Long-term safety of geological CO_2 storage: Lessons from Bravo Dome Natural CO_2 reservoir

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THE UNIVERSITY OF TEXAS AT AUSTIN

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Outline

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1. Introduction
   - Motivation
   - Bravo Dome natural CO_2 field in New Mexico
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   - Reservoir compartmentalization
   - Origins of subhydrostatic pressures
4. Implications for geological CO_2 storage

Acknowledgements

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National Science Foundation - Hydrologic Sciences
Department of Energy - Basic Energy Sciences

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Center for Frontiers in Subsurface Energy Security

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Bravo Dome collaborators:
Kiran Sataye, Daria Ahkbari, Kimberly Lankford, Martin Cassidy, Toti Larson, Dani Stoeckli, Changli Yuan, Gary Pope, OXY Bravo Dome team

Papers:
Sathaye, Hesse, Cassidy & Stockli (2014) *PNAS*
Sathaye, Larson, & Hesse (201X) *EPSL* Ahkbari & Hesse (201X) *in prep*

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Trapping contribution and time-scales

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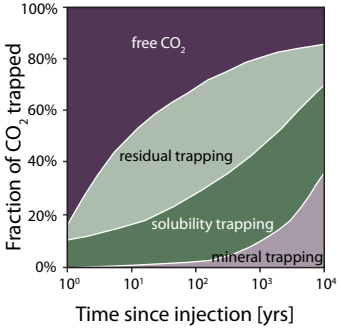
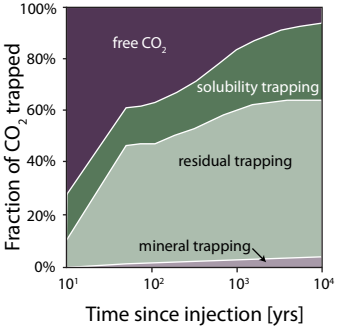
IPCC special report



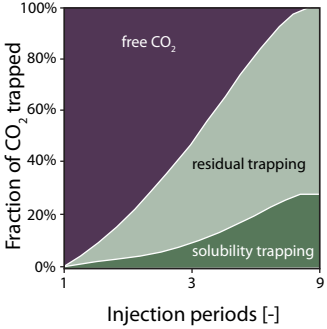
Benson et al. (2005)
IPCC Special Report

Reservoir simulation



Kumar et al. (2005)
SPE Journal, **10**(3)

Theoretical analysis



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J. Fluid Mech., **688**

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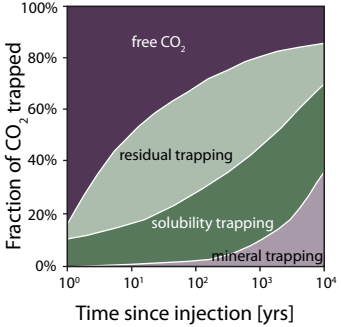

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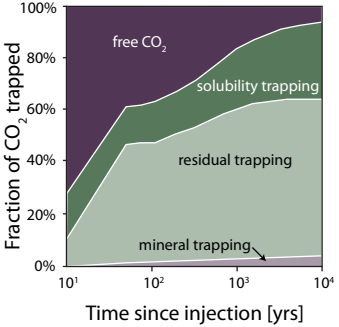

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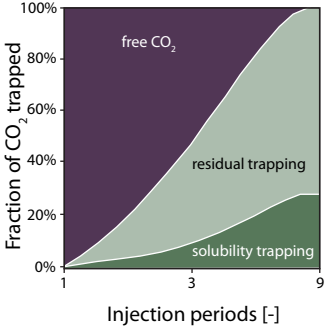

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Constrain trapping rates at Bravo Dome using field observations!

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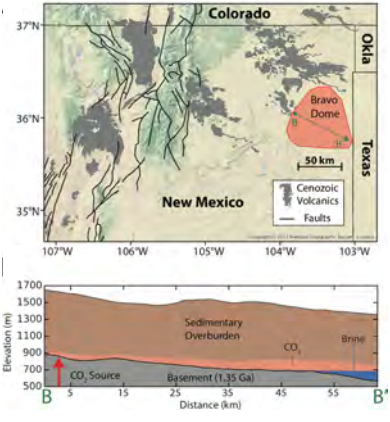
Bravo Dome natural gas field, New Mexico

Introduction Bravo Dome, NM

The numbers:

- Area: 3600 km^2



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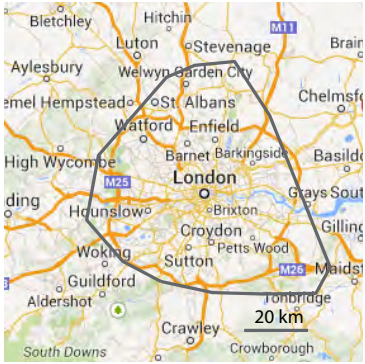

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Introduction Bravo Dome, NM

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The numbers:

- Area: 3600 km^2
- Gas-water contact: 1700 km^2
- Reserves: 22 tcf (10 tcf)
  Largest CO_2 field.
  Top 20 natural gas fields.

№	Field name	Country	Recoverable reserves[1]	
1	South Pars/North Dome	Iran and Qatar	$1,235 \times 10^{12}$ cu ft	35,000 km^3
2	Urengoy	Russia	222×10^{12} cu ft	6,300 km^3
3	Yamburg	Russia	138×10^{12} cu ft	3,900 km^3
4	Hassi R'Mel	Algeria	123×10^{12} cu ft	3,500 km^3
5	Shtokman	Russia	110×10^{12} cu ft	3,100 km^3
6	South Iolotan–Osman	Turkmenistan	98×10^{12} cu ft	2,800 km^3
7	Zapolyarnoye	Russia	95×10^{12} cu ft	2,700 km^3
8	Hugoton	USA (TX-OK-KS)	81×10^{12} cu ft	2,300 km^3
9	Groningen	Netherlands	73×10^{12} cu ft	2,100 km^3
10	Bovanenko	Russia	70×10^{12} cu ft	2,000 km^3
11	Medvezhye	Russia	68×10^{12} cu ft	1,900 km^3
12	North Pars	Iran	48×10^{12} cu ft	1,400 km^3
13	Dauletabad-Donmez	Turkmenistan	99×10^{12} cu ft	2,800 km^3
14	Karachaganak	Kazakhstan	46×10^{12} cu ft	1,300 km^3
15	Kish	Iran	45×10^{12} cu ft	1,300 km^3
16	Orenburg	Russia	45×10^{12} cu ft	1,300 km^3
17	Kharsavey	Russia	42×10^{12} cu ft	1,200 km^3
18	Shah Deniz	Azerbaijan	42×10^{12} cu ft	1,200 km^3
19	Golshan	Iran	30×10^{12} cu ft	850 km^3
20	Tabnak	Iran	22×10^{12} cu ft	620 km^3
21	Kangan	Iran	20×10^{12} cu ft	570 km^3

Introduction Bravo Dome, NM

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  Top 20 natural gas fields.
- Essentially pure CO_2

Component	Chemical mol. %
Carbon Monoxide	nd
Helium	nd
Hydrogen	nd
Argon	nd
Oxygen	nd
Nitrogen	0.13
Carbon Dioxide	99.87
Methane	0.0020
Ethane	0.0003

Introduction Bravo Dome, NM

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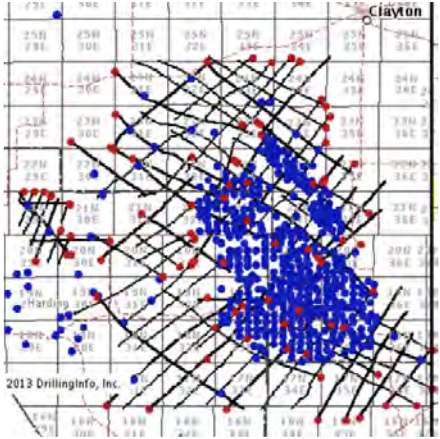
  Largest CO_2 field.
  Top 20 natural gas fields.
- Essentially pure CO_2
- Origin: volcanic gas
  (very high $^3He/^4He$)

Data available at Bravo Dome, NM

- 788 wells
  150 wells with digitized logs
- 42 cored wells
- 10 wells with stratigraphic logs
- 18 wells with noble gas/isotope data
- 3645 permeability and porosity measurements
- 21 drainage capillary pressure curves
- 40 2D seismic lines



Best data set to constrain the magnitude and rate of solubility trapping.

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Estimating dissolution from gas composition

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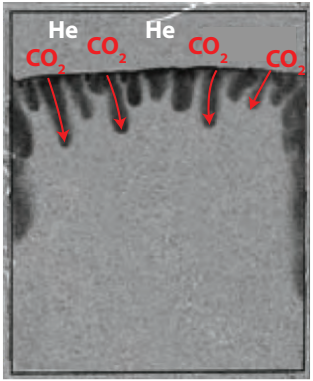
Convective dissolution of CO_2



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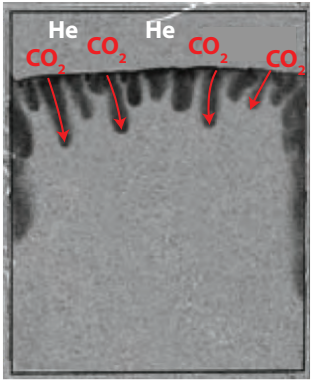
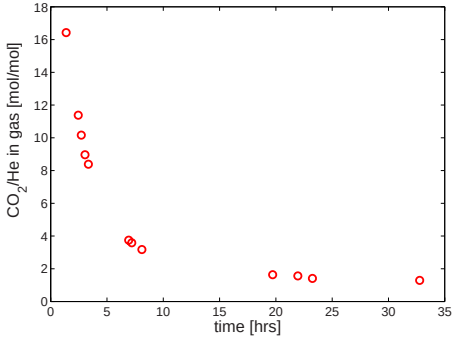
Convective dissolution of CO_2



$CO_2/^3$He-ratio in the gas



Fraction dissolved: $\mathcal{F} = 1 - \frac{[CO_2/He]_{final}}{[CO_2/He]_{initial}} \approx 1 - \frac{2}{16} \approx 0.9$

Mapping geochemistry into the reservoir

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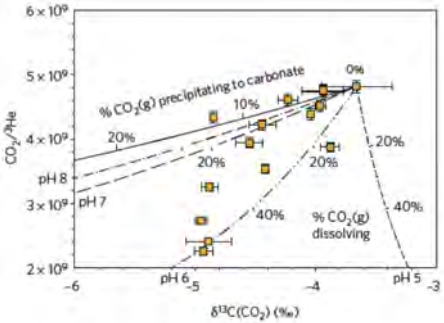
Gas geochemistry:



Gilfillan et al. (2009) *Nature*, **458**
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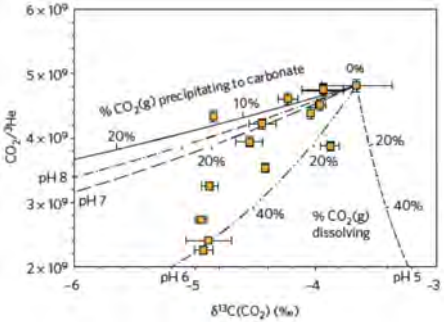

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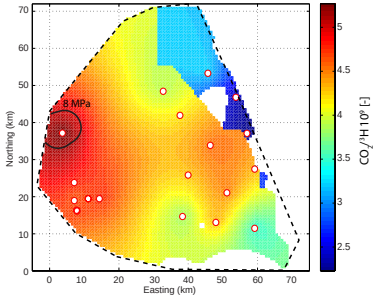
Compositional variation in the reservoir



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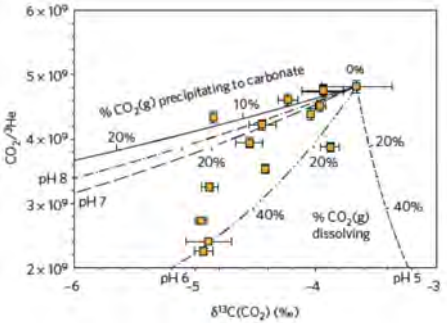

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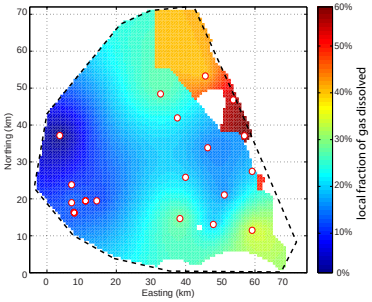

Gas mass per area: $m = \bar{\phi}\bar{S}\rho(\bar{p})h$

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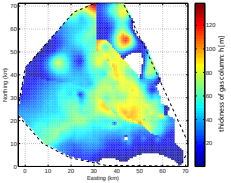
Thickness



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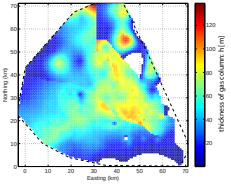
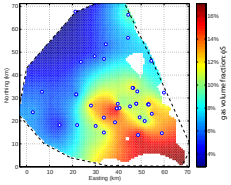


Volume fraction



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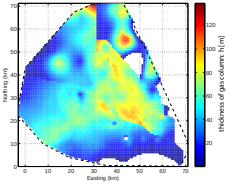

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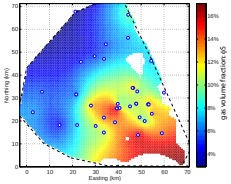
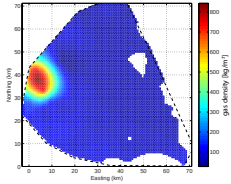


Density



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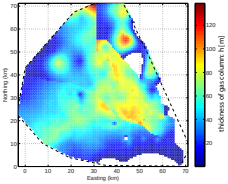

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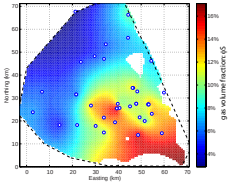
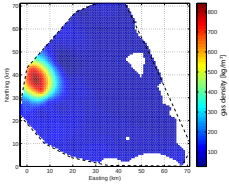
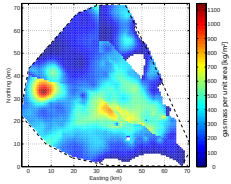


Density



Mass



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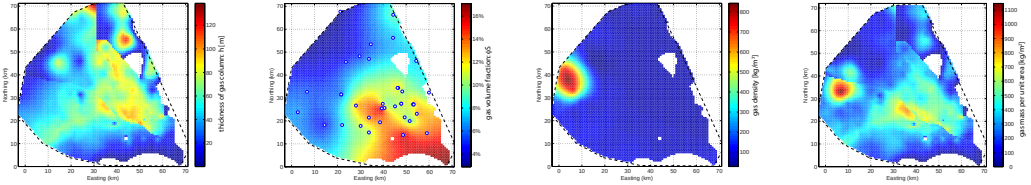
Thickness | Volume fraction | Density | Mass



Large spatial variations that need to be accounted for in mass balance.

Estimate of the local change in mass: Δm

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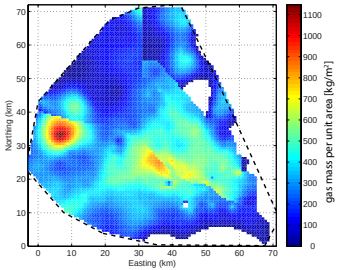
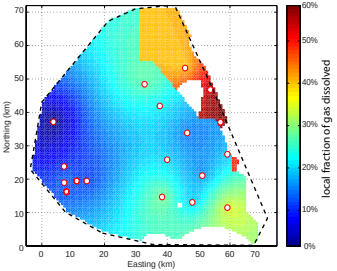
$$\Delta M = \iint \Delta m \, \mathrm{d}x\mathrm{d}y \approx \iint (1/\mathcal{F} - 1)\, m_f \, \mathrm{d}x\mathrm{d}y.$$

Mass/area: m_f



Fraction dissolved: $\mathcal{F}$



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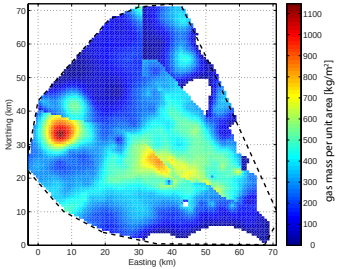

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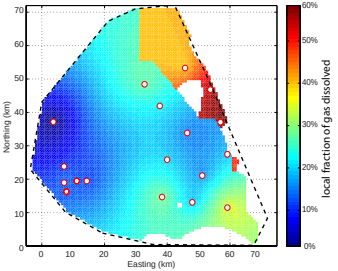
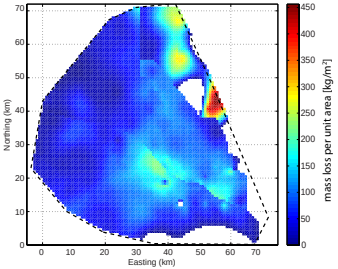


Change in mass, Δm



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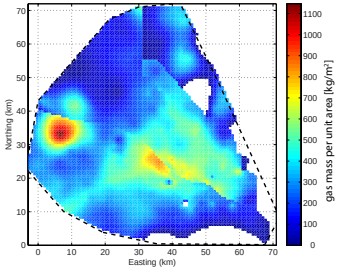
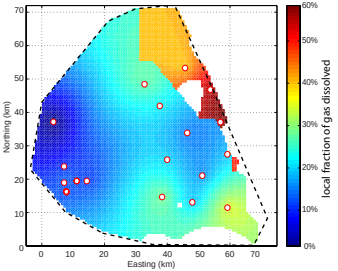
$$\Delta M = \iint \Delta m \, \mathrm{d}x\mathrm{d}y \approx \iint (1/\mathcal{F} - 1)\, m_f \, \mathrm{d}x\mathrm{d}y.$$

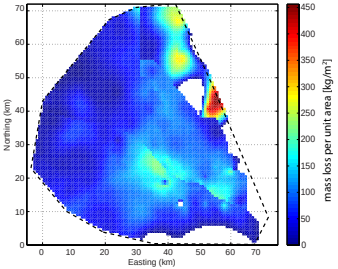
Mass/area: m_f



Fraction dissolved: $\mathcal{F}$



Change in mass, Δm



As expected, m_f is low where $\mathcal{F}$ is high $\rightarrow$ global fraction dissolved is less!

Magnitude of CO_2 dissolution at Bravo Dome

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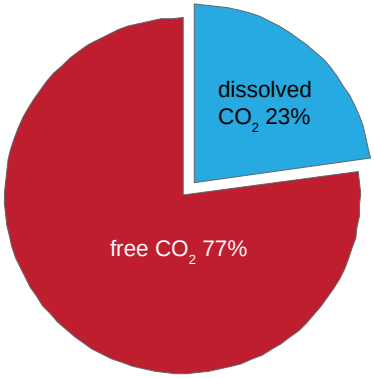
1. Mass of gas dissolved at Bravo Dome: $\mathbf{\Delta M = 366 \pm 122\ MtCO_2}$.
   Equivalent to 65 years of emissions from US coal power plant.
2. Total mass of CO_2 emplaced at Bravo Dome is $\mathbf{M_t = 1.6 \pm 0.7 GtCO_2}$.
   Equivalent to annual global volcanic CO_2 emissions.
3. At Bravo Dome only **22%±7%** of the emplaced CO_2 have dissolved.
   Much less than the maximum local dissolution in NE.



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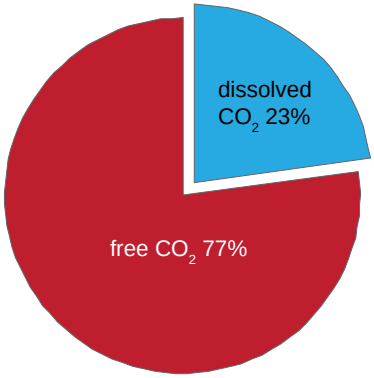

Uncertainty is mainly due to variations in height of gas column!

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Stratigraphic architecture of reservoir

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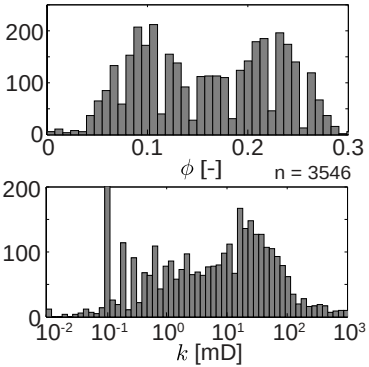
Porosity and permeability



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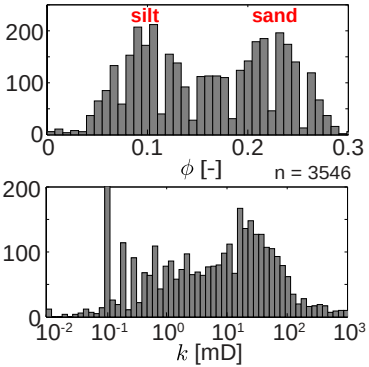

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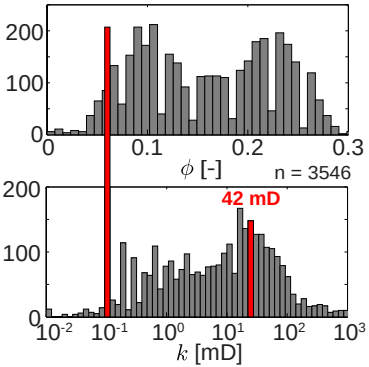

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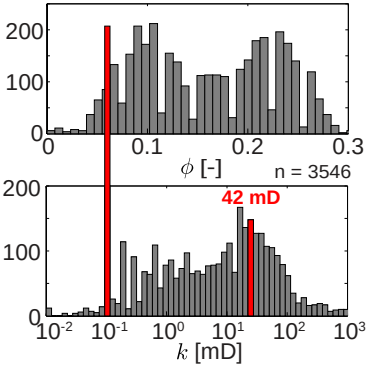
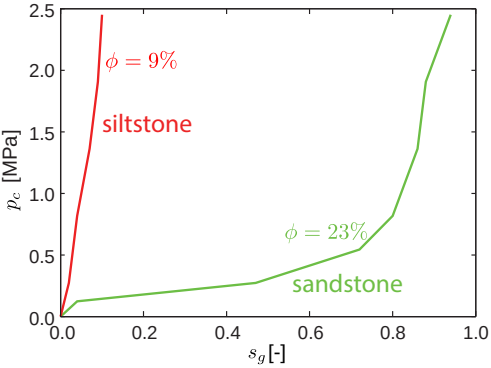


Capillary entry pressure



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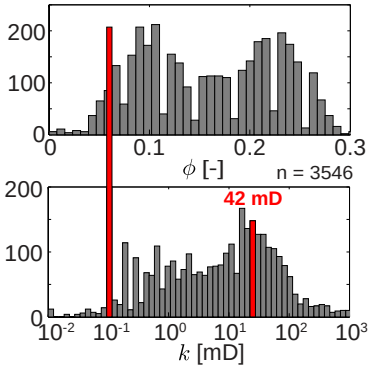

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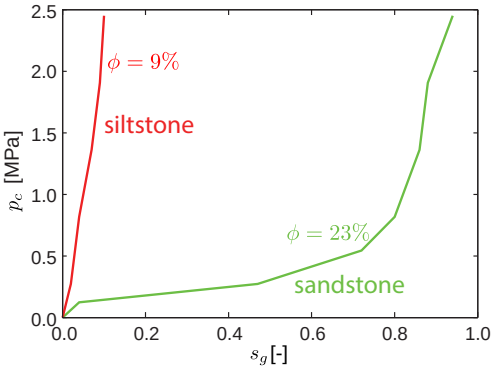
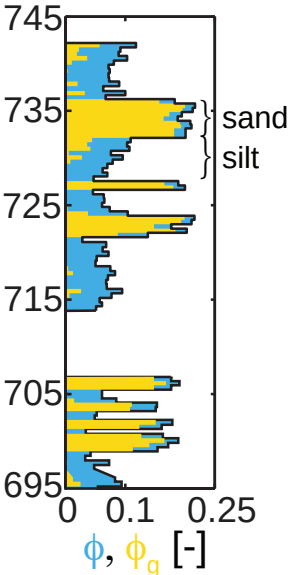
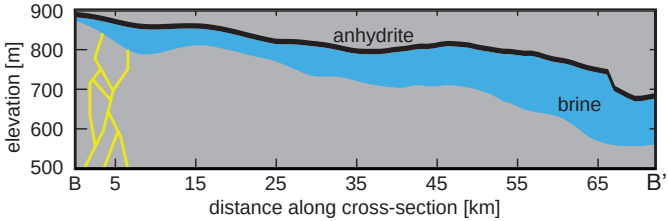


High capillary entry pressure prevents CO_2 entry into the siltstone.

Dissolution into residual brine during emplacement





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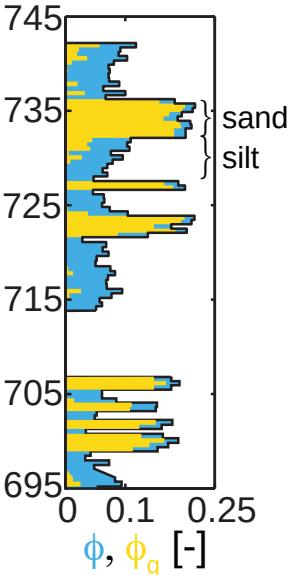

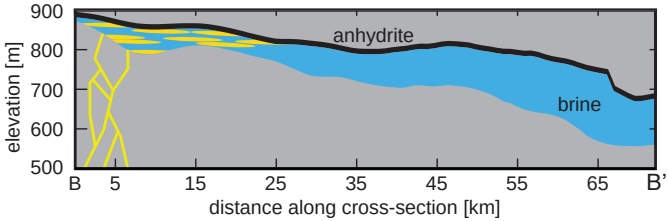

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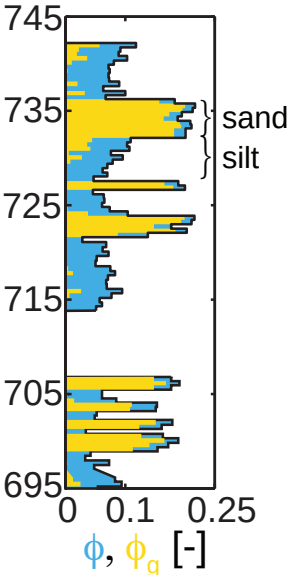

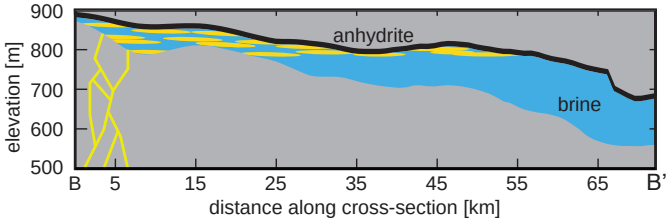

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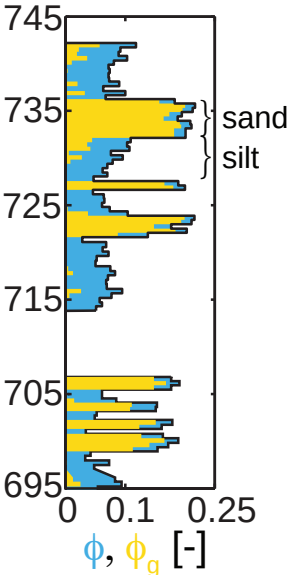

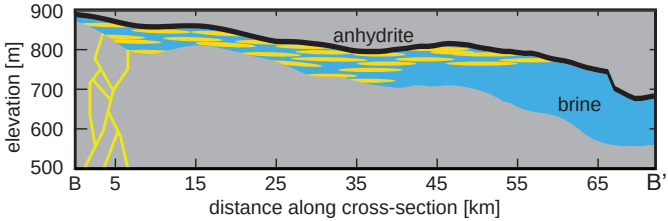

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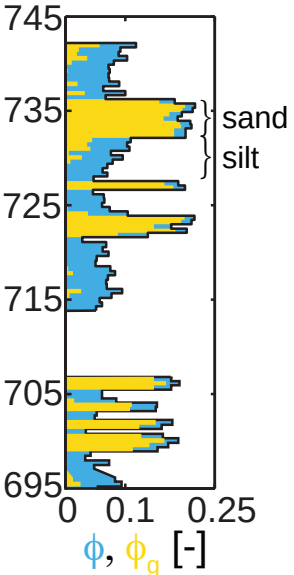

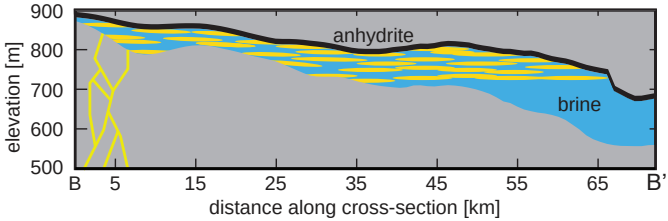

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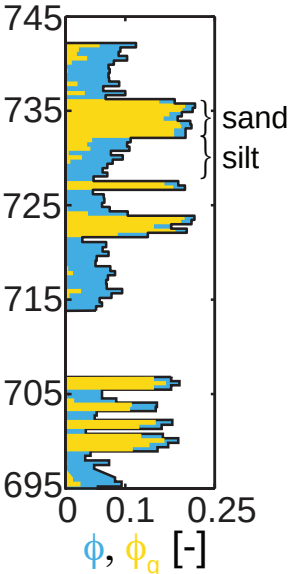

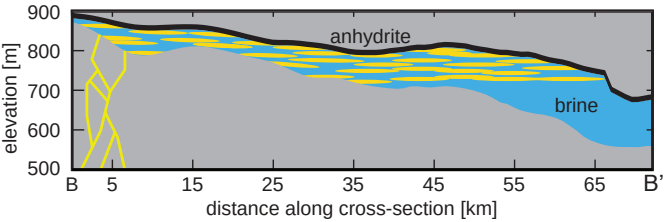

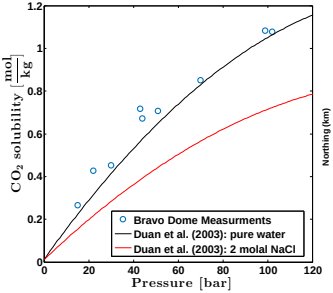

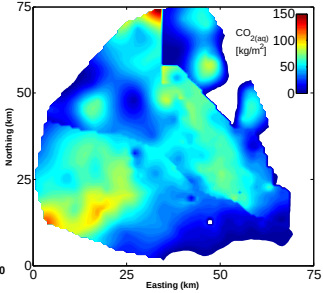

How much dissolved during emplacement

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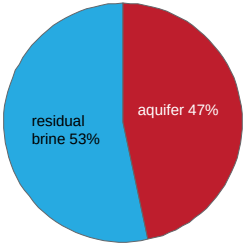
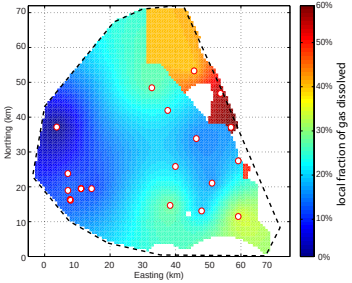
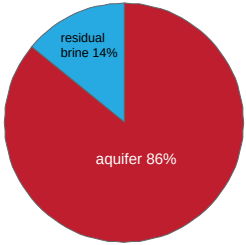
Main reservoir segment



Map of Bravo Dome:



NE reservoir segment:



1. Significant amounts dissolved into 'residual brine' during emplacement. *Highlights positive effect of heterogeneity on dissolution!*
2. Significant amounts dissolved into underlying aquifer after emplacement. *Provides field evidence for enhanced dissolution due to brine flow.*

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CO_2 emplacement and regional volcanism

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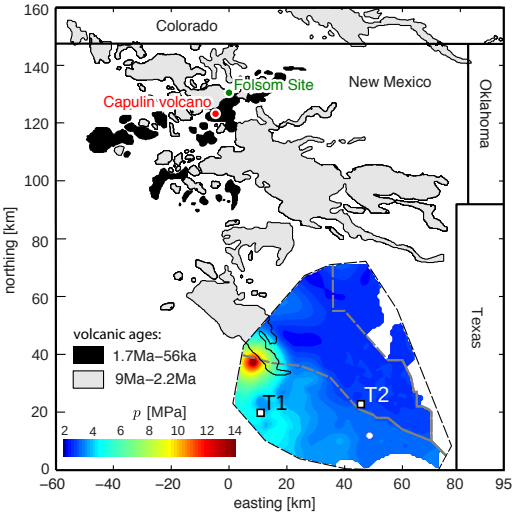
Distribution of regional volcanism



Stroud (1996) M.S. Thesis, NM Tech

Age of regional volcanism

Assumed age of Bravo Dome is 10ka.

Three major volcanic phases:

1. Raton phase: 9.0 - 3.5 Ma
2. Clayton phase: 3.0 -2.25 Ma
3. Capulin phase: 1.7 - 0.04 Ma

Independent estimate of CO_2 age!

Dating CO_2 emplacment with thermochronology

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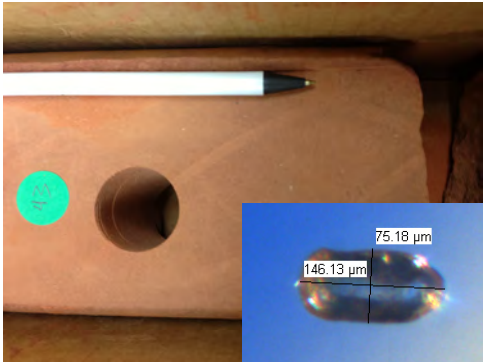
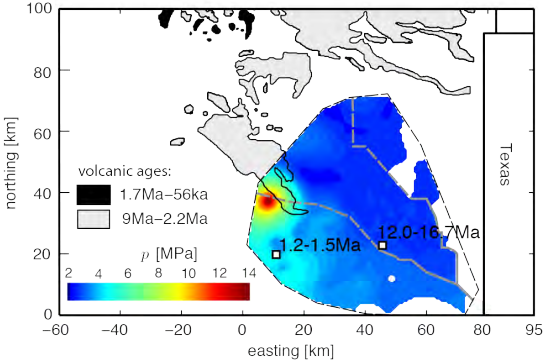
Core sample with Apatite crystal





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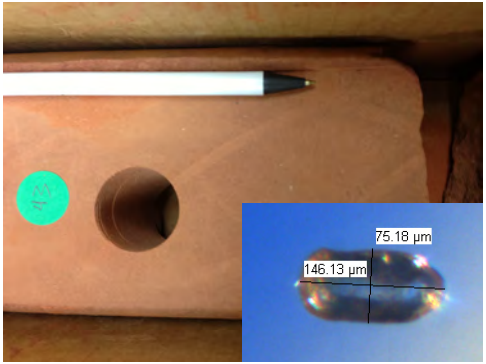
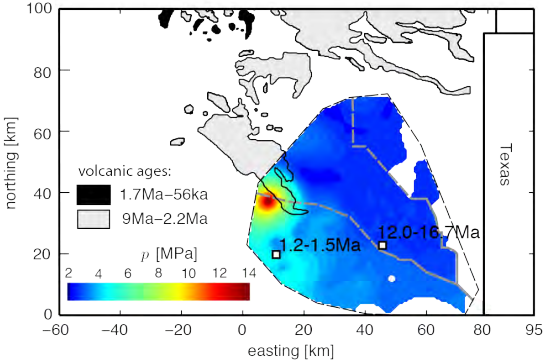


(U-Th)/He thermochronology



Apatite accumulates He from radioactive decay below $T = 75°\text{C}$.
Current reservoir conditions $T = 35°\text{C} \rightarrow$ heating by $\Delta T \approx 40°\text{C}$

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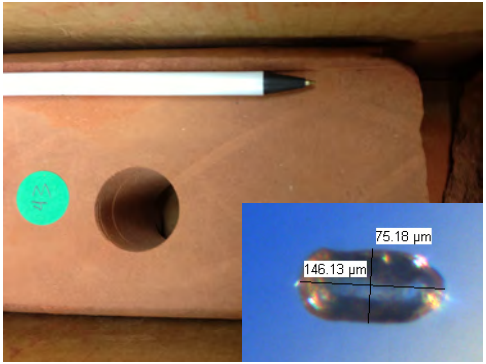

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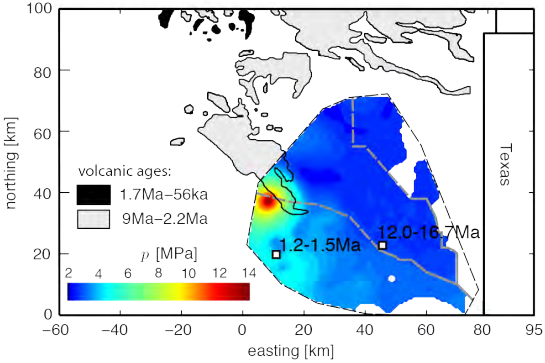

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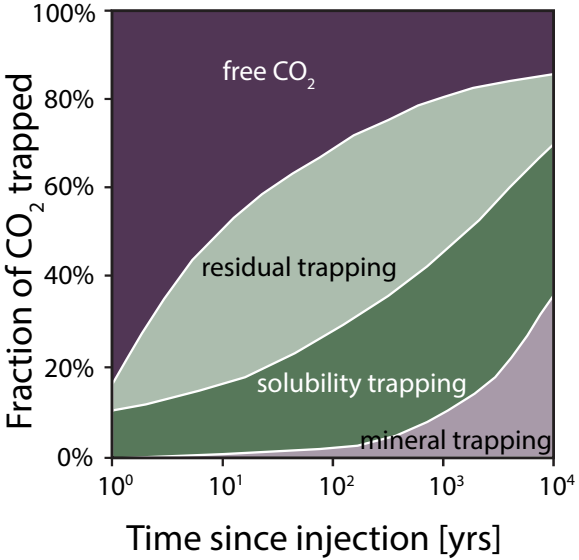
Hot volcanic CO_2 entered Bravo Dome 1.2-1.5 Ma ago.

Estimate IPCC–diagram for Bravo Dome



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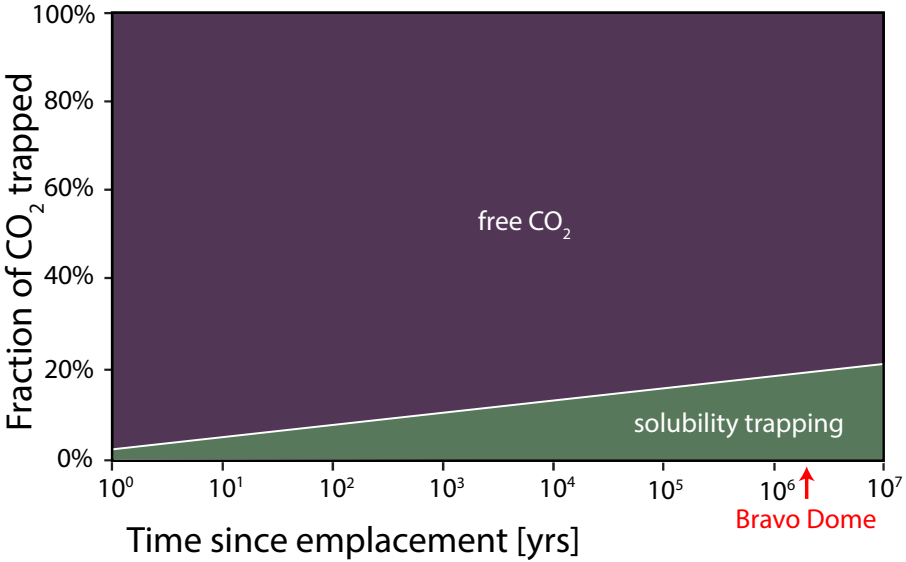

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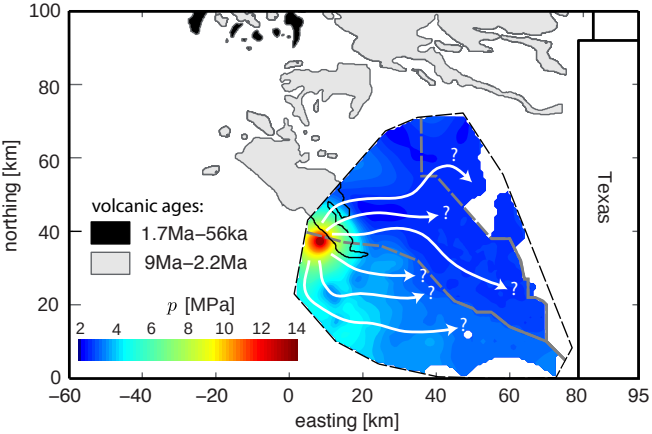
Pressures gradients at Bravo Dome



- Is the reservoir still filling?
- If not, why didn't the pressure gradient relax?

Sub-hydrostatic gas pressures at Bravo Dome

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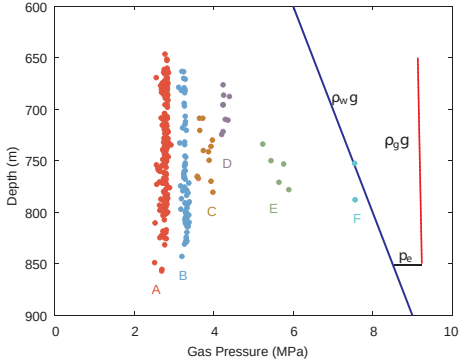
Bravo Dome gas pressure



Sub-hydrostatic gas pressures at Bravo Dome

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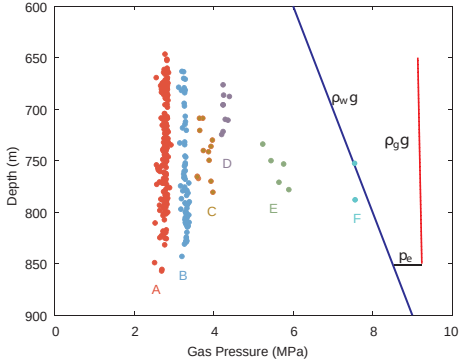
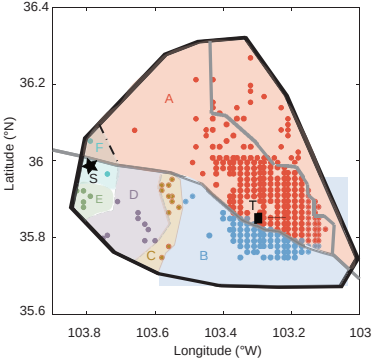
Bravo Dome gas pressure



Pressure compartments



Stratigraphic controls on compartmentalization

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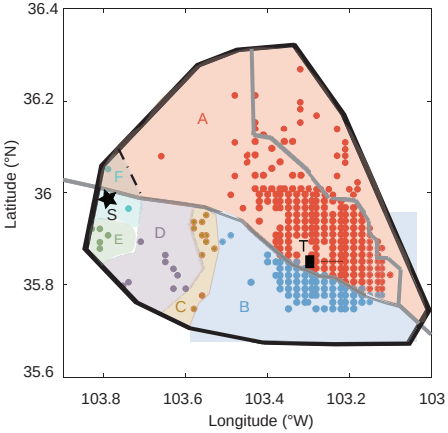
Pressure compartments



Stratigraphic controls on compartmentalization

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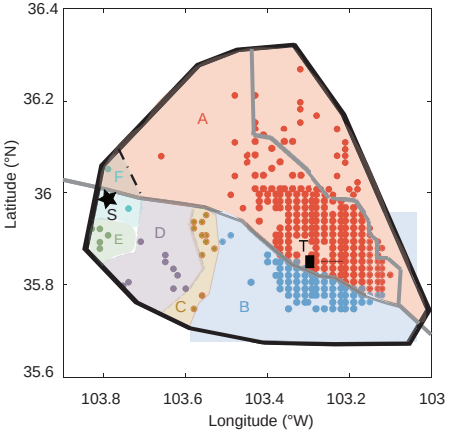
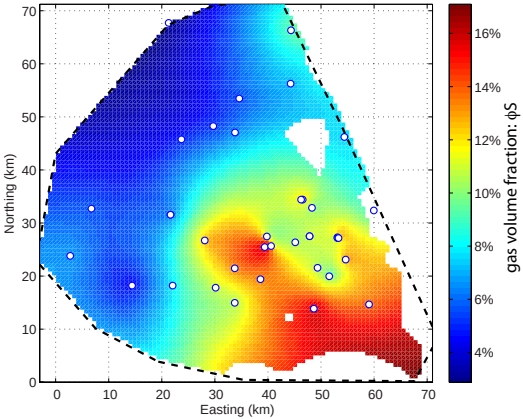
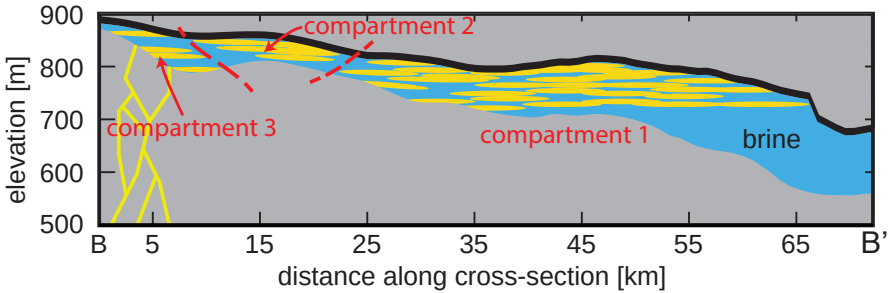
Pressure compartments



Gas volume fraction šand fraction



Stratigraphic controls on compartmentalization



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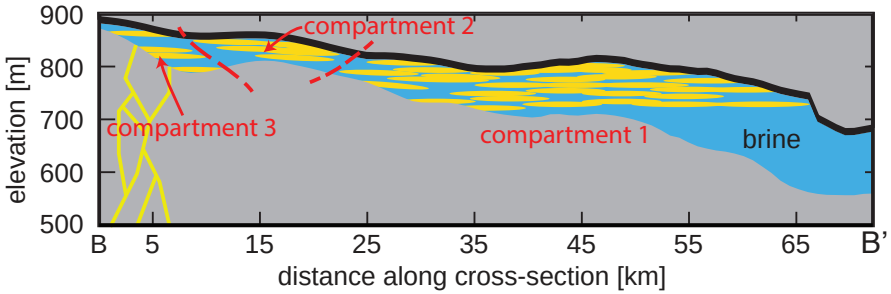

CO_2 is stored in a number of closed compartments?

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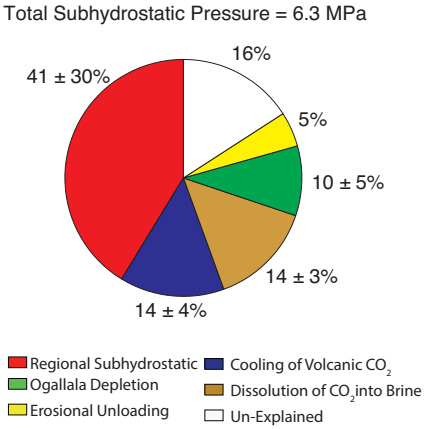
Sub-hydrostatic gas pressures at Bravo Dome



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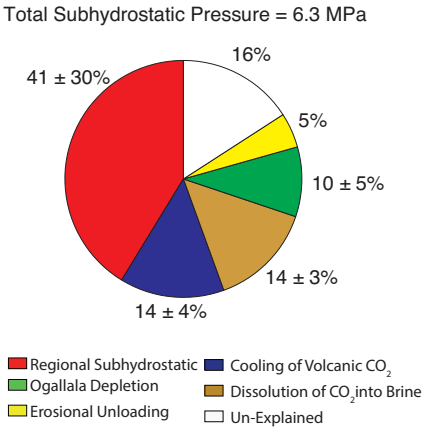
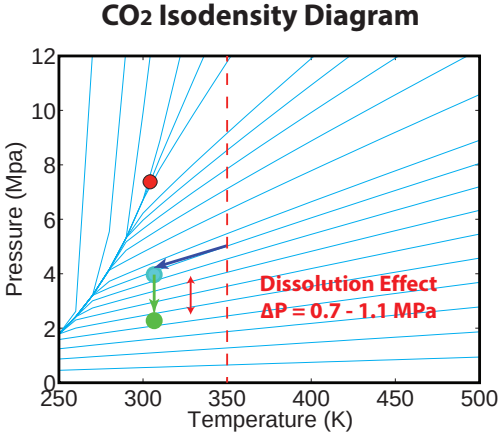
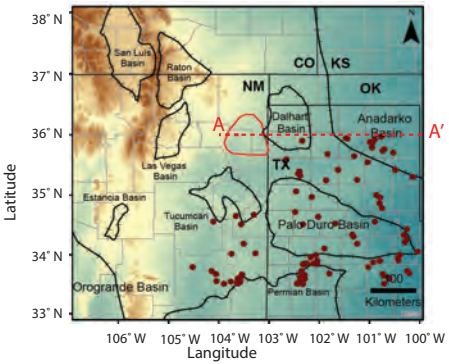




Regional underpressure



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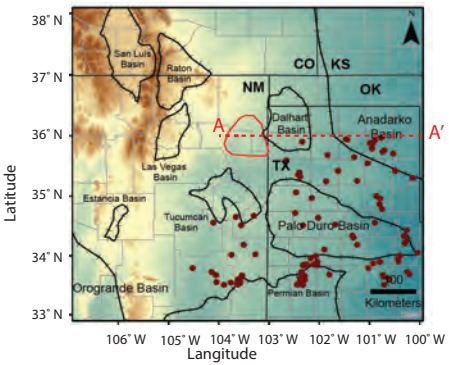
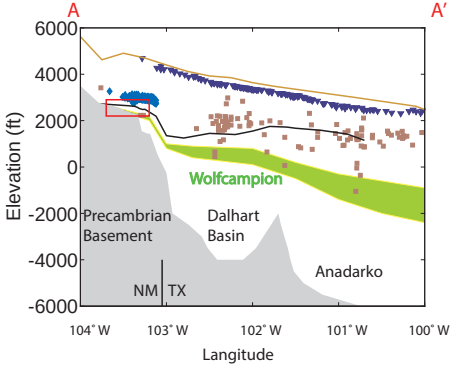
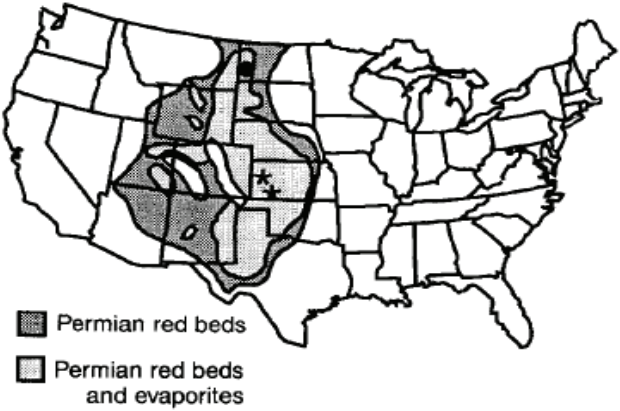




Underpressure due to regional evaporite



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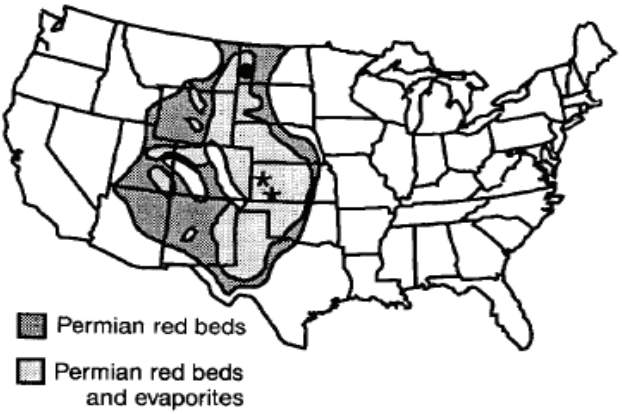
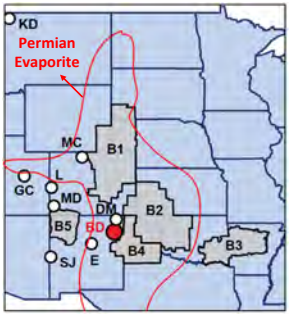
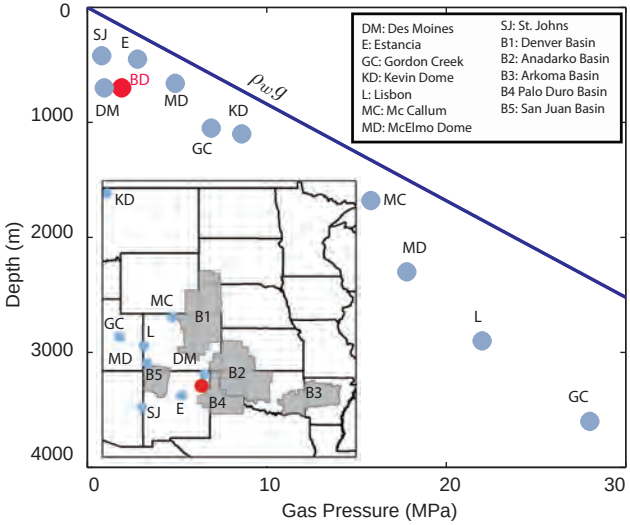




Underpressure is normal in natural CO_2 reservoirs



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Summary and conclusion

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Pressures at Bravo Dome

1. Pressure is significantly below hydrostatic (common).
2. CO_2 dissolution can reduce pressure in compartmentalized reservoir.
3. Permian evaporites are associated with large regional underpressure.

Implications for CO_2 storage

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Trapping and safety

1. Structural trapping contained large volume over millenial timescales.
2. Dissolution trapping is slower then expected.
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Thank you for your attention.