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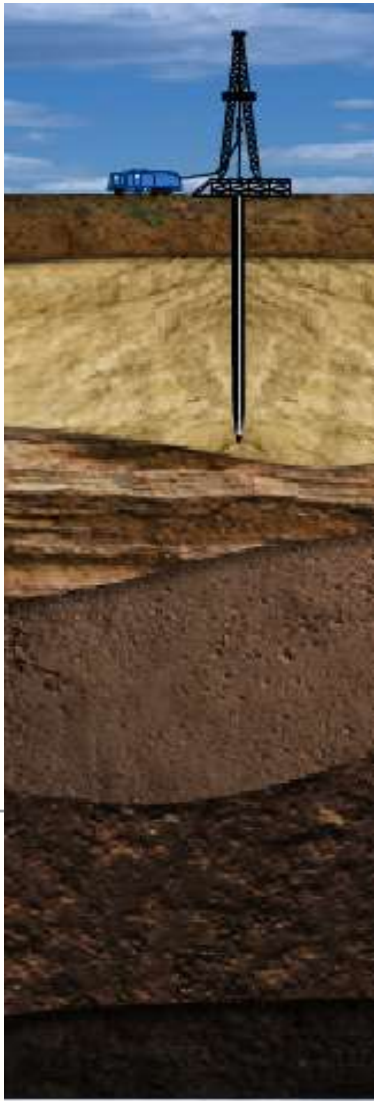
# Storage 2 – Leakage Pathways

## Wellbore Integrity

Andrew Duguid



July7 – 11, 2014

IEAGHG  Summer School, Austin, Texas

# Wellbore Integrity

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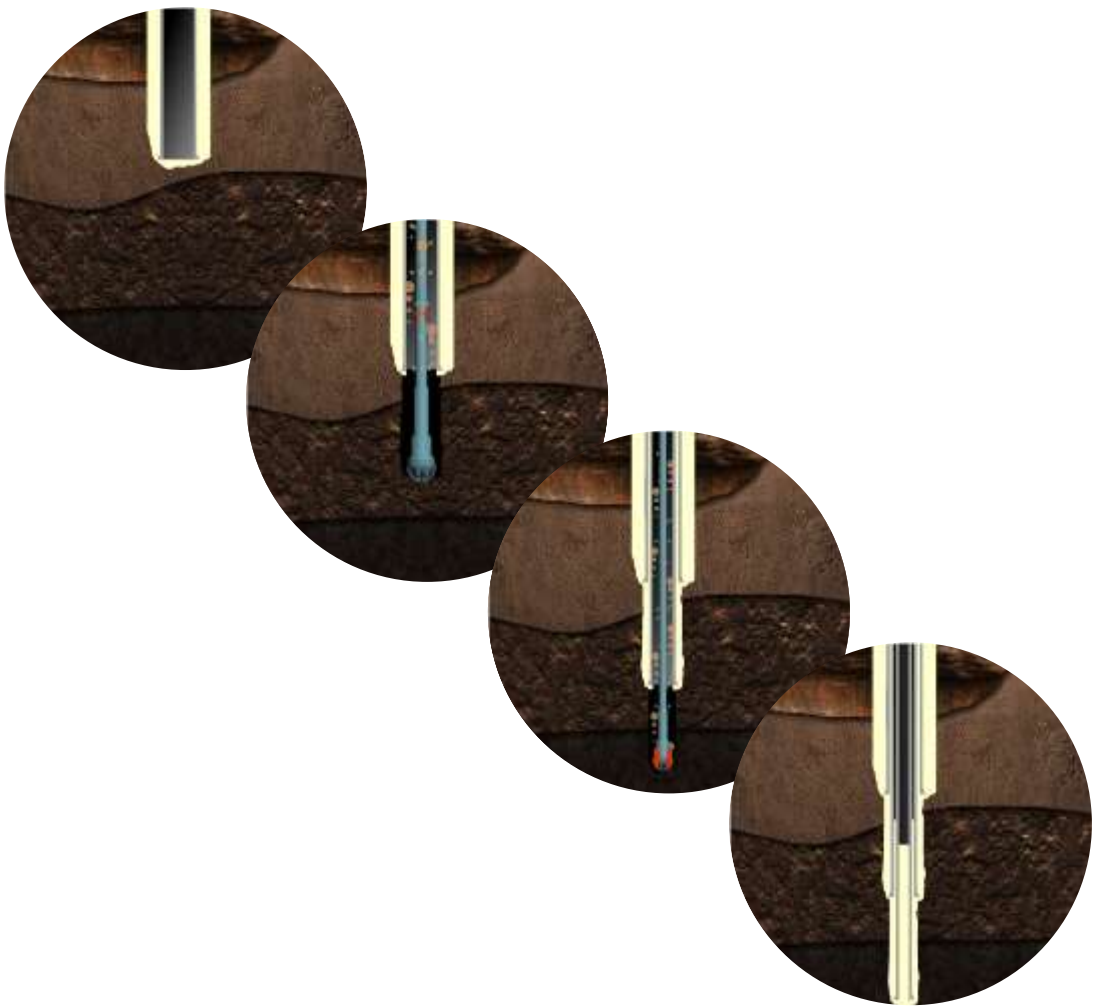
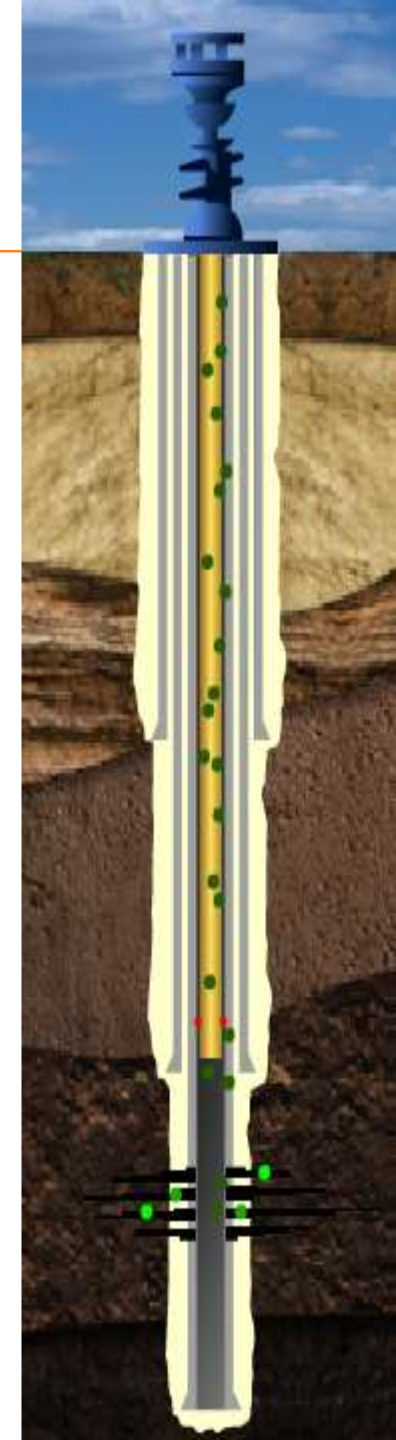
- A well: how it's made, what it does
- The wellbore challenge
- Key components and interfaces
- What could possibly go wrong ?
- How could you tell ?
- How can you fix it ?

# VIDEO: Drilling, Casing, and Completing a Well





# The wellbore challenge

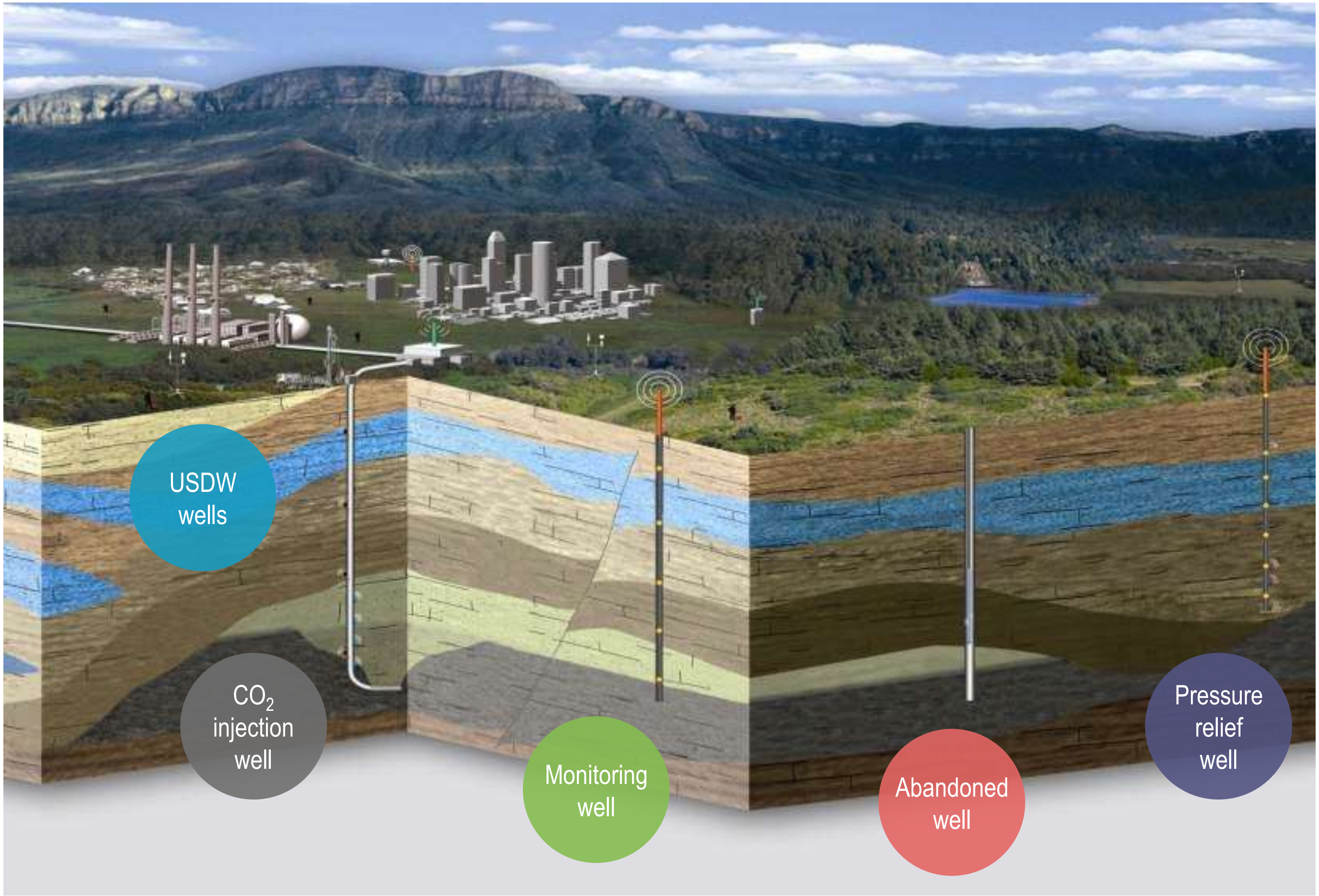
A well is not just ‘a hole in the ground’

– a complex hydro-mechanical system designed to fulfil many requirements:

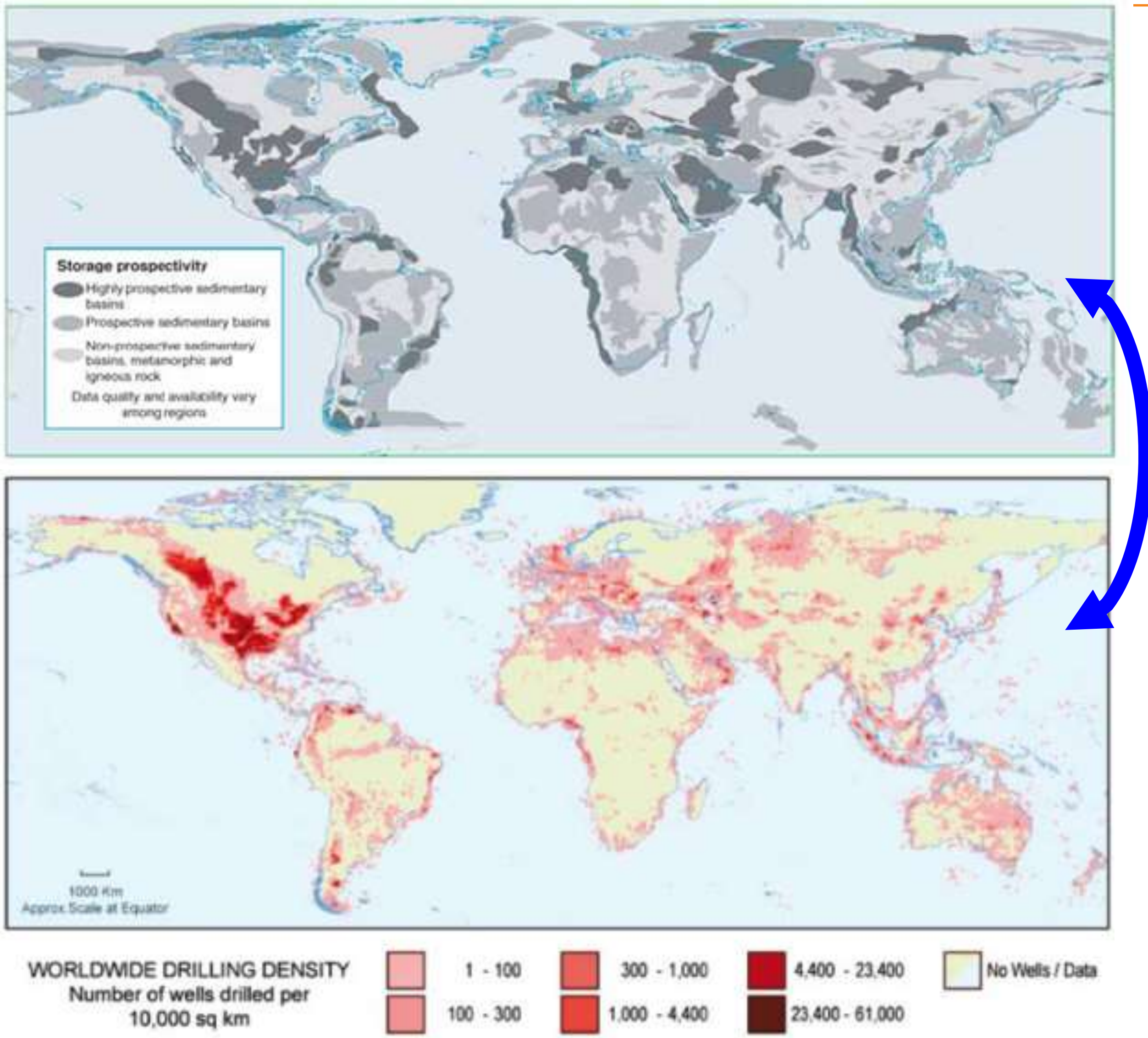
- Shape: ***Efficient*** (2km+ long, 20cm wide → 10,000 : 1 aspect ratio)
- Connects the surface to storage formation
- Long-term
- Compatible with injection stream ($CO_2$ and impurities)
- Materials – steel, cement, elastomers, annular fluids
- Barriers for fluid flow
- Economical – cost effective (construction, maintenance, abandonment)
- Repairable
- Geologically compatible (formations, stresses, fluids)
- Environmentally acceptable

6 inch line, 1pt = 432 : 1

# It's not just the injection well



# Why existing wells are important

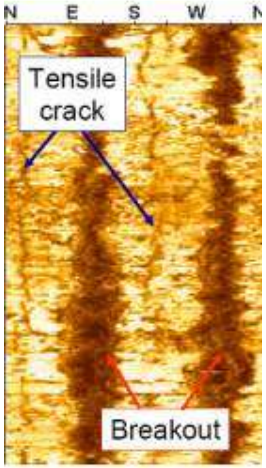



Strong Overlap On "Highly Prospective Sedimentary Basins

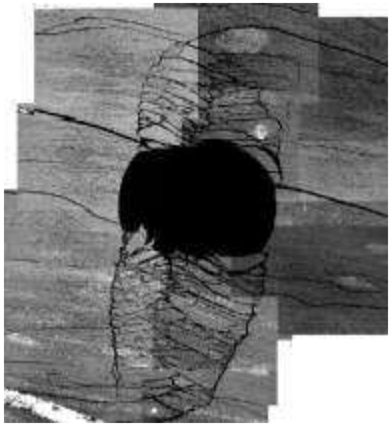
IPCC SRCCS, 2005

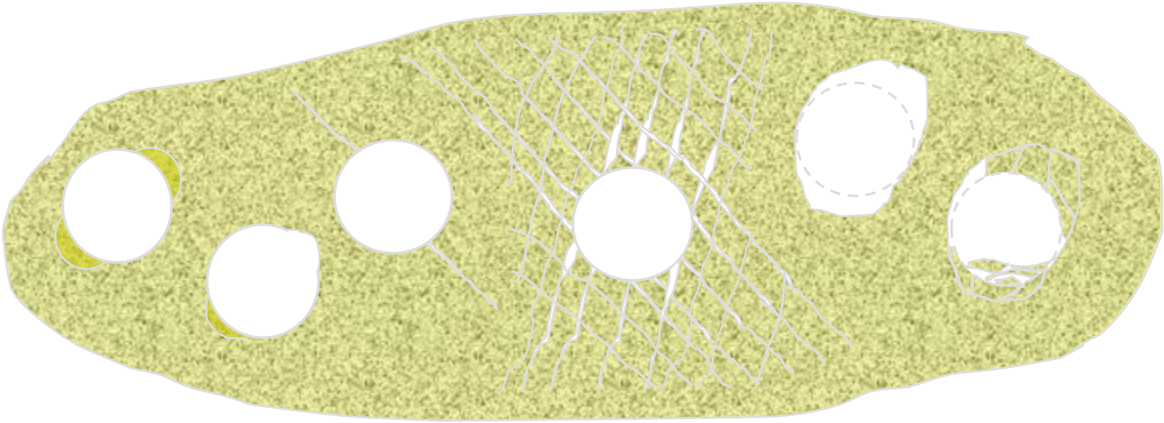
# Effects of drilling on the borehole

- Breakouts and fractures
  - Controlled by state of stress, mud weight, etc.
- Strong electro-osmotic effects (clay swelling/contraction)
  - Dependent on mud activity
- Breakout and washouts
  - Poor centralization ⟶ Channeling
- Keyway
  - Caused by drill-pipe wearing on one side of the borehole
- Near wellbore degradation




*Source: GMI training material*





# Interfaces – some critical points

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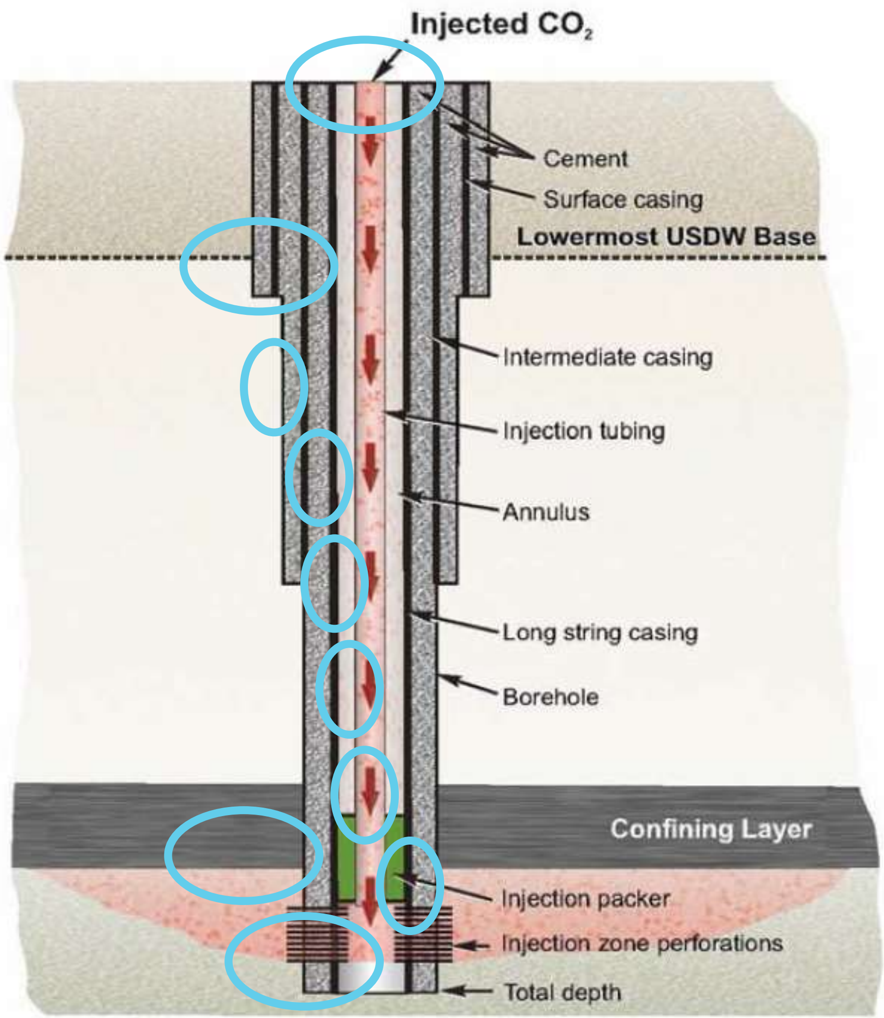
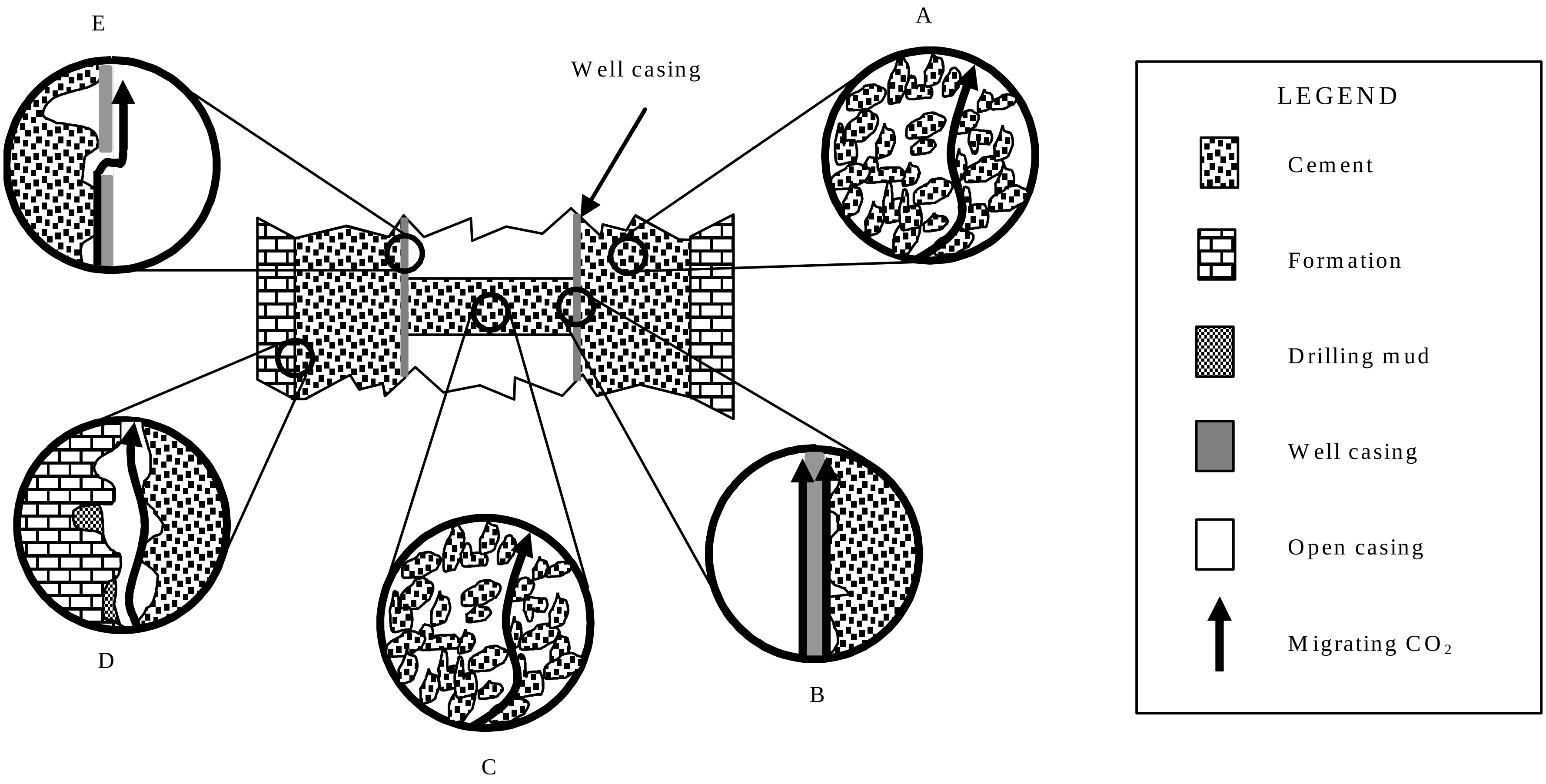
1. wellhead
2. USDW boundary
3. borehole – cement
4. cement – casing
5. casing – annulus
6. annulus – tubing
7. tubing – $CO_2$
8. packer – casing & tubing
9. caprock – storage formation
10. well – storage (perforations)




From US Environmental Protection Agency, Class VI well guidelines

# Potential avenues for leakage



# Construction: Cement sheath defects

## Placement defects

- Poorly centralized casing can lead to channels by bypassing the narrow side of the annulus
- Mud films can also create pathways and reduce zonal isolation

## Gas migration during cement hydration may cause channels

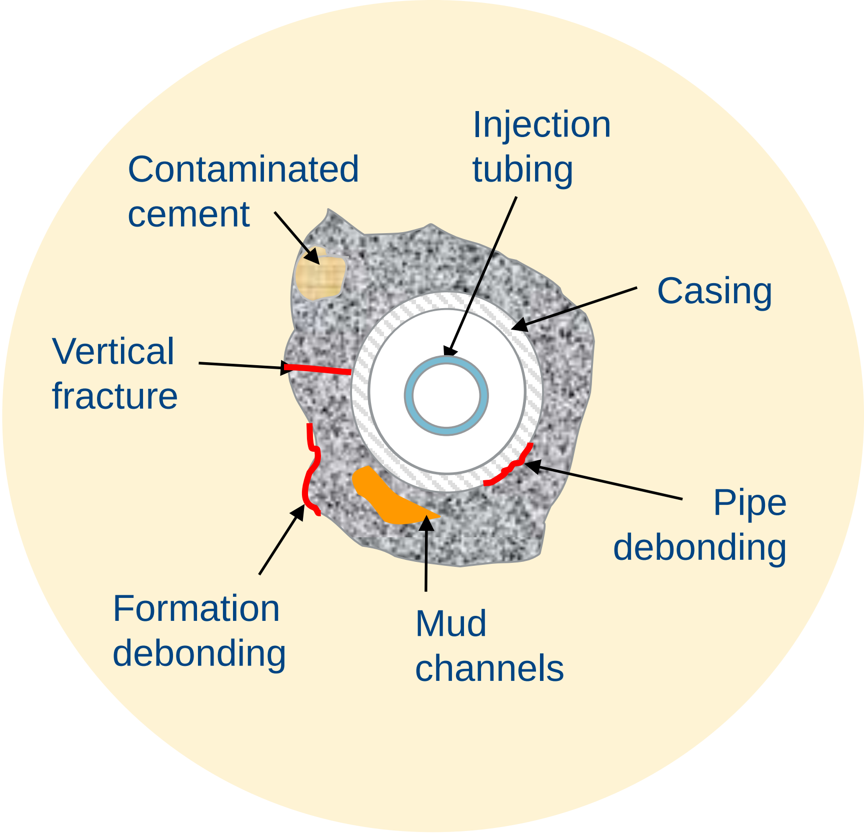
- Driven by a drop in cement pore pressure during hydration

## Thermomechanical effects

- Cracks caused by cement failure in compression/tension, microannuli caused by debonding at the interfaces with casing and/or rock

These can all lead to direct communication to the casing and may increase transport by establishing a communication path vertically

Construction practices should minimize the chances for defects in the well to be created and should include the use of centralizers and proper mix design.



# Typical well cement composition

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## Unhydrated

| Phase | Percent |
|---|---|
| $3CaO \bullet SiO_2$ | 50 |
| $2CaO \bullet SiO_2$ | 30 |
| $3CaO \bullet Al_2O_3$ | 5 |
| $4CaO \bullet Al_2O_3 \bullet Fe_3O_3$ | 12 |

## Hydrated

| Phase | Abbreviation | Percent |
|---|---|---|
| $Ca_3Si_2O_7 \bullet 4H_2O$ | C-S-H | 50-70 |
| $Ca(OH)_2$ | CH | 20-25 |
| $3(3CaO \bullet Al_2O_3 \bullet CaSO_4 \bullet 12H_2O)$ | AFm | 10-15 |
| $4CaO \bullet (Al,Fe_2O_3) \bullet 13H_2O$ | AFt | |

Data from Nelson, 1990

# Cement degradation reactions



$CO_2$ dissociation

$$CO_2 + H_2O \leftrightarrow H_2CO_3^* \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

Cement dissolution

$$Ca(OH)_2(s) + 2H^+ + CO_3^{2-} \longrightarrow CaCO_3(s) + 2H_2O$$

$$Ca_3Si_2O_7H \bullet 4H_2O(s) + 2H^+ + CO_3^{2-} \longrightarrow CaCO_3(s) + SiO_xOH_x(s)$$

$$Ca(OH)_2(s) + H^+ + HCO_3^- \longrightarrow CaCO_3(s) + 2H_2O$$

$$Ca_3Si_2O_7H \bullet 4H_2O(s) + H^+ + HCO_3^- \longrightarrow CaCO_3(s) + SiO_xOH_x(s)$$

Calcium carbonate dissolution

$$CO_2 + H_2O + CaCO_3(s) \leftrightarrow Ca^{2+} + 2HCO_3^-$$

$$2H^+ + CaCO_3(s) \leftrightarrow CO_2 + Ca^{2+} + H_2O$$

# Materials: Reactions At The Cement-Rock Interface--Lab

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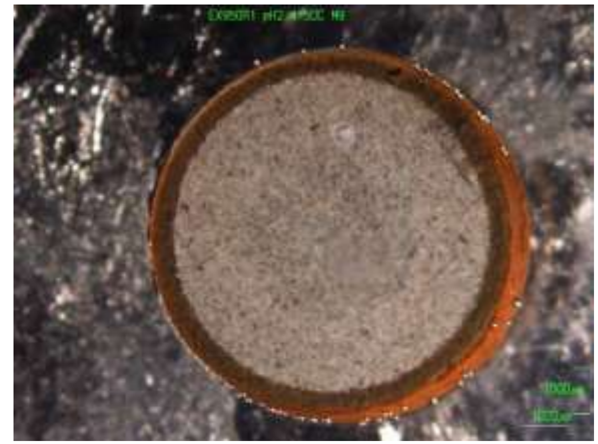
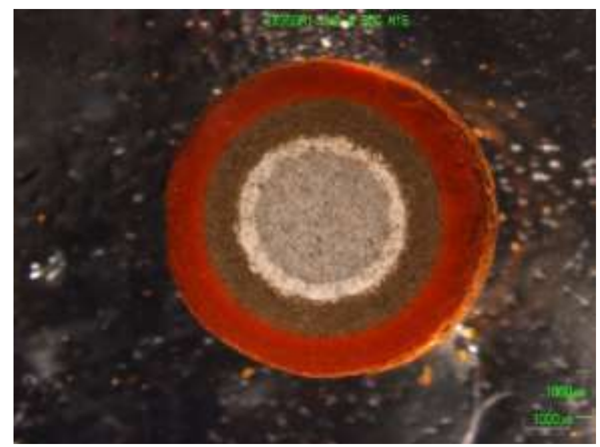
## Neat cement pH 2.4 and 50°C



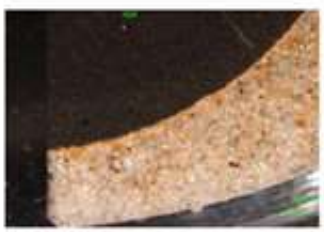


## Sandstone-cement at pH 3 and 20°C

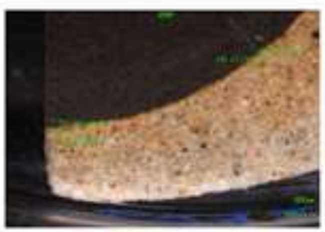
0 months

1 month

2 months



3 months



6 months

12 months

# Field experience

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**Fig. 1 – Photograph of samples recovered from well 49-6 showing the casing (left), gray cement with a dark rind adjacent to the casing, 5-cm core of gray cement, gray cement with an orange alteration zone in contact with a zone of fragmented shale, and the shale country rock.**

J.W. Carey et al., "Cement with 30 years of $CO_2$ exposure"
Int. J. GHG Control I (2007) 75-85

# Materials: $CO_2$-Resistant Cement



Cements for remediation and construction of new wells can still be portland based.

Field experience has shown that reactions in the ground are probably much slower than what has been seen in the lab [Crow et al., 2008 and Carey et al., 2006] but further research needs to be conducted. Field experience under much more severe (geothermal) conditions has shown complete degradation of well materials exposed to $CO_2$ [Milestone et al., 1986]

$CO_2$ resistant portland cements have been used and are currently available.

- Some $CO_2$ resistant cements work by reducing the amount of calcium hydroxide (CH) and increasing the amount of calcium silica hydrate (C-S-H). C-S-H is more resistant to $CO_2$ attach than CH. Additives such as pozzolans provide additional silicon to create additional C-S-H.
- Additives such as bentonite which require a large increase in the water-to-cement (W/C) ratio should be avoided. High W/C can lead to accelerated cement degradation

# Steel corrosion – key factors

- Steel quality/composition
- Pressure
- Temperature
- Injection  stream
- Ambient fluid
- Protective surface layers
- Flow conditions
- Pipe geometry

→ Overall design and selection of appropriate grade of materials is critical

- Must consider operation and shutdown scenarios

# Mitigation of leakage through design

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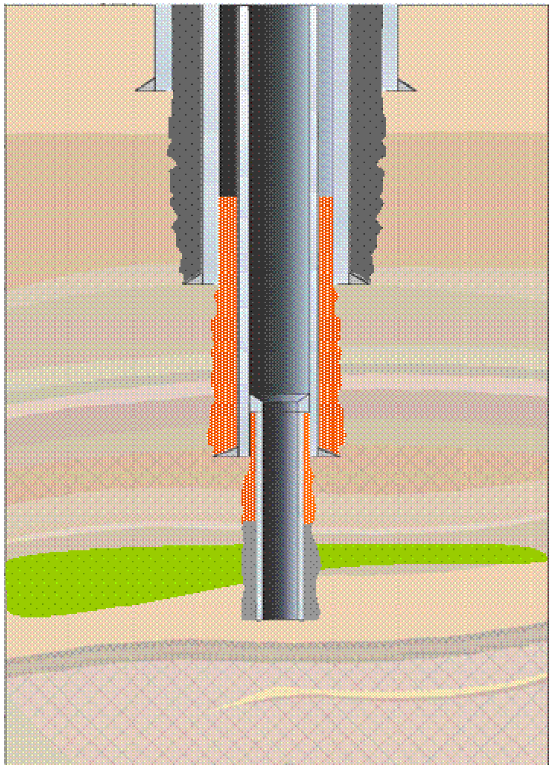
A full well design based on expected conditions over the lifetime of the **project**

- Regulations
- Operational needs of the project
- Geologic conditions
- Position of well components and materials
- Selection of materials

- Providing secondary barriers as much as possible

- Robust construction practices required



# Monitoring techniques

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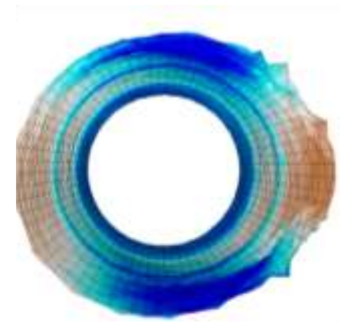
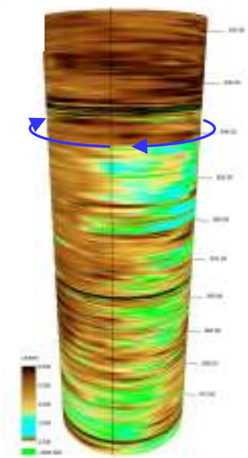
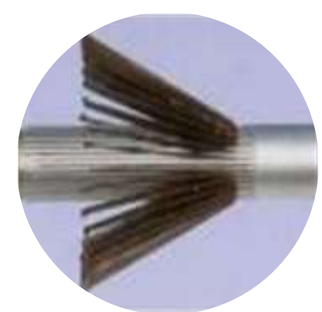




- Detection
  - Is something happening ?
- Quantification
  - How much ? How fast ?
  - Requires measuring $CO_2$ flowrate to estimate risk and impact

- Techniques:
  - Mechanical Integrity Testing → pressure at wellhead
  - Casing annulus pressure monitoring and sampling at surface
  - Downhole pressure and temperature monitoring along the well
  - Continuous temperature profile, e.g. Distributed temperature sensing
  - Noise logs to determine turbulent flow behind casing
  - Cement and corrosion monitoring tools
  - Soil gas surveys especially around abandoned wells



# Well logging, sampling, and testing

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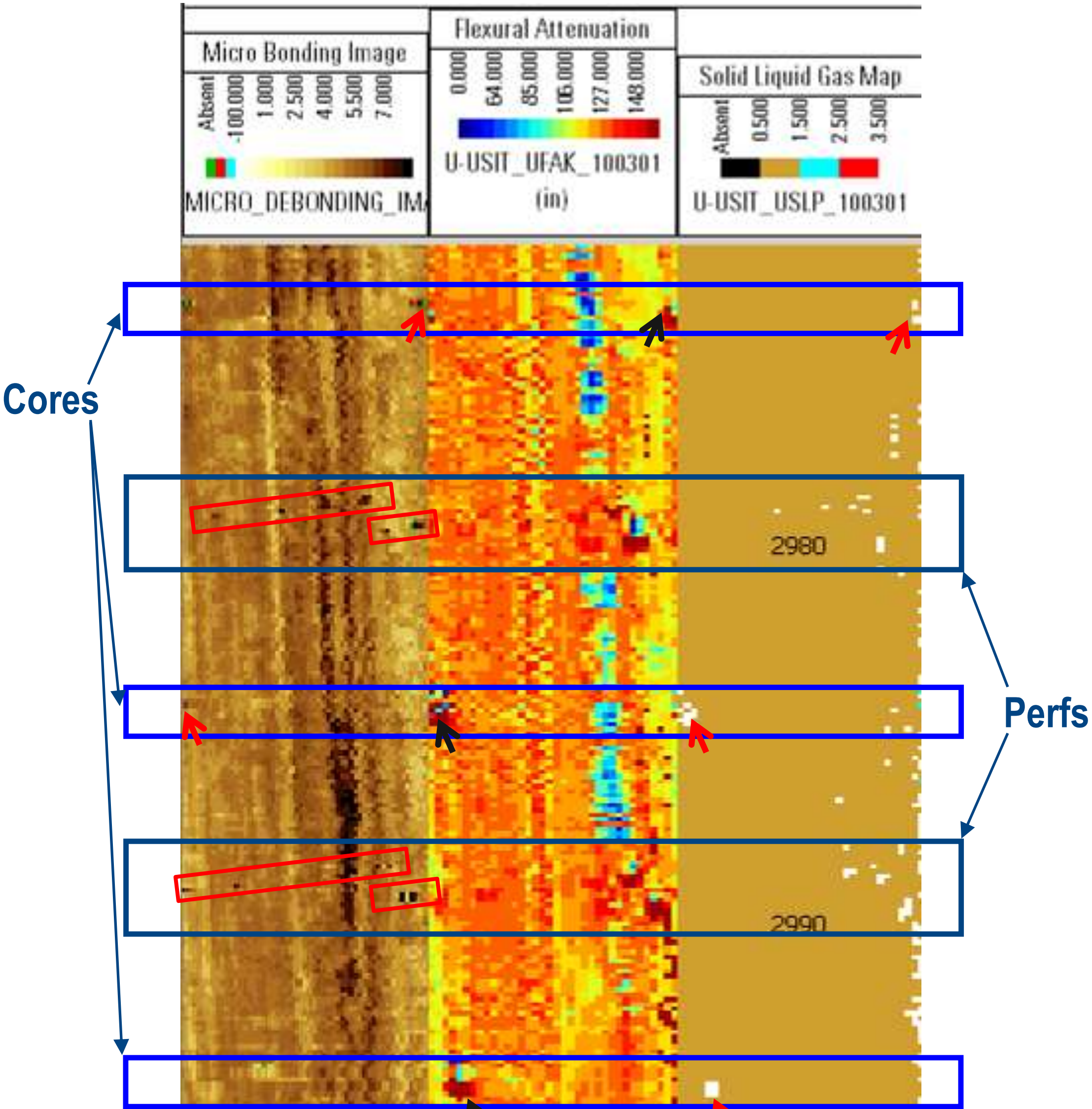
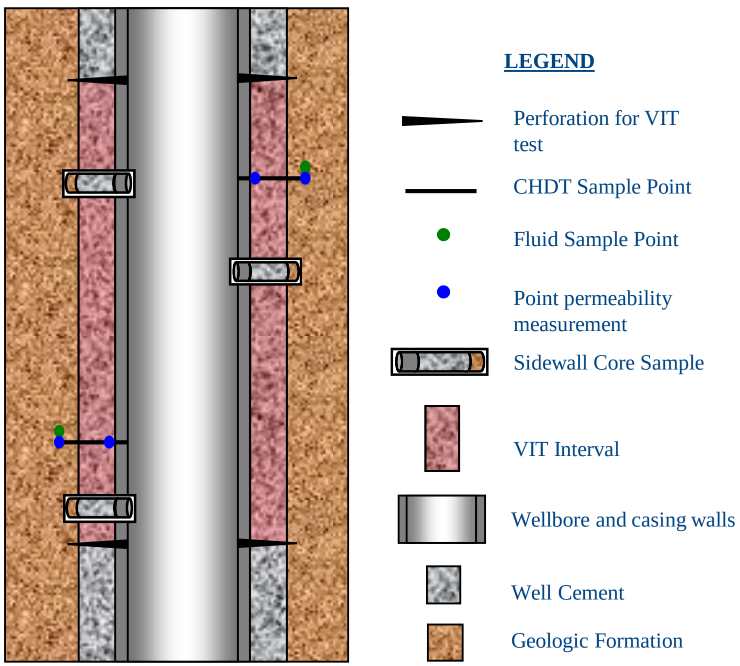
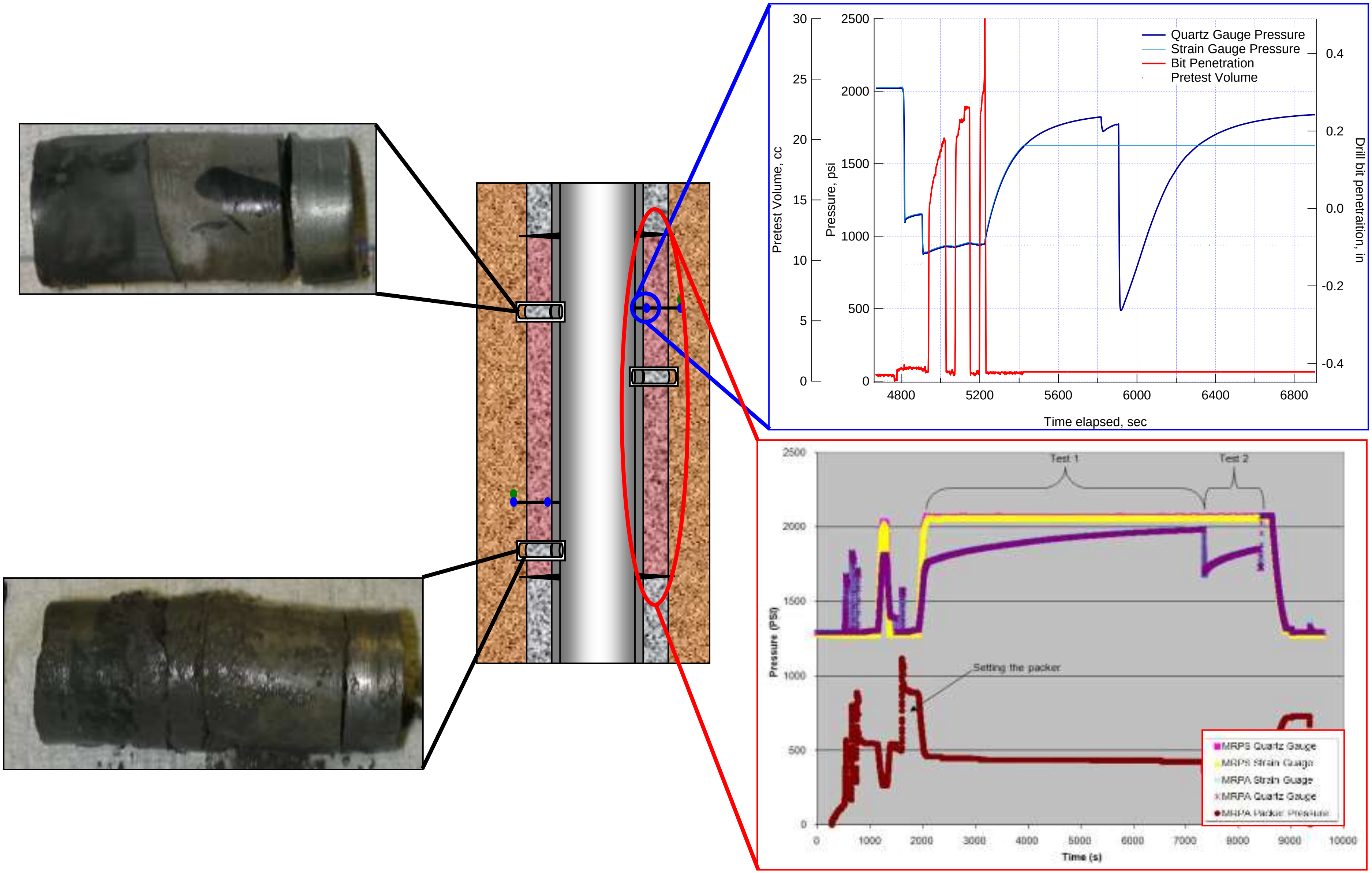


# Well sampling and testing



# Opportunities for intervention and remediation vary...

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Mississippi

$CO_2$ injection wellhead

Sleipner

Norwegian North Sea

Offshore platform

Snøhvit

160 km offshore

330m subsea wellhead

...however

- casing holes can be repaired
- cement channels filled

Photos courtesy of Statoil and US DOE

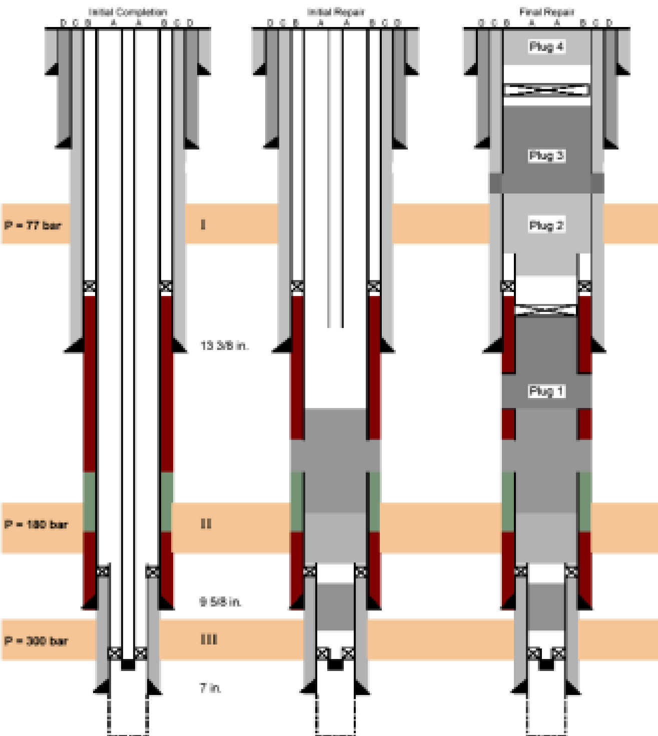
# Repair and Abandonment

Repair:

- “Squeeze job” → force liquid cement under pressure to seal long, thin pathways
- Casing patches or new sections

'Plugging and abandonment':

- Closure of access to storage formation
- Multiple steel / elastomer / cement plugs
- Material selection and optimal placement



# Process is important

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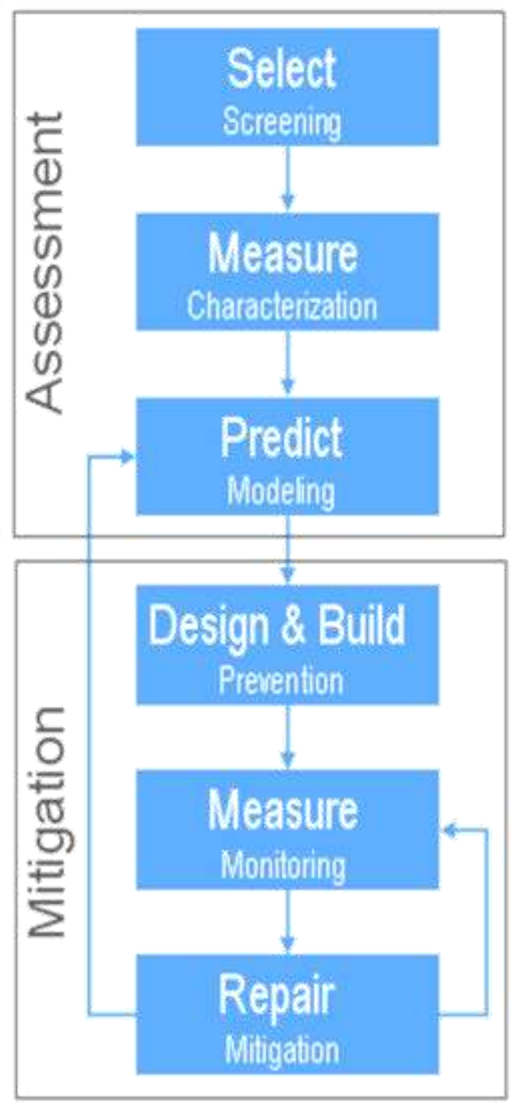
- As for all aspects of CCS, a formal process approach integrating risk assessment and management is critical to the construction of successful wells



# Wellbore Integrity – the solutions

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- Safety – the priority at all stages
- Understand $CO_2$ pathways
- Hole quality – drilling matters
- Design for life of the project
  - Lifecycle – design, construction, operation, decommissioning
  - Regulation
  - USDW – protecting underground sources of drinking water
  - Geology
  - Barriers – the key to integrity
- Existing wells – not just new ones
- Evaluation – measurements & monitoring
- Remediation – casing and cement repair

# Final thoughts …

- Remember, it's this shape (10,000 : 1 aspect ratio)
  - that makes it a ***long*** way between surface and storage

- A well in not just a 'hole in the ground'.

6 inch line, 1pt = 432 : 1