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Pore Structure and Diagenetic Controls on Relative Permeability: Implications for Enhanced Oil Recovery and CO_2 Storage

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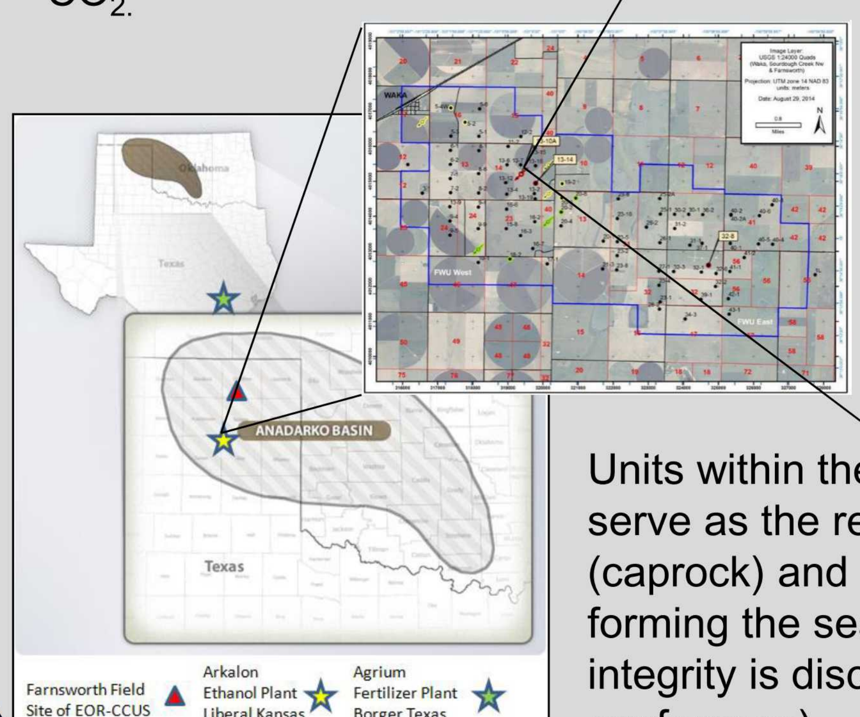
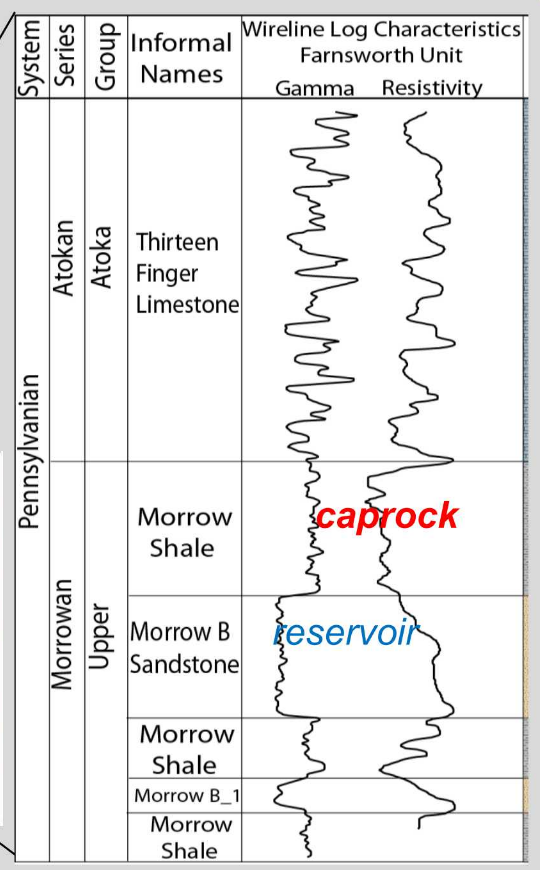
Introduction

Multiphase flow in clay-bearing sandstones of the Pennsylvanian Morrow Sandstone governs the efficiency of CO2 storage and enhanced oil recovery at the Farnsworth Unit, West Texas, USA. This formation is the target for enhanced oil recovery and injection of one million metric ton of anthropogenically-sourced CO2. The sandstone hosts eight major hydrologic flow units (HFUs) that exhibit distinct microstructural characteristics due to diagenesis, including: "clean" macro-porosity; quartz overgrowths constricting some pores; ghost grains; intergranular porosity filled by microporous authigenic clay; and feldspar dissolution. We examine the microstructural controls on macroscale (core scale) relative permeability and capillary pressure behavior through mercury porosimetry, petrography, X-ray computed tomography,imaging, and relative permeability and capillary pressure in the laboratory using CO2 and brine at reservoir pressure and effective stress conditions. The combined data sets inform links between patterns of diagenesis and multiphase flow. These data support multiphase reservoir simulation and performance assessment by the Southwest Regional Partnership on Carbon Sequestration (SWP).

Background

The FWU is undergoing CO_2 enhanced oil recovery (EOR) using 100% anthropogenically-sourced CO_2. The SWP is cuurently monitoring the injection of 1 million metric tons of anthropogenic CO_2.





Units within the Morrow-B Sandstone serve as the reservoir with overlying (caprock) and underlying Morrow shales forming the seals. Analysis of caprock integrity is discussed by Trujillo et al. (this conference)

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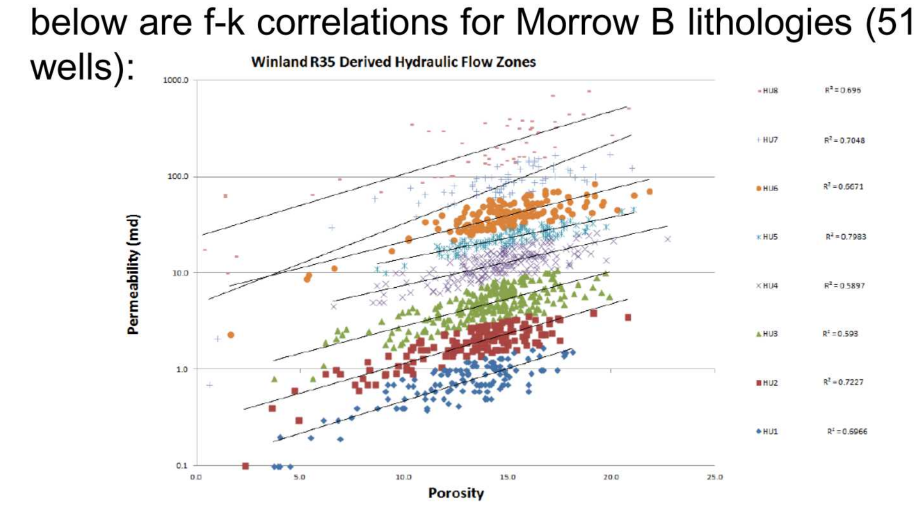
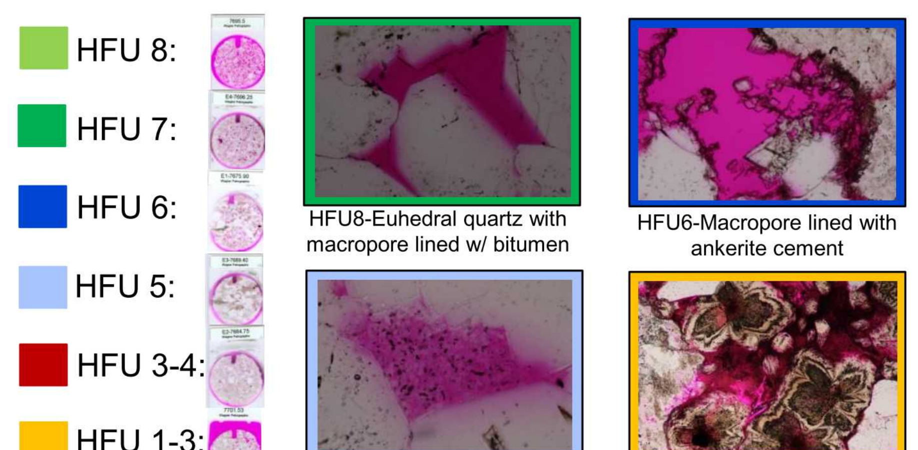
Hydrologic Flow Units & MICP

Rose-Coss et al. (2016) used the Winland R35 method to distinguish HFUs in the Morrow B. Shown below are f-k correlations for Morrow B lithologies (51 wells):





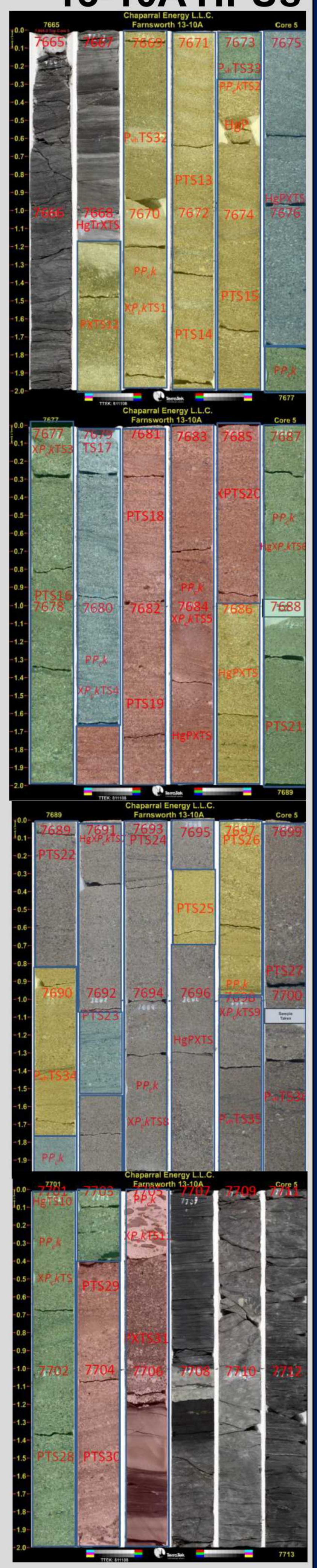
HFU8-Euhedral quartz with macropore lined w/ bitumen

HFU6-Macropore lined with ankerite cement

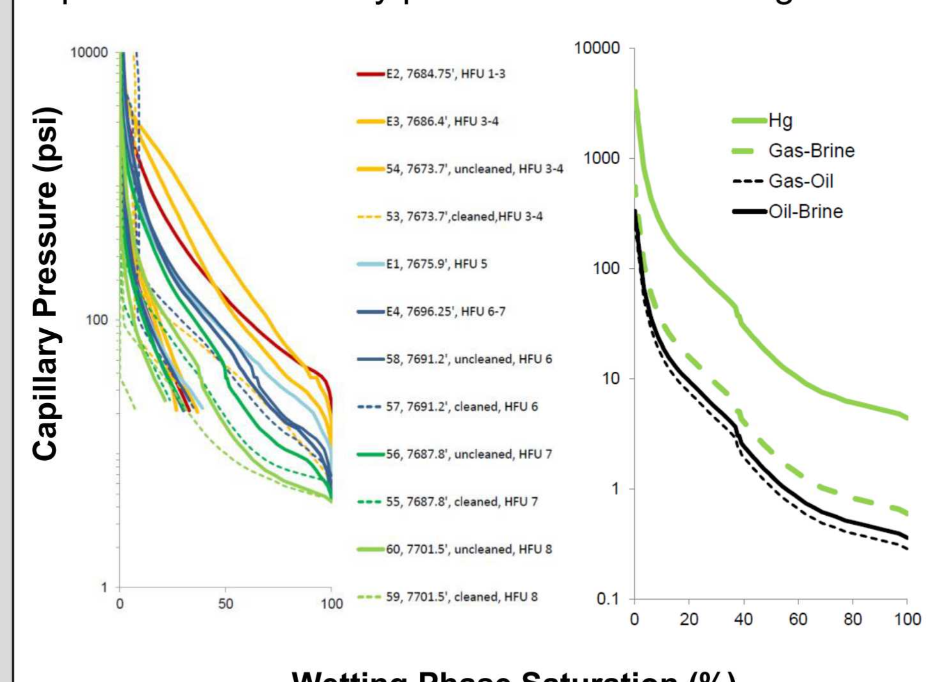
HFU5-Microporosity within kaolinite-filled pore & bitumen

HFU1-3 –Porosity occluded by sphaerosiderite cement

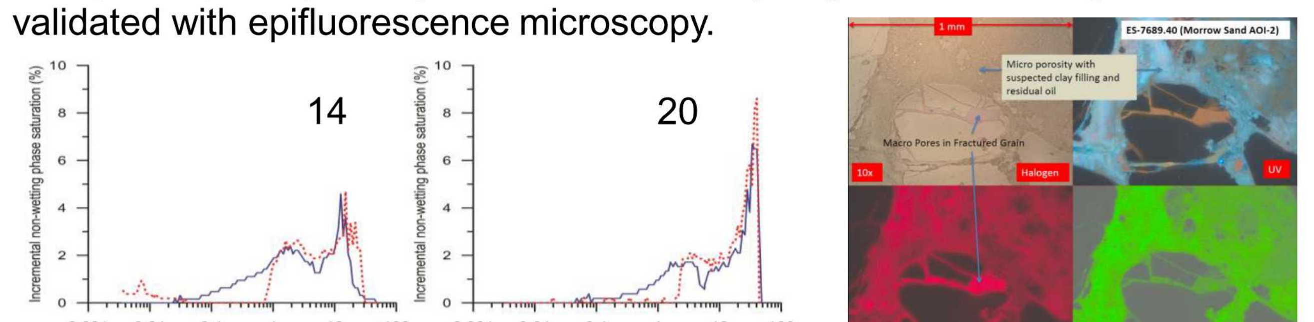
13-10A HFUs



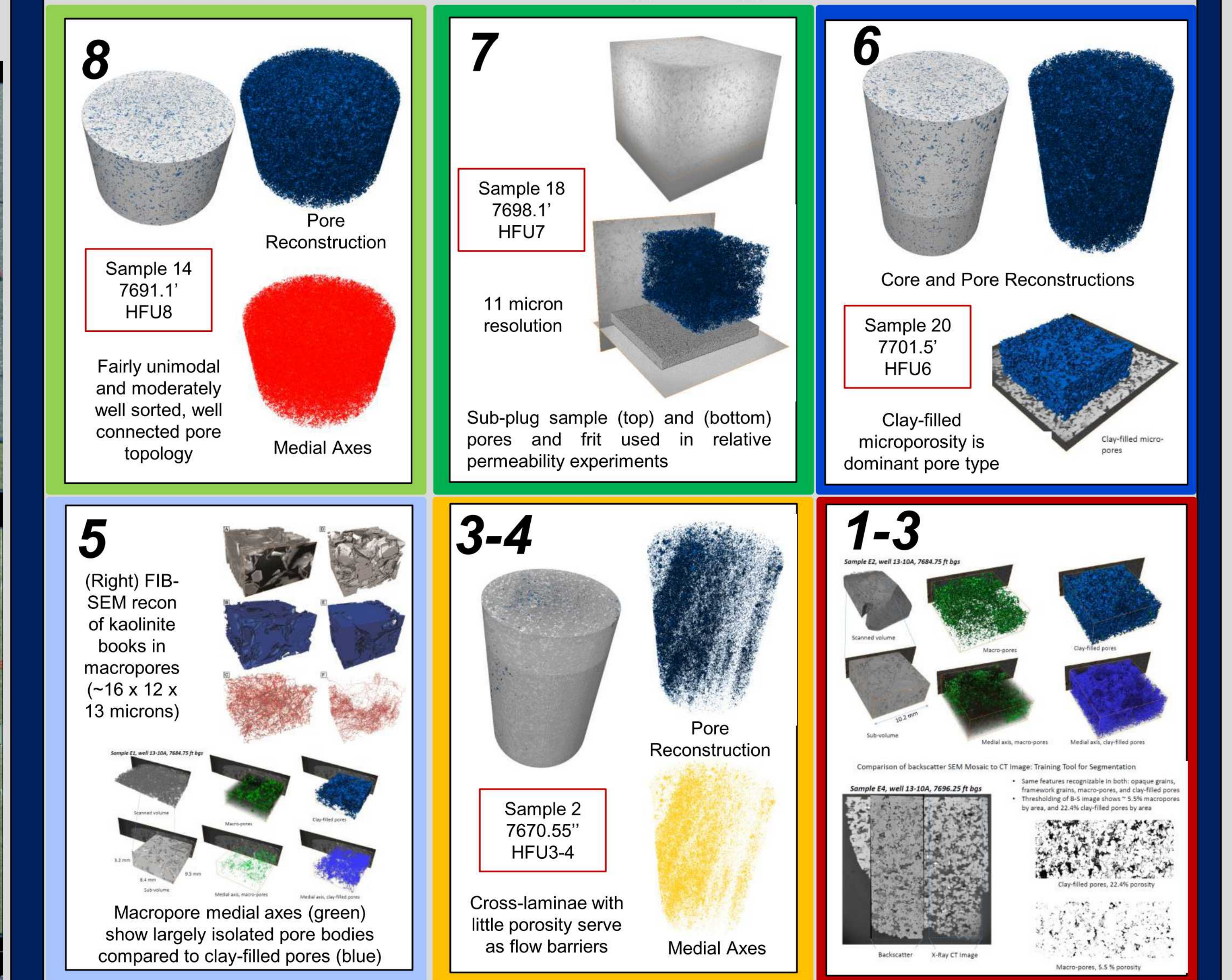
Mercury porosimetry of end butts and small plugs of 13-10A samples show capillary pressure-saturation curves with higher numbered HFU's exhibiting lower entry pressures. Extrapolating wettability to other phases lowers entry pressures relative to Hg.



MICP with Dean-Stark cleaned plugs suggest presence of bitumen within finer pores (microporosity associated with clay, e.g. kaolinite, filling. This is validated with epifluorescence microscopy.



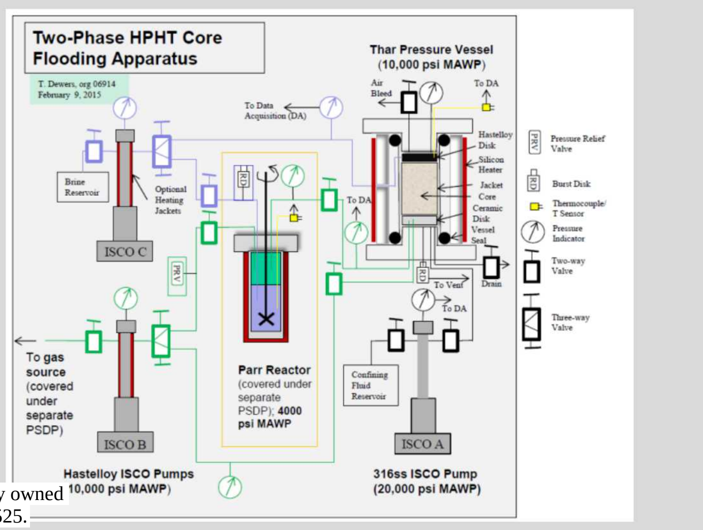
Micro-CT Imaging of HFUs



Imaging of core plugs and end-butts of plugs was performed using a North Star Imaging Inc. Micro-CT. Resolutions range from 11 to 16 microns. FIB/SEM serial sectioning and imaging was performed using an FEI Helios 600 Nanolab Dual Beam instrument

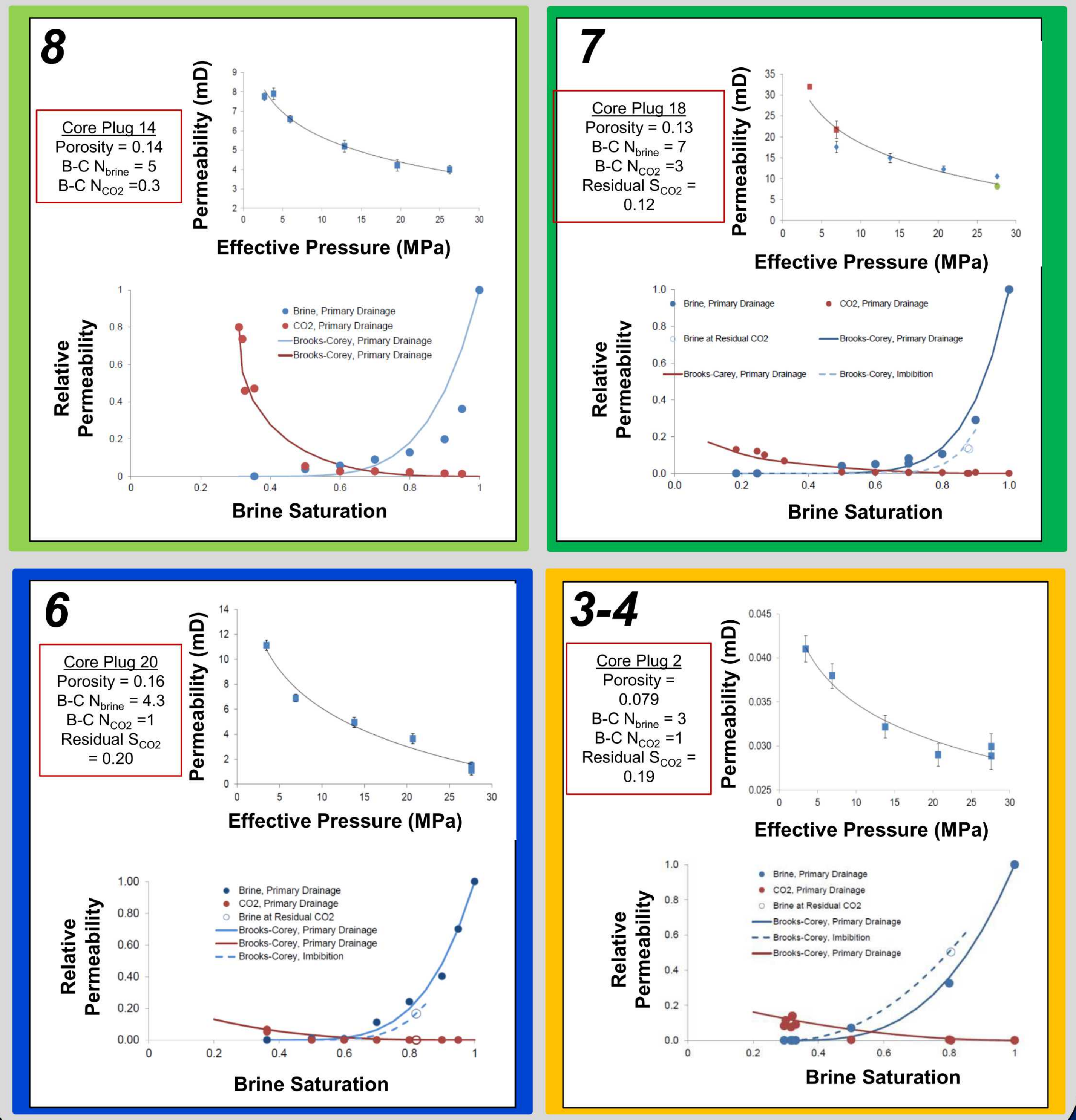
Experimental Methods

- Horizontal plugs 1.5' in diameter and ~3' in length were prepared by Terra Tek and SNL. Plug ends were used for thin section prep and MICP.
- Samples were jacketed in hybrid nickel foil-teflon-UV-cured polyurethane coating with wire wraps. End pieces were composed of titanium, and 3mm thick porous hastelloy frits were placed between end piece and jacket to mitigate end effects. And distribute flow. Samples were flushed with CO2(g) and then vacuum impregnated with pore solution prior to pressurizing.
- Tests were conducted in a HIP pressure vessel, using hastelloy plumbing.
- Fluid pressure and metering were performed with Teledyne-ISCO syringe pumps with hastelloy cylinders.
- All tests were run at ~ 76°C, ~27.6 MPa pore pressure and 55.2 MPa confining pressure with 4000 mg/L NaCl solutions to simulate in situ conditions. Pore solutions and $scCO_2$ were pre-equilibrated by circulating in a high pressure "bubbler" prior to injection.



Relative Permeability Results

Testing procedure included 1. Single phase permeability as a function of effective pressure; 2. flushing sample with mixtures of H_2O /CO_2 at increasing ratios at flow rates up to 20 ml/min; 3. CO_2 flow near irreducible water saturations (Sw, ir) was done at multiple flow rates using the method of Pini and Benson (2014). 4. Imbibition water floods were performed to measure residual CO_2. 5. A 2nd drainage was performed to obtain $S_{w,i}$ also measured on core by evaporation in an oven.



Conclusions

- **8 HFUs are recognizable in the Morrow-B on basis of porosity and perm at surface conditions (Rose-Coss et al., 2016) and on the basis of MICP and CT-imaging.**
- **Authigenic clays and cements have a first order control on single and 2-phase permeability of HFUs.**
- **HFUs exhibit mixed-wettability, and bitumen was recovered during testing from CO2 effluent. Lower value HFUs contain most of the residual oil. Higher HFUs represent "fast paths" that may thwart efforts at broad sweep efficiency for EOR.**
- **Residual (trapped) CO2 amounts range of saturation values of 10 to 15% in the tested HFUs.**

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