Fracture mechanics and seal capacity in a natural CO_2 system

Jonathan R Major[1], Peter Eichhubl[1], Thomas A. Dewers[2]
1. Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, TX, United States
2. Geomechanics, Sandia National Laboratories, Albuquerque, NM, United States

ABSTRACT

Evaluation of changes in the coupled chemical and mechanical properties of reservoir and seal rocks is critical for ensuring both short and long-term security of injected CO_2. Natural analogs are advantageous for understanding these properties on longer time scales than possible using laboratory or numerical experiments. The Crystal Geyser site in Utah was studied to assess the potential for leakage via fracturing or capillary failure of reservoir and seal rocks altered by natural, long-term CO_2-water-rock interactions.

Fracture mechanics testing using the double torsion method was performed on a suite of naturally altered and unaltered rocks exposed at Crystal Geyser. Fracture toughness measurements demonstrate that CO_2-related alteration has weakened one reservoir sandstone unit by approximately 50%, but did not affect subcritical index. In contrast, the fracture toughness measured of a weak, poorly-cemented sandstone unit was increased due to enhanced calcite cementation, and a similar effect was observed in shale samples tested.

Mercury intrusion capillary pressure (MICP) analyses on shale from a fault-perpendicular transect show relatively low capillary seal capacity nearest the fault where CO_2-alteration is most intense. Seal capacity increases by nearly an order of magnitude where measured bulk calcite is highest then gradually declines laterally away from the fault. SEM imaging shows matrix replacement with calcite is primarily responsible for increased seal capacity.

This study demonstrates that CO_2-water-rock interaction driven by changes in the geochemical environment have significantly changed rock geomechanical and flow properties over geologic time scales. Alteration and dissolution of grains and cements in reservoir and seal rock can potentially lead to leakage by favoring fracturing and/or lowering capillary seal capacity. Alternatively, where CO_2-rich fluids drive significant precipitation of carbonate minerals, fracture growth may be hindered and capillary seal capacity increased.

1- INTRODUCTION

BIG QUESTION:

1- How does CO_2 alter the geomechanical properties of rock over long time scales, potentially leading to leakage of subsurface reservoirs?

Two failure mechanisms:

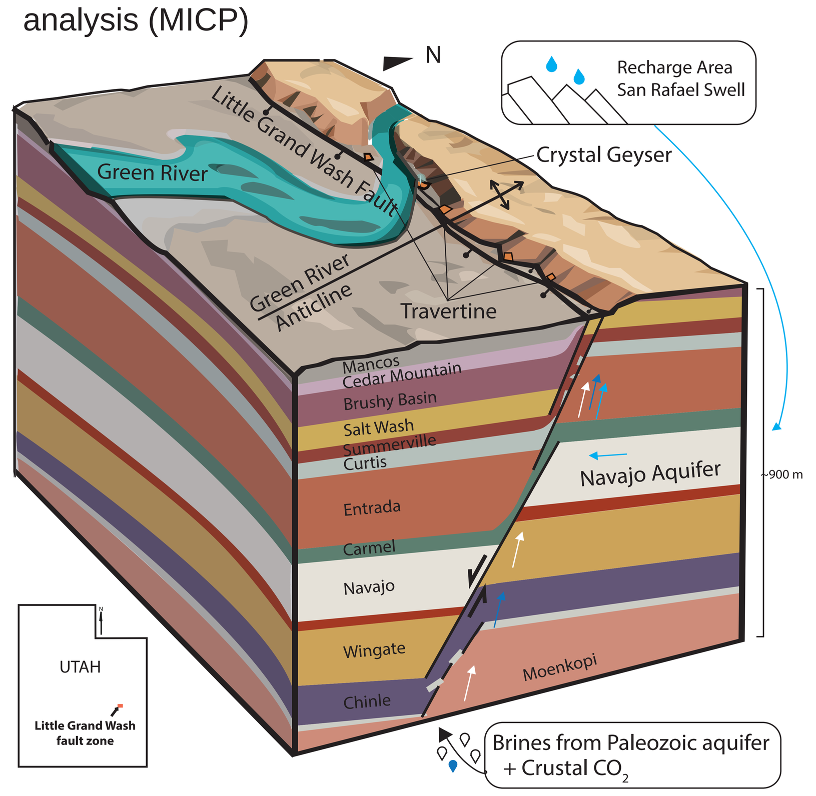
a. Fracturing
b. Capillary failure

APPROACH:

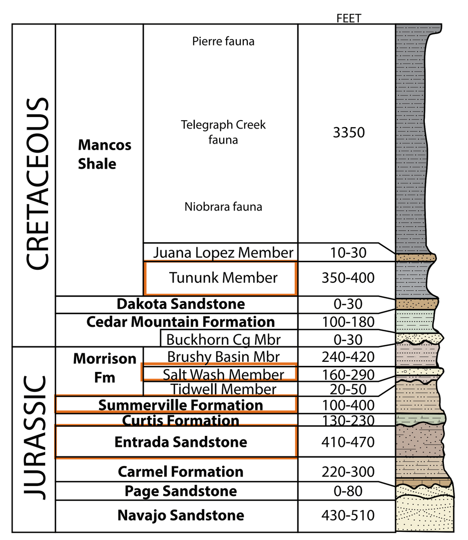
1- Characterize a range of rocks naturally altered by CO_2-water-rock interactions over geologic time scales: XRD, stable isotopes, petrography

2- Measure and compare fracture mechanics parameters: fracture toughness (K_{IC}), subcritical index (SCI)

3- Measure and compare seal/flow properties: mercury-intrusion capillary pressure analysis (MICP)



RIGHT: Block diagram of Crystal Geyser field site, Utah. Geology constrained by mapping (Urquhart, 2011), published data, and detailed study of the Moab fault found 50 km to the SE (Eichhubl et al., 2009).



After Hintze & Kowallis, 2009

ABOVE: Stratigraphy of the Green River, Utah area with main units of study highlighted.

II- FRACTURE MECHANICS TESTING

Geomechanical effect of CO_2-related alteration

Fracture mechanics parameters, the fracture toughness (K_{IC}) and subcritical index (SCI) of reservoir and seal units are important inputs for assessing storage capacity, leakage potential, and planned injection rates for numerical models of carbon sequestration sites.

We evaluate whether CO_2-related alteration affect these parameters by testing naturally altered rocks. These rocks may better represent the end-products of alteration than what can be measured under laboratory conditions and time scales.

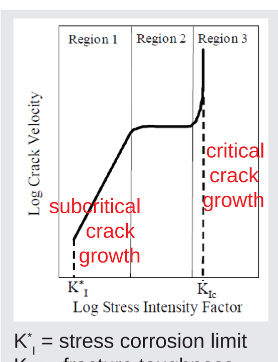
Fracture toughness describes the ability of a material containing a crack to resist fracture, or in other words, the fracture toughness is the stress intensity required to initiate new fracturing.

Subcritical crack growth may be an important mechanism for and control on fracturing in reservoir and seal units at Crystal Geyser and in subsurface CO_2 reservoirs. Subcritical crack growth is largely controlled by stress corrosion, which is related to chemical reactions at the fracture tip. The subcritical crack index, n, is the exponent in the power law relationship below and describes the velocity dependence of fractures propagating under subcritical conditions:

$$V = A\left(\frac{K_I}{K_{IC}}\right)^n$$

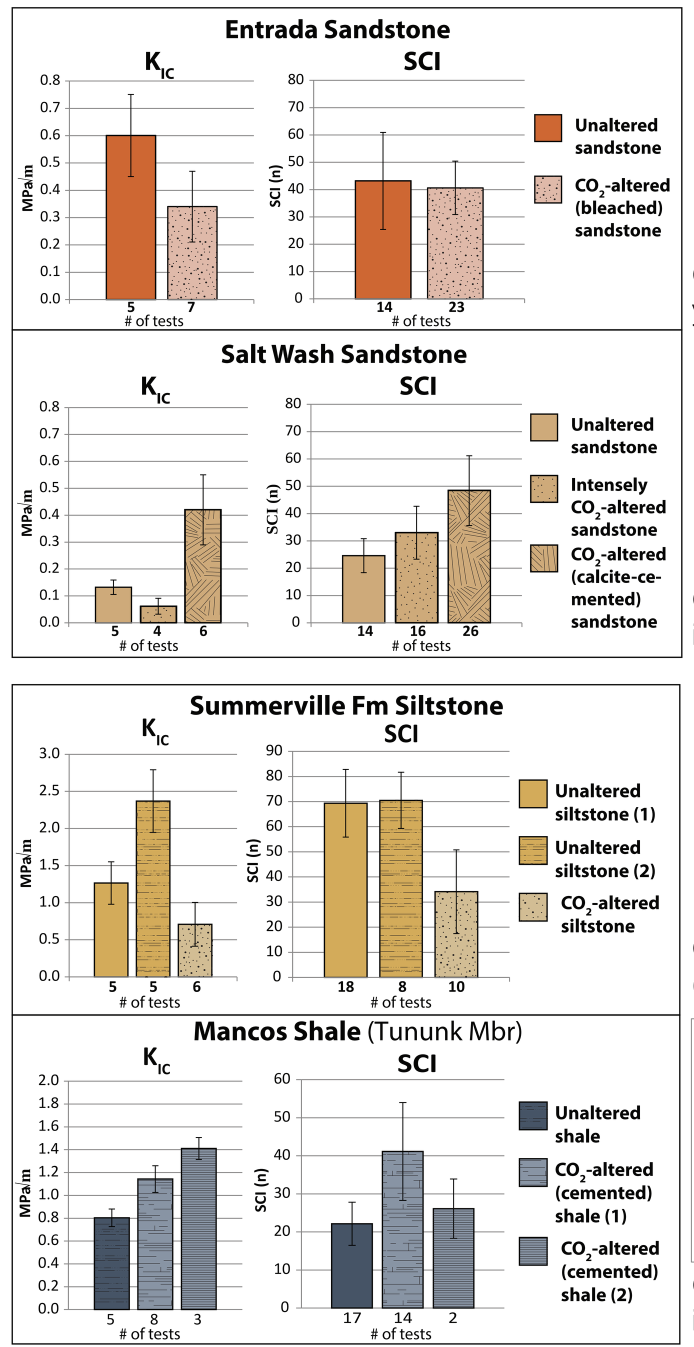
where

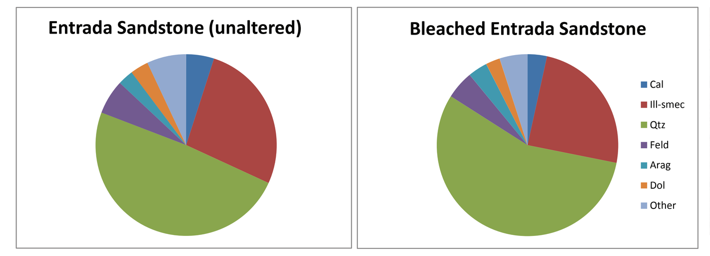
V : fracture propagation velocity
K_I : mode-I stress intensity factor,
K_{IC} : mode-I critical stress intensity factor (fracture toughness)
A : a pre-exponential constant
(Atkinson, 1984; Swanson 1984)



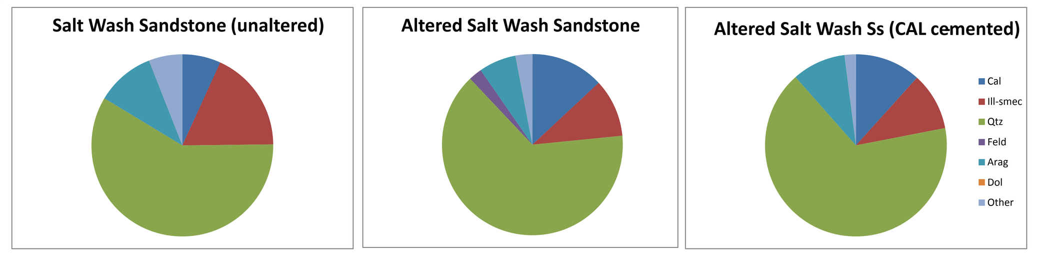
K_I^* = stress corrosion limit
K_{IC} = fracture toughness

Together, **these parameters have been shown to control the geometry of emerging fracture patterns, such as fracture lengths, spacing, and clustering, which in turn may effect connectivity and flow properties** (Olson, 1993 & 2004).

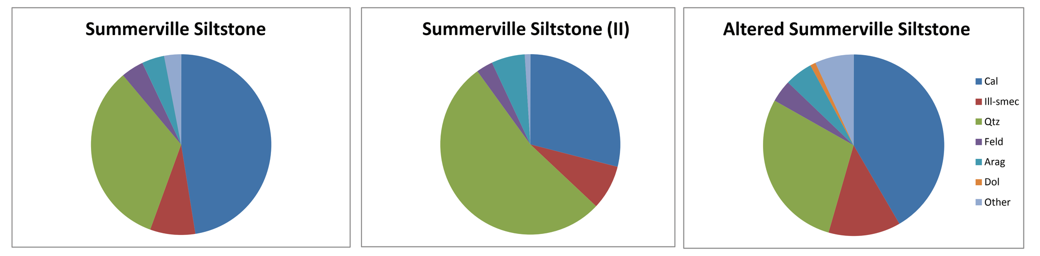




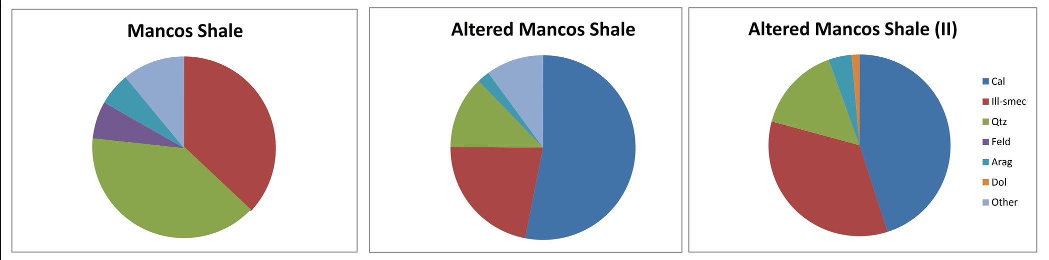
CO_2-related bleaching of Entrada sandstone slightly altered bulk mineralogy, yet it measurably impacts fracture toughness. Field shot on right.



CO_2-related alteration characterized by slight increases in calcite, which increases fracture toughness. The most intensely altered sample is weakest.



CO_2 alteration in siltstone characterized by increase in amount of clays (illite-smectite). This alteration also decreases fracture toughness.



CO_2-alteration characterized by large increases in calcite content, which helps increase fracture toughness.

III- MERCURY INTRUSION CAPILLARY PRESSURE ANALYSIS (MICP)

Effect of CO_2-alteration on seal capacity

The flow properties, and seal capacity of seal rocks such as shales may change due to CO_2-water-rock interactions. Coupled chemical-mechanical effects have implications for long term storage and injection scenarios. Decreases in seal capacity over time due to alteration may lead to leakage. Conversely, alteration that leads to precipitation of new minerals may increase seal capacity, enhancing storage security.

MICP analysis is a standard approach for measuring capillary entry pressure (Pe), permeability (k), grain density (ρ), and pore aperture size distributions of fine-grained rocks such as shale.

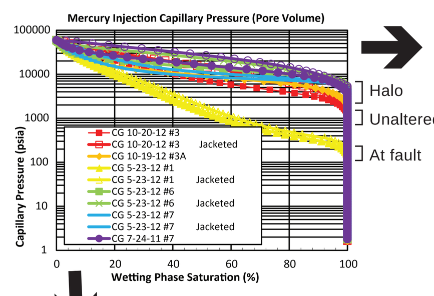
EQ: $P_e = (2\,\gamma \cos r)/\theta$

where Pe is capillary entry pressure (in Pa), γ is surface tension (in N/m), θ is wetting angle (in degrees), and r is average pore throat radius (in m)

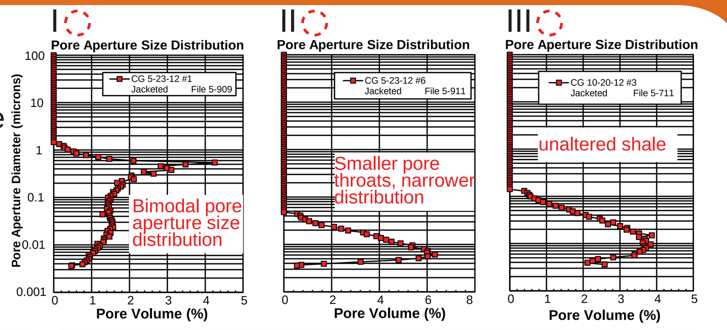
Samples were taken from a fault-perpendicular transect in the Mancos Shale and bulk composition measured using XRD.

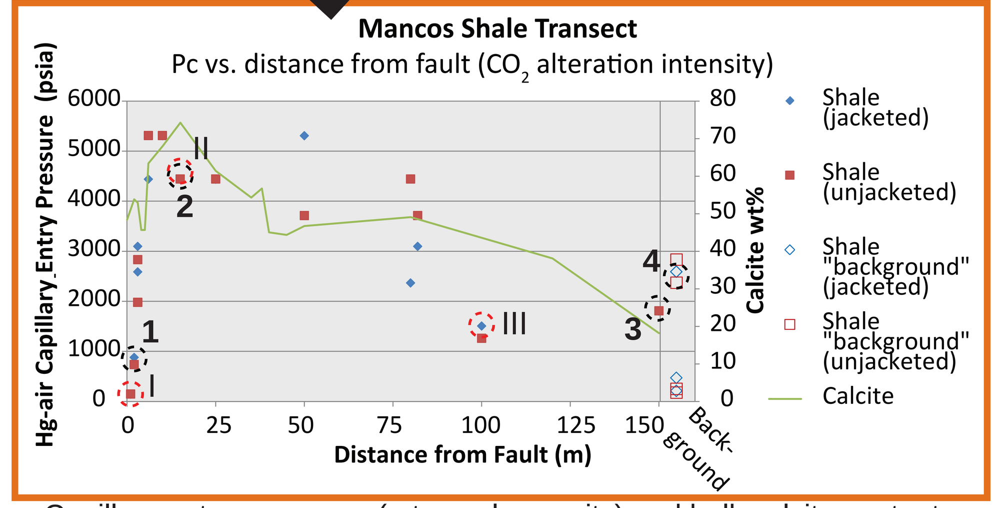
MICP Analysis Data

RIGHT: Capillary entry pressure (Pe) calculated at rollover point



RIGHT: Altered/unaltered shale ample pore aperture size distributions. See center plot for transect location.





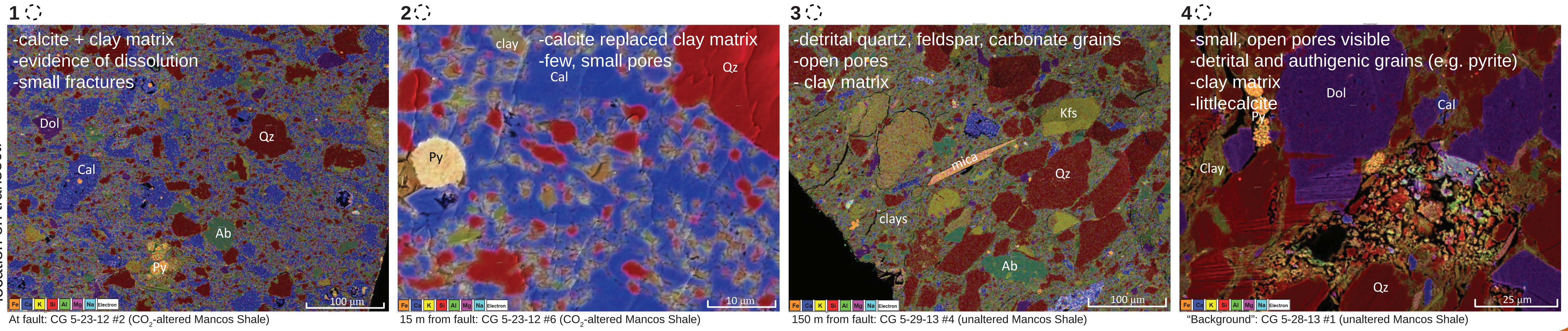
Capillary entry pressures (α to seal capacity) and bulk calcite content plotted against distance (alteration intensity)

Summary

Strong spatial trends in seal capacity correlate with bulk calcite content. Seal capacity is:

- lowest near the fault where alteration is presumably most intense
- highest 5-25 m from the fault where bulk calcite content is highest
- decreasing further away from the fault, following the bulk calcite trend

Seal capacity is reduced where alteration is most intense and higher where CO_2-alteration has driven precipitation of calcite. SEM images (BELOW) confirms that mineral dissolution and precipitation has altered pore networks in the shale, changing its flow properties.



SEM- EDS images of ion-milled shale samples. See center plot for location on transect.

1: At fault: CG 5-23-12 #2 (CO_2-altered Mancos Shale) — -calcite + clay matrix; -evidence of dissolution; -small fractures

2: 15 m from fault: CG 5-23-12 #6 (CO_2-altered Mancos Shale) — -calcite replaced clay matrix; -few, small pores

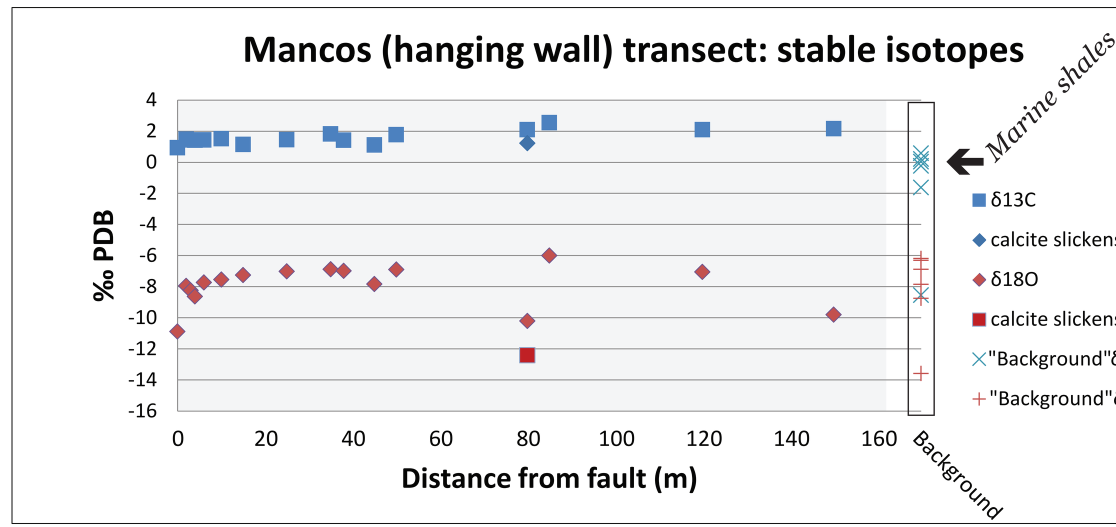
3: 150 m from fault: CG 5-29-13 #4 (unaltered Mancos Shale) — -detrital quartz, feldspar, carbonate grains; -open pores; - clay matrix

4: "Background": CG 5-28-13 #1 (unaltered Mancos Shale) — -small, open pores visible; -detrital and authigenic grains (e.g. pyrite); -clay matrix; -littlecalcite

IV- IDENTIFY AND MEASURE EXTENT OF ALTERATION

Stable isotope data

XRD data strongly suggests that the alteration at Crystal Geyser is related to interaction with CO_2-rich fluids, but weathering reactions can also effect rock mineralogy in similar ways. Stable isotope data can help confirm that the rocks at Crystal Geyser are effected by CO_2-water-rock interactions.



Stable isotope data of shale samples taken from a fault-perpendicular transect at the Crystal Geyser field site. Elevated δ13C values are indicative of CO_2-related alteration. Background samples plot near 0‰ (PDB), as expected for a marine shale. Scatter is greater in δ18O values, but shows similar trends. Light isotopes preferentially fractionate with degassing CO_2, and heavier isotopes tend to remain in calcite and other precipitated minerals.

V- CONCLUSIONS AND IMPLICATIONS

Impact of CO_2 -related alteration on reservoir & seal rocks:

- Geomechanical effects:
  - CO_2 alteration which is characterized by mineral dissolution and precipitation of secondary clays can weaken rocks to fracturing by up to 50% in sandstone
  - CO_2 alteration which is characterized by precipitation of carbonate cement can increases K_{IC} in shale samples by ~30-50%
- Permeability & seal capacity :
  - Intense alteration lowers seal capacity of shale by nearly half an order of magnitude through dissolution of grains and cement
  - Enhanced precipitation of carbonate cements in shale increases seal capacity by 3-5X
  - CO_2 alteration significantly impacts permeability in all lithologies

IMPLICATIONS

1. Subsurface CO_2 injection and storage involves inherently coupled chemical-mechanical processes
2. Diagenetic reactions affect fracture mechanics properties and matrix flow of reservoir and seal rocks
3. Comparable chemical reactions can also affect reservoir and seal rocks in EOR operations, wastewater and CO_2 injection because fluids are out of chemical equilibrium with the host formation

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