Mitigation Strategies for CO_2 Migration through Wellbores

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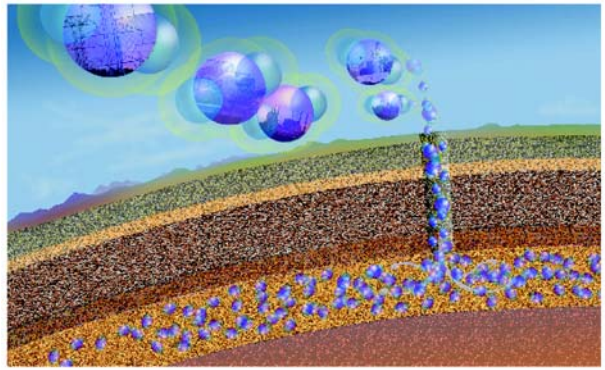
Motivation and Approach

- Well integrity identified as the largest risk from analogs.
  - Portland cement not thermodynamically stable in CO_2 environments.
    - Cement failure
    - Long-term zonal isolation (thousands of years) required in CO_2 sequestration wells



- Not adequately addressed by industry specifications.

- Develop standard laboratory equipment to test materials in presence of CO_2 as wet supercritical fluid and dissolved in water.

- Develop standard procedure/method to assess its long term durability

- Adopt a step approach towards the ideal solution to durability.

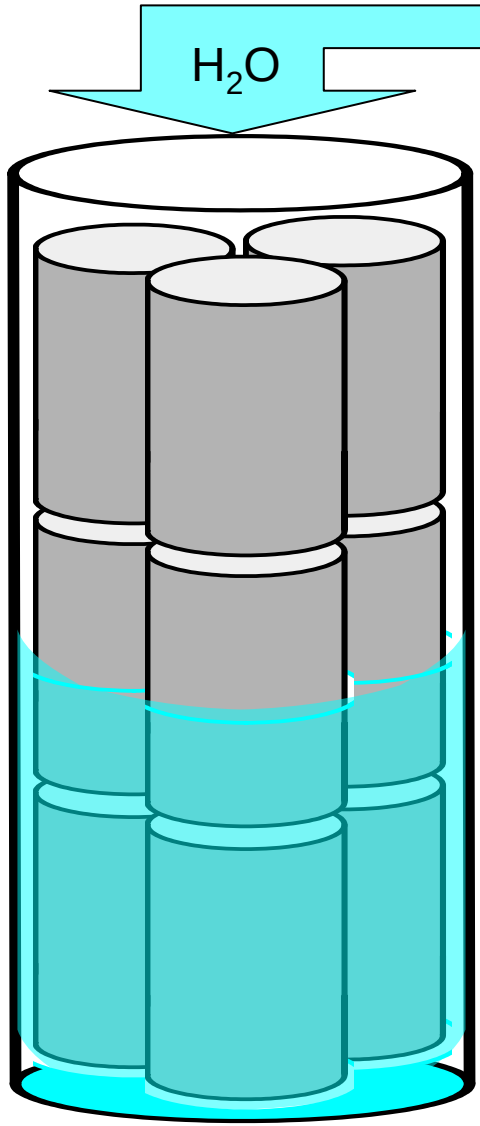
- Develop in-situ measurements to determine cement integrity.

Issues with Current Practices

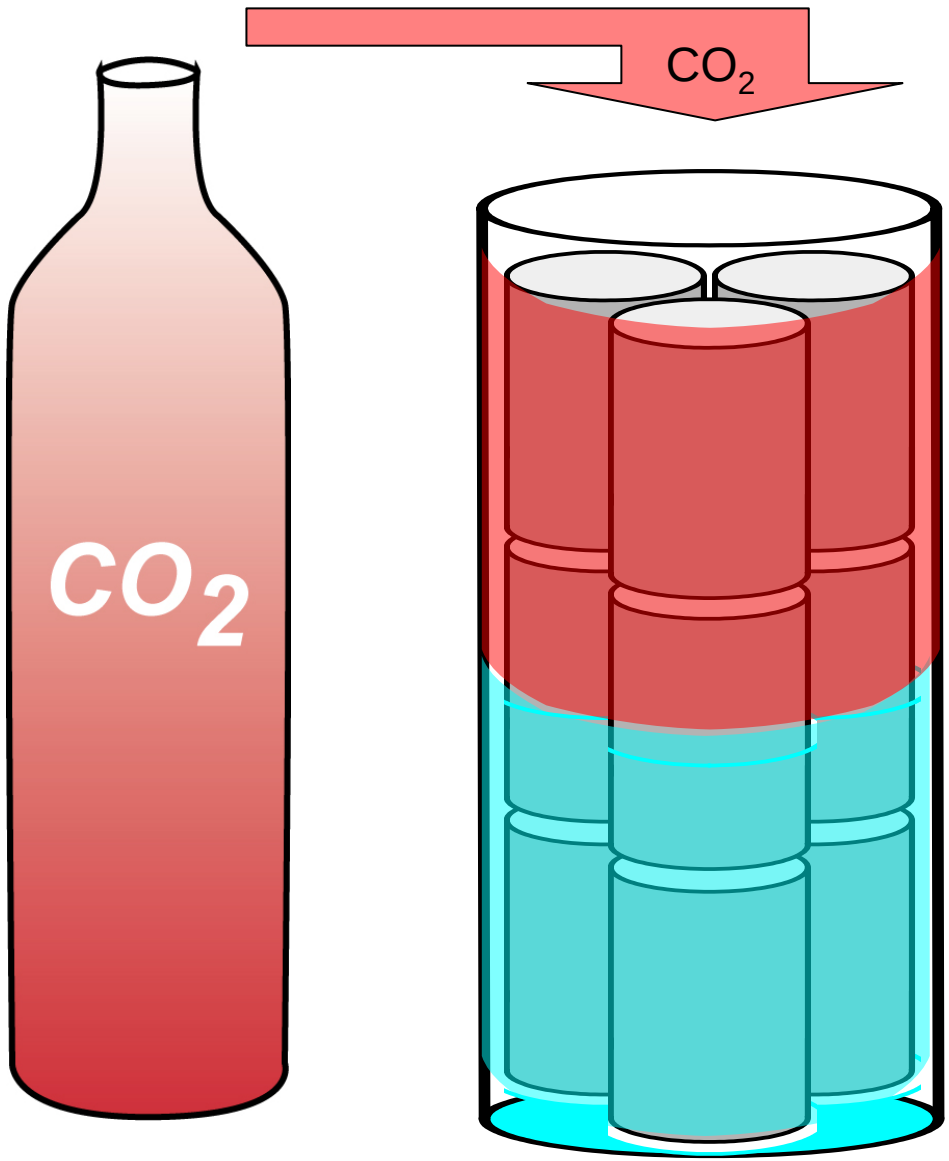
- Does conventional testing simulate actual conditions?
- What needs to be measured to qualify and quantify the carbonation process?
- How does Portland-cement carbonation proceed in the presence of wet supercritical CO_2?

An experimental approach

Experimental Apparatus



Experimental Apparatus



Supercritical CO_2 phase saturated with water

Liquid H_2O phase saturated with CO_2

Measurements to identify and quantify the carbonation process

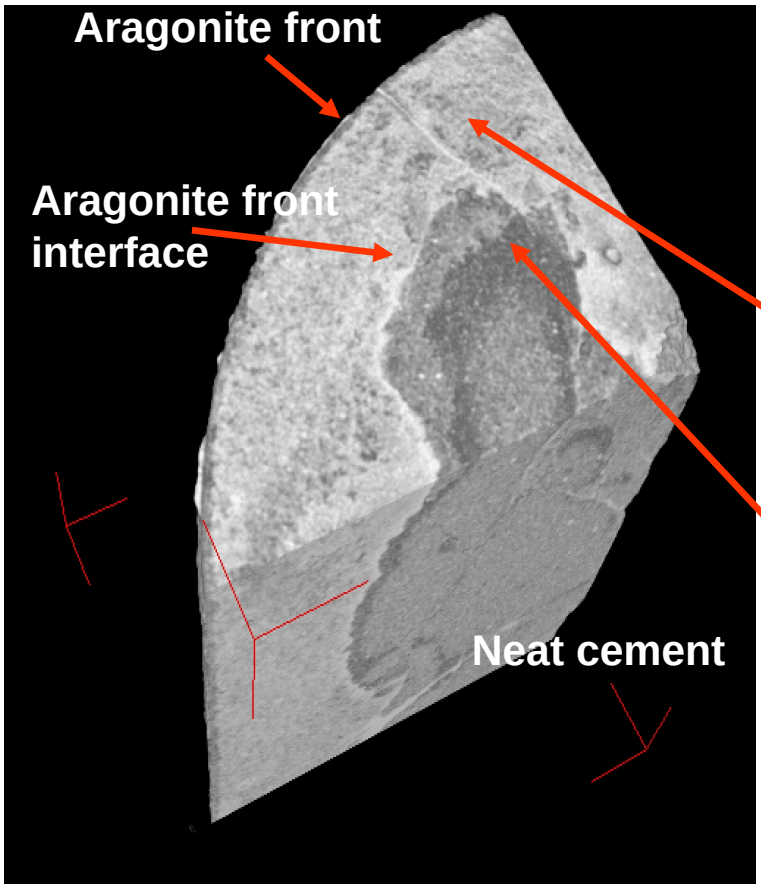
- Chemical and mineral matrix composition before and after CO_2 attack:
  - Weight variation measurement
  - **Thickness of the alteration front**
  - XRD analysis
  - **SEM-EDS analysis**

- Characterization and visualization of matrix porosity and/or permeability:
  - **BSE imaging**
  - Variation of %water loss versus square-root-of-time measurement
  - **Laboratory visualization of cement-CO_2 interaction**

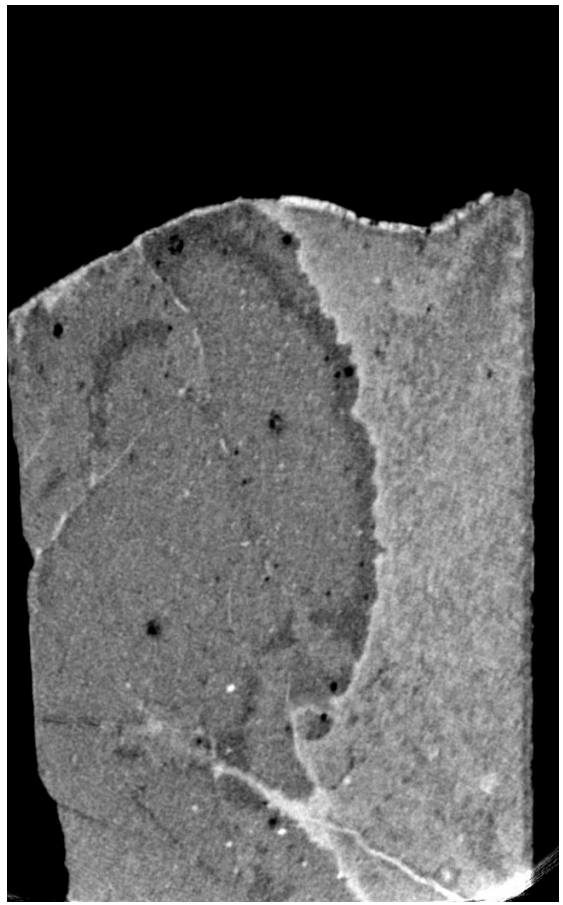
- Fluid analysis:
  - pH variation
  - Water production

XR microtomography visualization with Virtual Reality software to evaluate well cement samples after CO_2 attack

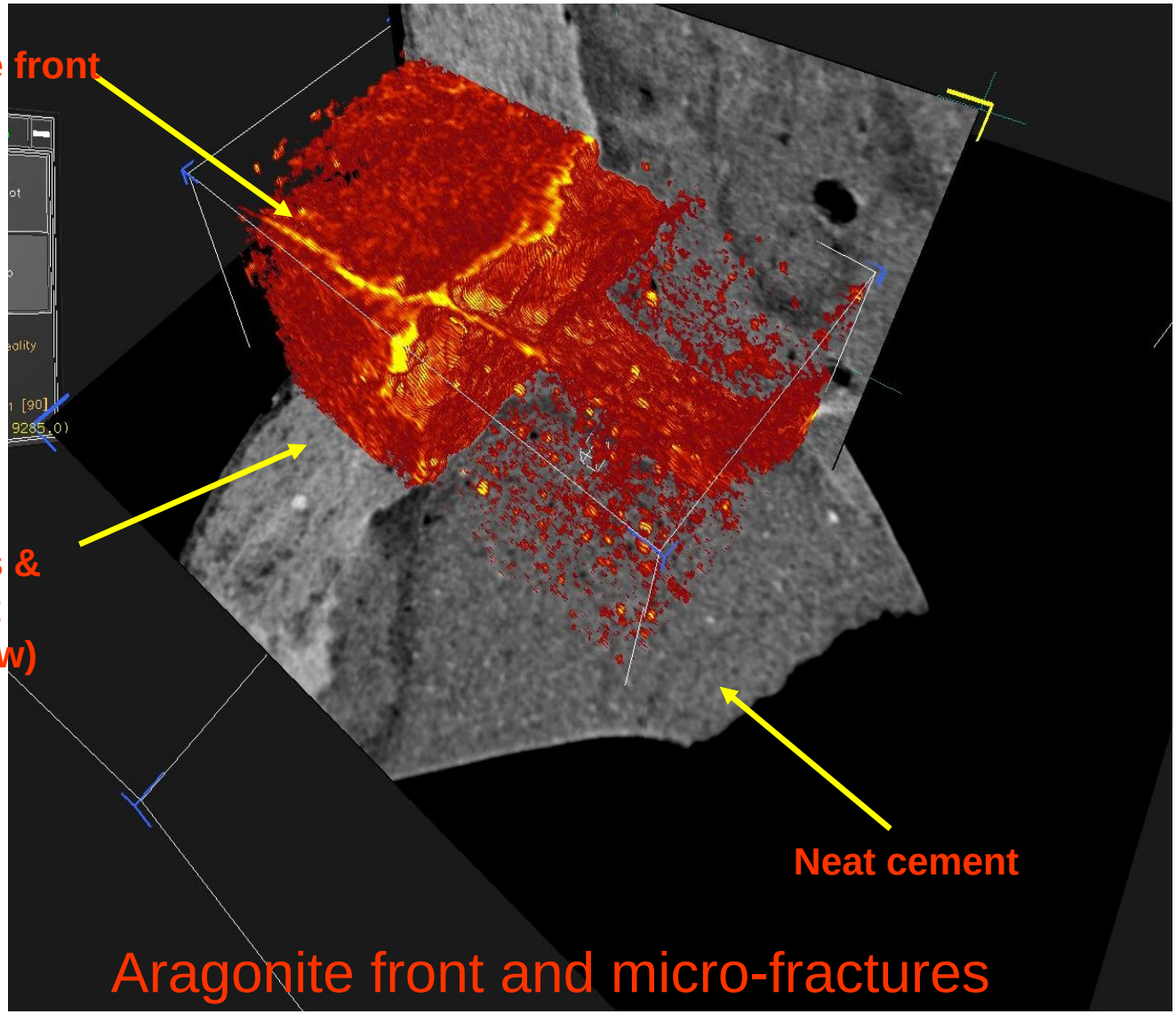
view of CT scanned sample.
Voxel size/Resolution: ~ 19 μm



XZ slice



VR images – CO_2 attacked sample



Reactions of Portland Cement Hydrates with CO_2

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

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

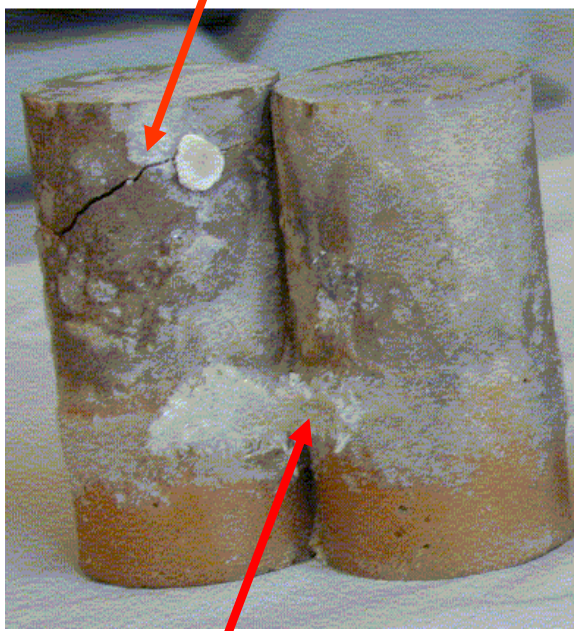
$$\text{C-S-H phase} + H^+ + HCO_3^- \longrightarrow CaCO_3 + \text{amorphous silica gel}$$

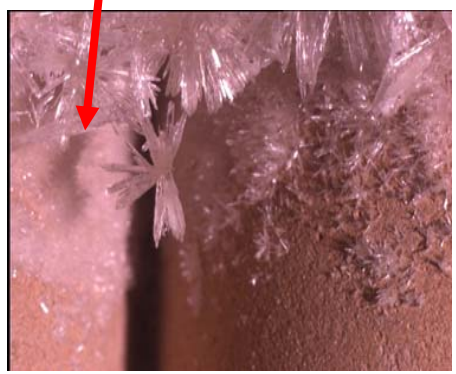
$$CO_2 + H_2O + CaCO_3 \longrightarrow Ca(HCO_3)_2$$

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightleftharpoons 2CaCO_3 + H_2O$$

What happens to neat cement?

Cracks in wet CO_2 supercritical environment





Strong alteration rims

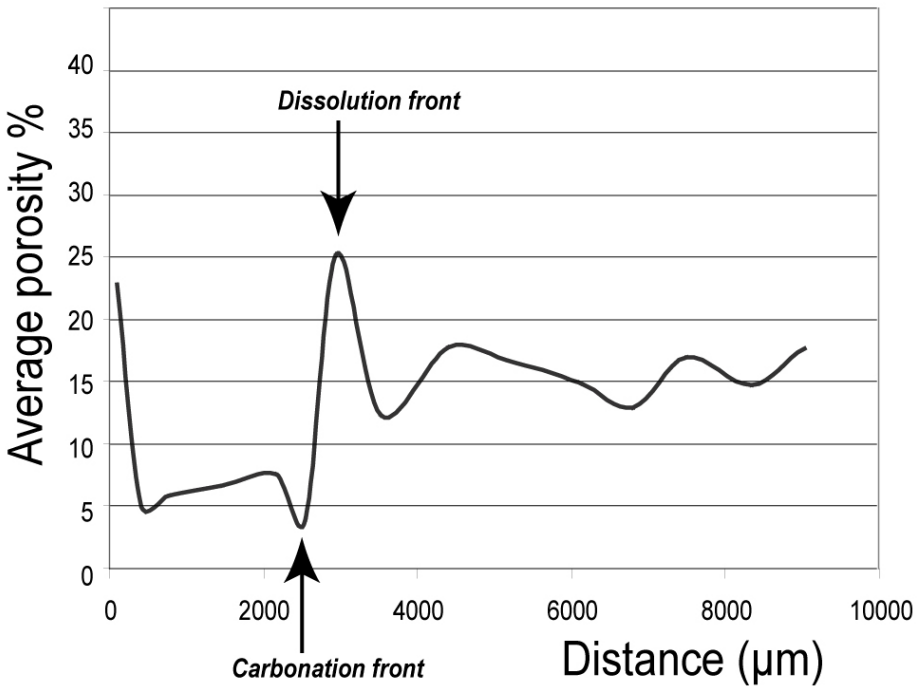
Strong carbonation in the external fluid mainly located at the fluids interface (Aragonite)

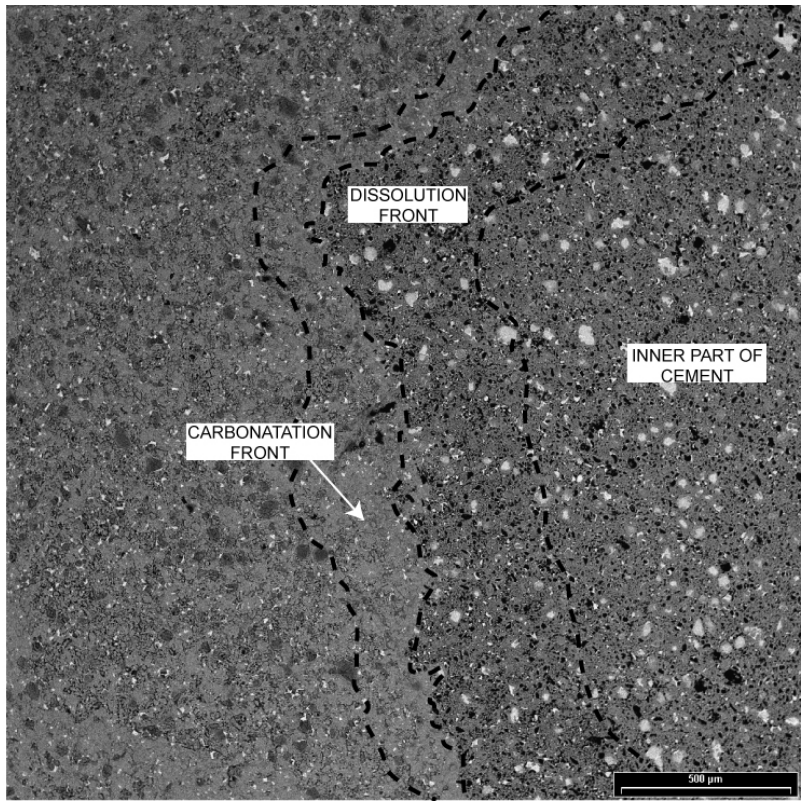
After one month at 90°C and 280 bars under wet CO_2 supercritical environment

Carbonation/Dissolution Processes
Neat cement – 90°C, 280 bars – 88 hours

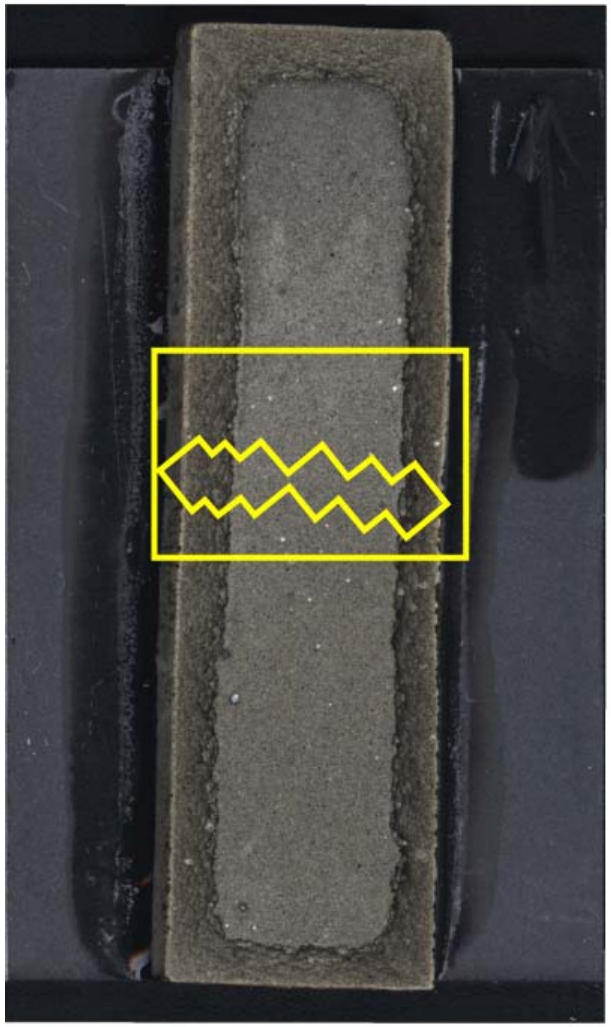
Estimate of porosity variations
→ Using SEM/BSE image analysis of the alteration rim

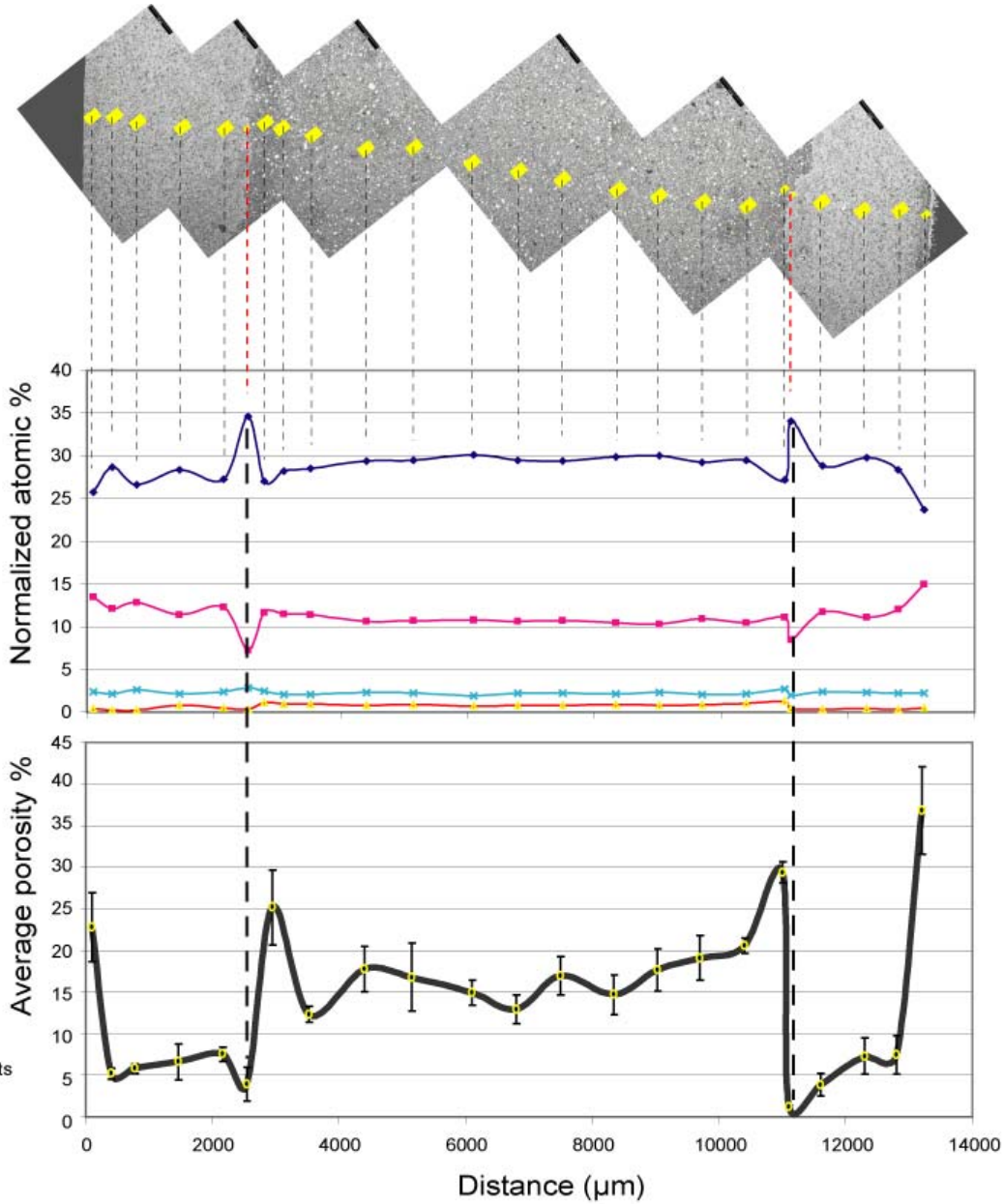
Porosity (in black) measurements using BSE image analysis (300x300 µm images)



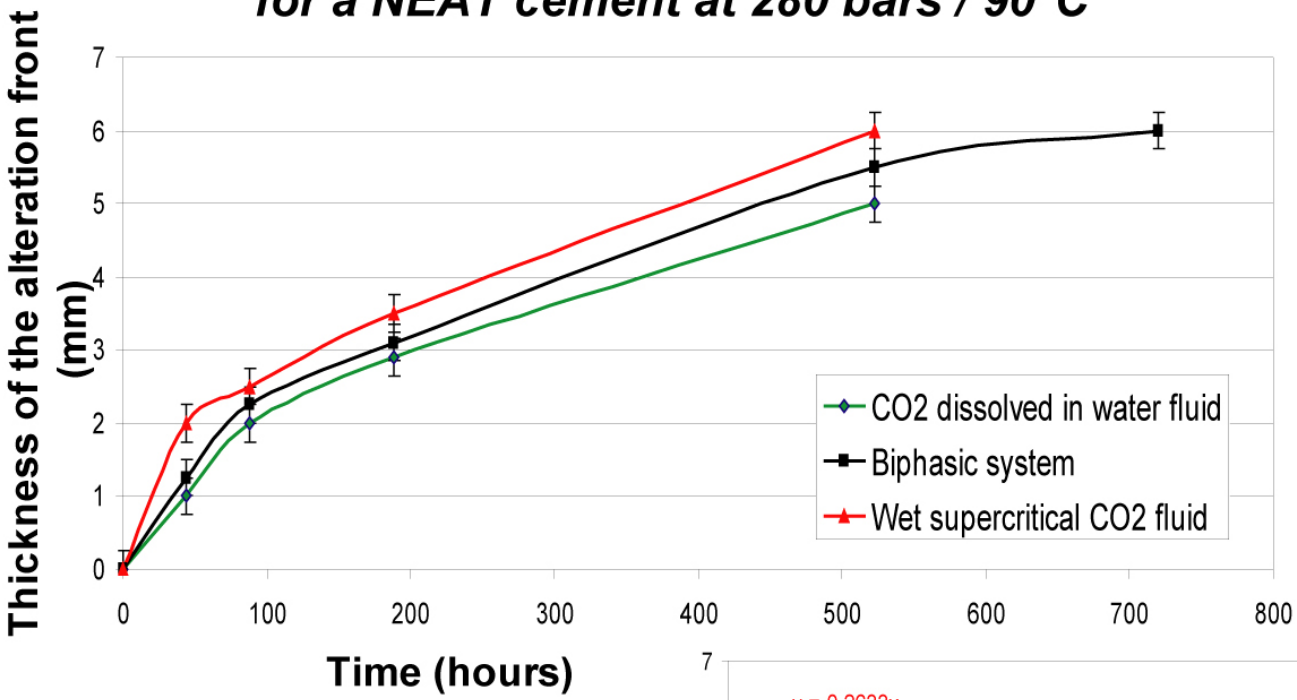


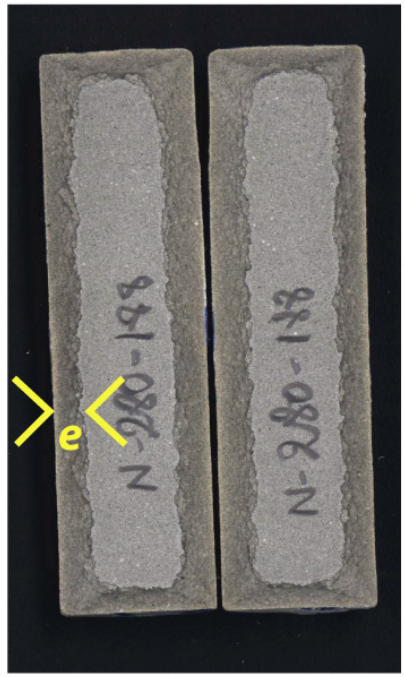
N-280-88



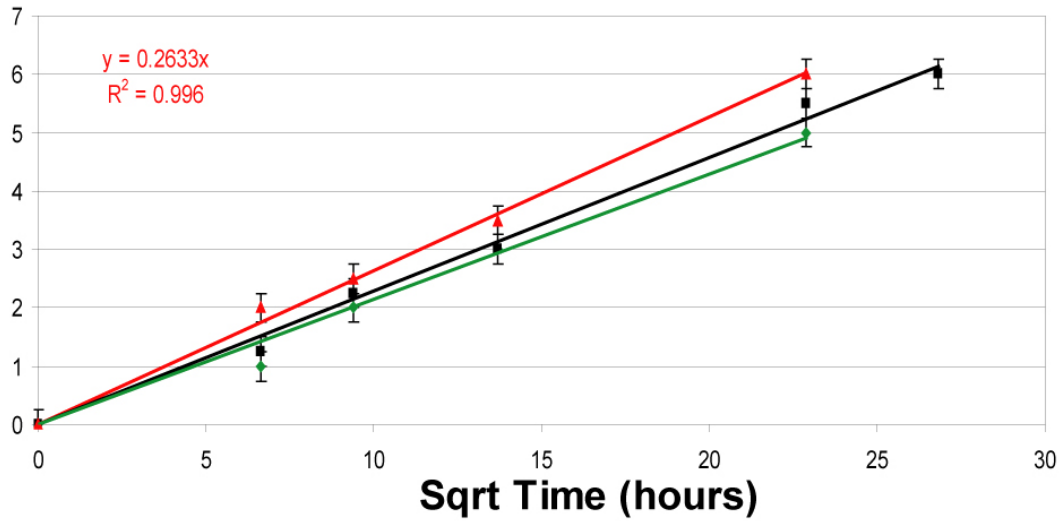

Ca
Si
S
Fe
Normalized atomic %
0
5
10
15
20
25
30
35
40
Average porosity %
0
5
10
15
20
25
30
35
40
45
Porosity measurements
0
2000
4000
6000
8000
10000
12000
14000
Distance (µm)

Evolution of alteration process with time for a NEAT cement at 280 bars / 90°C



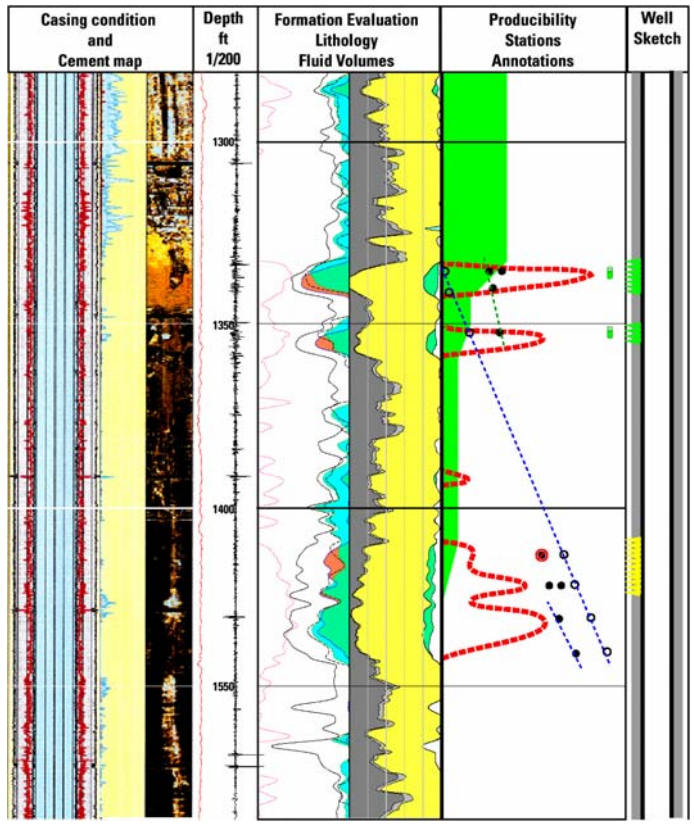


Data acquisition for fluid flow - geochemistry modeling

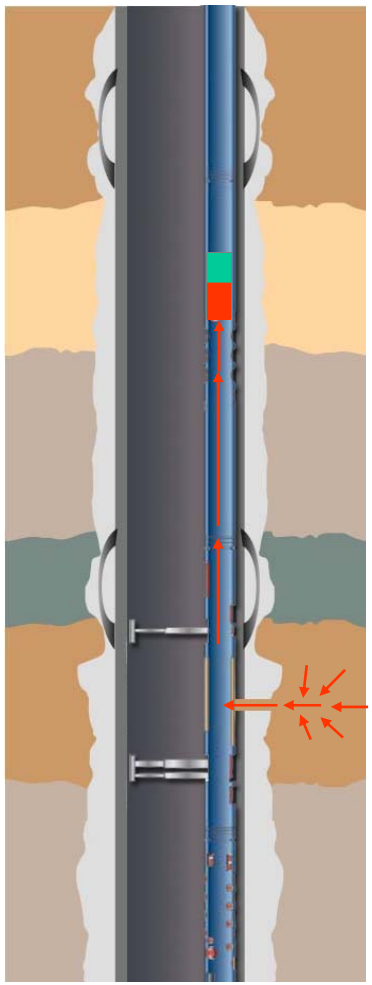


Novel Wellbore Monitoring Technologies for Cement Integrity

- Testing & Sampling through Casing
  - Cased Hole Dynamic Tester
- Novel Sonic Tool
  - Modular Sonic Imager (MSIP)
  - Multiple depths of Investigation
  - Azimuthal Mapping



Cased Hole Dynamics Tester
Testing & Sampling behind the Casing for CO_2



- Drills
  - Through casing
  - Through cement
  - Into the formation
- Measures
  - Reservoir pressure
  - Fluid resistivity
- Collects
  - Fluid samples
- Plugs the hole
  - 10,000-psi bidirectional seal
- Used in the Teapot Dome experiment (Princeton)

Modular Sonic Imaging Platform

- Provides a family of advanced acoustic measurements
  - Borehole-compensated monopole with long and short spacings
  - Cross dipole
  - Cement evaluation
- First industry tool with three-dimensional acoustic map from axial, radial, and azimuthal measurements

Conclusions

- Carbonation of Portland cement in supercritical wet CO_2 is a very efficient process (about 0.2 mm/day for a neat cement).

- Carbonation is comparable to a metasomatic process, with local equilibrium progressing from the external side associated with local and transitory decrease of porosity.

- Portlandite and CSH are progressively consumed
  - to produce carbonates (aragonite and calcite), silica and water
  - at the rear of the carbonation front, the neoformed carbonate and silica are dissolved, increasing the porosity and resulting in serious cement degradation.

- New technologies developed for through-casing wellbore measurements.