Laboratory seismic and electrical resistivity monitoring of supercritical CO_2 flooding in sandstone cores

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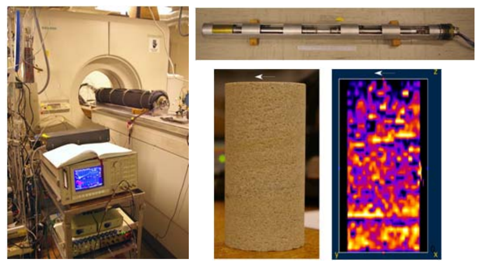
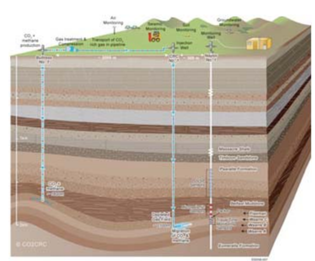


Introduction

Monitoring of CO_2 geological storage requires:

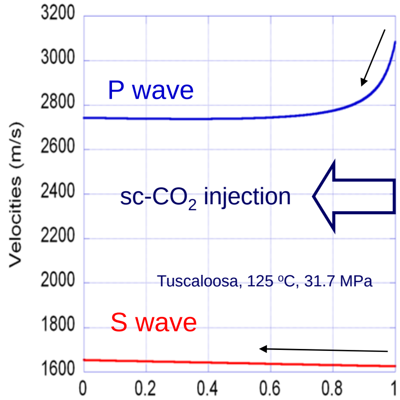
- Understanding of spatial distribution of CO_2
—Where is it?
- Understanding of CO_2 saturation in reservoir
—How much can we store?



To answer these and other questions:
- Laboratory measurements to define the relationship between CO_2 in rock and its geophysical signatures ("Rock Physics")
- Interpretation of field geophysical measurements
- Integrate with reservoir modeling (for fluid movement)

Introduction

- A simplistic relationship—Gassmann Model (1951)



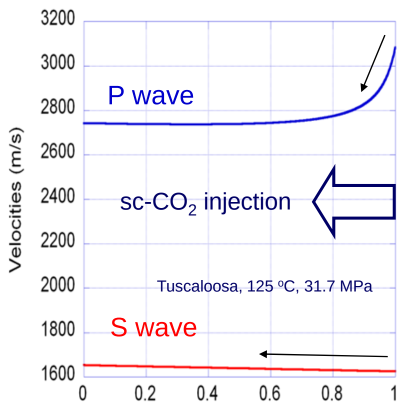
Water Saturation
(1- $scCO_2$ Saturation)

Vp drops rapidly near 100% saturation

Slight increases in Vs due to density changes

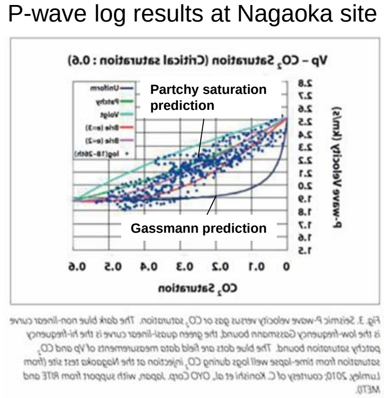
Introduction

- A simplistic relationship—Gassmann Model (1951)



Water Saturation
(1- $scCO_2$ Saturation)

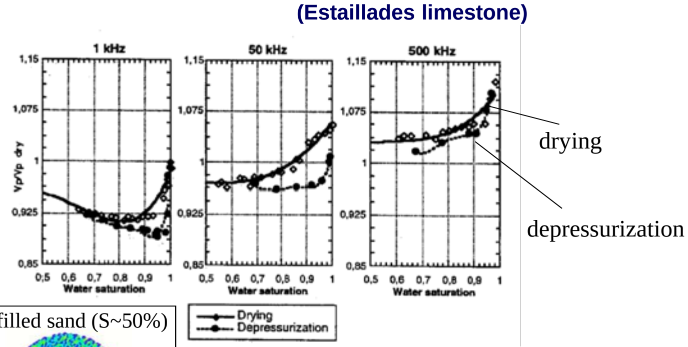
P-wave log results at Nagaoka site



(Azuma, et al., Energy Procedia, 2011)

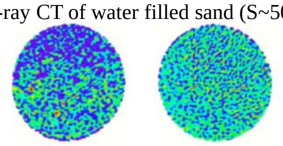
Introduction

Frequency and saturating phase geometry effect on P wave velocity (Estaillades limestone)



Cadoret et al.(1995)

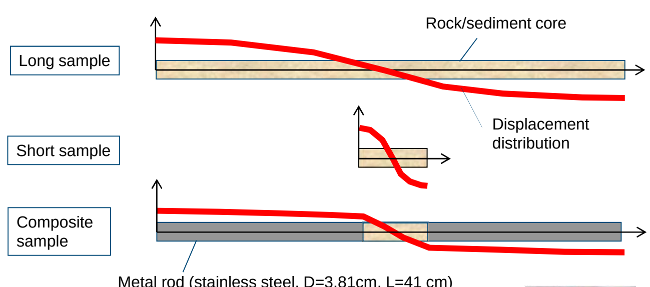
X-ray CT of water filled sand (S~50%)



imbibition depressurization

(From Liu (2001))

Split Hopkinson Resonant Bar (SHRB) Test



- Mass effect
- Length effect

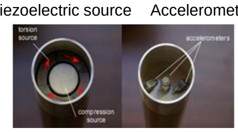
(e.g. Tittmann, 1977)

⇨ Reduction of resonance frequency

Jacketed rock /sediment core

Thermal sensor (RTD)

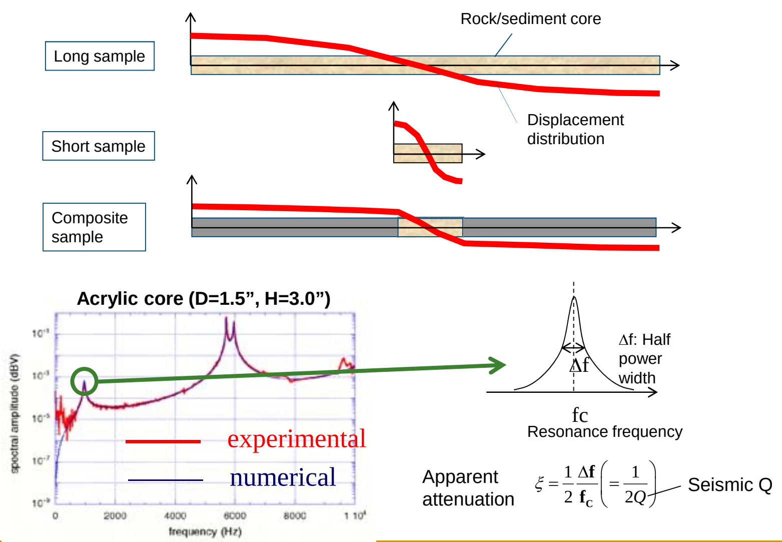
Piezoelectric source Accelerometers



Experiment is conducted within a gas (N_2) confining cell

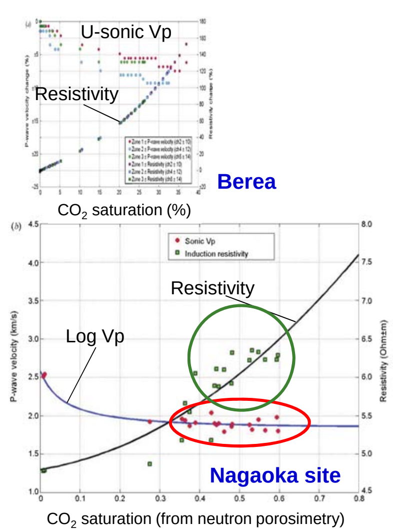
(Nakagawa, Rev. Sci. Instr., 2011)

Split Hopkinson Resonant Bar (SHRB) Test



(Nakagawa, Rev. Sci. Instr., 2011)

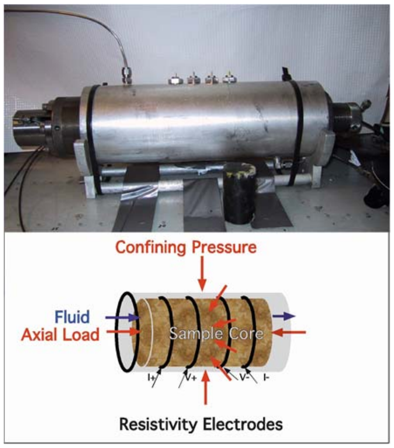
Electrial Resistivity Measurement



- Better sensitivity than seismic for high CO2 saturation
- For clean sand, basic empirical models (e.g. Archie's Law) apply well

(Xue and Watanebe, 2008; Kim et al., 2011)

Electrial Resistivity Measurement



- Perform core flood at reservoir conditions with $scCO_2$
- Quantify resistivity versus $scCO_2$ saturation
- Use CT scanning to quantify CO_2 saturation distribution (patch geometry)
- Correlate to seismic measurements

CO2 flooding experiment

Step I: Brine injection (Initially dry sample)
Step II: sc-CO_2 injection (Initially brine saturated)
Step III: Brine re-injection
Step IV: brine removal (de-gassing)

X-ray CT imaging
⇒CO_2 distribution & saturation

Resonant bar test
⇒Seismic properties

Berea
Porosity: 21.0%
Permeability: **680 mD**

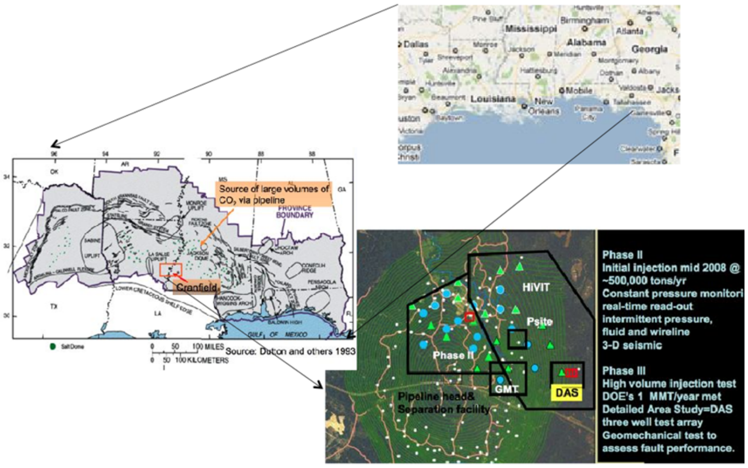
T=35˚C
Pc=1,500 psi
Pp=1,000 psi
Brine: 5% KCl aq.

Cranfield (reservoir)
Porosity: 20.2%
Permeability: **~15.5 mD**

T=65˚C
Pc=3,500 psi
Pp=2,800 psi
Brine: Syn. Reservoir brine

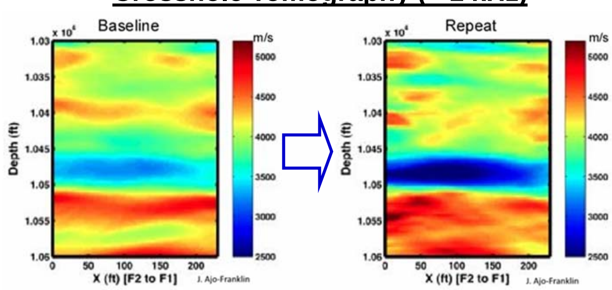
CO2 flooding experiment

SECARB Cranfield Monitoring



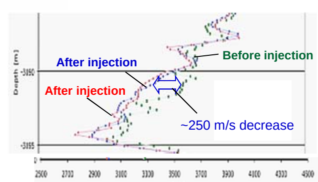
Example III: CO2 monitoring

Crosshole Tomography (~ 1 kHz)



(processing by Ajo-Franklin) (processing by Ajo-Franklin)

Sonic log of the injection interval by Schlumberger (~20 kHz)



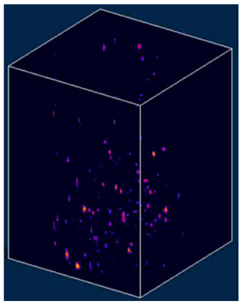
Tomography: 500-700 m/s change
Sonic log: ~250 m/s change

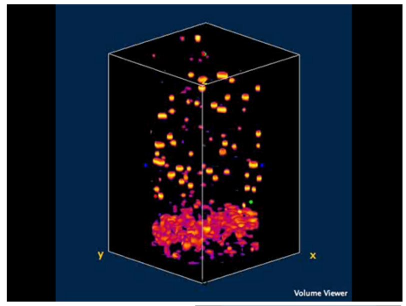
CO2 flooding experiment

Example III: CO2 monitoring

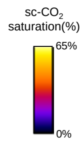
sc-CO2 injection experiment

Berea | Cranfield

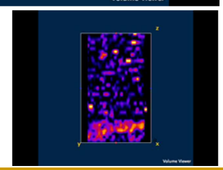




0.8 mm /min



0.22 mm/min

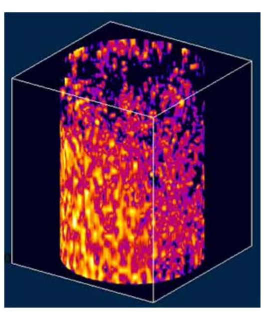


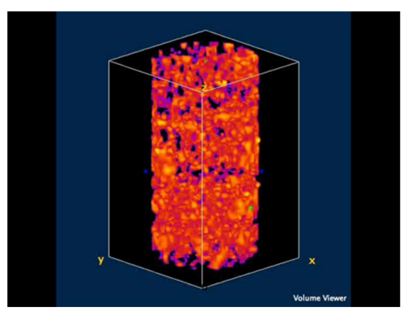
CO2 flooding experiment

Example III: CO2 monitoring

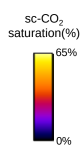
sc-CO2 removal experiment

Berea | Cranfield

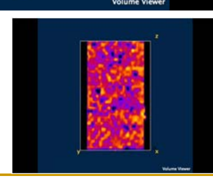




2mm/min

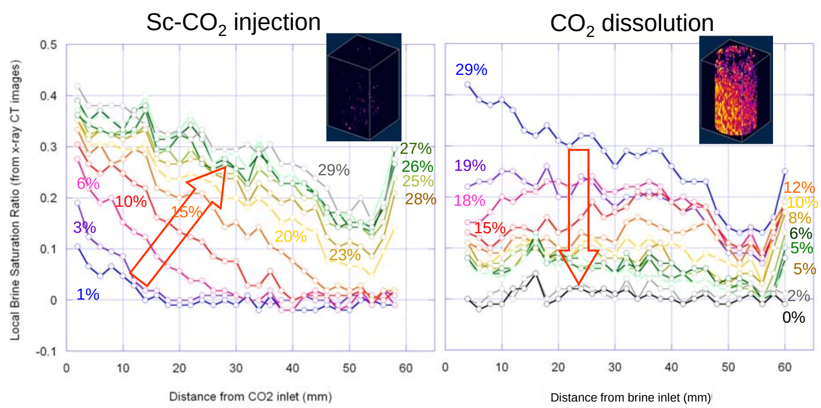


0.87 mm/hr



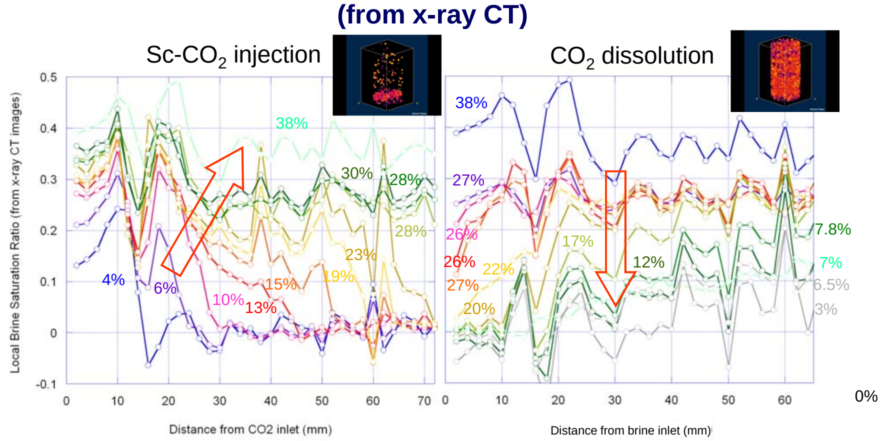
CO2 flooding experiment

Brine saturation profiles along a high-perm Berea core (from x-ray CT)



CO2 flooding experiment

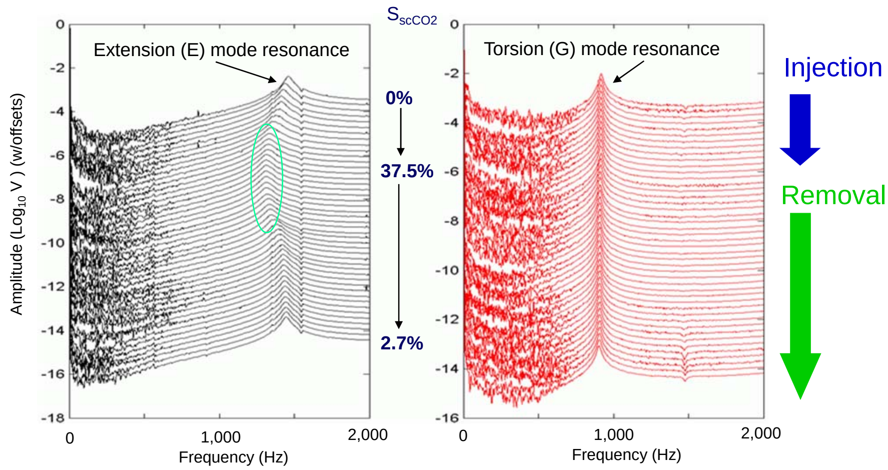
Brine saturation profiles along a medium-perm Cranfield core (from x-ray CT)



CO2 flooding experiment

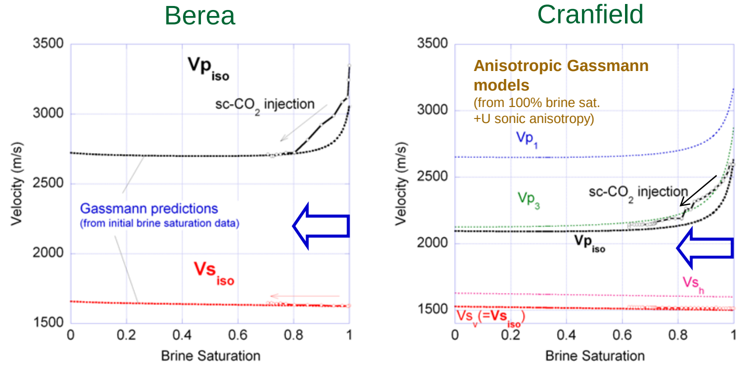
Example III: CO2 monitoring

Resonance curves (Cranfield sample)



CO2 flooding experiment

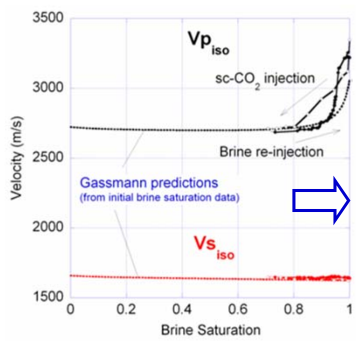
Example III: CO2 monitoring



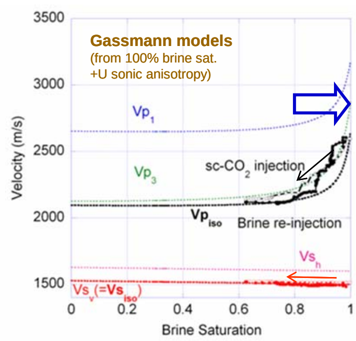
CO2 flooding experiment

Example III: CO2 monitoring

Berea



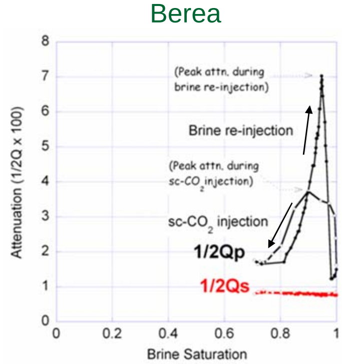
Cranfield



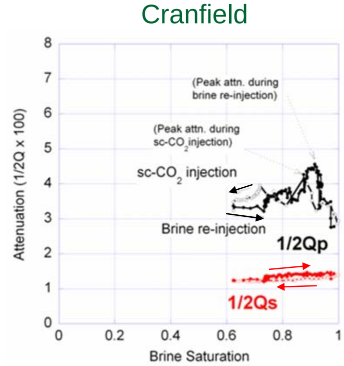
CO2 flooding experiment

Example III: CO2 monitoring

Berea



Cranfield



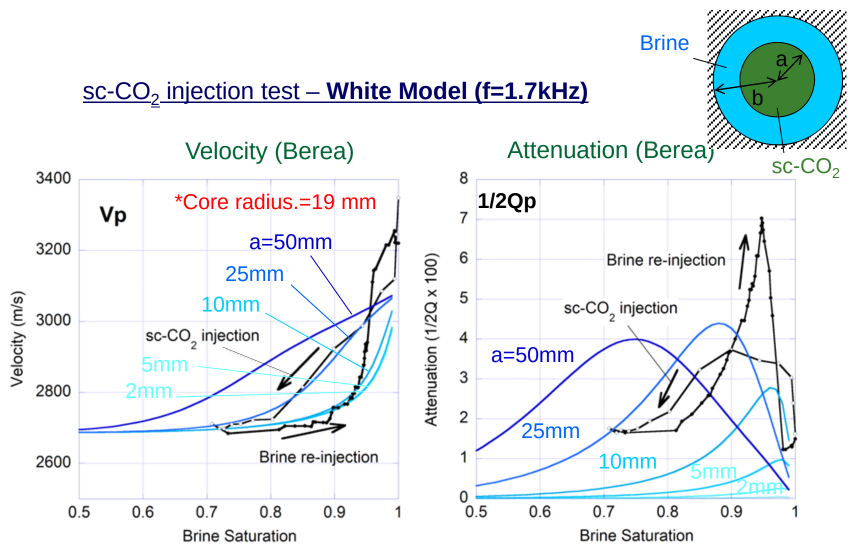
High perm, homogeneous Berea
- Large attenuation changes
- Large hysteresis

Low perm, heterogeneous Cranfield
- Small attenuation changes
- Generally large attenuation
- Small hysteresis

Planned experiments on cores….

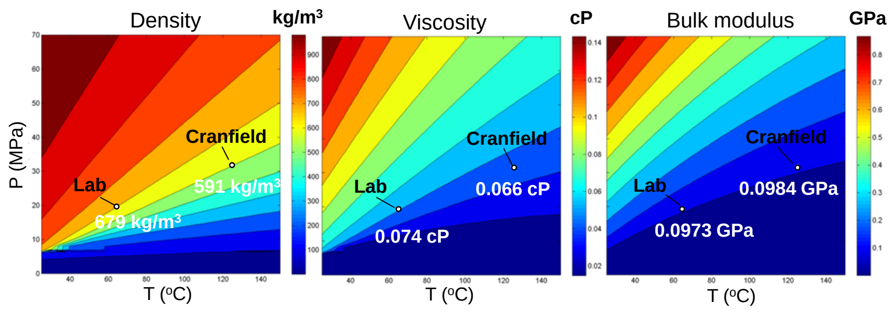
- Baseline seismic and permeability measurements
  - -Both cap and reservoir rocks (~4 each)
  - -Stress sensitivity measurements for seismic
  - -Multiple cores (~3) from each unit
- Seismic and permeability anisotropy measurements
- sc-CO2 flooding experiments
  - -Reservoir rock only
  - -Seismic measurements (SHRB)
  - -Electrical resistivity measurements

CO2 flooding experiment



CO2 flooding experiment

CO_2 Properties



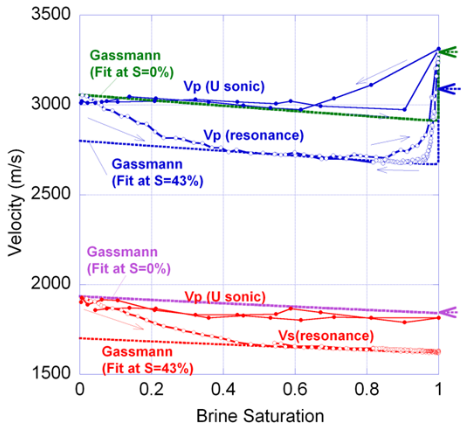
Cranfield: 125 °C, Pp= 4,600 psi (31.7 MPa), Pc=10,550 psi (72.8 MPa)
Lab experiment: 65 °C, Pp=2,800 psi (19.3 MPa), Pc=3,500 psi (24.1 MPa)

Special Thanks to…

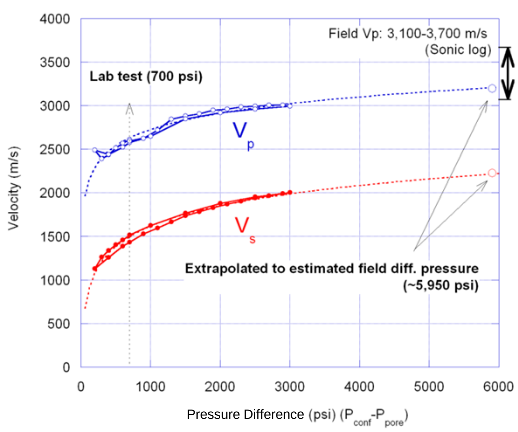
- Steven Ferreira (Fabrication of SHRB setup)
- Andrew Mei (Preparation of rock cores and fab. of seismic source)
- Katherine Blair (Student; CT image processing)

CO2 flooding experiment

Brine injection/drainage test (Berea)



CO2 flooding experiment



CO2 flooding experiment

Fluid Parameters

	Water ρ(kg/m3)	Vp(m/s)	μ (cP)	K (GPa)
T=25^{o}C, P=0.1 MPa (15 psi)	997.05	1496.7	0.890	2.234
T=65^{o}C, P=19.3 MPa (2,800 psi)	988.80	1589.0	0.438	2.497
T=125^{o}C, P=31.7 MPa (4,600 psi)	954.29	1584.0	0.230	2.394

Synthetic Cranfield Brine
$MgCl_2 \cdot 2H_2O$ 10.7 g/L
$CaCl_2 \cdot 2H_2O$ 35.0 g/L
$NaCl_2$ 107 g/L

At room P (0.1 MPa)/T (25 ^{o}C)
Cranfield Brine: 1,086 kg/m3, 2.64 GPa
Water: 997 kg/m3, 2.23 GPa

Cranfield core

61.6% Quartz
3.8% Kaolinite Al2Si2O5(OH)4
11.06% Chlorite
14.53% Microcline KAlSi3O8
1.68% Muscovite KAl2(AlSi3O10)(F,OH)2
3.82% Albite NaAlSi3O8
0.43% Calcite
0.1% Siderite
0.32% Halite
2.65% Anatase TiO2