Investigation on wellbore cement degradation under geologic CO_2 storage conditions by micro-CT scanning and 3D image reconstruction

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2020.5.5

Acknowledgement

NSFC

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Outline

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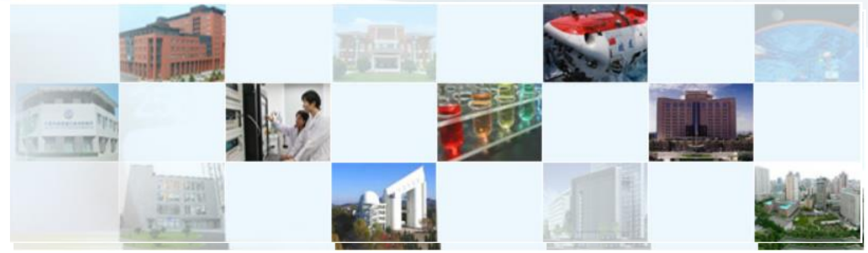


- **Linchpin of China's drive to explore and harness high technology and natural sciences for the benefit of China and the world**
- **More than 60,000 research scientists and 124 institutions nationwide**
- **With high research reputation in the world--ranked the 1st by Nature Index 7 years in a row**

nature INDEX

https://www.natureindex.com/annual-tables/2019/institution/all/all

2018	Institution	FC 2017	FC 2018	AC 2018	Change in Adjusted FC 2017-2018 *
1	Chinese Academy of Sciences (CAS), China	1529.78	1698.14	4842	6.7% ↑
2	Harvard University, United States of America (USA)	906.36	874.68	2371	-7.3% ↓
3	Max Planck Society, Germany	745.16	757.32	2431	-2.3% ↓
4	French National Centre for Scientific Research (CNRS), France	723.81	689.86	4085	-8.4% ↓
5	Stanford University, United States of America (USA)	613.94	622.01	1507	-2.6% ↓
6	Massachusetts Institute of Technology (MIT), United States of America (USA)	530.36	560.28	1698	1.5% ↑
7	Helmholtz Association of German Research Centres, Germany	502.42	483.23	2078	-7.6% ↓
8	University of Cambridge, United Kingdom (UK)	417.57	437.83	1283	0.8% ↑
9	The University of Tokyo (UTokyo), Japan	470.39	430.86	1100	-12.0% ↓
10	Peking University (PKU), China	393.64	411.85	1427	0.5% ↑
11	Swiss Federal Institute of Technology Zurich (ETH Zurich), Switzerland	382.31	406.52	1017	2.2% ↑
12	University of Oxford, United Kingdom (UK)	405.45	403.77	1197	-4.3% ↓

Chinese Academy of Sciences is the largest and the most prestigious research organization in China

Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

Main office building of IRSM

- Founded in 1958, IRSM-CAS is the only research institution in CAS dedicated to the basic research and applications of geomechanics and related fields

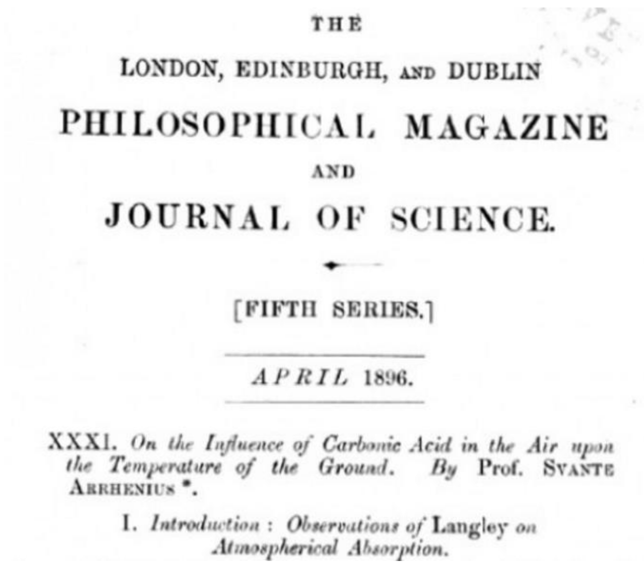
- Located in the beautiful city of Wuhan near the Yangtze River

- We welcome foreign researchers and students for short term visiting. For students, grants and fellowships are available

Research background

Greenhouse gas effect

- In 1895, Chemist Arrhenius presented a paper to the Stockholm Physical Society.
- This article described an energy budget model considering the radiative forcing effects of CO_2 and water vapor on surface temperature.


THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

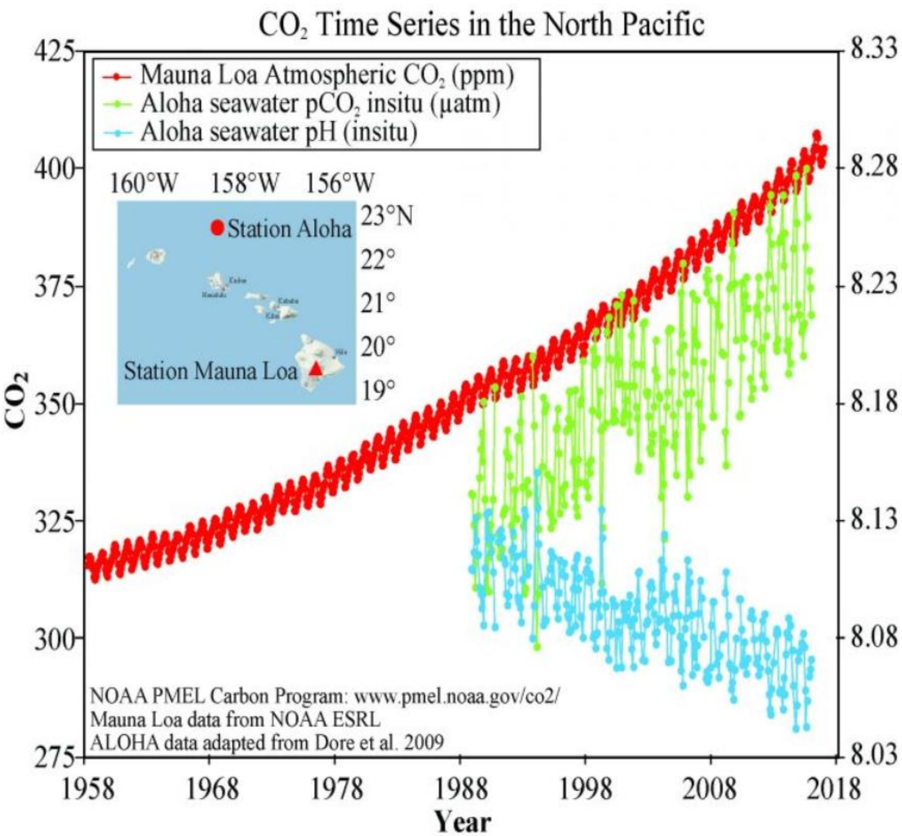
XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

I. *Introduction: Observations of* Langley *on Atmospherical Absorption.*

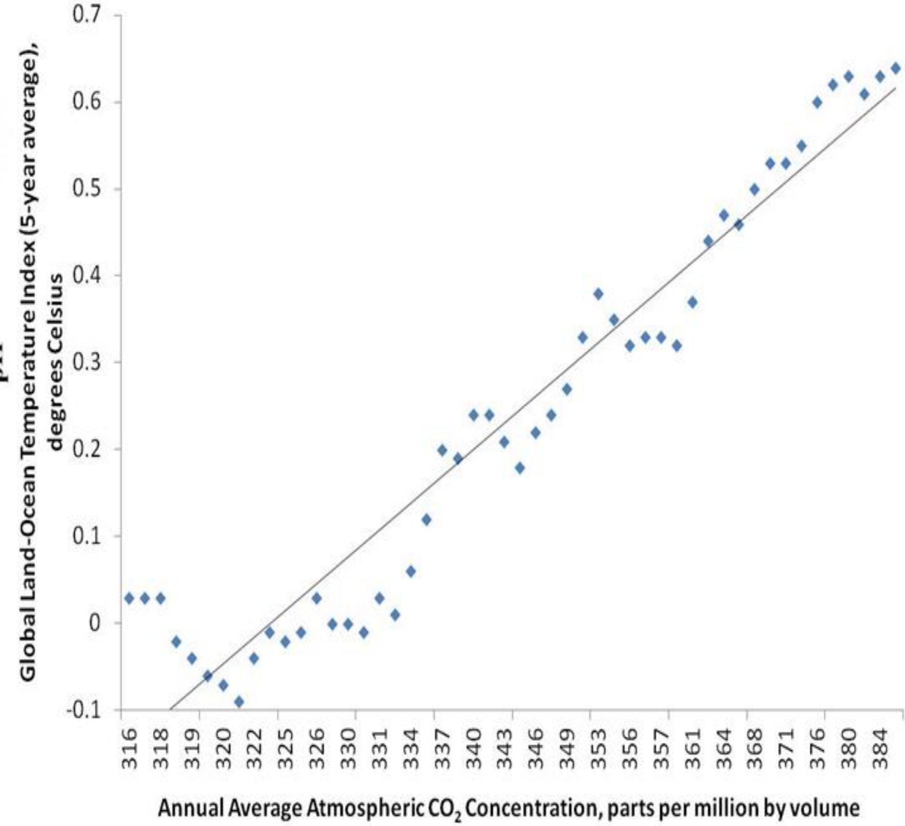
On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground

First paper to link atmospheric CO_2 to heat budget of the Earth

Svante A. Arrhenius (1859-1927)



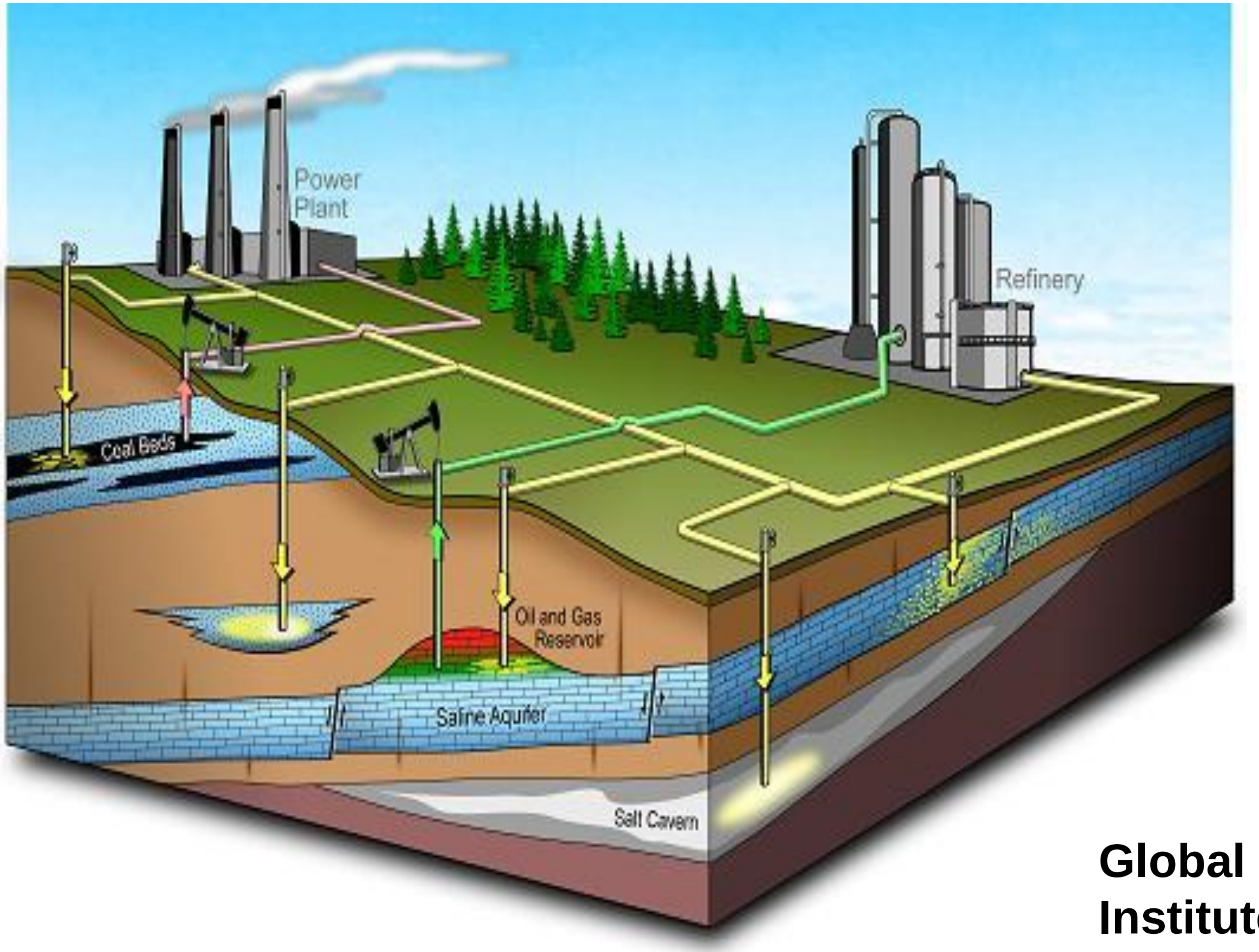
https://www.c2es.org/content/climate-impacts/



NASA Goddard Institute for Space Studies (GISTEMP Team), 2016

Positive correlation between atmospheric CO_2 concentration and temperature

Carbon Capture, Utilization and Storage (CCUS)—a promising technology to reduce atmospheric CO_2 concentration



Global CCS Institute, 2017

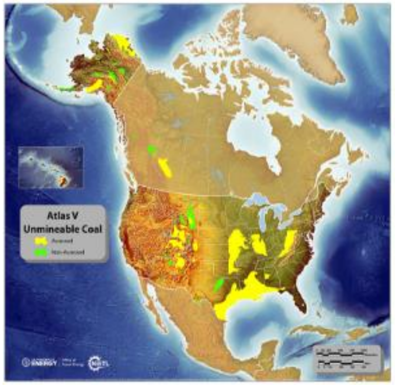
Geologic CO_2 Sink Capacity Estimates (North America)

NA total CO_2 emissions ~ 7.2 Gt CO_2 / yr

(Source: https://climateactiontracker.org/countries/usa/; Environment and Climate Change Canada, 2019)

Oil Reservoirs

Saline Formations



Unmineable Coal Seams

Estimated North American CO_2 Storage Potential (Gigatonnes)

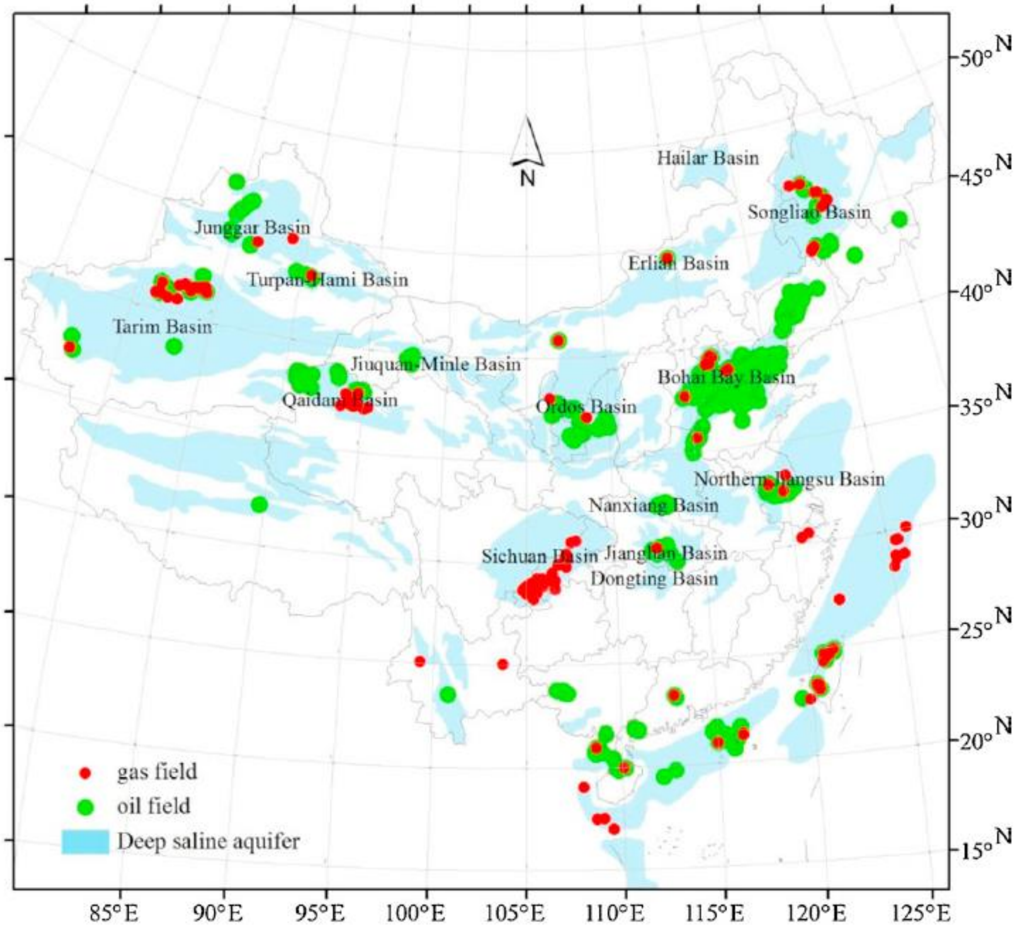
Conservative resource assessment

Sink Type	Low	High
Oil Reservoirs	186	232
Saline Formations	2,379	21,633
Unmineable Coal Seams	54	113

Source: Carbon Storage Atlas (5th Edition), NETL, U.S. DOE (2015)

Hundreds of years CO_2 storage potential

Estimation of geologic CO_2 storage capacity in China



Oil/gas fields and saline aquifers in China (Wei et al., 2013)

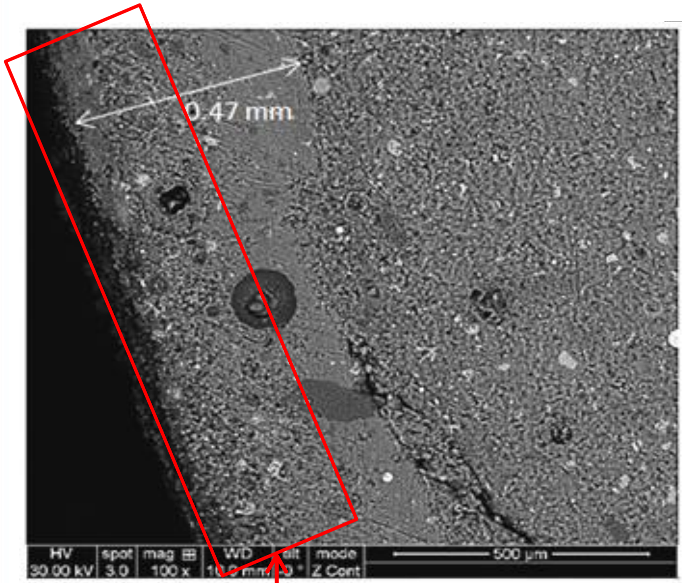
Suitability	Scores without emission sources	Percentage of total area	Capacity with 50% confidence by the USDOE method (gigatons)
Very high suitability	0.6–0.68	18%	746
High suitability	0.52–0.6	11%	331
Normal suitability	0.46–0.52	14%	276
Low suitability	0.3–0.46	11%	183
Very low suitability	0.24–0.3	4%	37
Not suitable	<0.24	42%	Not evaluated
Total with suitability	0.24–0.68	58%	1573

Total geologic CO_2 storage capacity in China is ~1,573 Gt (50% confidence, Wei et al., 2013); China's total CO_2 emissions were 13 Gt/yr in 2017 (https://climateactiontracker.org/countries/china/)

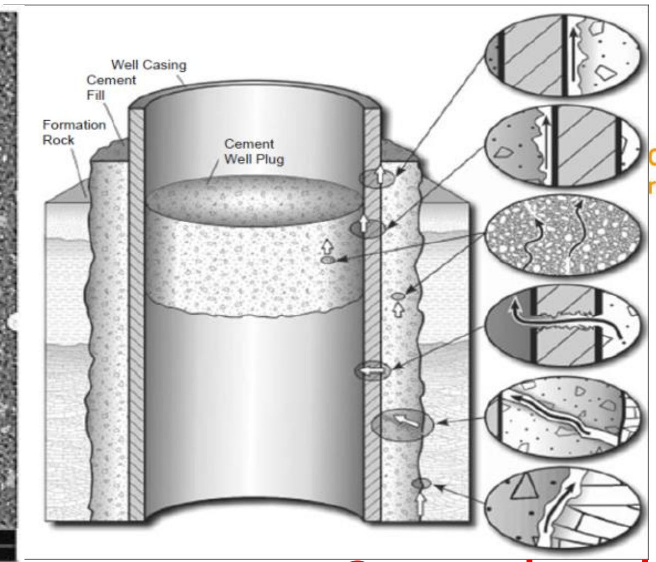
120+ years CO_2 storage potential

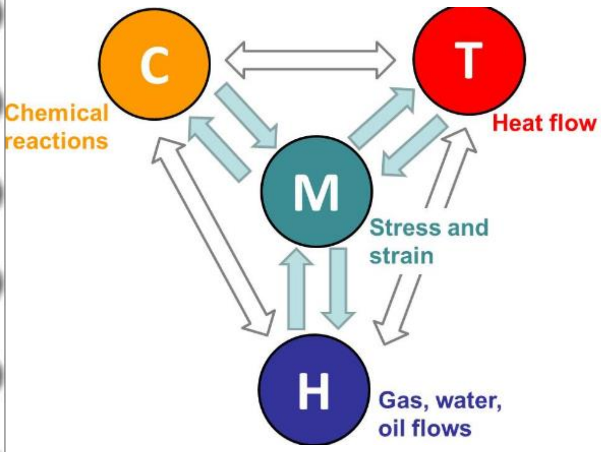
Motivation

- CCUS conditions: Low pH, high concentrations of CO_2, H_2S, SO_4^{2-}, etc.
- Exposure of wellbore cement to CCUS conditions: Permeability and porosity increase and loss of cement integrity



Permeability and porosity increase at reaction zone





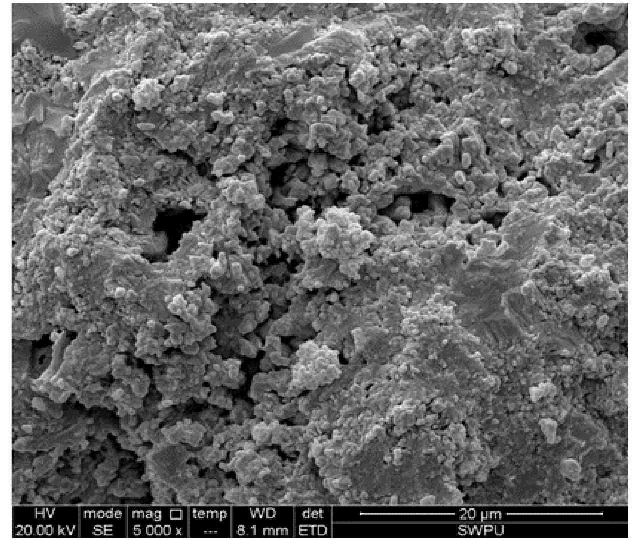
Cement degradation: complex process affected by THMC coupling

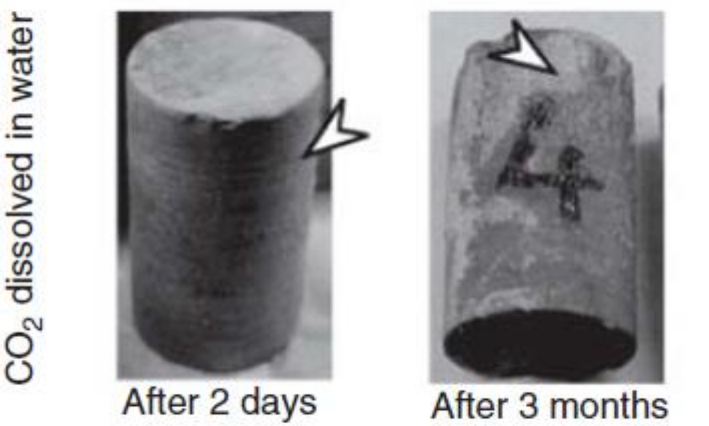
Previous studies

Before reaction

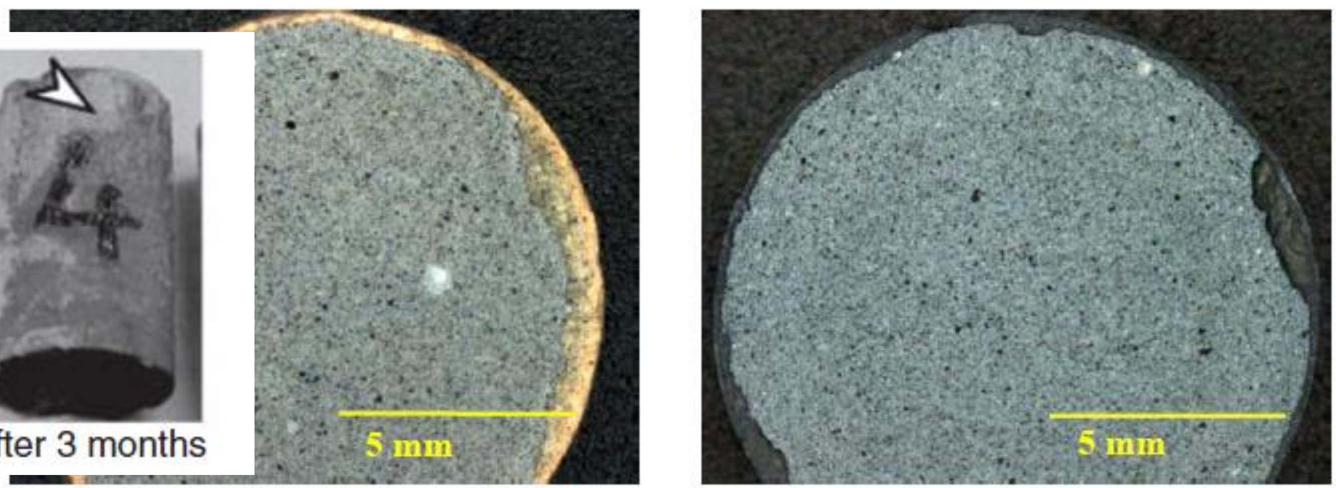
After reaction

Cheng et al., 2018





Barlett et al., 2007

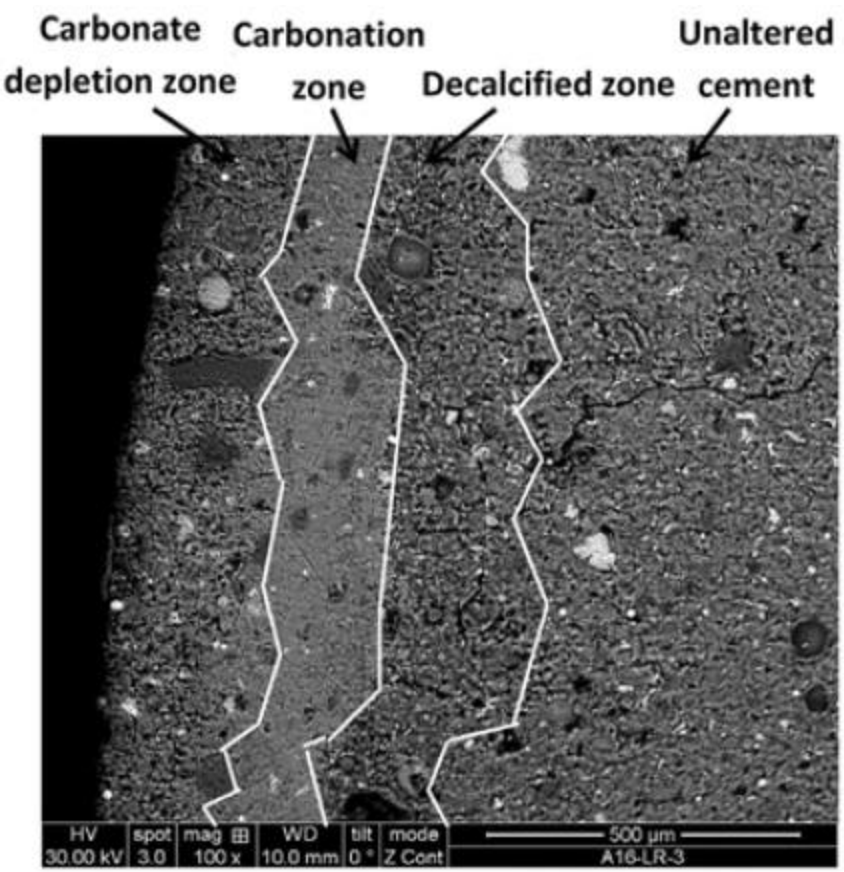


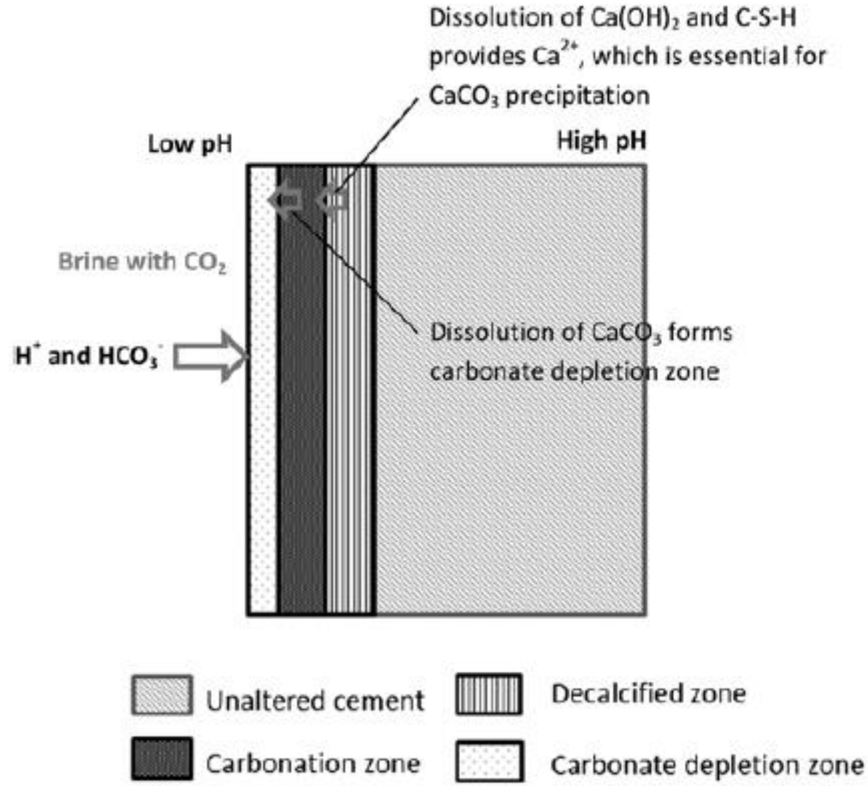
Kutchko et al., 2011

Mechanism of cement degradation under CCUS conditions

Mechanism of cement degradation under CCUS conditions

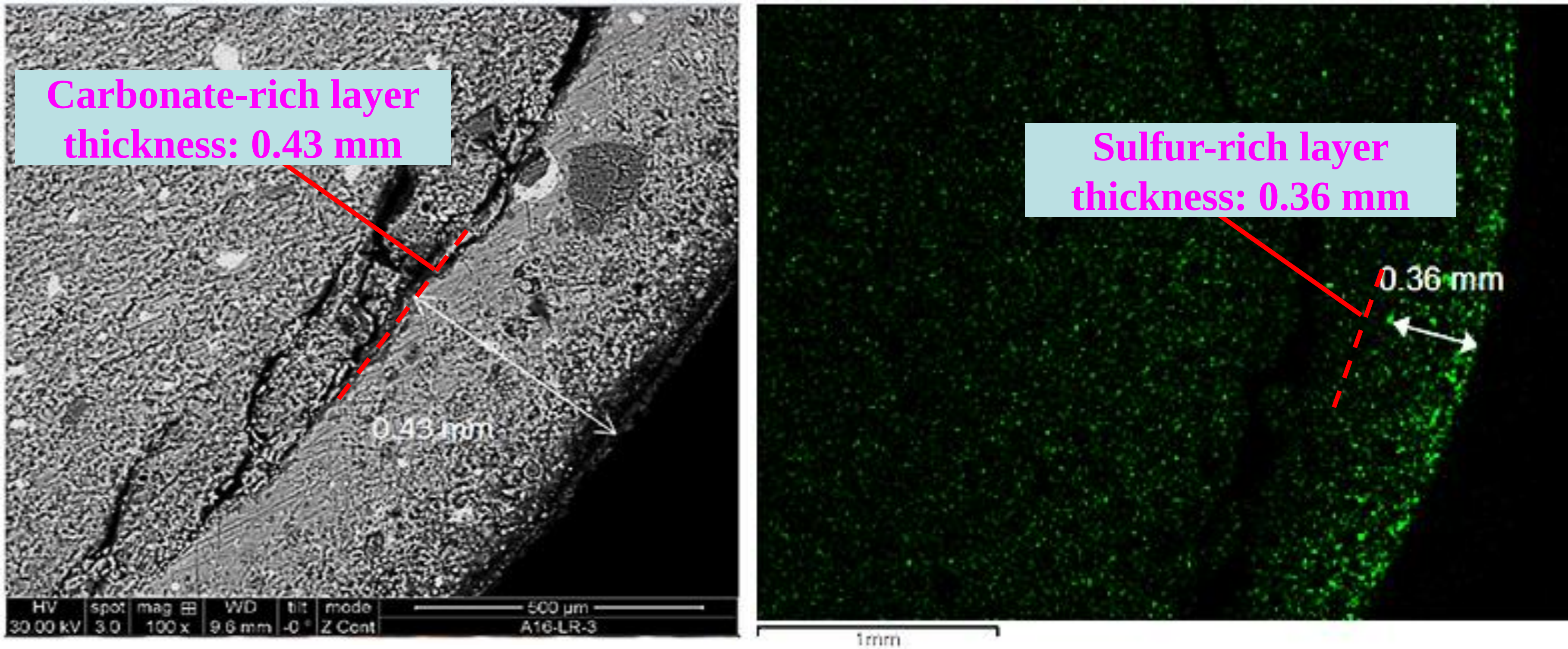
- Dissolution of $Ca(OH)_2$ and C-S-H after reacting with H^+
- Formation of carbonate layer due to reaction between Ca^{2+} and HCO_3^-
- Dissolution at the surface of carbonate layer due to H^+ attack





Zhang et al., 2015

CO_2 and H_2S reaction with wellbore cement

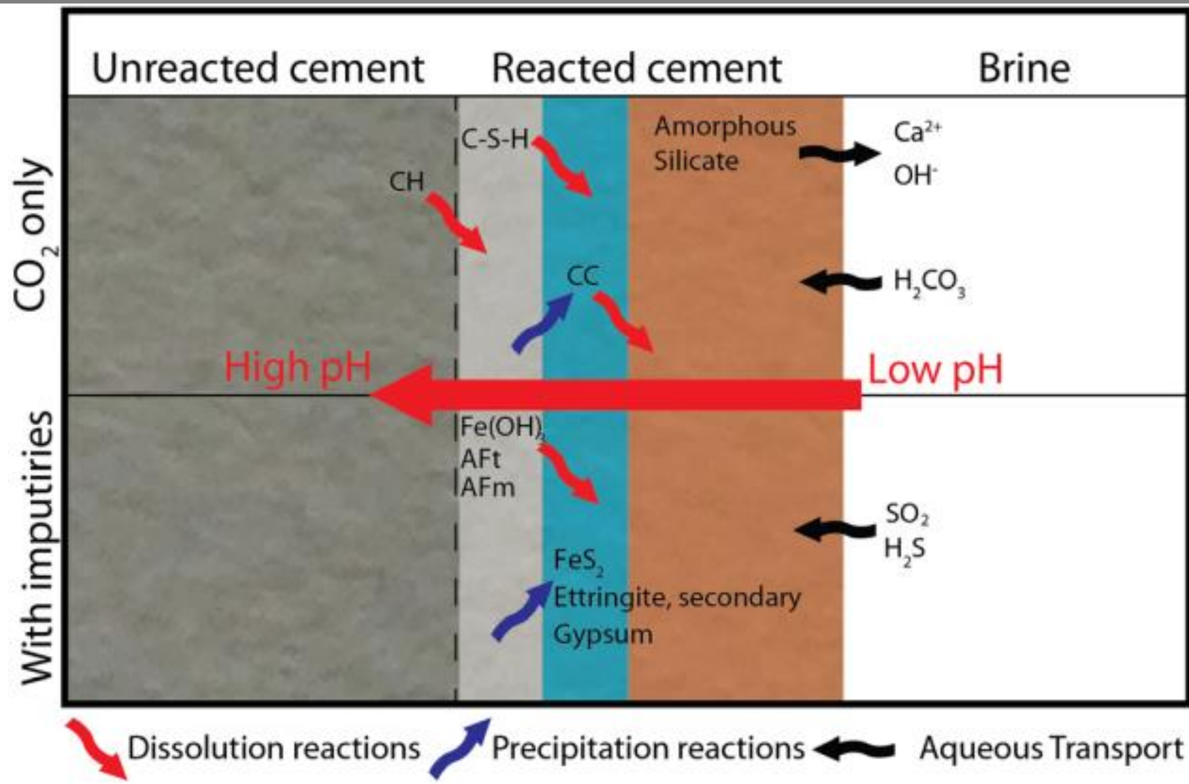


Zhang et al., Int. J. Greenhouse Gas Control, 2014, 27: 299-308

- Evidences of carbonation and H_2S-induced sulfurization were observed at sample surface
- Carbonation front migration was slightly faster than sulfurization front migration

Mechanism of H_2S-induced cement degradation under CCUS conditions

- **Dissolution of $Ca(OH)_2$, C-S-H and Fe(III)-bearing species after reacting with H^+**
- **Formation of pyrite and ettringite after reacting with H_2S**



Carroll et al., IJGGC, 2016

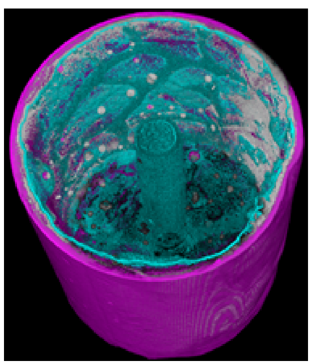
Description of the workflow for CT characterization of wellbore cement degradation

Research objectives

- **Develop a reliable workflow to conduct CT characterization of wellbore cement after exposure to CO_2 under geologic CO_2 storage conditions**
- **Understand matrix and pore structure evolution of wellbore cement after exposure to CO_2**
- **Visualize and quantify cement carbonation due to exposure to CO_2**

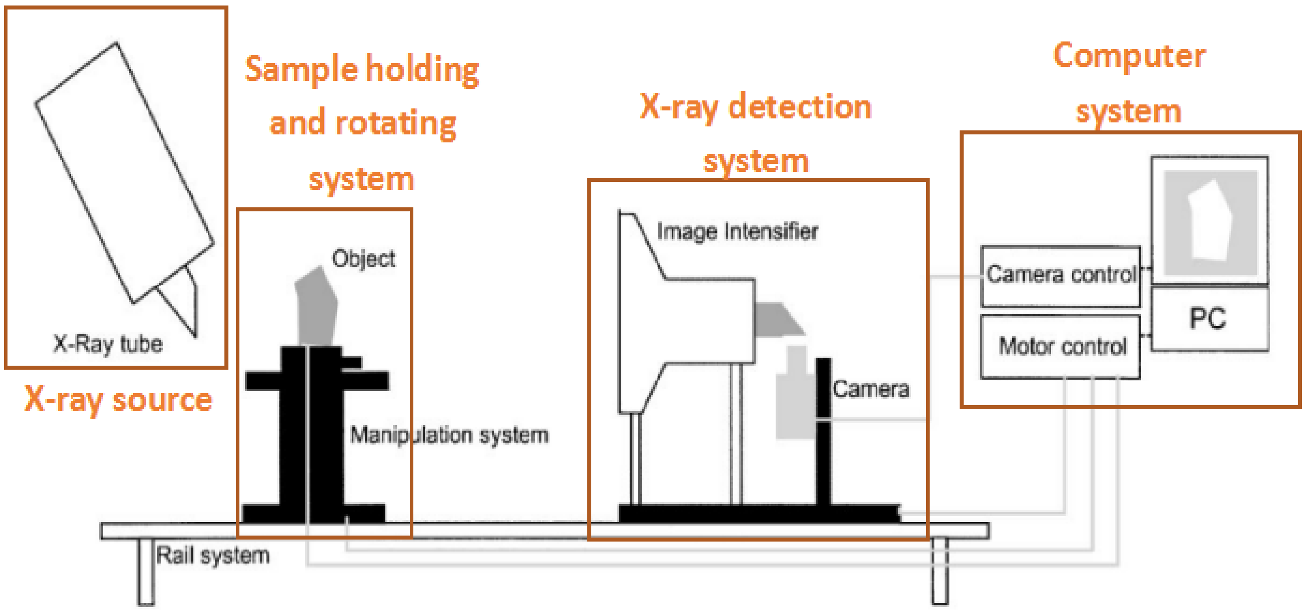
The workflow

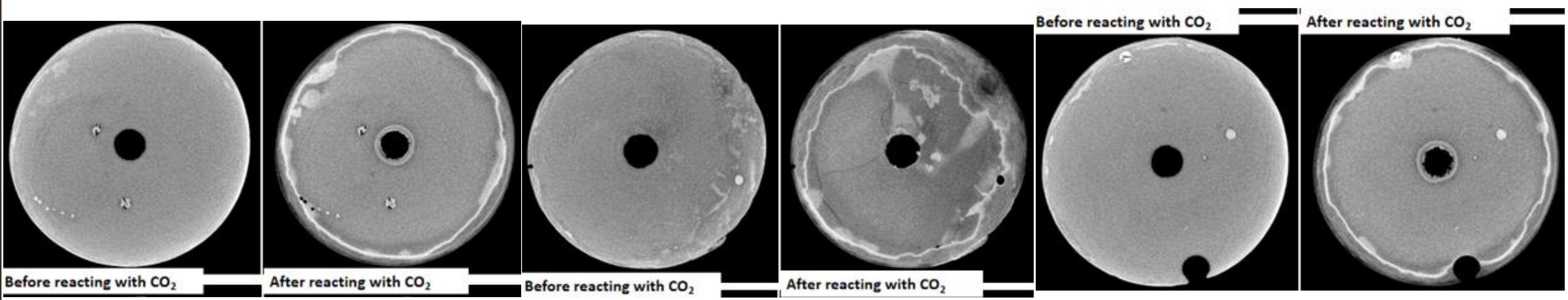
Acquisition of raw CT images before and after reaction with CO_2 → Image registration and alignment → Noise filtering and artifact removal → Acquisition of grayscale difference images → Convert gray scale difference into pore content change → Image segmentation and 3D re-construction → Image post-processing like image rendering



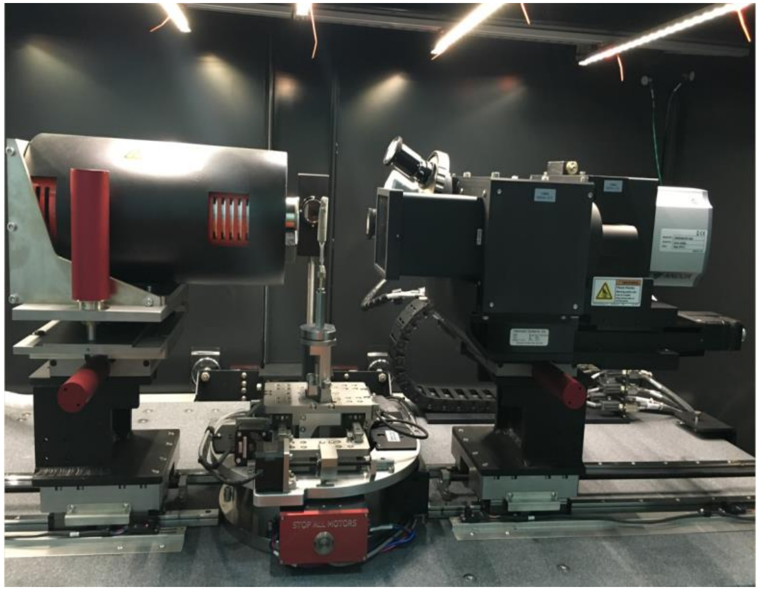
3-D visualization of cement degradation by CO_2

Acquisition of raw CT images





2-D CT scanning slices



Apparatus: Xradia 410 micro-CT scanner

X-ray source： 40 to 150 kV (10W maximum)

2k x 2k high-resolution 16-bit CCD digital camera assembly

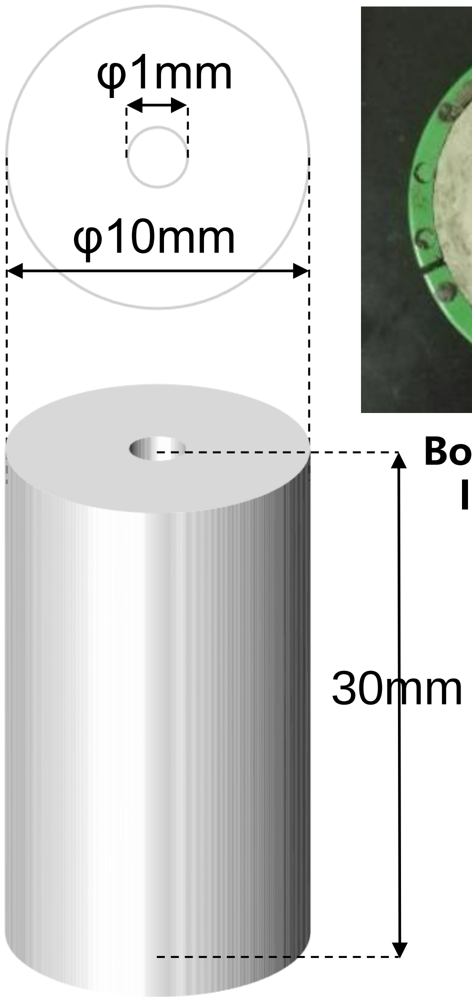
Voxel Size ≥0.9µm

Lens:Macro (0.4X)； 4X； 20X

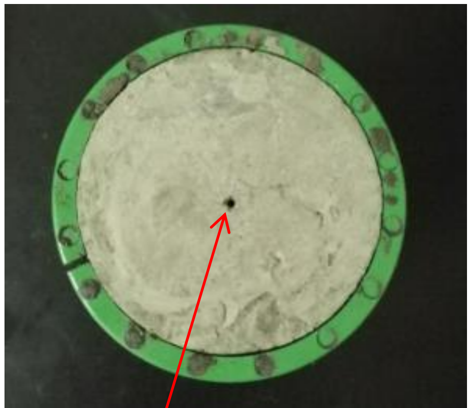
Load Capacity： 15 kg

Sample Stage Travel
X-Direction： 45 mm； Y-Direction： 100 mm；
Z-Direction： 50 mm； Rotation： 360°

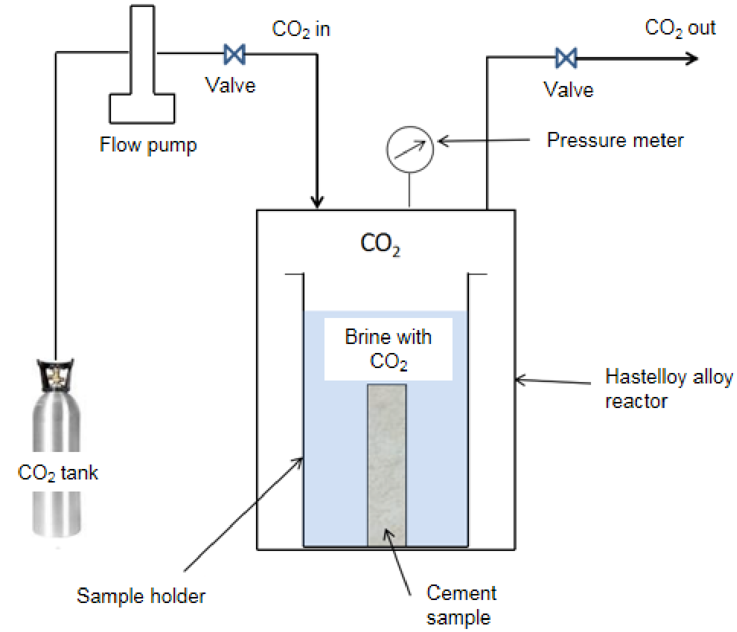
CO_2 exposure experiment



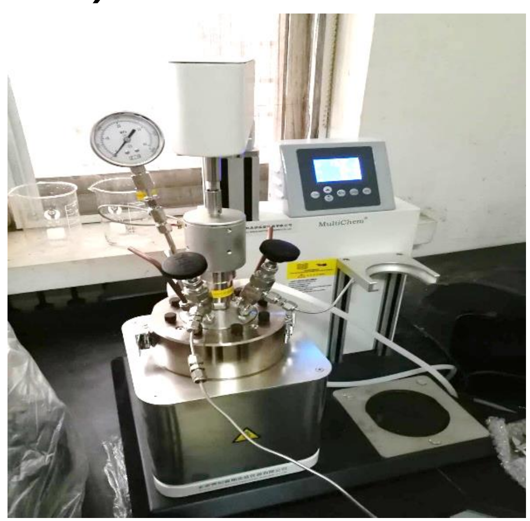
Cement sample



Borehole (mimicking a leakage pathway in cement)



Experimental set-up



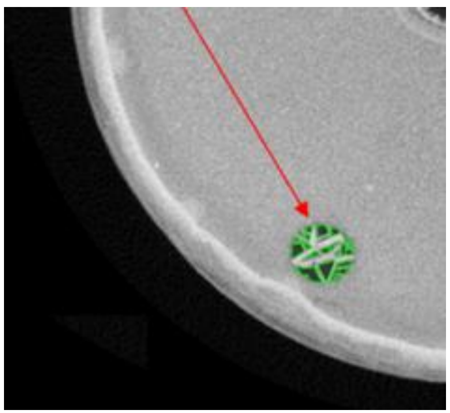
Hastelloy alloy reactor

CO_2 pumps

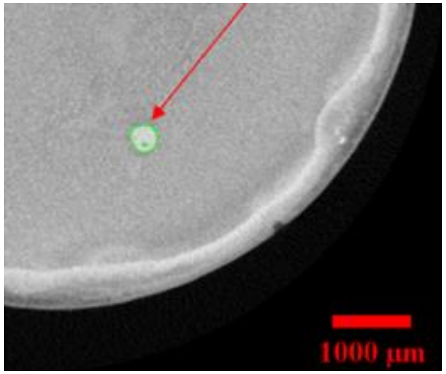
Image registration: ensure that the comparisons are made at the same locations before and after reacting with CO_2

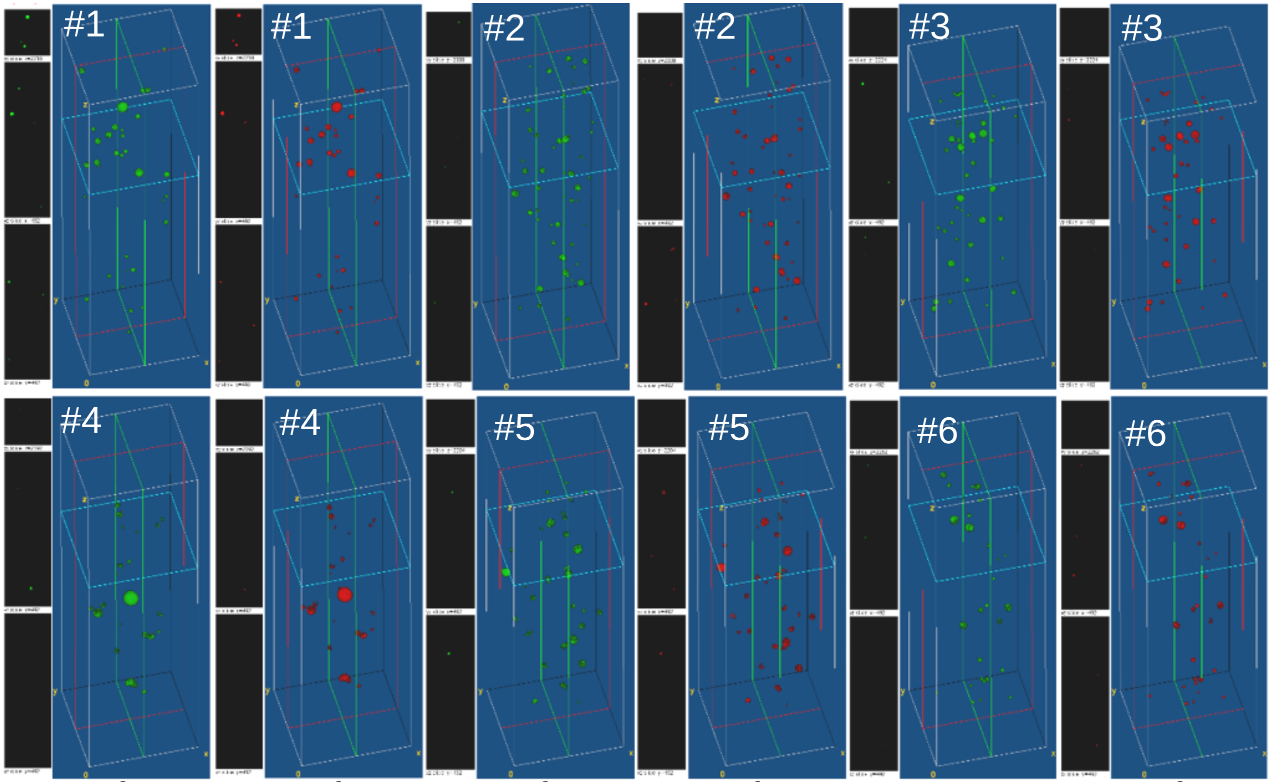
Characteristic particles in cement are picked as "reference spots" for image registration

Reference spot #1



Reference spot #2



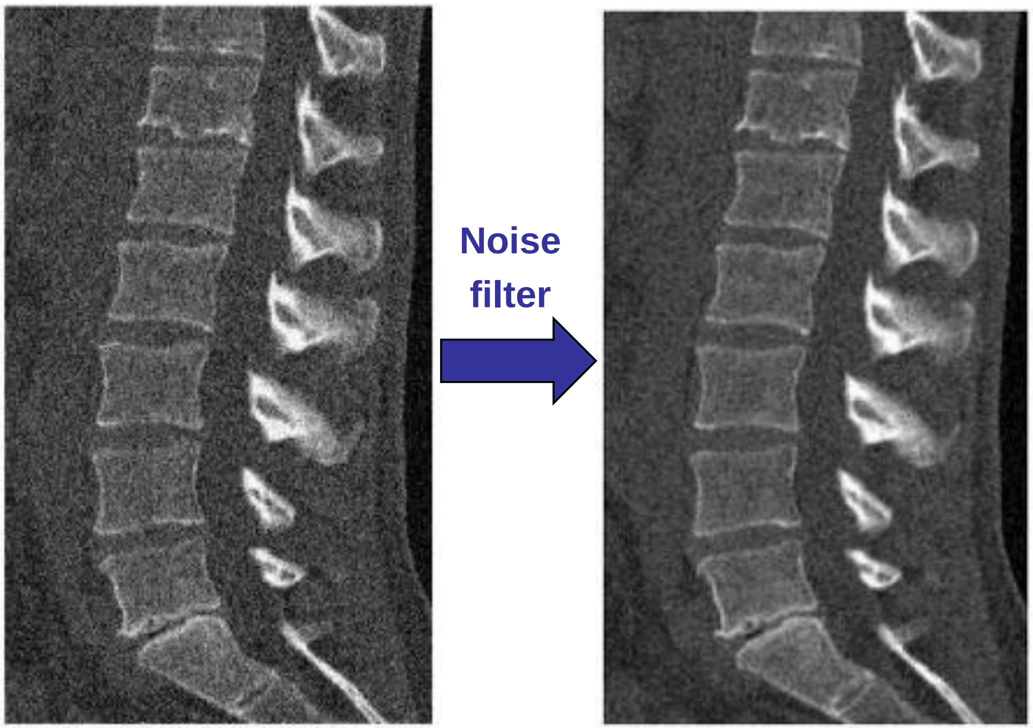


Before reaction | After reaction | Before reaction | After reaction | Before reaction | After reaction

Locations of the reference spots before and after reaction with CO_2 (6 samples)

Noise filtering: necessary to minimize suppression of edges, blurring boundaries, loss of important features, etc. caused by noise

Source of noise: physical (optical) interference on the acquisition device or inappropriate set up of CT (e.g., X-ray energy is too high)

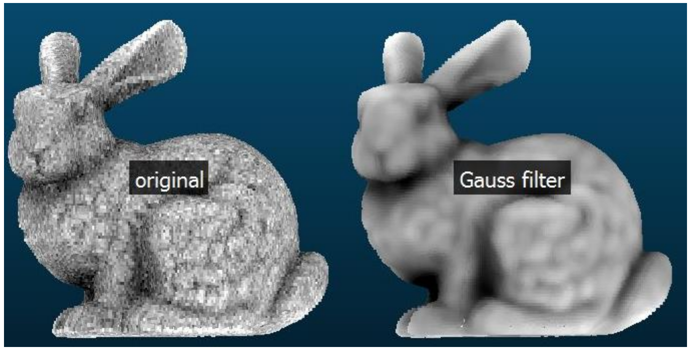


Before filtering

After filtering

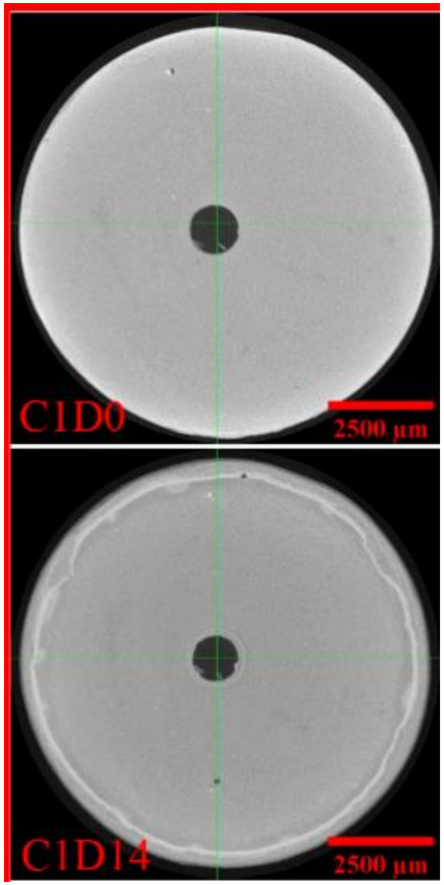
Senthilraja, et al., 2014

In this study, a Gaussian filter is used to remove noise in CT images.
Side effect: when noise is removed, some details may be removed as well.

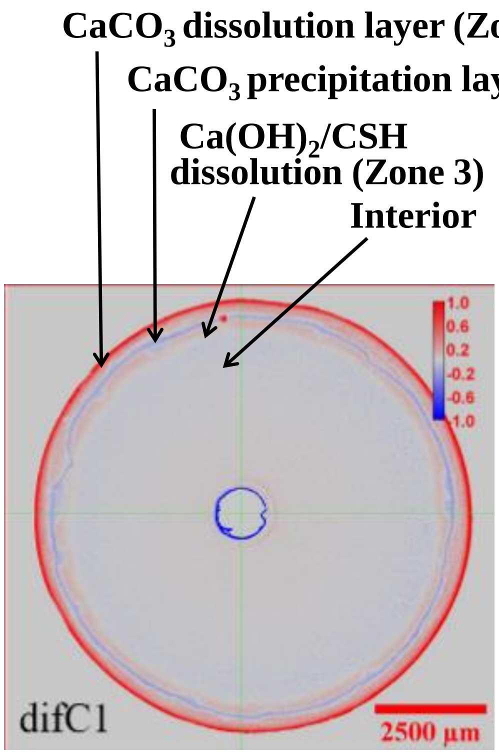


http://www.cloudcompare.org/doc/wiki/images/5/5f/Cc_sf_gaussian_filter.jpg

Acquisition of grayscale intensity difference images

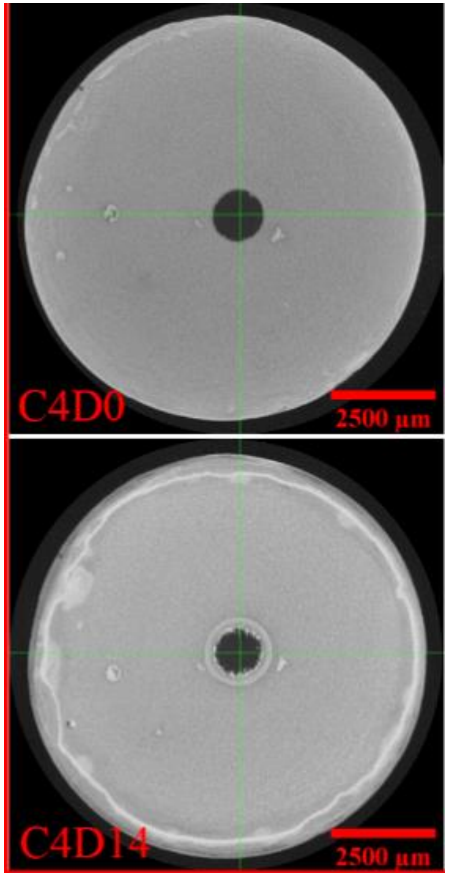


Grayscale intensity images before and after reaction for Sample #1

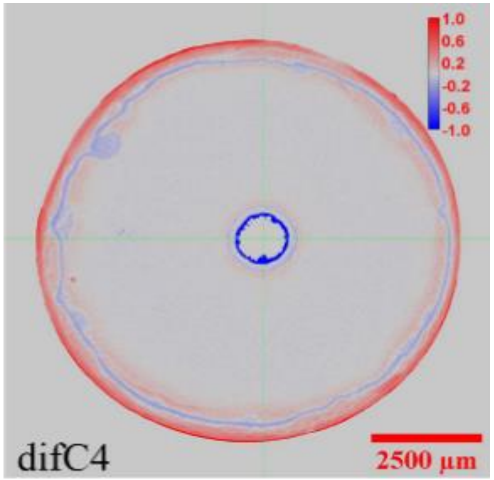


Grayscale intensity difference image for Sample #1

"Sandwich" pattern

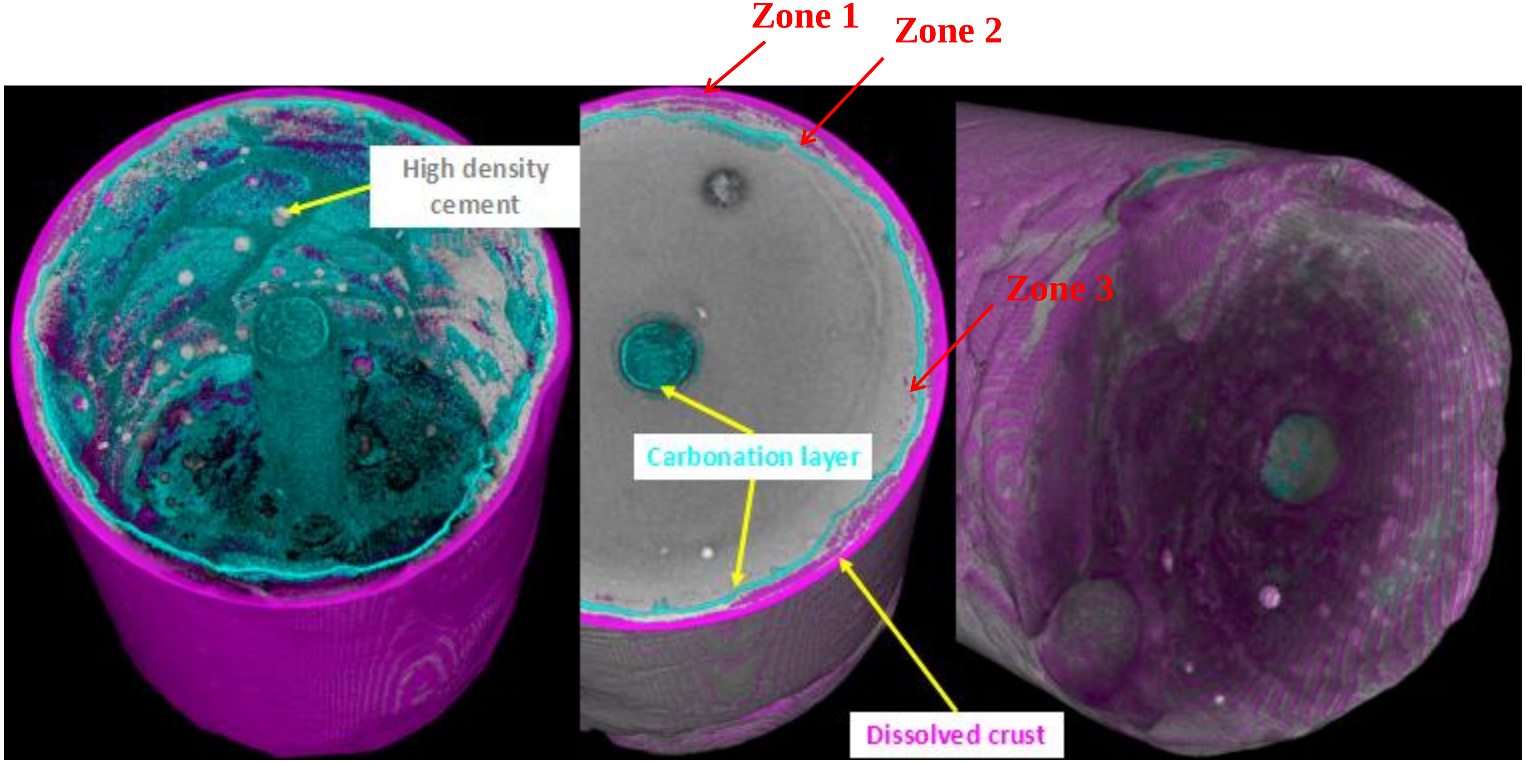


Grayscale intensity images before and after reaction for Sample #4



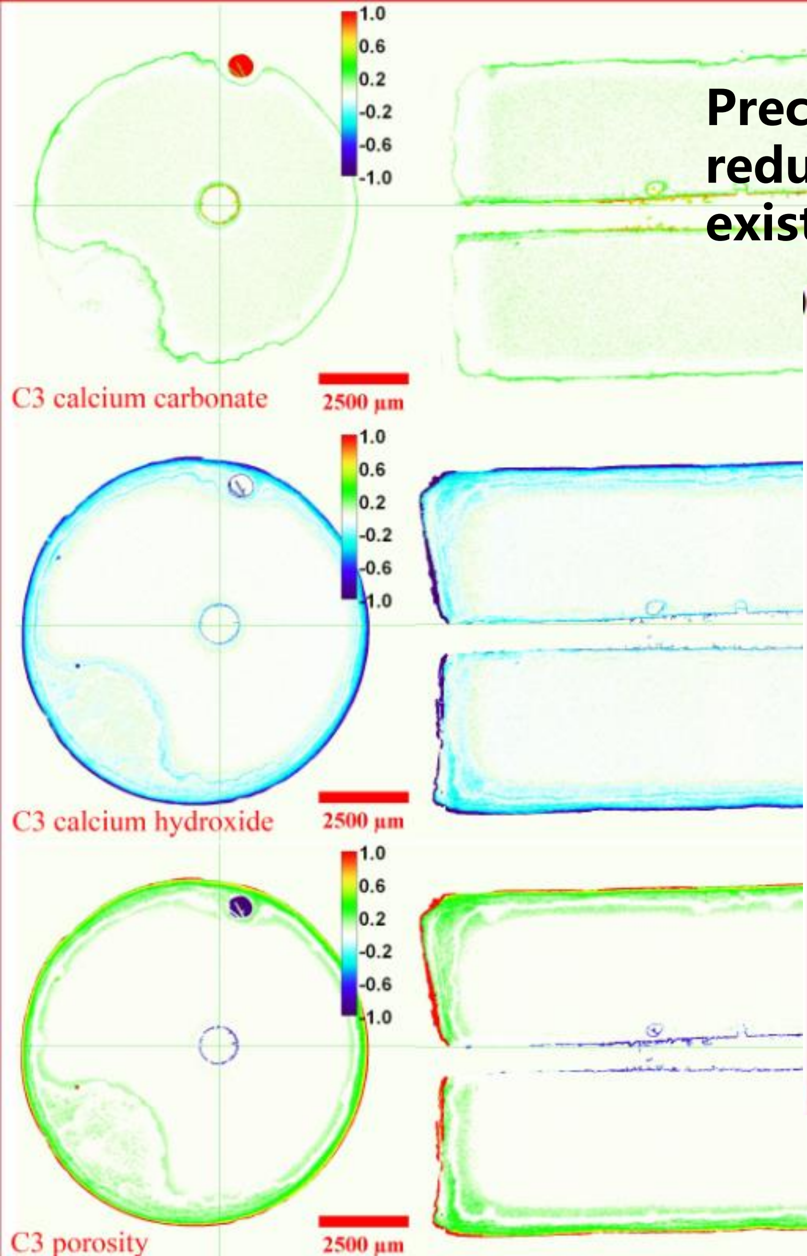
Grayscale intensity difference image for Sample #4

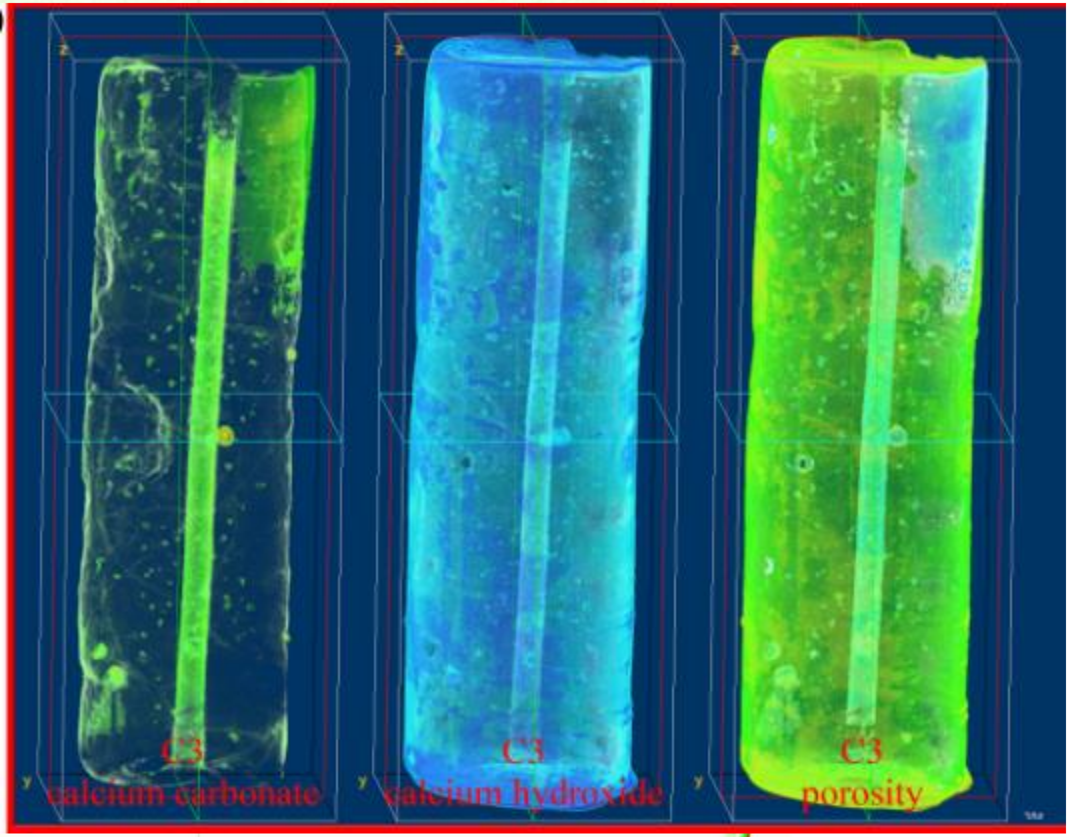
3D visulization of the cement sample after reacting with CO_2



- The 3 reaction zones and the "sandwich pattern" were observed
- Dissolution mainly occurred at the exterior, and no dissolution was observed within the borehole mimicking a leakage pathway in cement

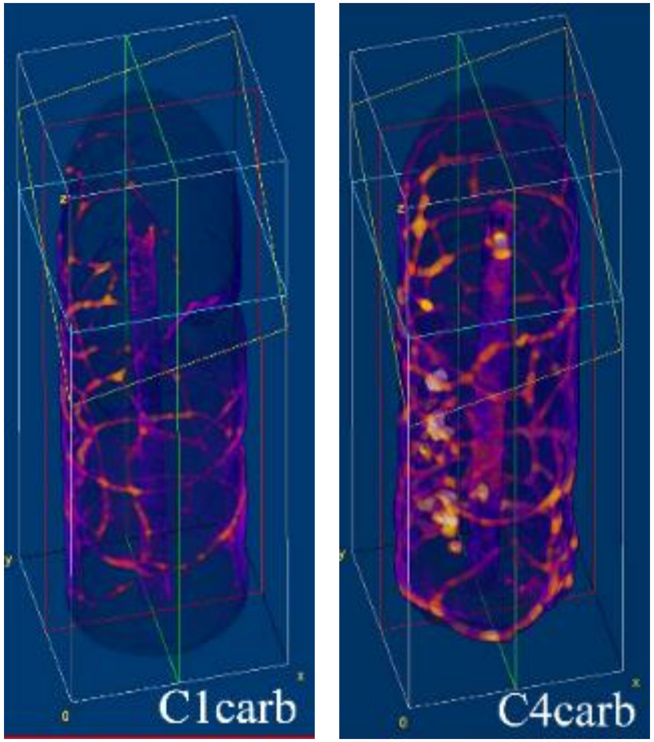
Precipitation of $CaCO_3$ within the borehole reduces the risk of CO_2 leakage through a pre-existing leakage pathway





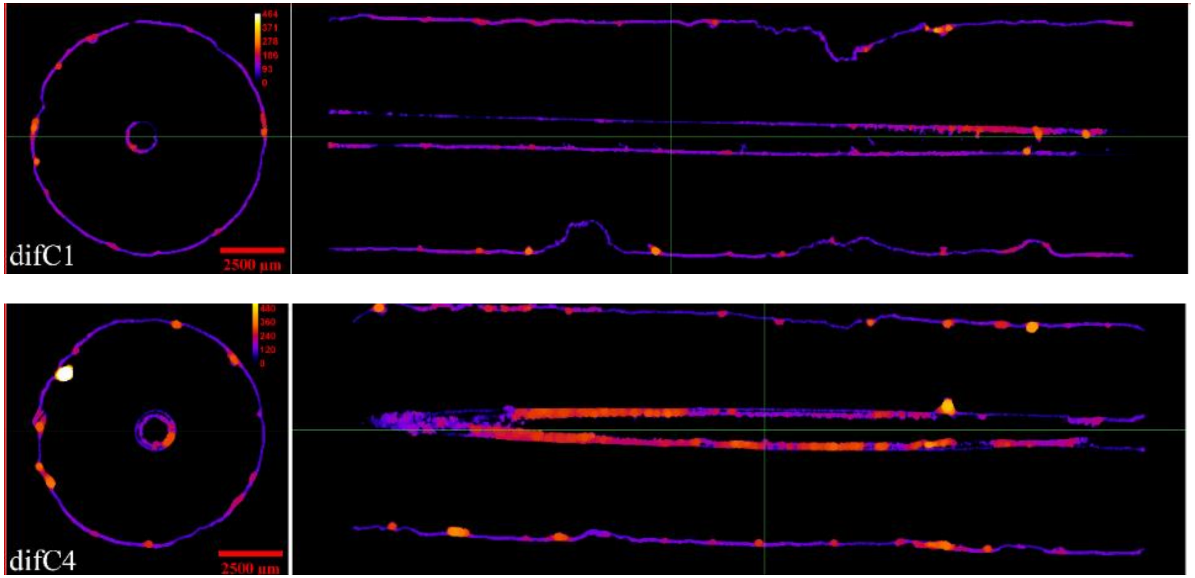
Miao et al., 2020

The thickness of the carbonate layer can be quantified--a criterion to evaluate cement degradation

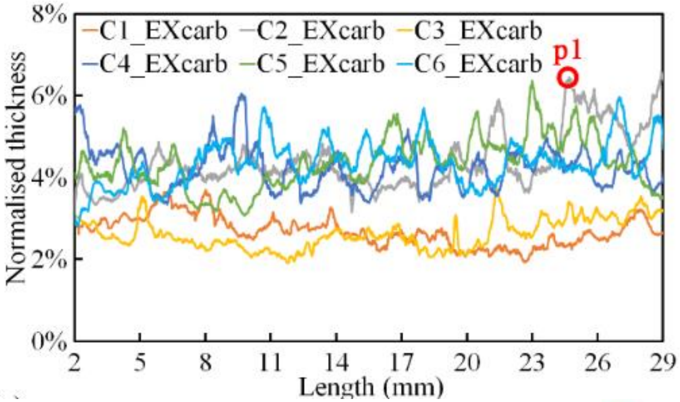


3D view of the carbonate layer after reacting with CO_2 for Samples #1 and #4

Miao et al., 2020



2D plan and cross-section view of the carbonate layer



Normalized carbonate layer thicknesses for Samples #1 to #6

Distribution of carbonate is not uniform in the layer--probably due to the non-uniformity of the pre-exposure cement samples

Summary

- **A workflow for CT characterization of wellbore cement degradation under geologic CO_2 storage conditions was developed.**
- **3-D visulization of the cement sample after reacting with CO_2 reveals the 3 reaction zones and the dissolution-precipitation-dissolution “sandwich” pattern.**
- **Dissolution mainly occurred at the exterior, and no dissolution was observed at the interior of cement.**
- **The thickness of the carbonate layer can be quantified, which can be used to evaluate cement degradation as a result of exposure to CO_2**
- **Precipitation of $CaCO_3$ reduces the risk of CO_2 leakage through a pre-existing leakage pathway in cement.**

Thank you！

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