Well Integrity and Long-Term Well Performance Assessment
(Insights from work on CO_2 Sequestration)

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How Is Wellbore Integrity Achieved?

- **Operational measures**
  - **Adequate weight drilling mud**
  - **Monitoring pressure for gas intrusion ("gas kick")**
  - **Blowout preventers**
- **Design measures**
  - **Steel**
  - **Portland cement**
- **Guidelines: API HF1 (hydraulic fracturing),**

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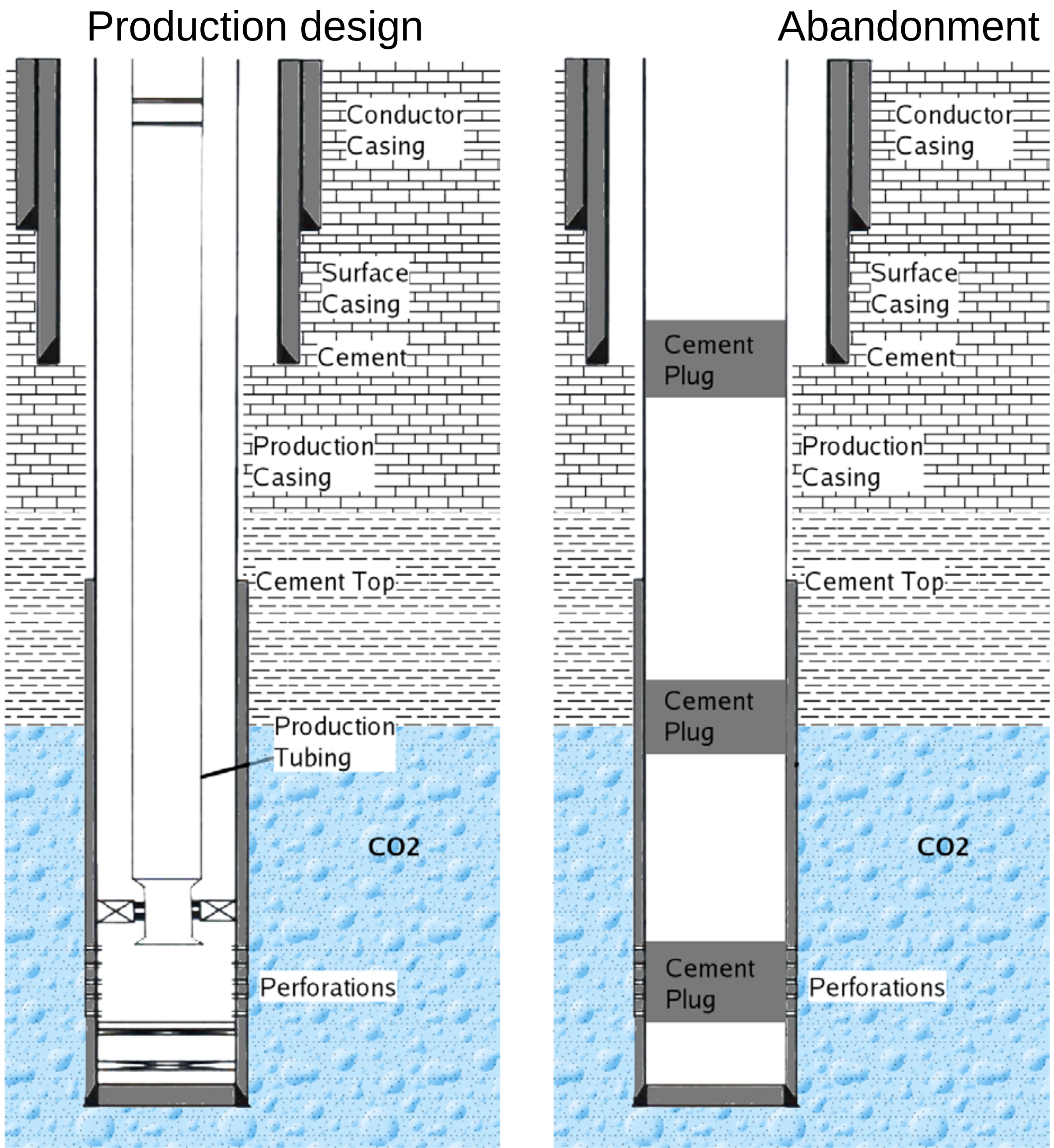


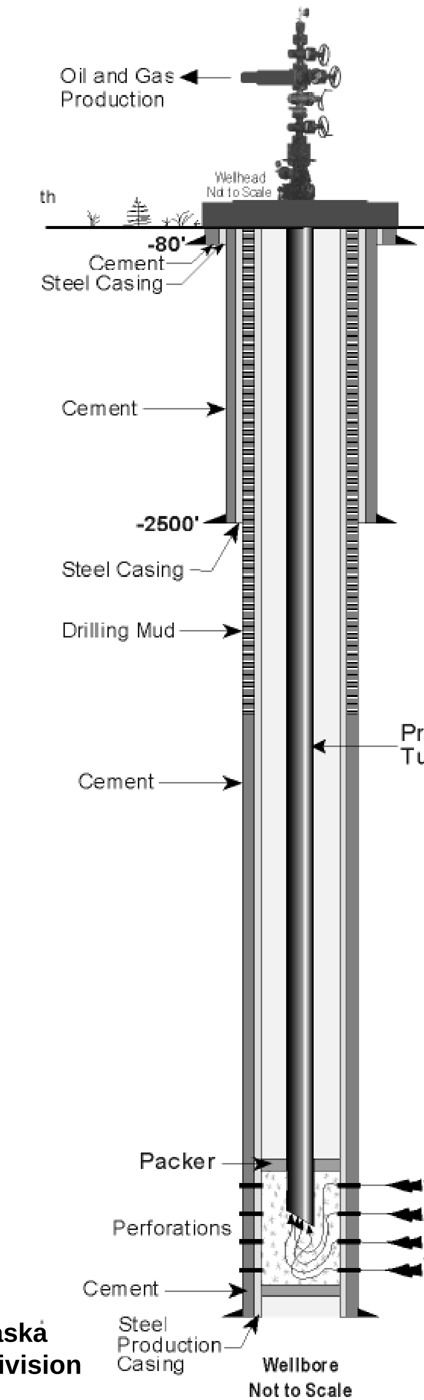
Why do wells leak?

Pre-Production

- Formation damage during drilling (caving)
- Casing centralization (incomplete cementing)
- Adequate drilling mud removal
- Incomplete cement placement (pockets)
- Inadequate cement-formation, cement-casing bond
- Insufficient cement coverage of well length
- Cement shrinkage
- Contamination of cement by mud or formation fluids

Post-Production

- Mechanical or thermal stress/strain
  - Formation of micro-annulus at casing-cement interface
  - disruption of cement-formation bond
  - Fracture formation within cement
- Geochemical attack
  - Corrosion of steel casing
  - Degradation of Portland cement
    - Carbonation
    - Hydrogen sulfide
    - Sulfate attack
    - Acid attack



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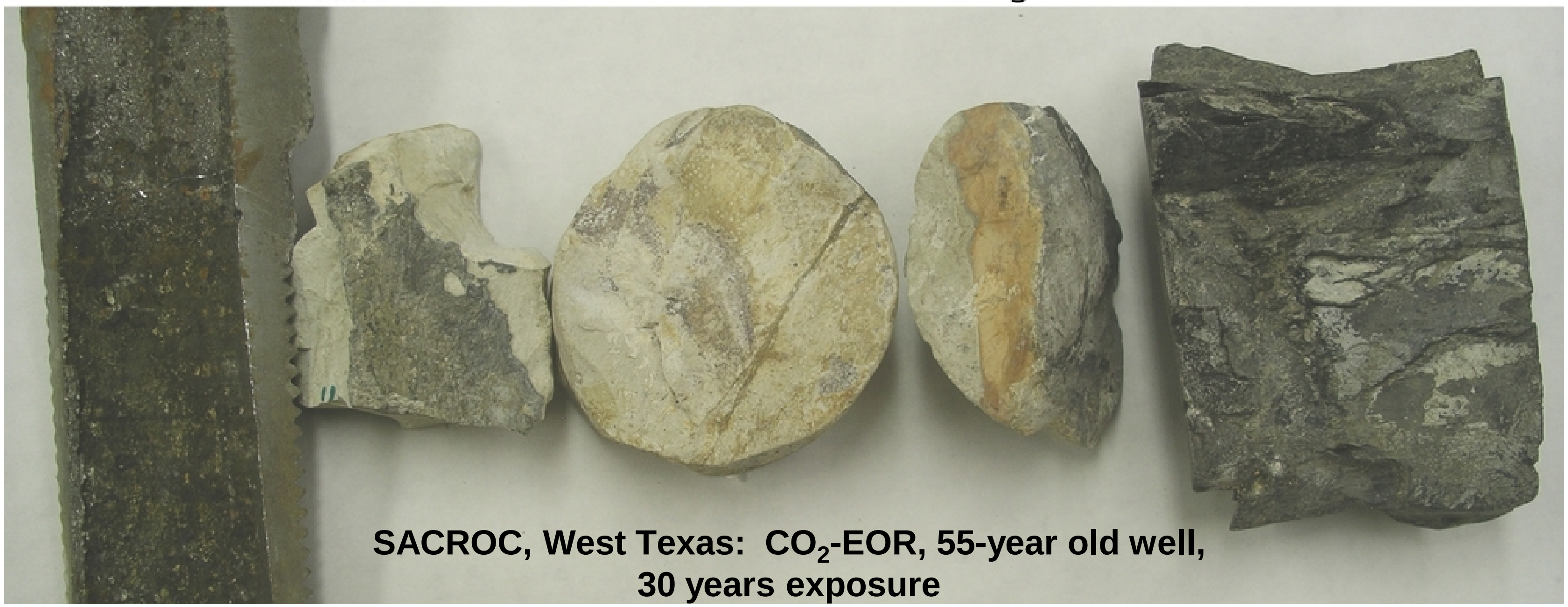
Field Observations: Role of Interfaces

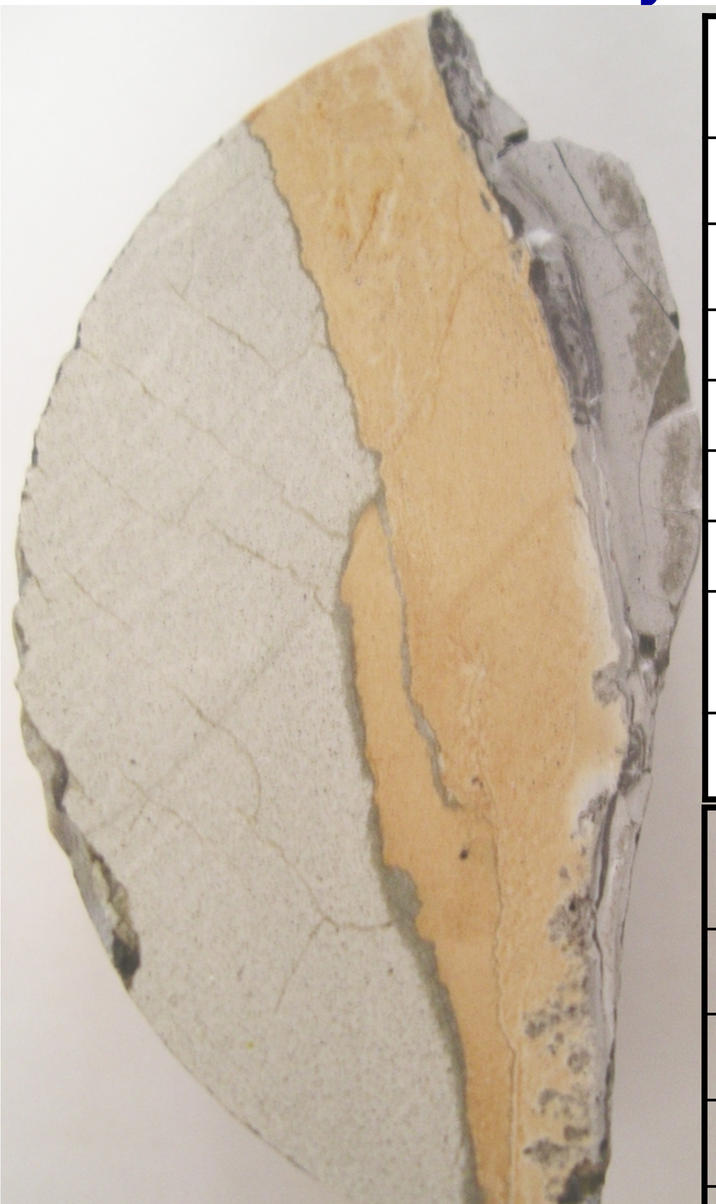


SACROC, West Texas: CO_2-EOR, 55-year old well, 30 years exposure

- **Evidence for CO_2 migration at cement-caprock interface (carbonate deposit)**
- **Evidence for CO_2 migration at casing-cement interface (orange, carbonated cement)**
- **Steel not corroded (but cathodic protection)**
- **Healed fractures in cement**
- **SACROC, West Texas: CO_2-EOR, 55-year old well, 30 years exposure**

Carey et al. IJGGC (2007)

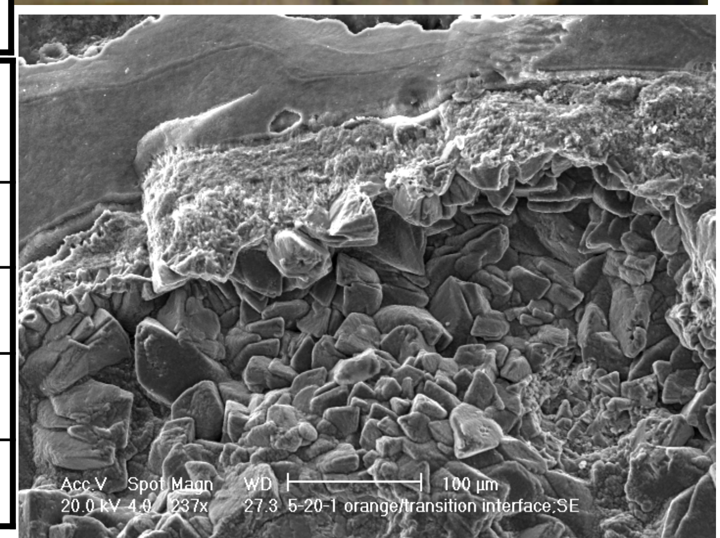
SACROC—Cement-CO_2 reactions Fracture Permeability



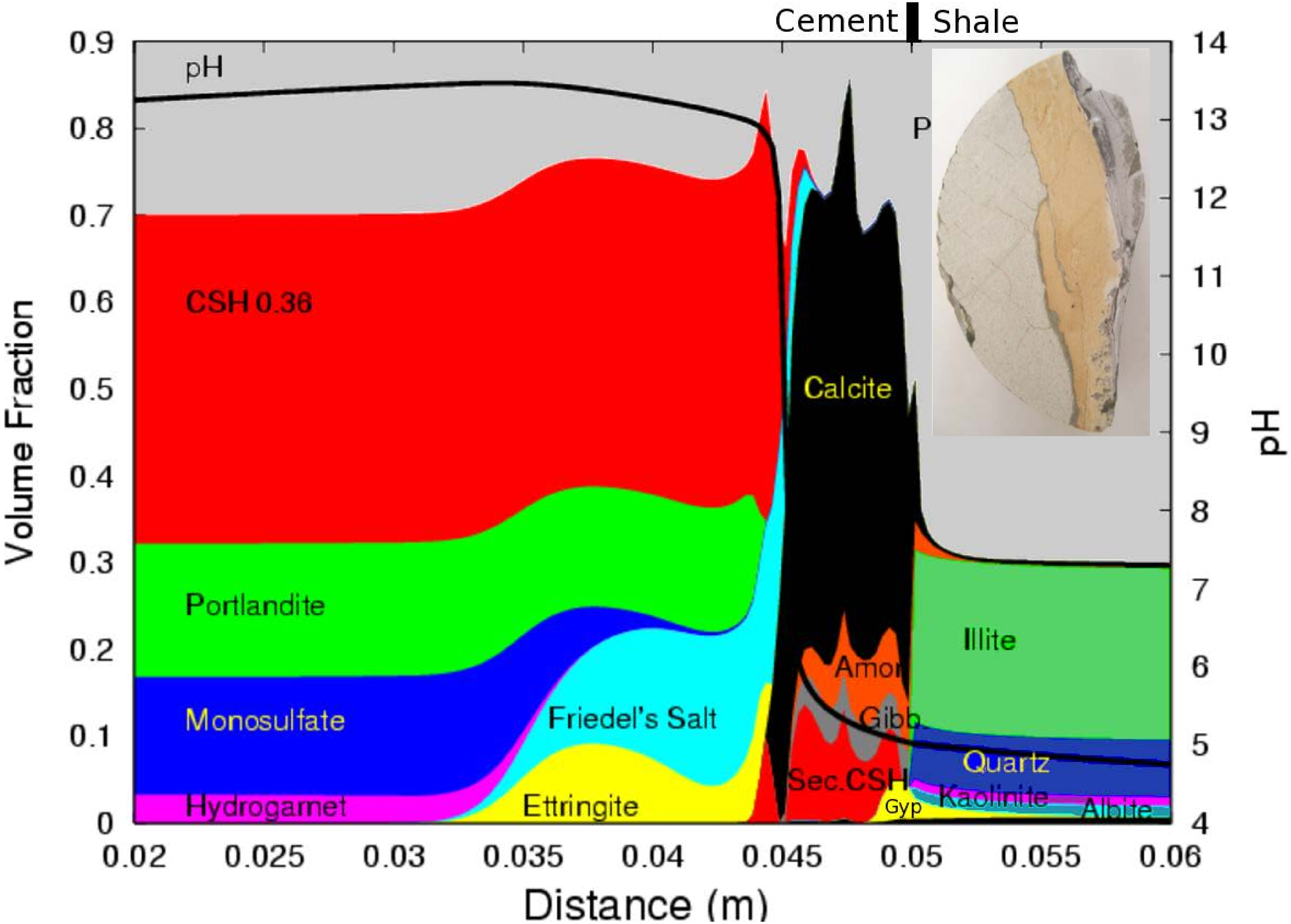
Carey et al. IJGGC (2007)

Phase	Gray Zone
Amorphous	Major
Portlandite	15-58%
Calcite	0-28%
Katoite	22-26%
Brucite	3-9%
Ettringite	3-4%
Friedel's Salt	2-4%
Halite	9-32%

Phase	Orange Zone
Calcite	44%
Aragonite	8%
Vaterite	33%
Halite	13%



Simulation of SACROC: Accurate account of cement mineralogy

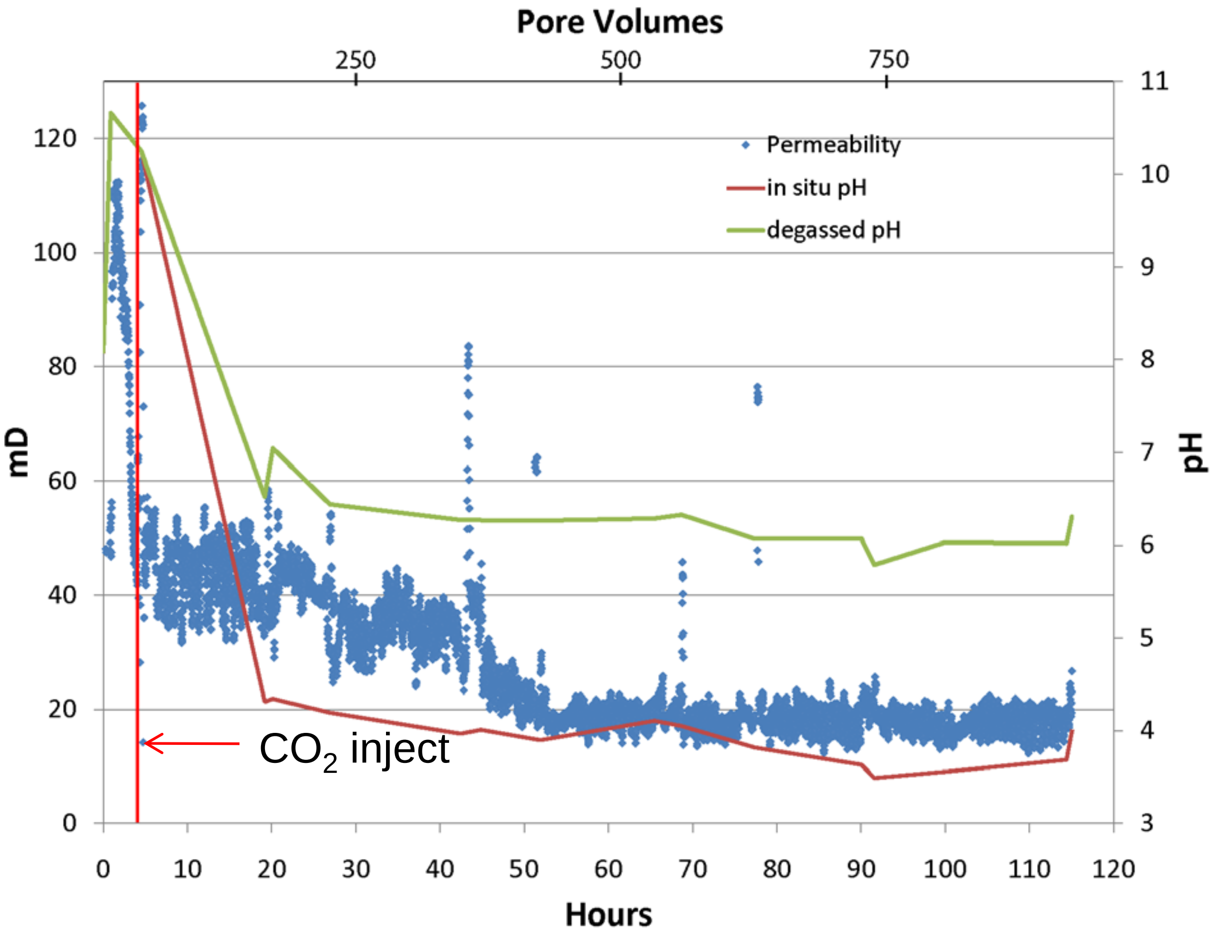


Carey and Lichtner (2007)

Experimental studies: Permeability of Cement-Caprock Interfaces

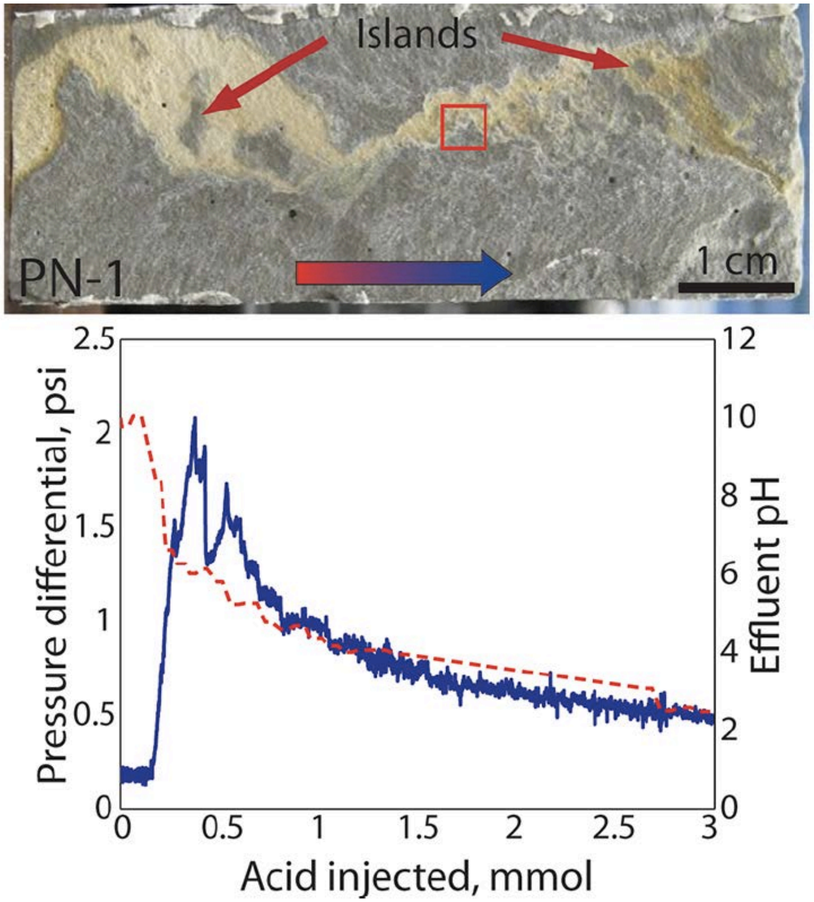
- Class G fly-ash Portland cement - fine grain quartz sandstone composite
- Interface of crushed sandstone (80%) and cured cement (20%): 125-250 µm
- 1500 psi pore (~10 Mpa), ~2600 psi confining (~18 Mpa), 60°C
- Brine flow (I = 0.04 M): 0.15 to 0.25 ml/min
- $scCO_2$ flow: 0.048 to 0.08 ml/min
- Fractional flow CO_2 = 0.24;

Permeability and pH: Self-healing

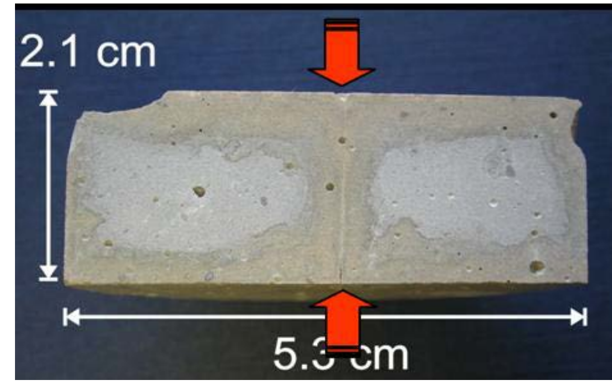


- **Permeability of SS-Cement interface**
  - **Assumes flow only along interface**
- **1461 ml brine; 460 ml CO_2 (~140 g)**
- **~890 interface pore volumes**
- **Steady state perm: ~500 pore volumes**
- **In situ pH calculated (Newell et al., 2008)**

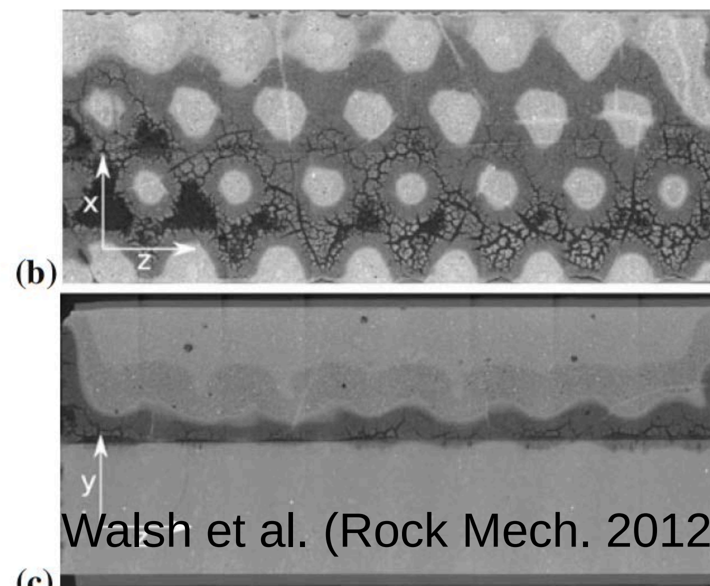
Coreflood experiments: Self-Healing Behavior in Cement-Cement Interfaces



Huerta et al. (ES&T 2013)



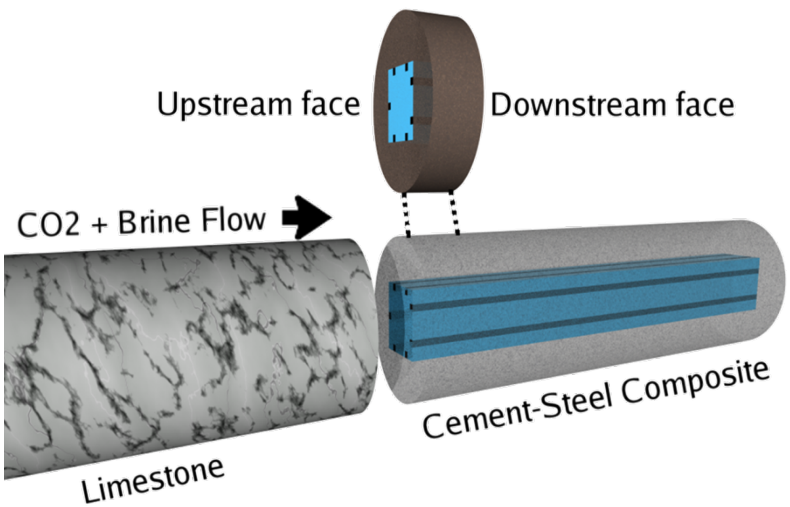
Wigand et al. (Chem. Geol. 2009)

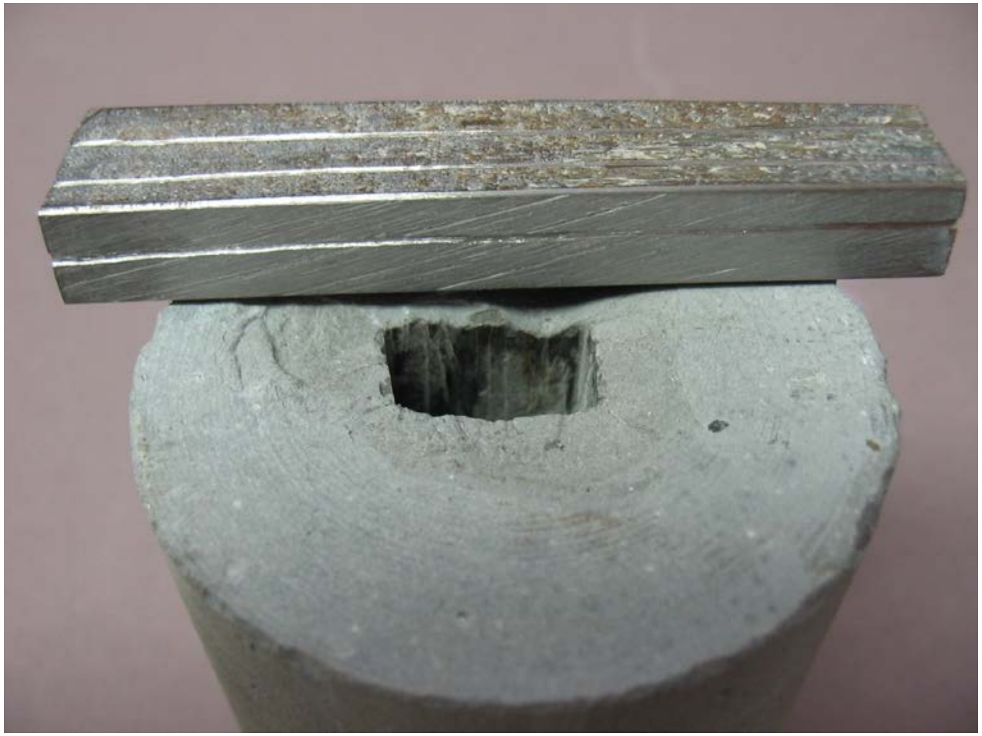


Walsh et al. (Rock Mech. 2012)

Experimental Studies of Corrosion at the Steel-Cement Interface

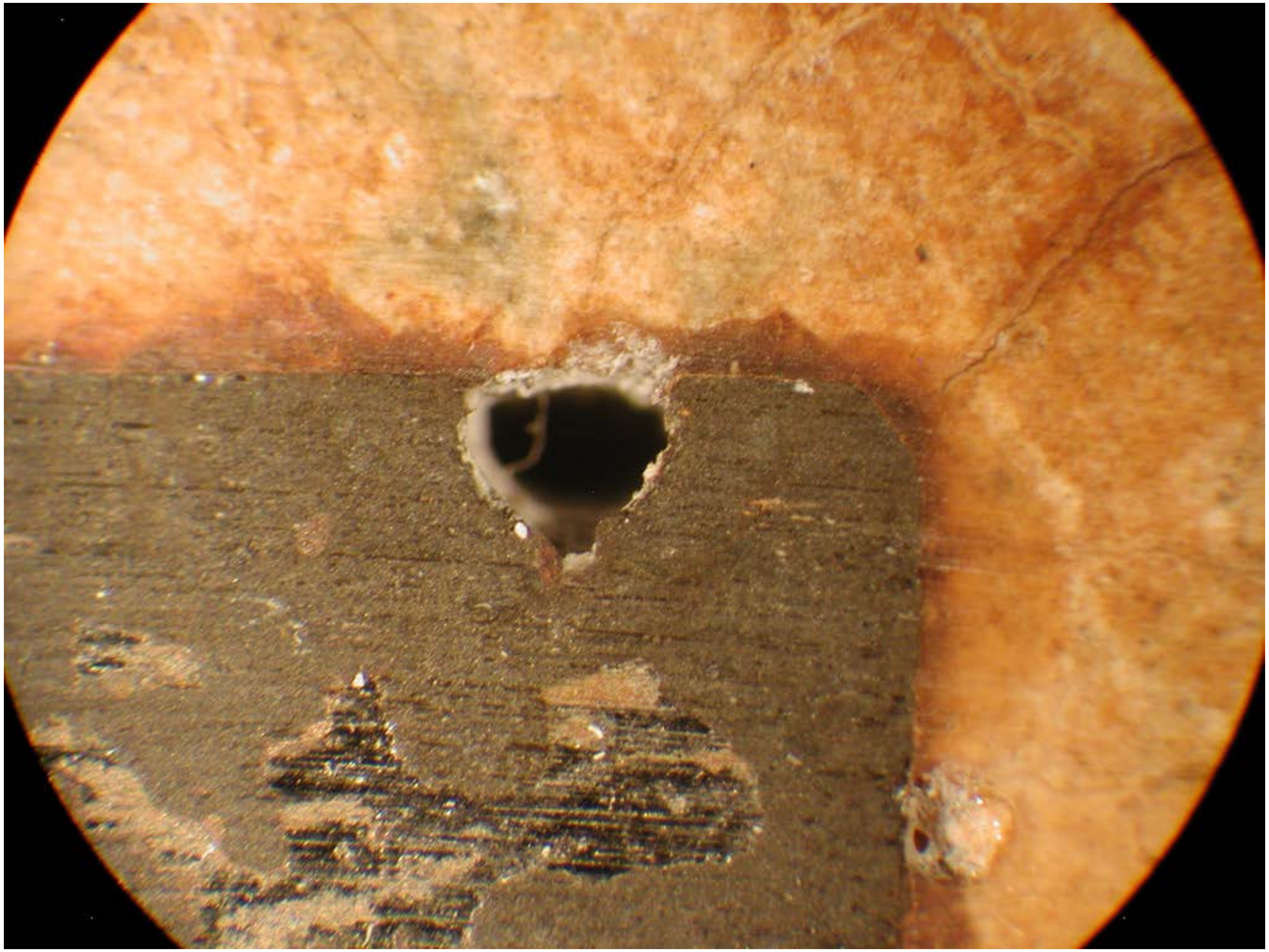
- **Flow-through experiments**
  - **50:50 CO_2-Brine (30,000 ppm, NaCl-rich) mixture (41,000 PV)**
  - **20 ml/hour for 274 hours; 10 ml/hour for 120 hours; 6200 ml total**
  - **40 ^oC; 14 MPa inlet pressure; 28 MPa confining pressure**
- **~ 10 cm Limestone against ~ 6 cm Portland Cement**



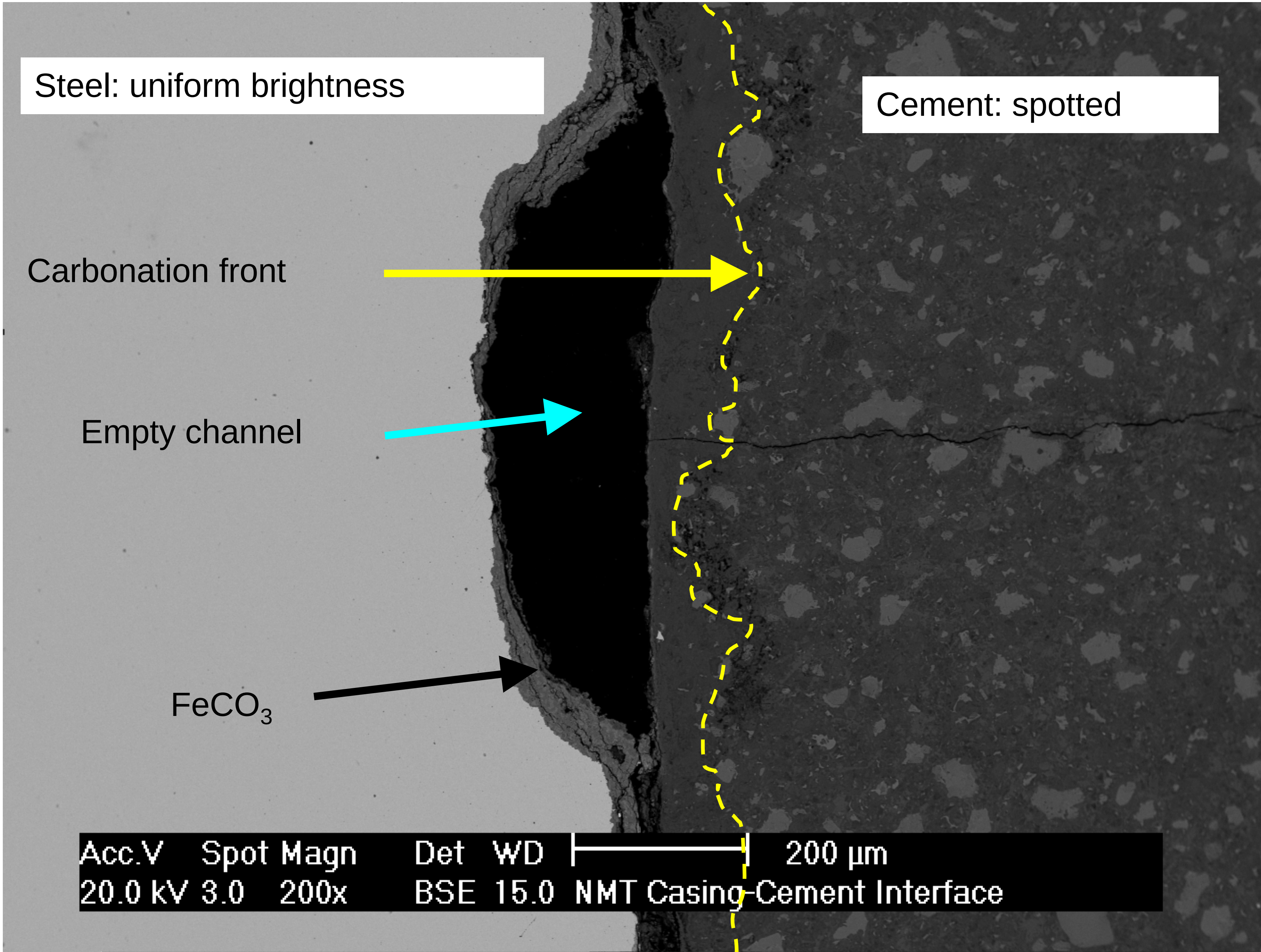


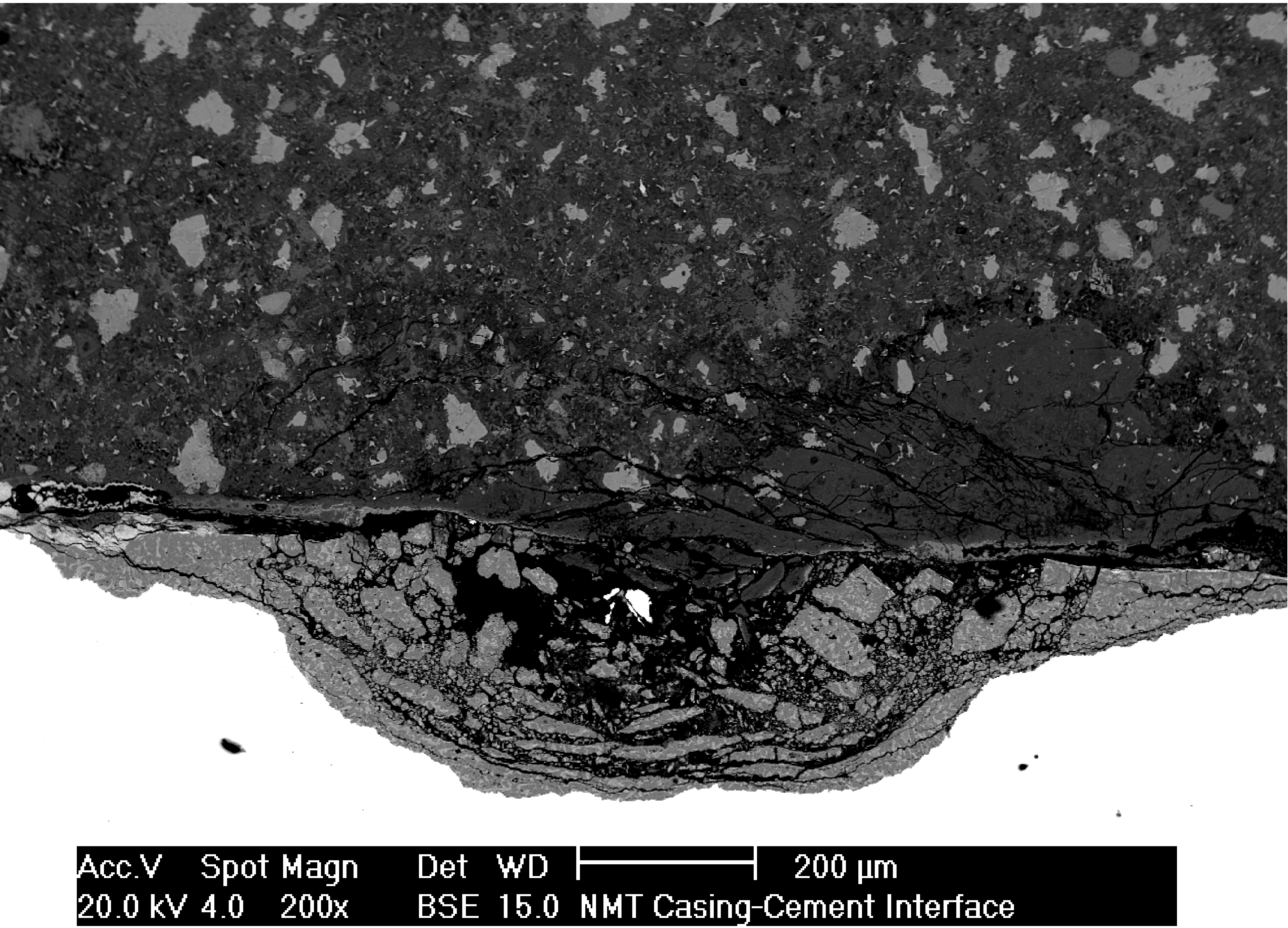
Carey et al. (2010) Int. J. Greenhouse Gas Control

Extensive corrosion at inlet



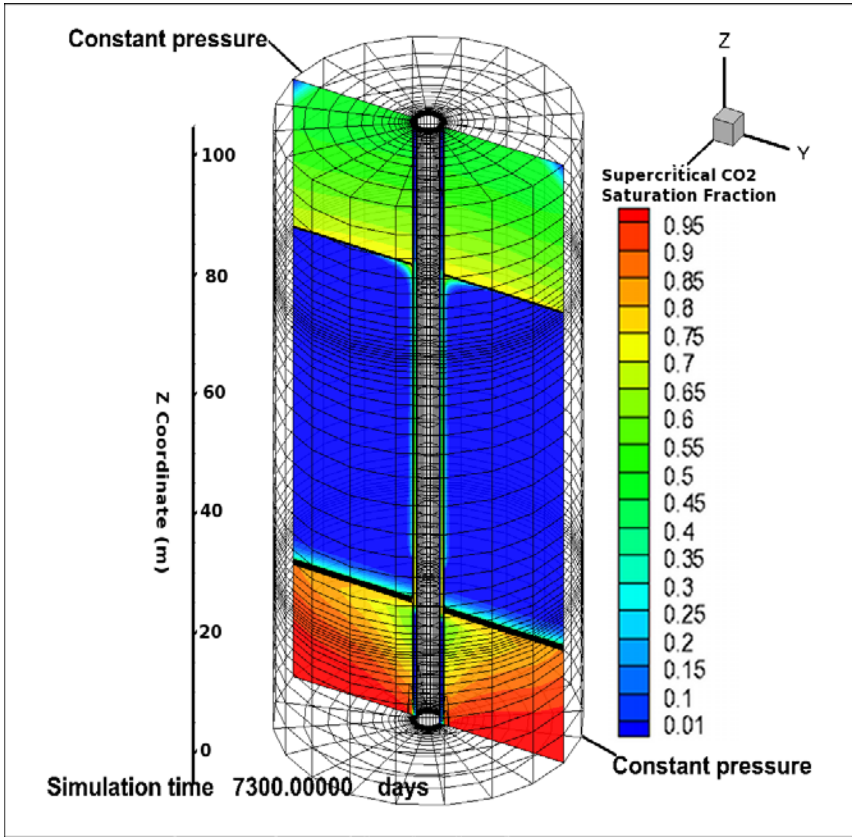
Backscatter Electron Images of Cement-Casing Interface

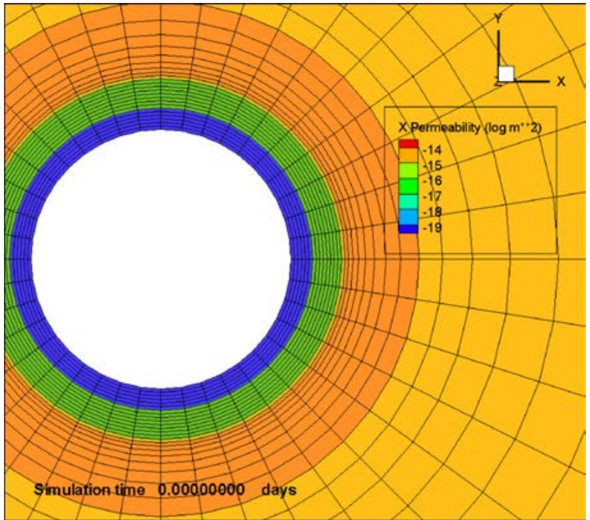



Acc.V Spot Magn Det WD 200 µm
20.0 kV 4.0 200x BSE 15.0 NMT Casing-Cement Interface

Geomechanical Behavior of Wells

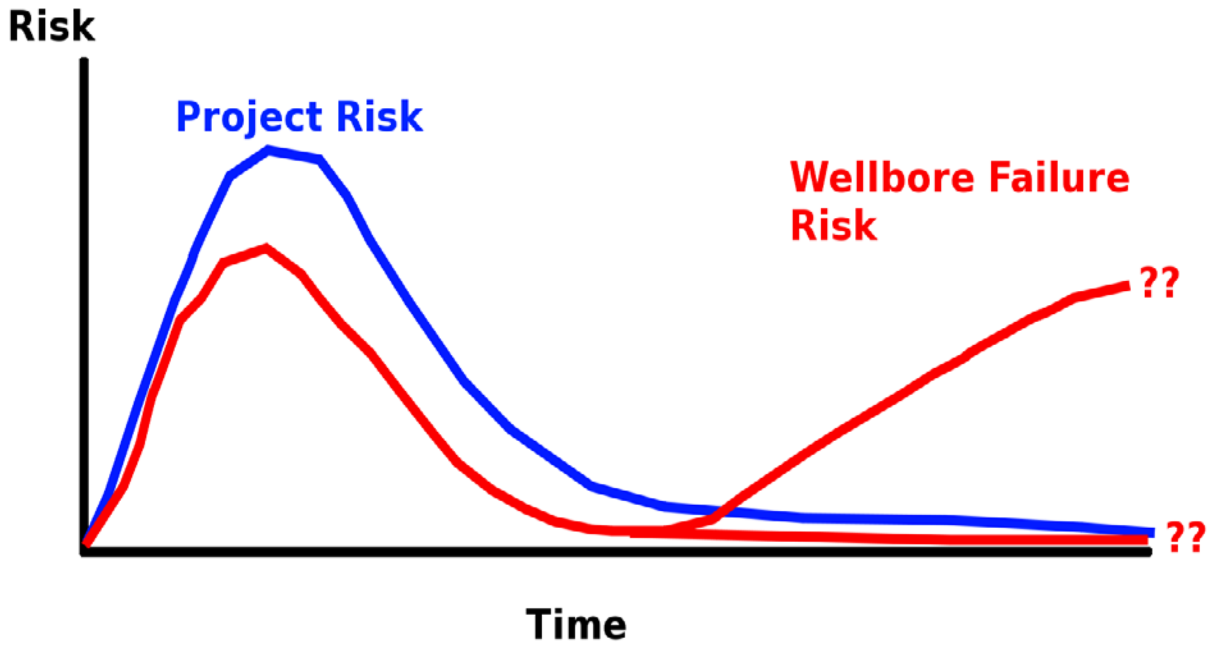
- Critical in hydraulic fracturing
- Casing expands and stresses cement
- Cement behaves plastically at elevated confining pressure (Liteanu et al. 2009)
- What does hydraulic fracture pressure do to cement bond, cement?
- Can hydraulic fracture pressures communicate with older wells?





Carey et al. (2012) GHGT-11

Short-Term Versus Long-Term Risk



- Wells are an important part of project risk at early stages
- Late-stage risk is assumed to decrease
- What happens to the wellbore over long times?

Conclusions

- **Wellbore systems are susceptible to flow at interfaces (cement-steel, cement-caprock, cement fractures)**
- **Experiments and field observations have demonstrated some degree of self-limiting permeability at interfaces (at least with CO_2; Carey, Huerta, Walsh et al.)**
- **Cement deforms plastically at elevated depths and its geomechanical behavior is critical to assessing potential damage**
- **Steel response to hydraulic pressure key to assessing damage to isolation**
- **Coupled mechanical and hydrologic field observations, experiments and models will help resolve threats to zonal isolation**

Future Work

- What are the limits (in terms of flow-rate) of self-healing behavior?
- Does carbonated cement protect steel?
- What are the hydrologic and mechanical consequences of cement carbonation?
- Are special formulations of cement and stainless steel necessary in CO_2 sequestration projects?
- Coupled mechanical and chemical experiments and models are needed

Acknowledgements

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