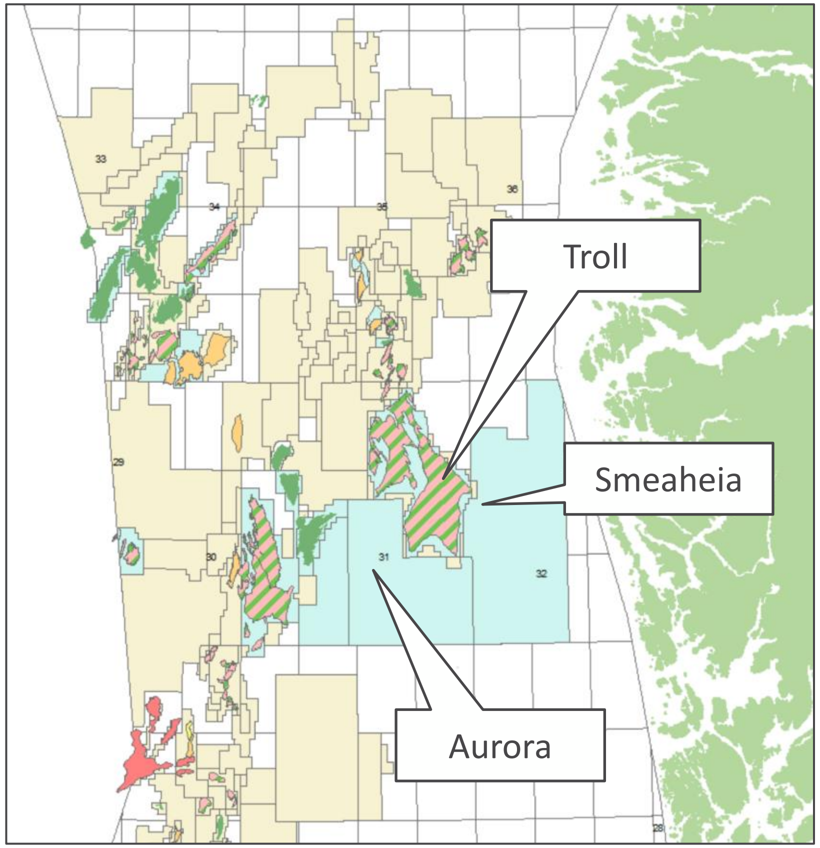
This threshold can be used to constrain injectivity rate modelling and ensure that an economic rate can be safely achieved.

The most sensitive parameter is the uncertainty around the Lower Bound Curve (i.e. fracture gradient).

This information can be used to optimise an appraisal programme.

In this case, a more targeted group of LOTs (perhaps focused on the relevant stratigraphic interval) could reduce the fracture gradient uncertainty.

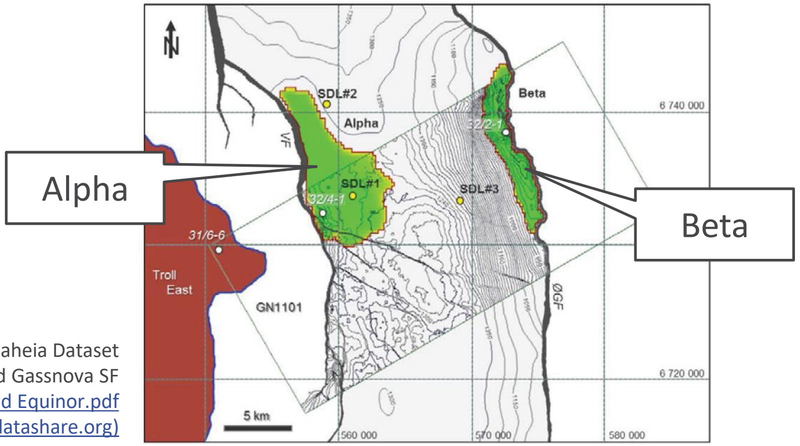
Smeaheia, Norway



Shapefiles from NPD

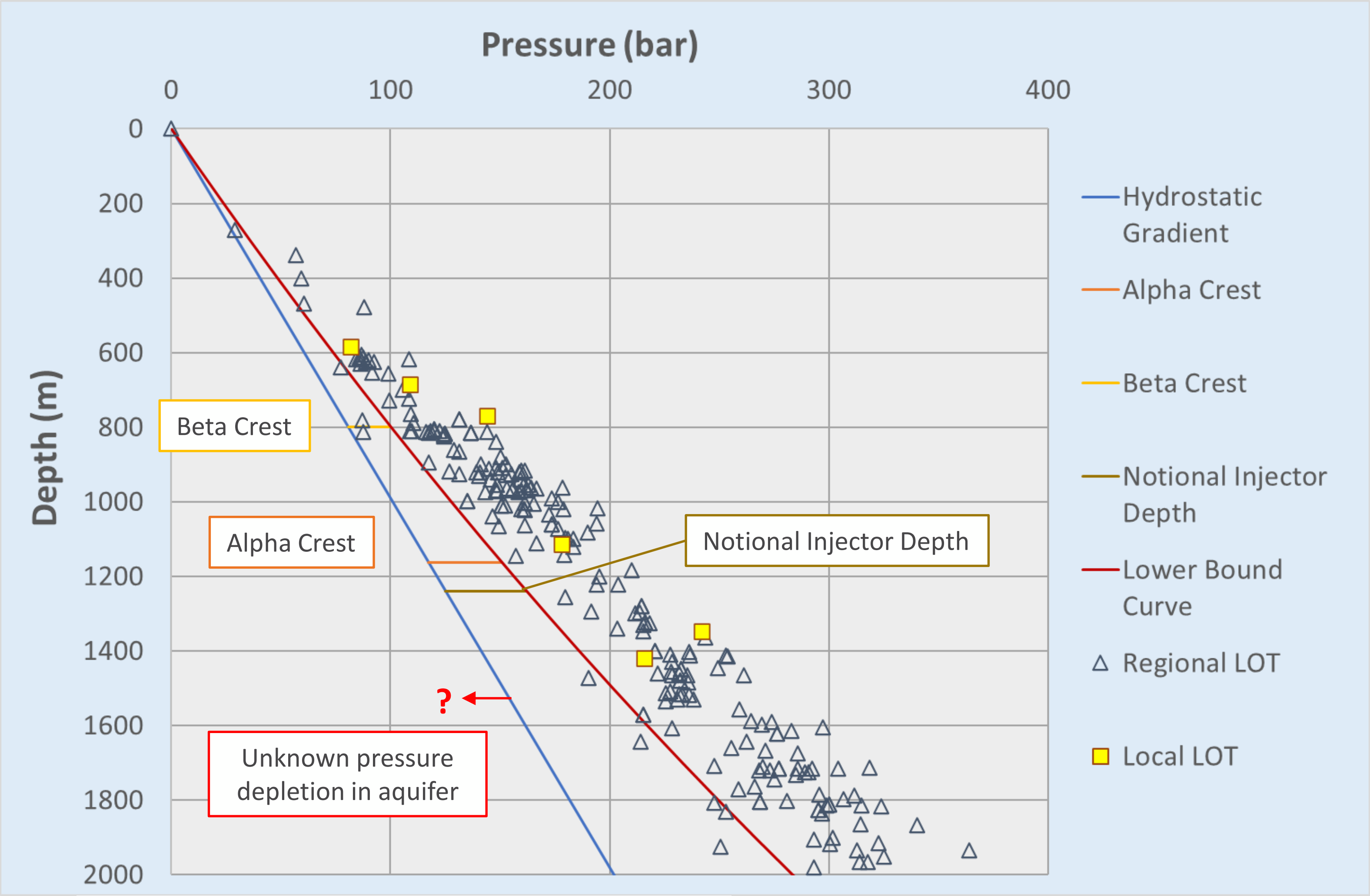
- Smeaheia consists of two structural culminations: Alpha and Beta.
- Injection would be into aquifers in the Sognefjord and Fensfjord Formations.
- Draupne Formation shales provide the primary seal.
- Both Alpha and Beta have been penetrated by pre-existing (dry) exploration wells.
- Each structure could store up to 100 Mt CO_2.

Statoil (2016)



From the CO2 Storage Data Consortium, Smeaheia Dataset
Data Owners: Equinor ASA and Gassnova SF

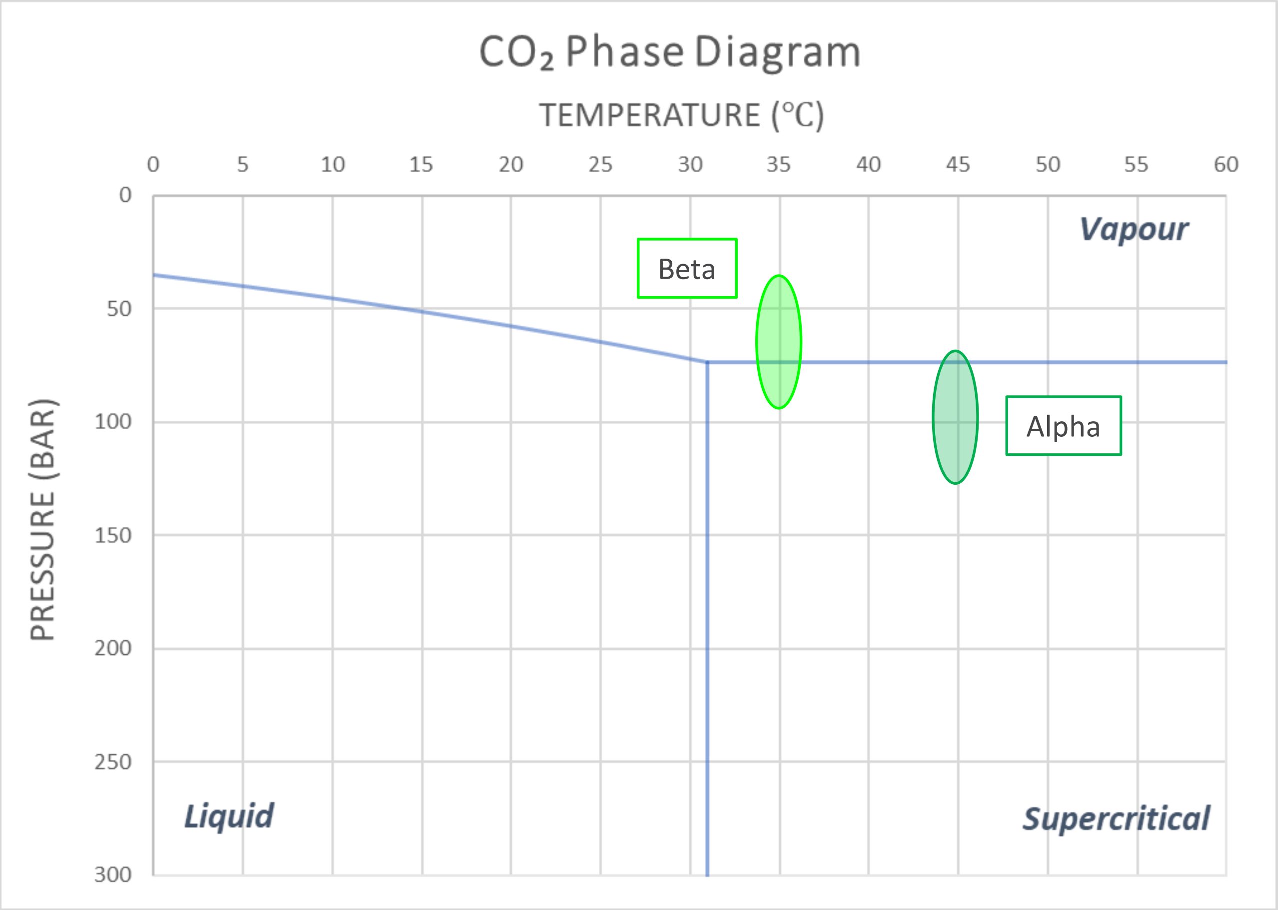
Smeaheia Pressure Context



LOT from: https://factpages.npd.no/en/wellbore/TableView/With/CasongAndLot

- One of the biggest uncertainties for the Smeaheia project is the aquifer pressure.
- Depletion from production at Troll could mean the aquifer is under-pressured by up to 50 bar.

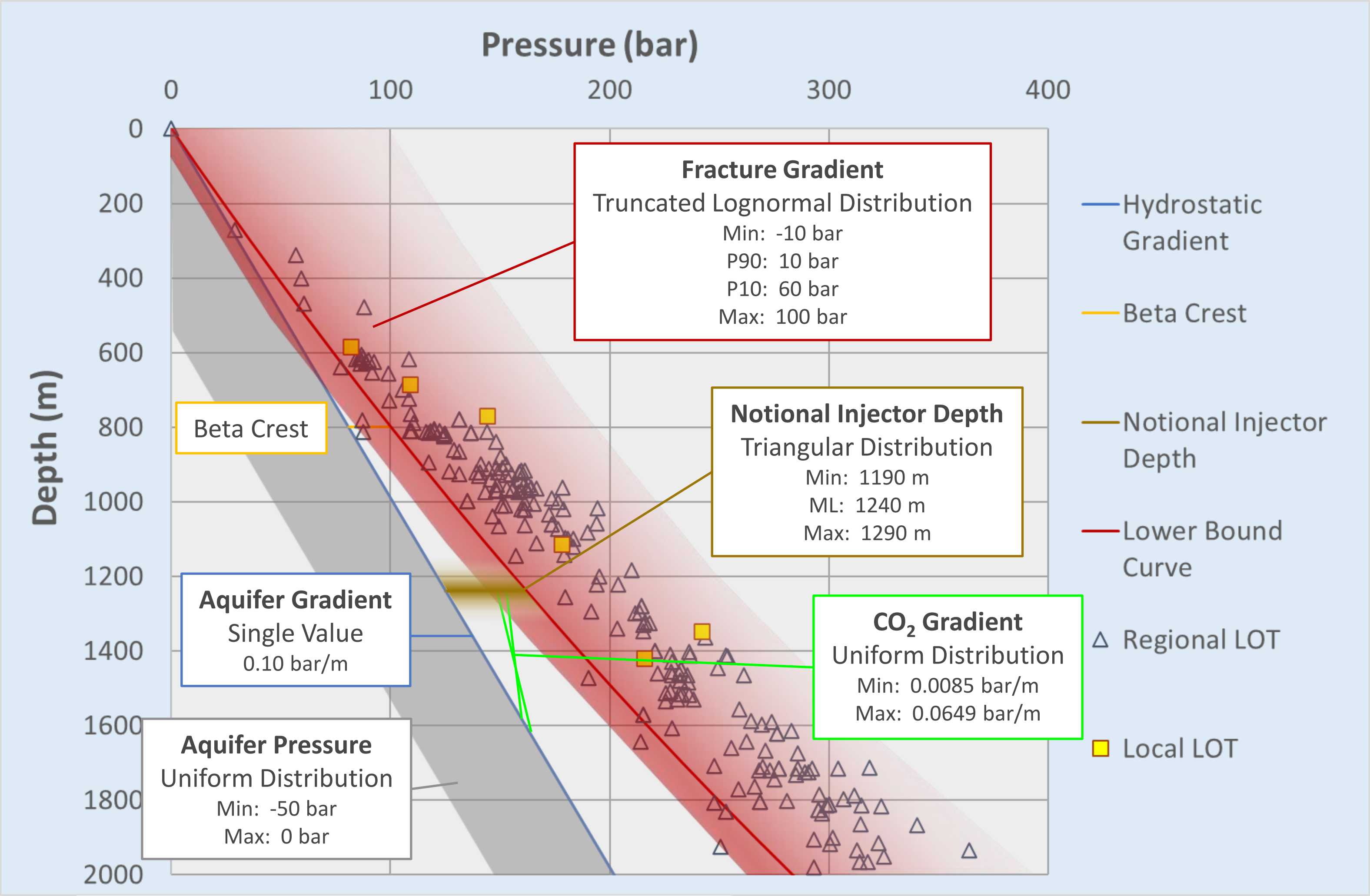
Impact of Uncertain Pressure and Temperature on CO_2 Properties



Pressure and Temperature from Statoil (2016)

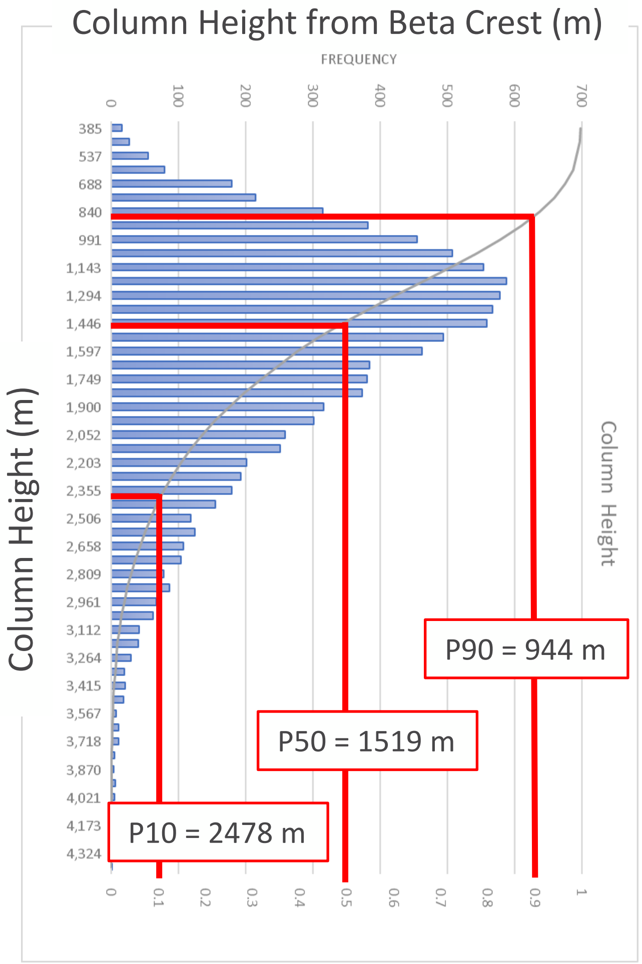
- Uncertainty on the pressure-temperature conditions at Smeaheia gives rise to uncertainty in the phase of injected CO_2.
- This puts a risk on the storage capacity if CO_2 is not in a supercritical (dense) phase.
- Also puts a large error bar onto the modelled CO_2 fluid gradient.

Model Inputs (Smeaheia Beta)



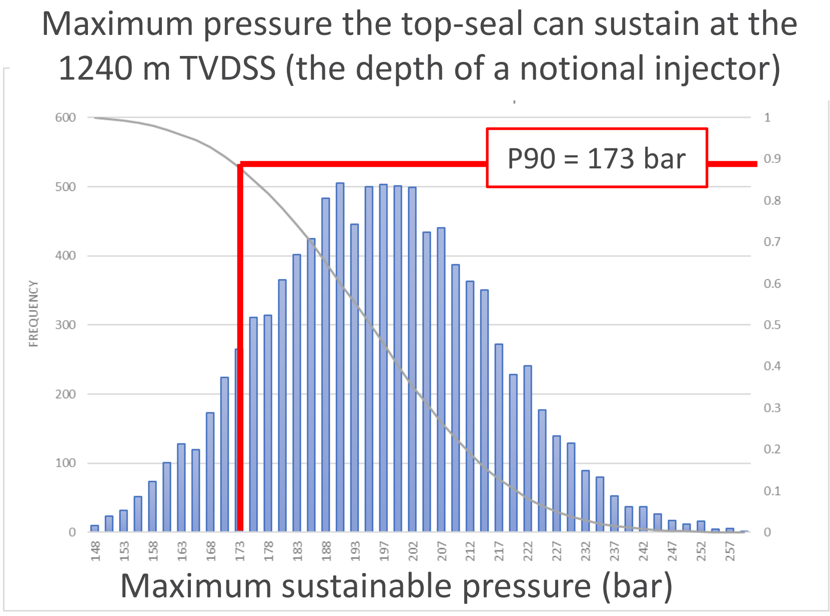
LOT from: https://factpages.npd.no/en/wellbore/TableView/With/CasongAndLot

Stochastic Results (Smeaheia, Beta)



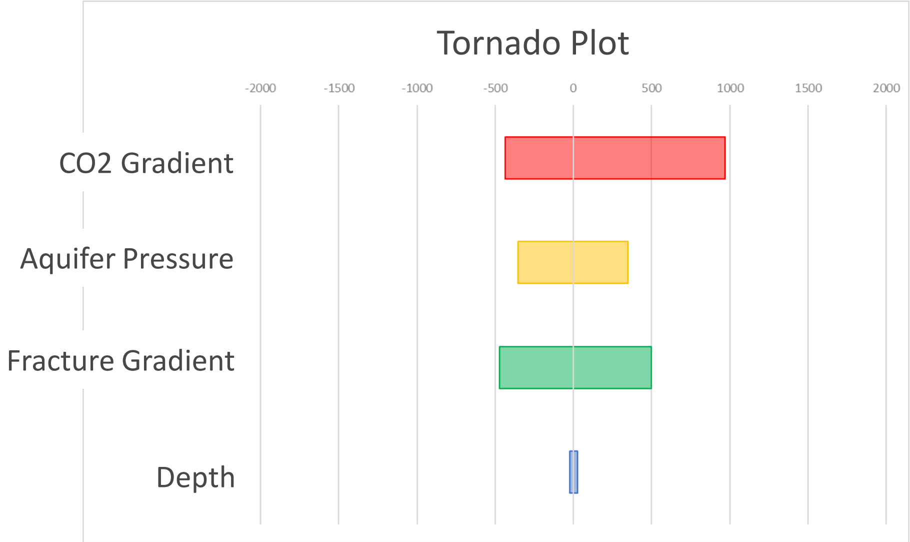
The top-seal at Beta is capable of retaining very tall CO_2 columns without fracturing.

This provides a quick, early check to make sure the storage project is safe for an economically viable quantity of CO_2.



173 bar is the P90 pressure the top-seal is able to able to sustain for a notional injector penetrating the Sognefjord at 1240 m.

This threshold can be used to constrain injectivity rate modelling and ensure that an economic rate can be safely achieved.



The most sensitive parameter at Smeaheia is CO_2 gradient (related to uncertainty in the aquifer pressure).

This sensitivity could be reduced by drilling an appraisal well, like the Eos well at Aurora.

Conclusions

- Understanding the risk of top-seal fracture is a key part of evaluating the containment risk of a potential CO_2 storage site.
- A stochastic modification to the deterministic pressure workflow can be used for projects which aren't yet mature enough to warrant 3D modelling, but which would benefit from a more sophisticated approach than the simple deterministic method.
- Stochastic modelling can be used to identify:

The likelihood that the top-seal at a potential CO_2 storage site is strong enough to sustain an economic quantity of CO_2.	Can make or break a project at the screening stage.
The pressure increase a caprock is able to sustain before the risk of fracture becomes too high.	Used to ensure an economic rate of CO_2 can be safely injected.
Which input parameters contribute the most uncertainty to the outputs.	Appraisal budgets can be targeted more effectively.

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