Geologic carbon sequestration:

a primer based on Wyoming's state sequestration initiative

Carol Frost

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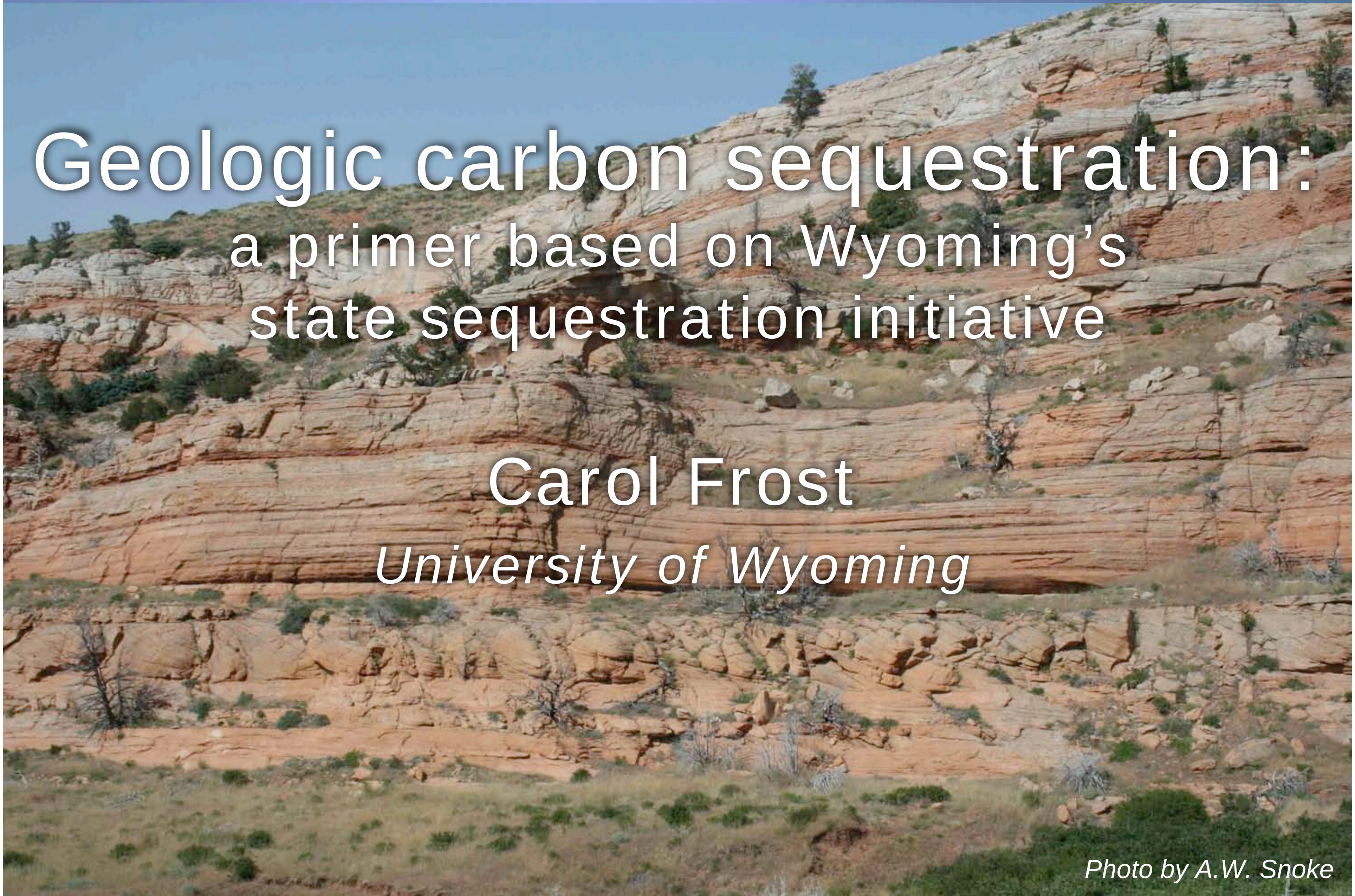
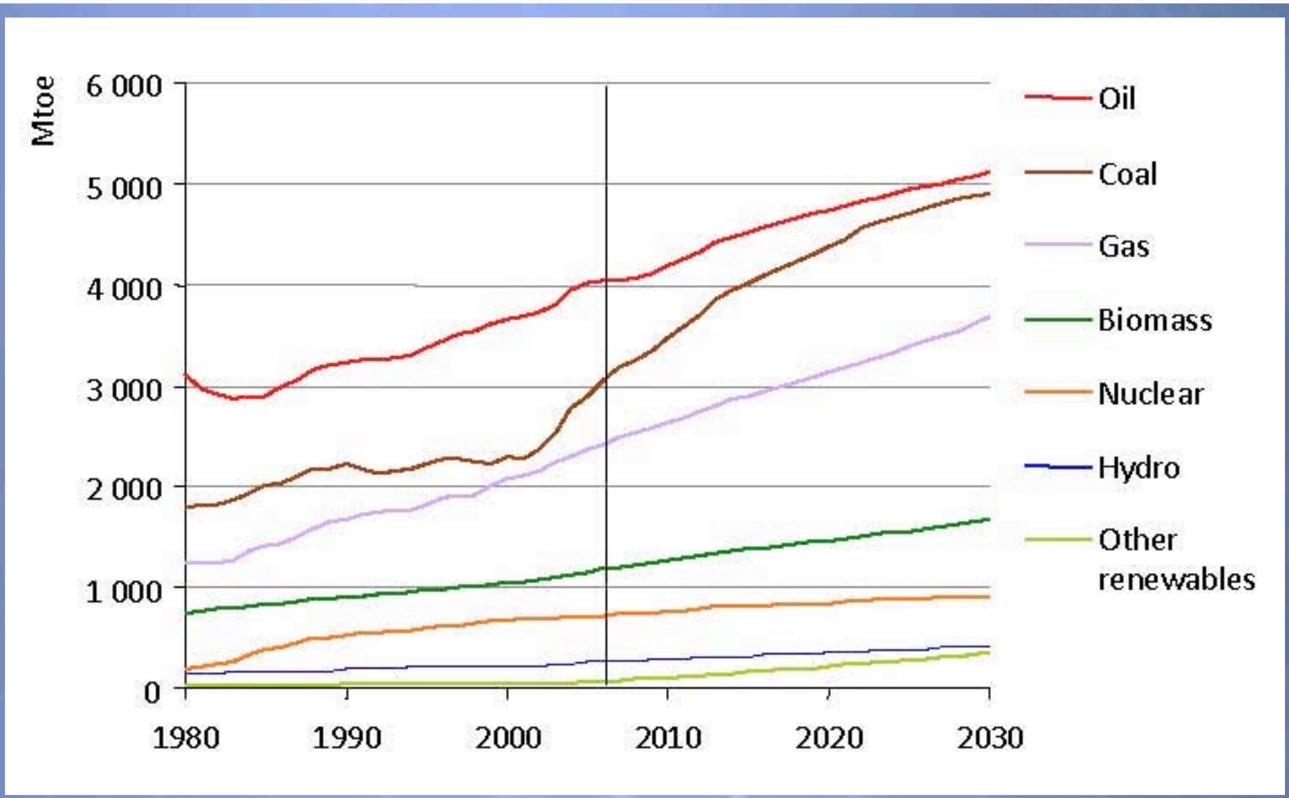


Photo by A.W. Snoke

The Global Energy Landscape



IEA World Energy Outlook 2008

- World energy demand will increase by 45% between now and 2030
- Coal accounts for a third of the overall rise

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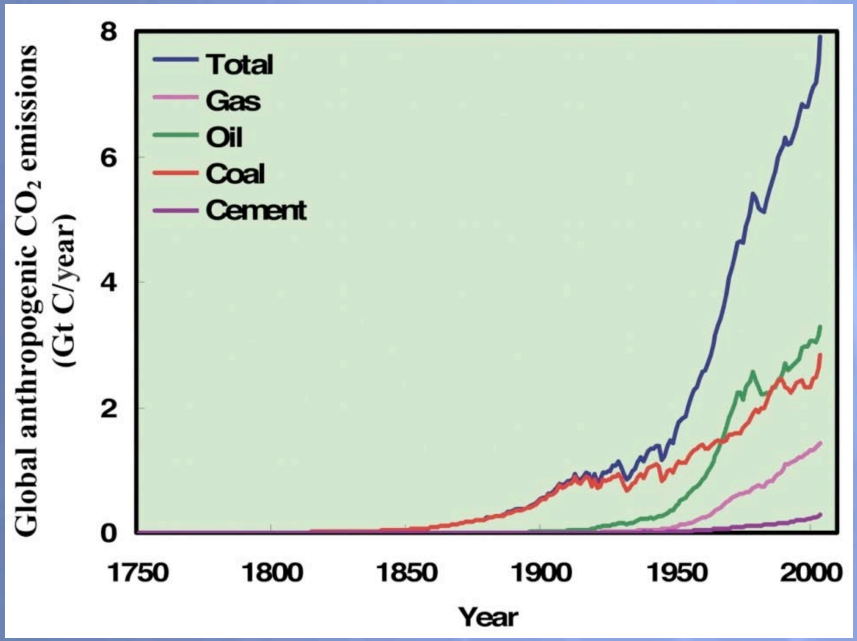
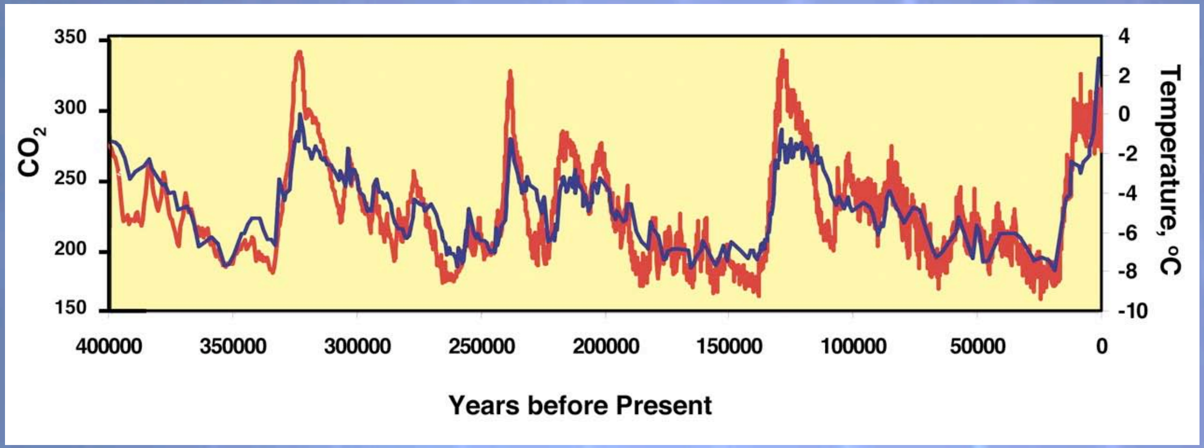
Energy and Climate



- Anthropogenic CO_2 emissions have raised atm. CO_2 levels to 385 ppm
- Atm. CO_2 correlates with global T



Oelkers & Cole 2008

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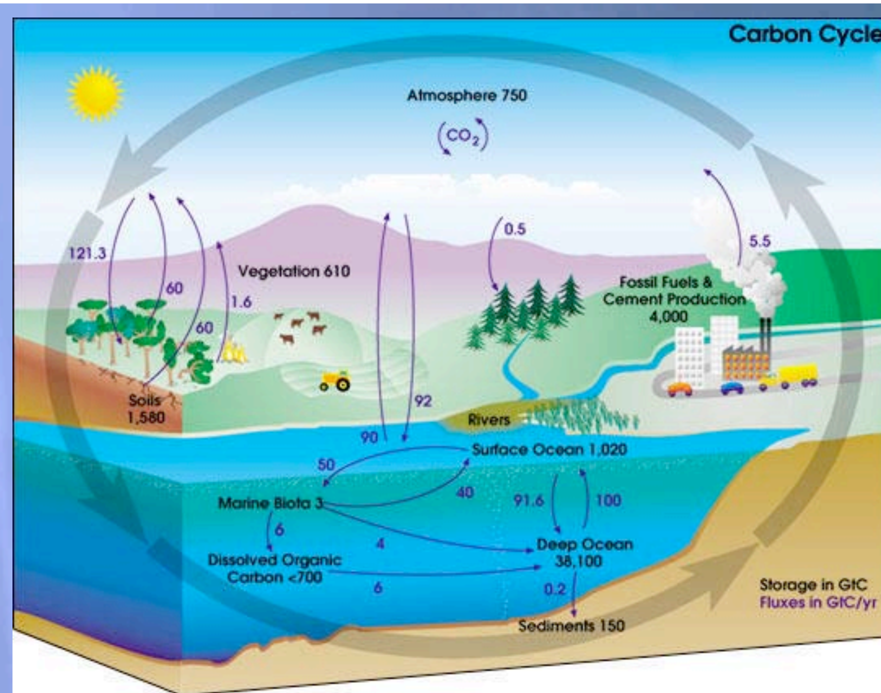
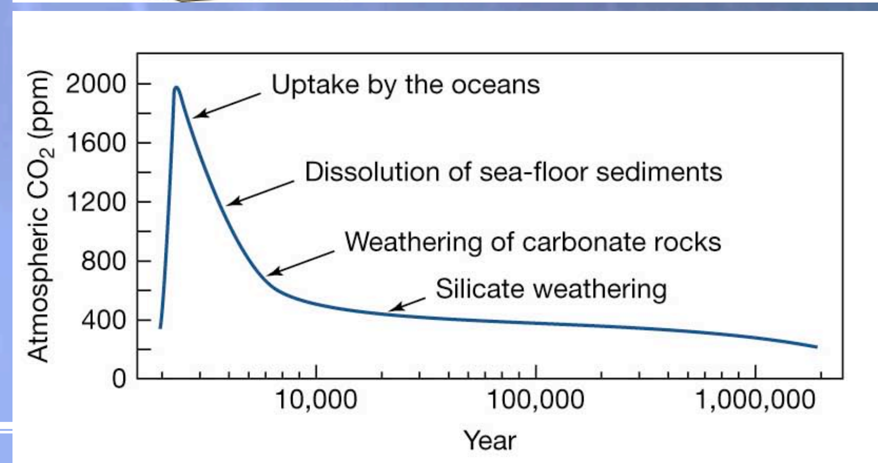
Climate regulation

NASA



- ✦ CO_2 is taken up in surface and deep ocean, in sediment, by weathering of rocks
- ✦ Rate of CO_2 rise is unprecedented
- ✦ Uncertain climate response



Kump et al. 2004

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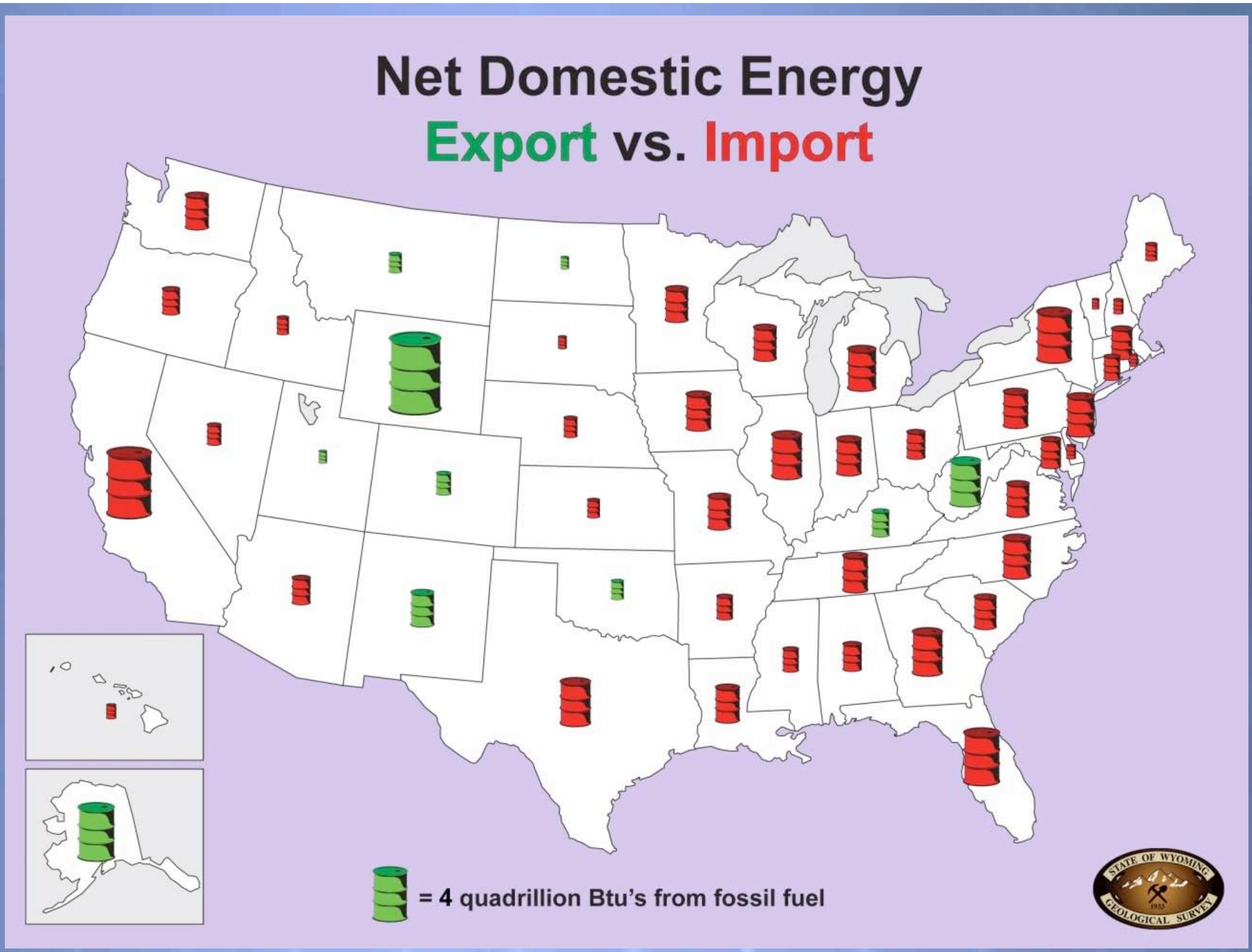
U.S. and Wyoming's Energy Landscape



Wyoming State Geological Survey

Our carbon footprint

- Individual CO_2 emissions: autos

  - $CH_2 + 1.5\ O_2 = CO_2 + H_2O$
  - CH_2: 14 g/mol CO_2: 44 g/mol
  - 1 kg gasoline produces 3.1 kg CO_2
  - 0.73 kg/l gas x 100 l (25 gal) tank = 73 kg gas per tank ---> 226 kg CO_2 per tank
  - 24 fill-ups per year = 5.4 metric tons CO_2
- U.S. *per capita* CO_2 emissions= 20.6 tons CO_2/yr

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Wyoming's carbon footprint

- Per capita CO_2 emissions:
  - U.S. 20.6 tons CO_2/yr
  - Wyoming 127 tons CO_2/yr
- Wyoming emissions per capita are #1 in U.S.

Wyoming's coal-fired power plants produce more carbon dioxide in just eight hours than the power generators of more populous Vermont do in a year.

Seth Borenstein, Associated Press, 2007

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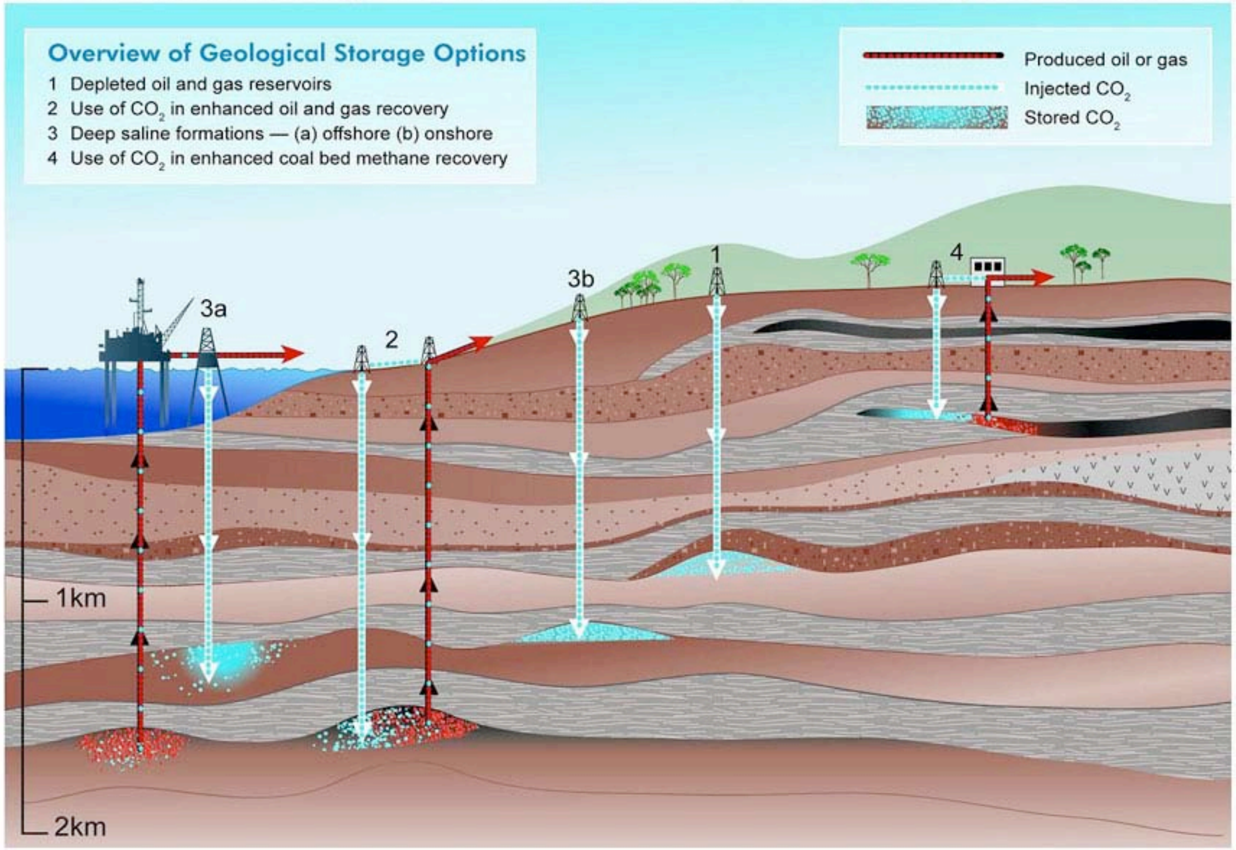
U.S. and Wyoming's energy and climate challenge

- Climate legislation is upon us
  - 9/29/06 California SB 1368 standard for power: not to exceed CO_2 emissions of gas power plants
  - 2/17/09 EPA reconsidering regulating CO_2 from coal-fired power plants
  - FY2010 budget includes carbon cap-and-trade
  - President's Energy Goals: reduce CO_2 emissions by 80% by 2050
  - UN Climate Summit Copenhagen, Dec 2009

- Coal is under special scrutiny
  - Gas 117 lb CO_2/million Btu energy
  - Coal 208 lb CO_2/million Btu energy 78% more than gas

Carbon capture & storage (CCS): Geologic carbon sequestration

Methods for storing CO2 in deep underground geological formations



IPCC (2005)

Minimum injection depth of 800 m to ensure CO_2 in supercritical state

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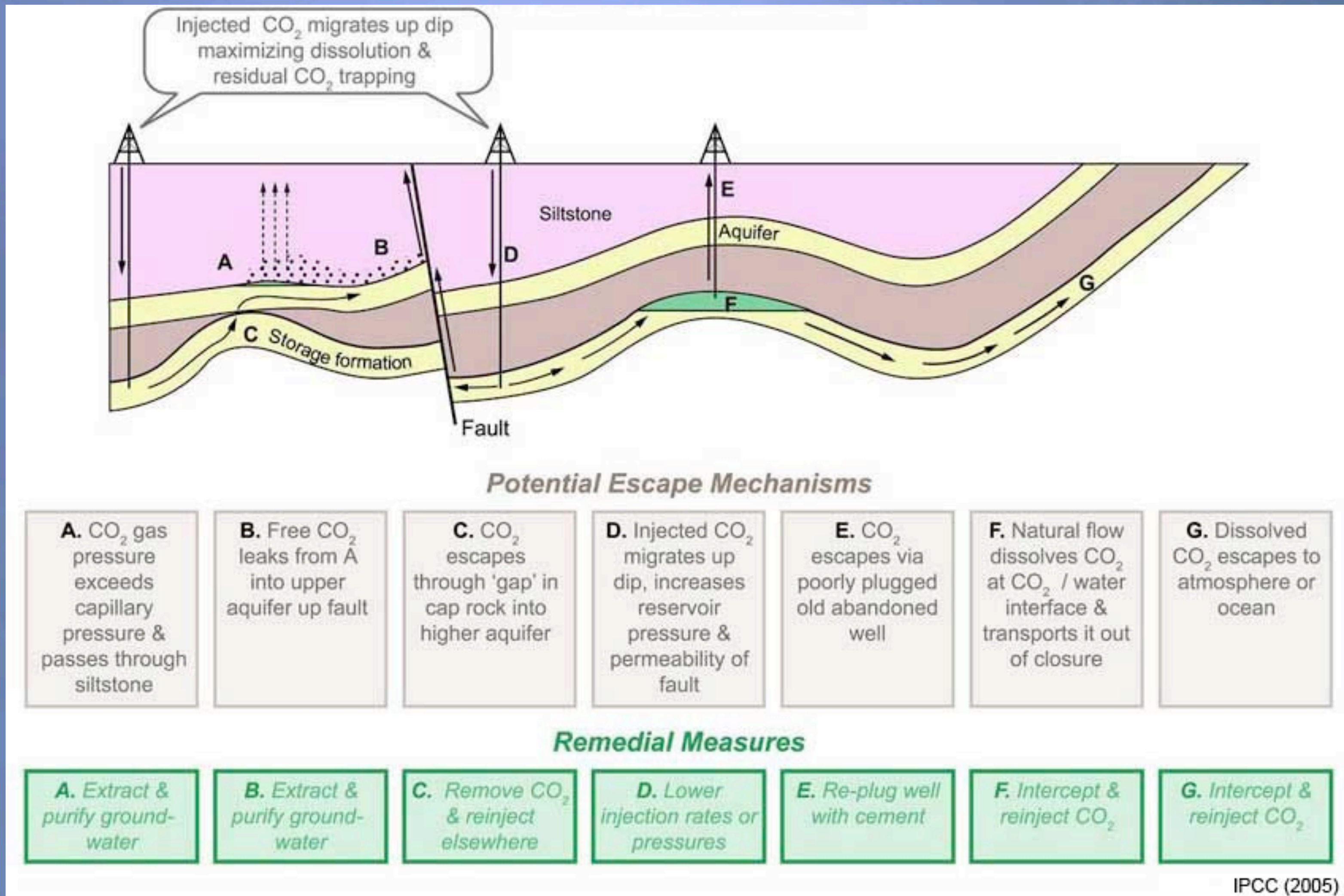
Geologic carbon sequestration: leakage concerns



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Geologic carbon sequestration

- Essential elements
  - Porous rock formations at > 1 km depth
  - Saline water
  - Impermeable cap rock
  - No leakage pathways (faults, wells)
- Wyoming's situation
  - Many suitable saline formations
  - Multiple caprocks
  - Oil, gas, CO_2, He suggest no leakage

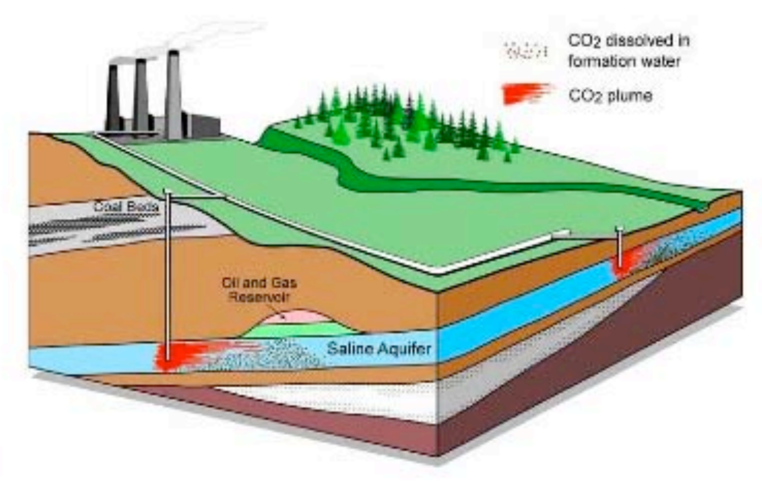

Figure 1. Image source: Dan McGee, Alberta Geological Survey

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Wyoming on energy and climate: what have we done?

- Legislation
  - Pore space ownership, liability, unitization
- Regulation
  - DEQ regulatory authority, CSWG financial assurance mechanisms
- Science and Technology
  - Enhanced Oil Recovery Institute, School of Energy Resources
  - Clean Coal Research Program
  - High Plains Gasification Advanced Technology Center
  - Geologic carbon sequestration

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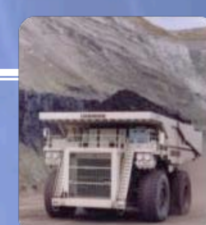


Legislation

- HB 89 – Ownership of pore space
- HB 90 – Permitting of CCS activities
- HB 57 – We really mean it
- HB 58 – You inject it you own it
- HB 80 – Unitization

HB 89 W.S. 34-1-152 (2008)

- Pore Space is part of the surface estate
- All instruments of transfer of surface include pore space unless specifically describe otherwise
- Severance is a matter of contract
  - Instrument transferring pore space must describe rights to use of surface, or none is granted
- Must be specifically described or are void
- Mineral estate is dominant

HB 90 W.S. 35-11-313 (2008)

- Permitting Process placed with Wyoming Department of Environmental Quality
- Permitting requirements
- Bonds or financial assurances
- Rulemaking authority
- Study Group
  - Financial assurances
  - Risks of CCS Activities
  - Report September 30, 2009

HB 57 W.S. 34-1-152(e) (2009)

- The mineral estate is dominant over the severed pore space estate.

HB 58 – W.S. 34-1-153 (2009)

- Injector is presumed to be the owner of injected materials
  - Presumption may be rebutted by a person claiming contrary ownership
- Mere consent alone does not give the surface owner liability for sequestration activities

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HB 80 W.S. 35-11-315

- Protection of Corresponding Rights
- Allows bringing in 20% of owners if have consent of other 80%
- Process
- Heard in front of WOGCC
  - WOGCC makes ownership decisions
  - DEQ makes environmental decisions

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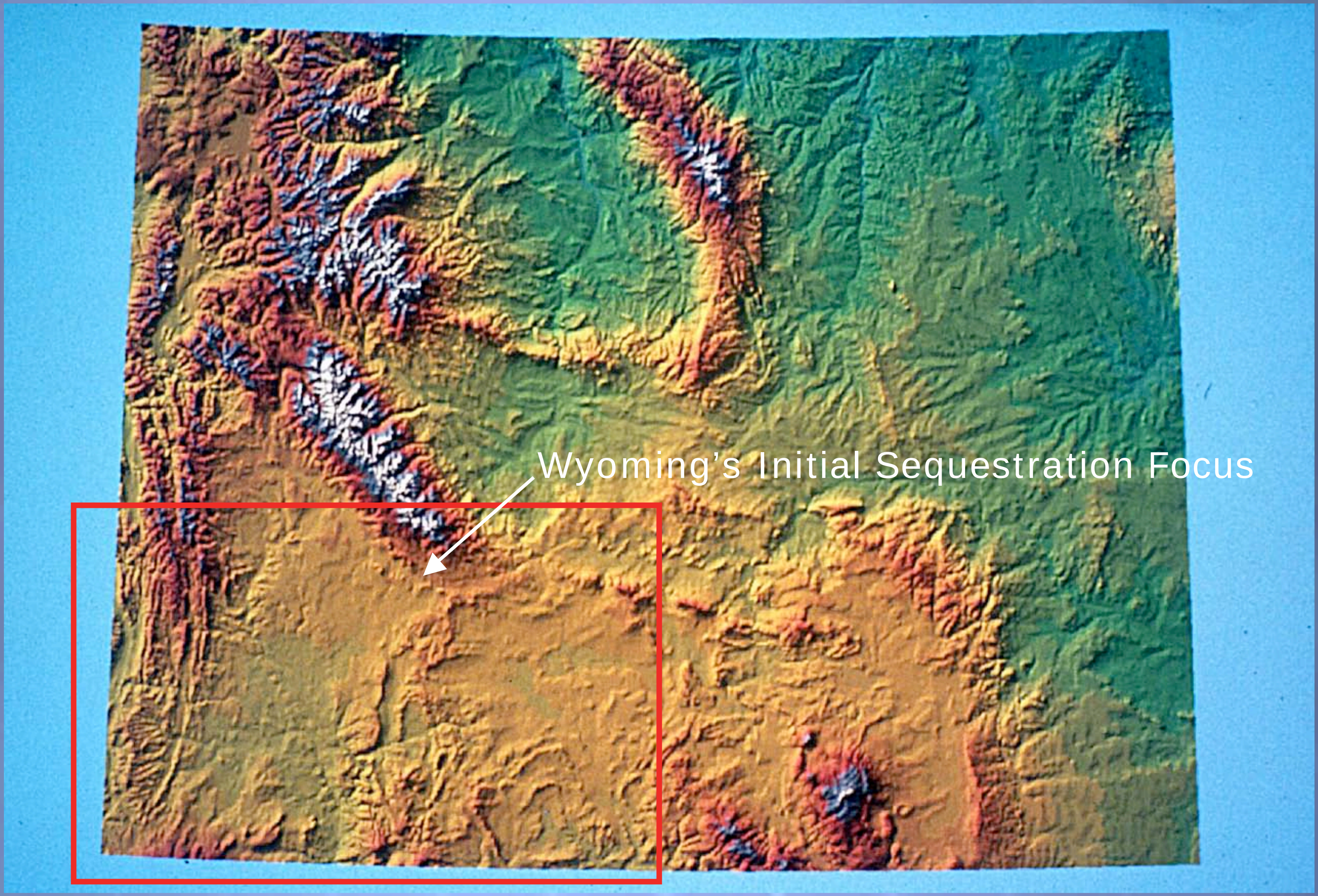
Elements of a Sequestration Project



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Thrust belt from northern Moxa Arch

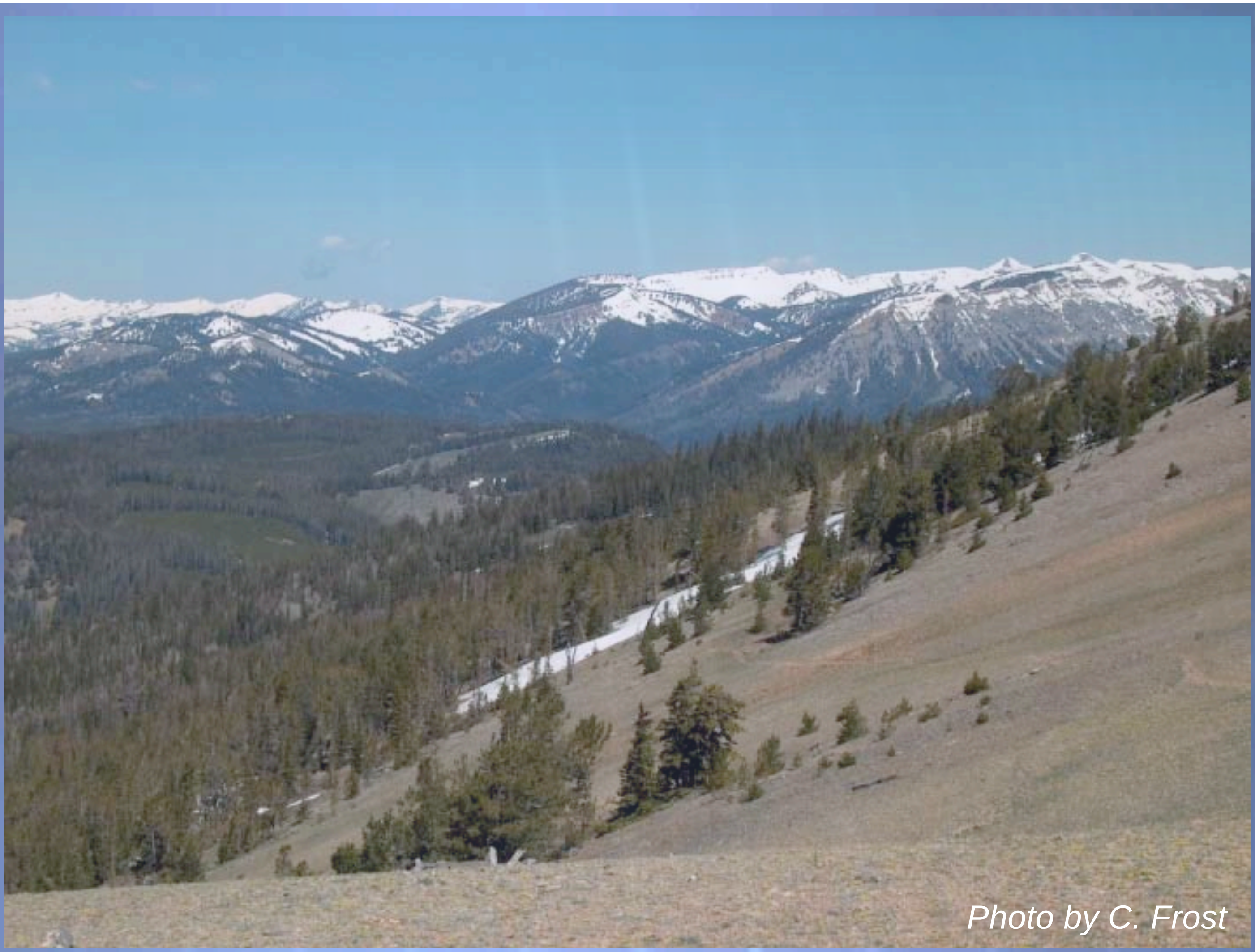

Photo by C. Frost

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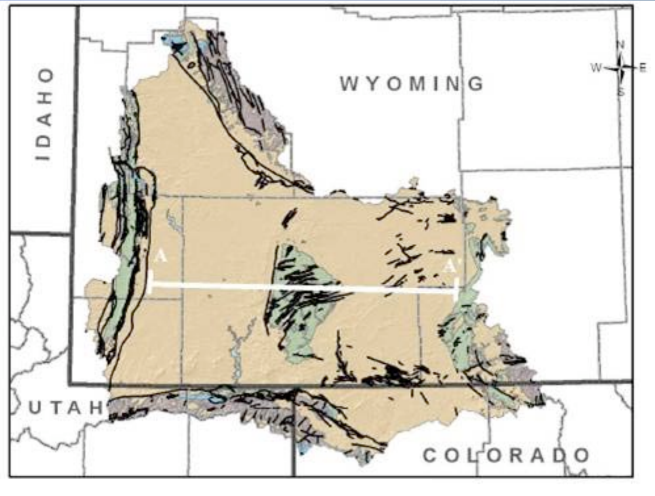
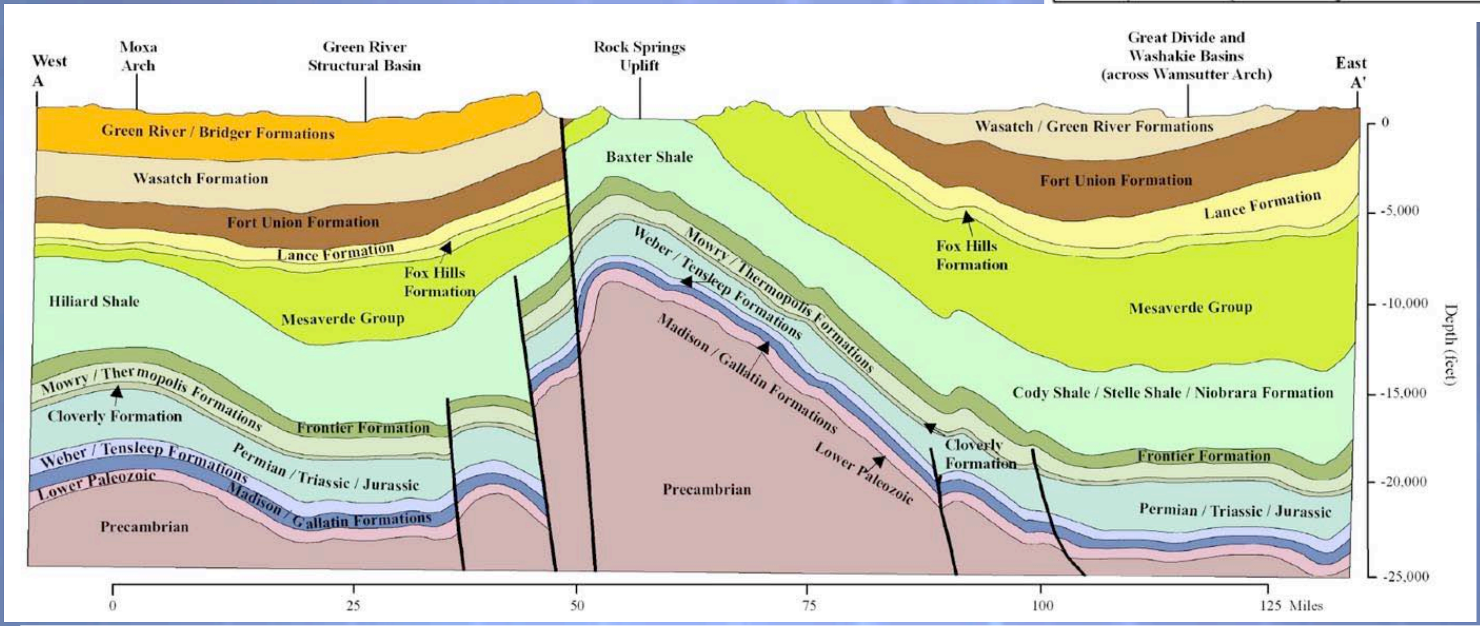
Appropriate geologic structures, formations

- Locations
  - Rock Springs Uplift
  - Moxa Arch
- Receiving formations
  - Sandstone: Nugget, Tensleep/Weber
  - Carbonate: Madison, Bighorn





Clarey et al., 2008

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Proximal source of CO_2

- Jim Bridger 2.1GW coal-fired power plant, Point of Rocks
- ExxonMobil Shute Creek facility operating since 1986
  - Largest gas sweetening facility in the world (Solexol process)
  - Largest helium recovery plant in the world
  - Processes the lowest hydrocarbon content gas in industry
- EOR/Industrial CO_2 sales @ 4-5 MT/Y, increasing to 7 MT/y in 2010
- Large scale CO_2/H_2S injection, 40% CO_2, 60% H_2S, 2 wells sequester 0.6 MT CO_2/Y
- Receiving formation Madison Ls, >18,000 ft.

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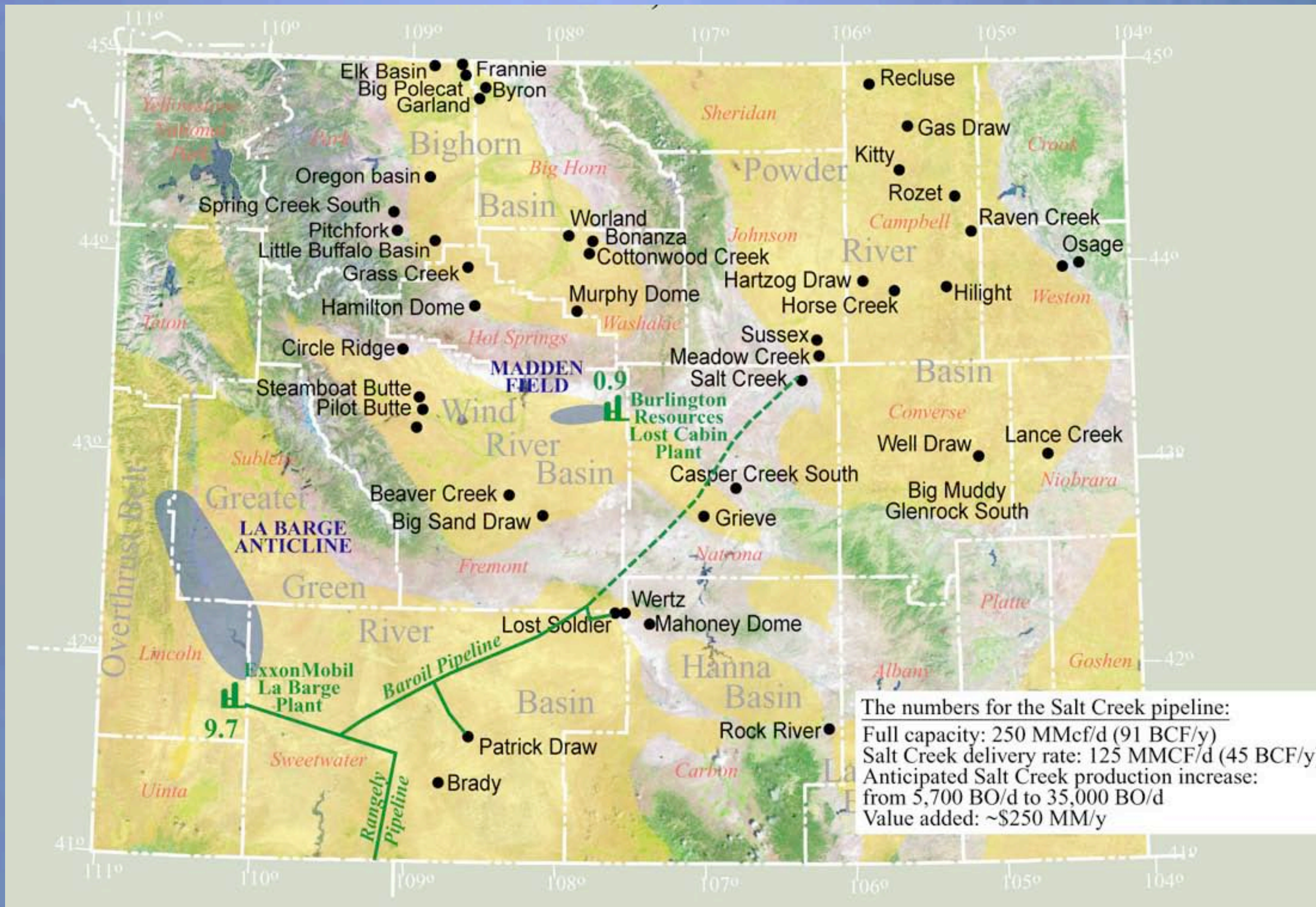
Pipeline infrastructure:
Carbon dioxide pipelines in Wyoming



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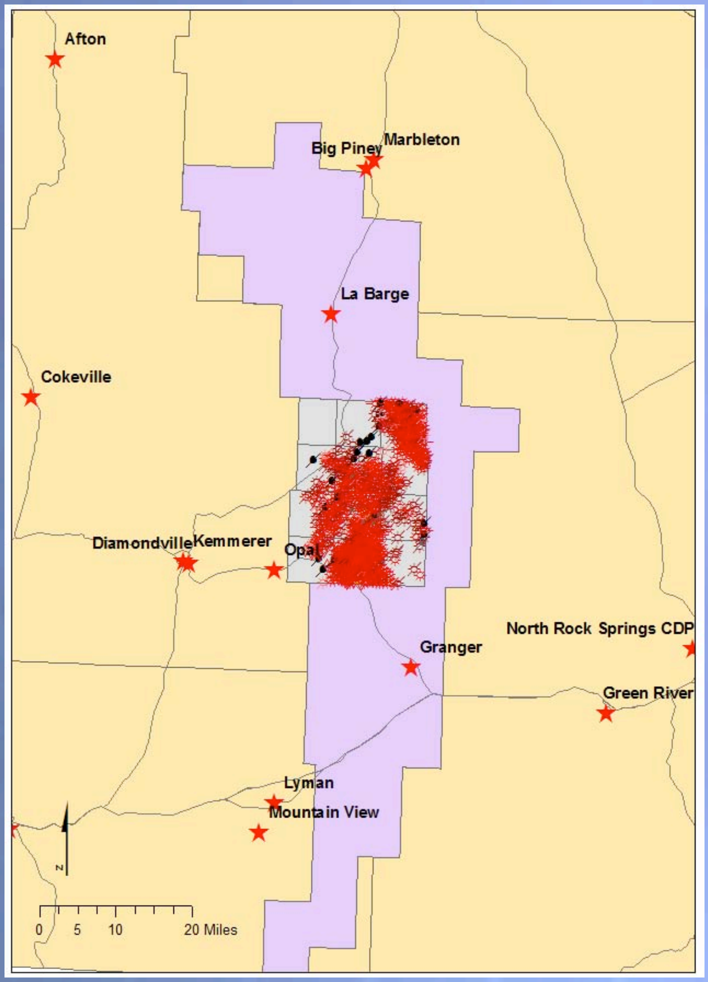
Cataloged Well Penetrations



- Identify "area of review"
  - -Moxa Arch (purple) is 120 mi by 28 mi
  - -12 townships (gray region) centered on Shute Creek
- Compile wells
  - -EPA and WDEQ proposed regulations require "…a compilation of all wells and other drill holes within and adjacent to the AOR…"
  - -1725 wells in WOGCC database
- PI J. Myers is developing standard operating procedures for compiling a well catalog for Class VI permits

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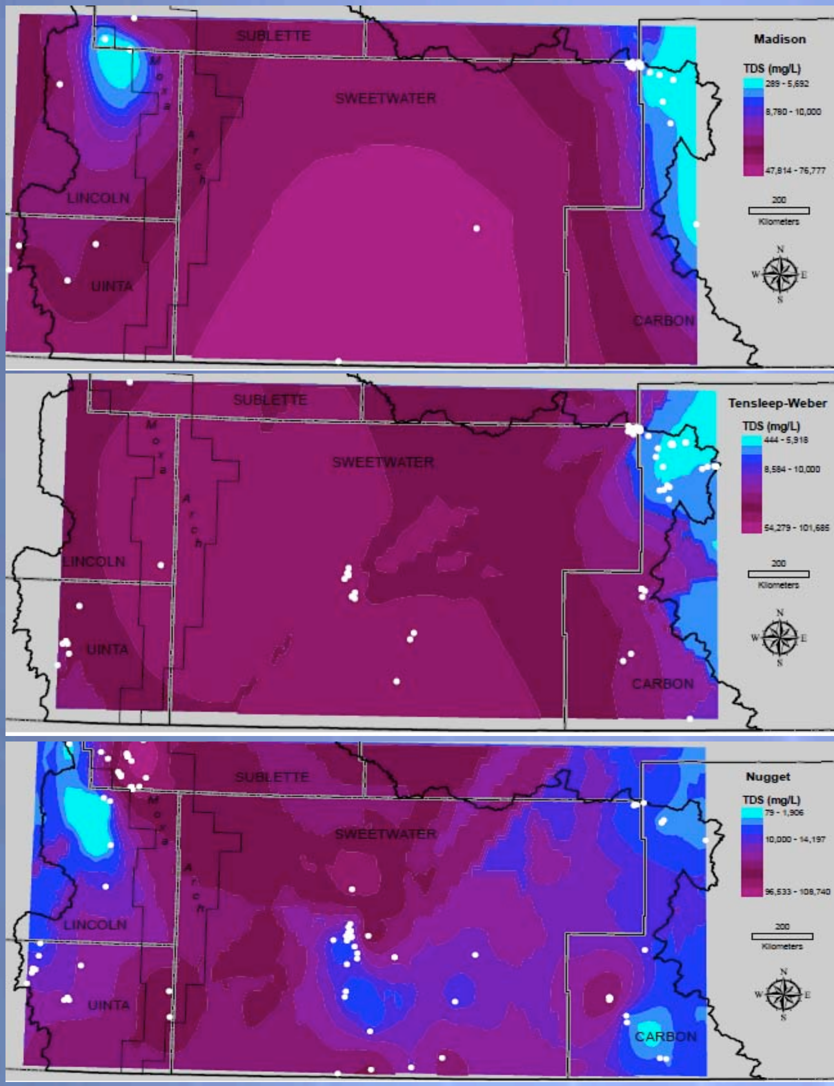
Geochemical characterization of saline aquifer



- Compile geochemical data in the public domain (USGS, WOGCC and WRDS)
- Madison, Bighorn and Tensleep-Weber formation waters meet the EPA Class VI well requirements in the majority of the basin.
- Nugget formation waters are <10,000 ppm TDS at Rock Springs Uplift
- PI: S. Sharma

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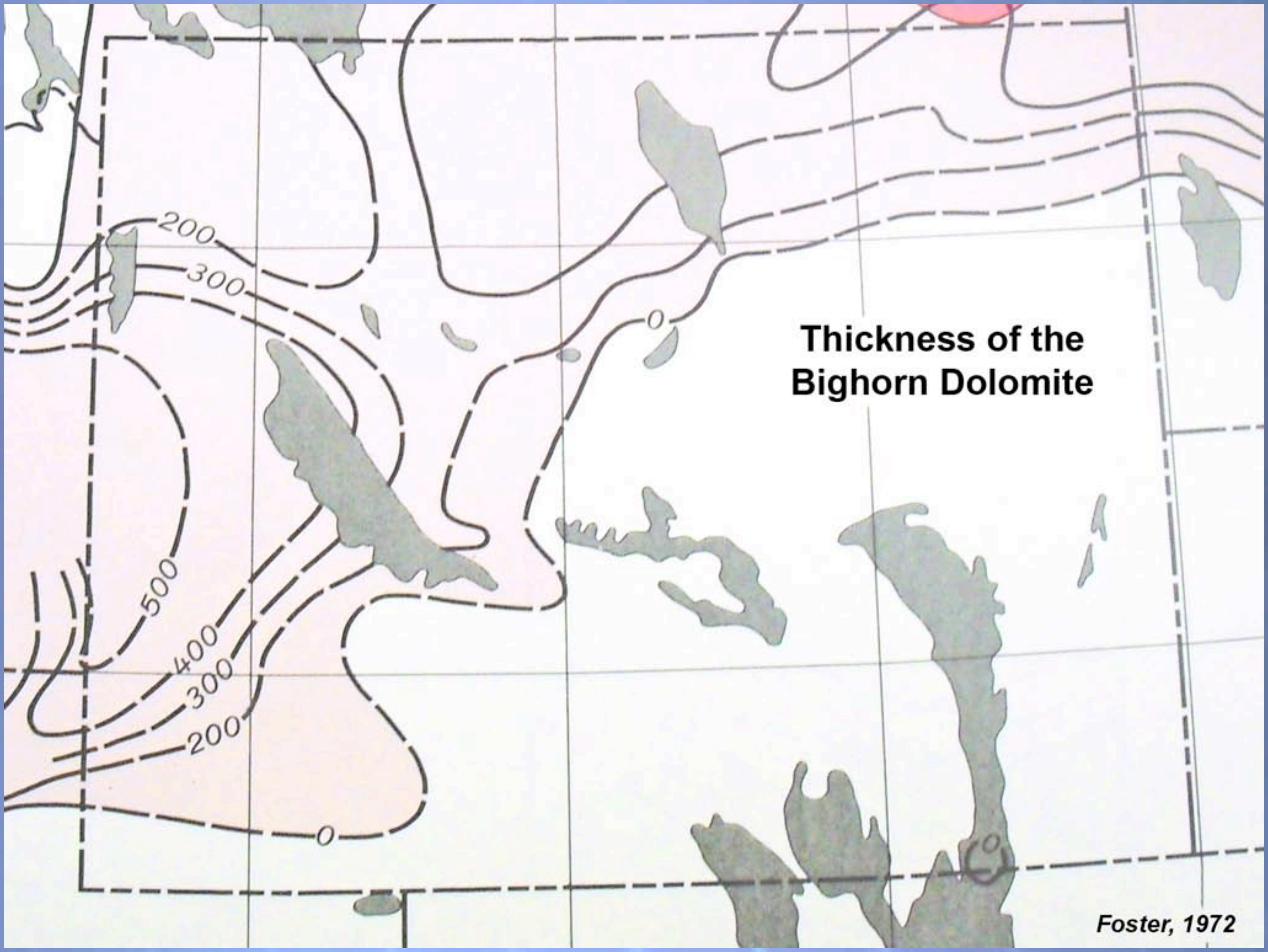
Formation characteristics: thickness, porosity, permeability, heterogeneity



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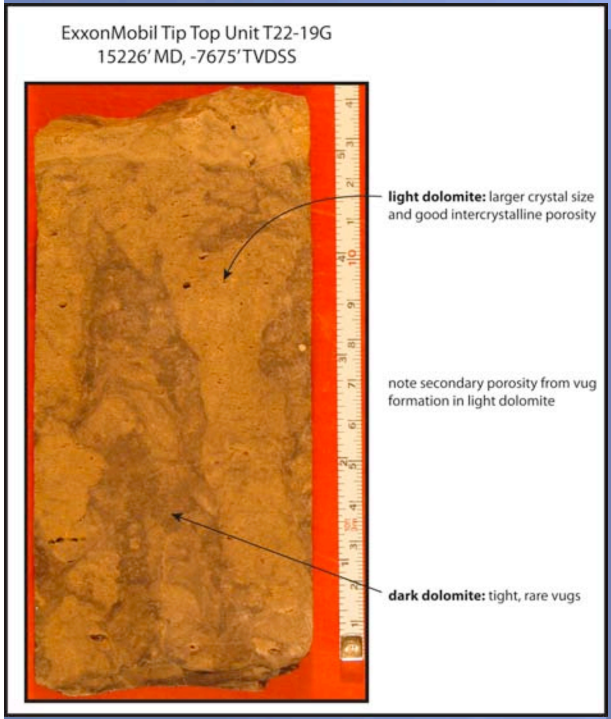
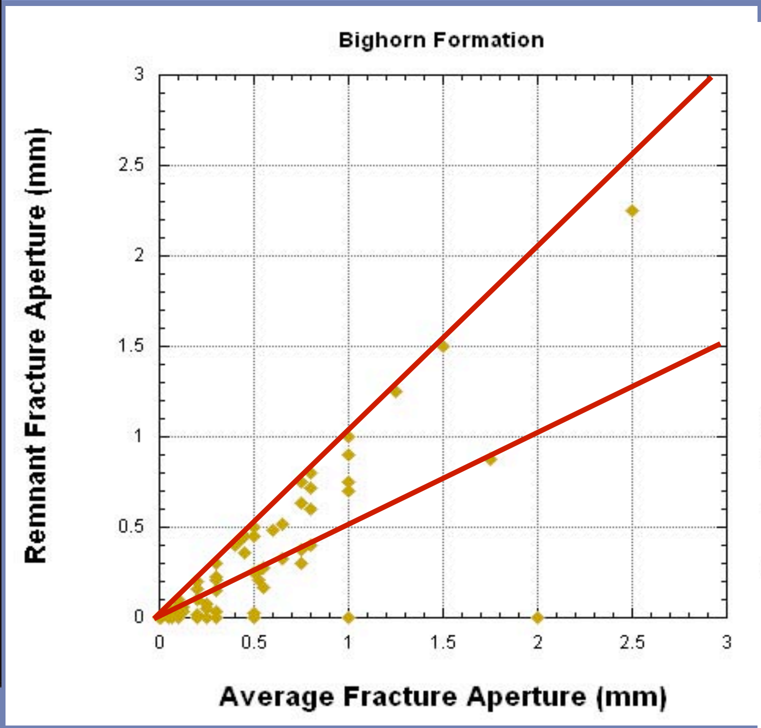
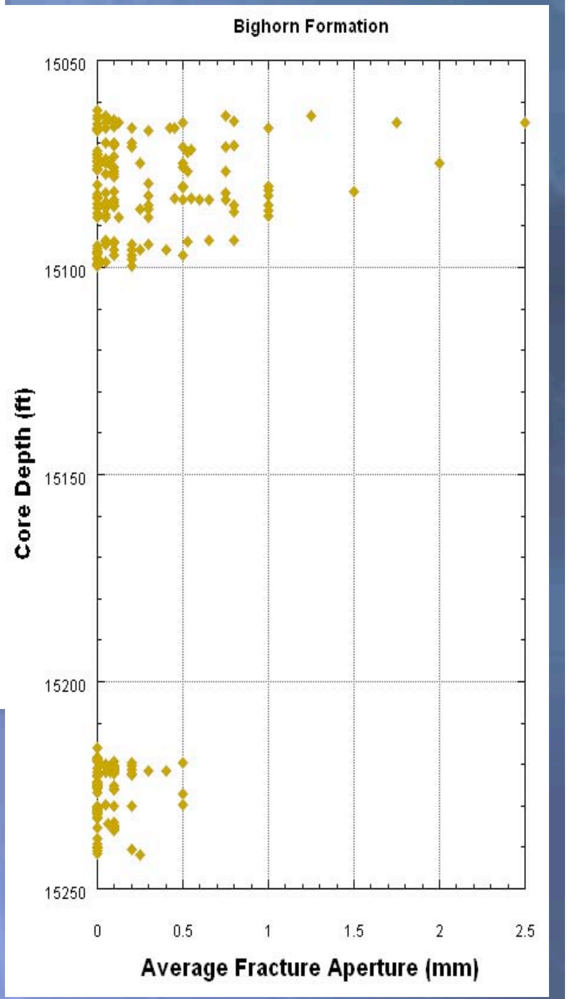
Fractures and faults: subsurface information







- Bighorn core from crest of Moxa Arch-mottled (burrows)
- Measured porosities 1.5-18%
- Variable fracture filling, 0 to 60%
- Larger, more open fractures at top
- PI: E. Campbell-Stone

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Fractures and faults: surface information

Madison limestone, Wind River Canyon

Bighorn dolomite, Bighorn Mts.

- Sparse subsurface data available
- Laramide uplifts expose Bighorn, Madison, Tensleep, Nugget
- Wind River uplift is analogous structure to Moxa Arch
- Outcrop study of faults, fractures
- PI: A. Snoke

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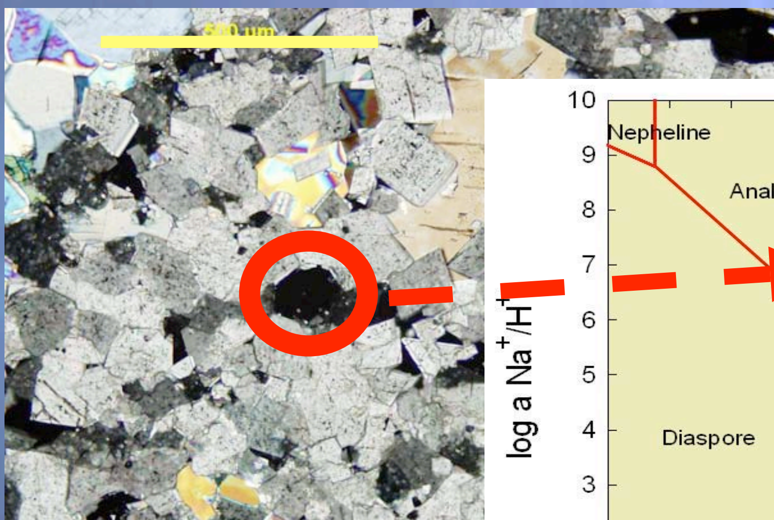
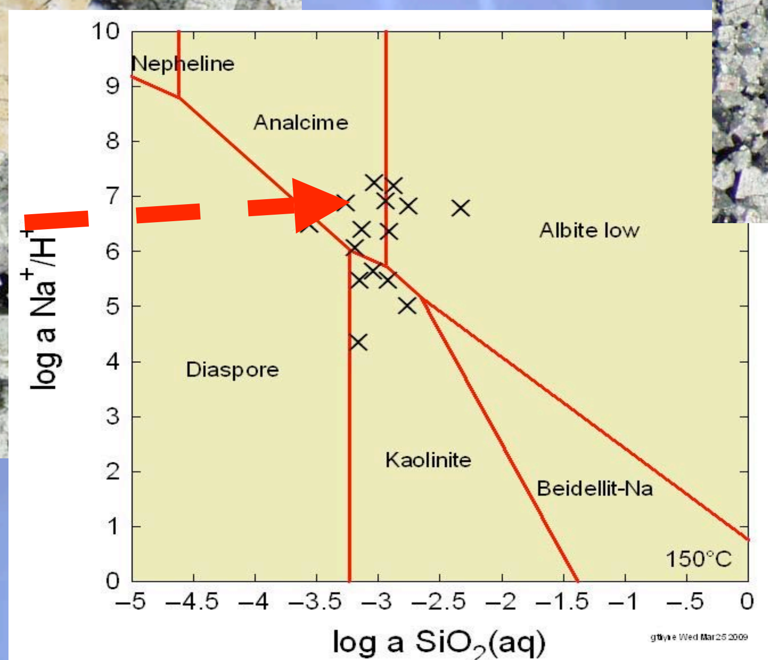
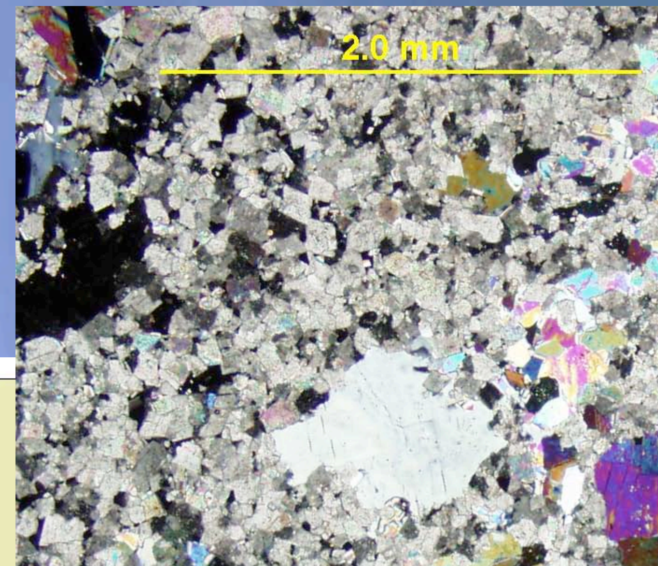
Petrography and experimental geochemistry

Church Buttes: 18,706’



Dolomite + secondary Anhydrite + Analcime + Sulfur (?)





Recrystallization/dedolomitization appears to create smooth surfaces, possibly related to mineralization in fractures

- PI: J. Kaszuba

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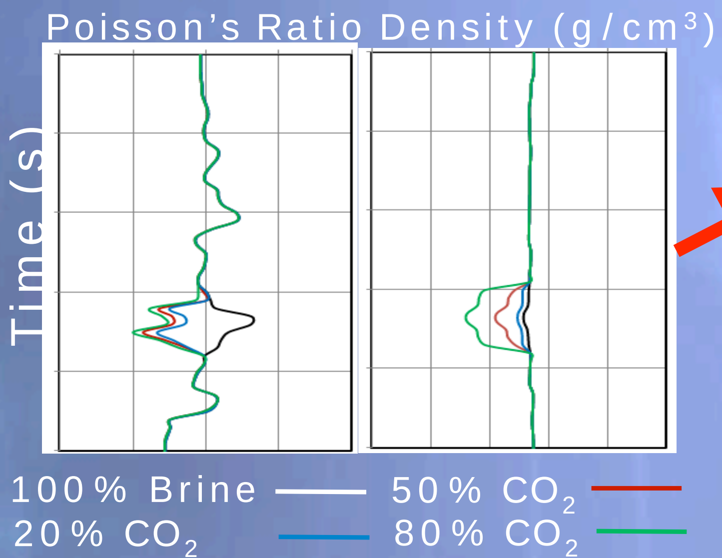
Geophysical monitoring

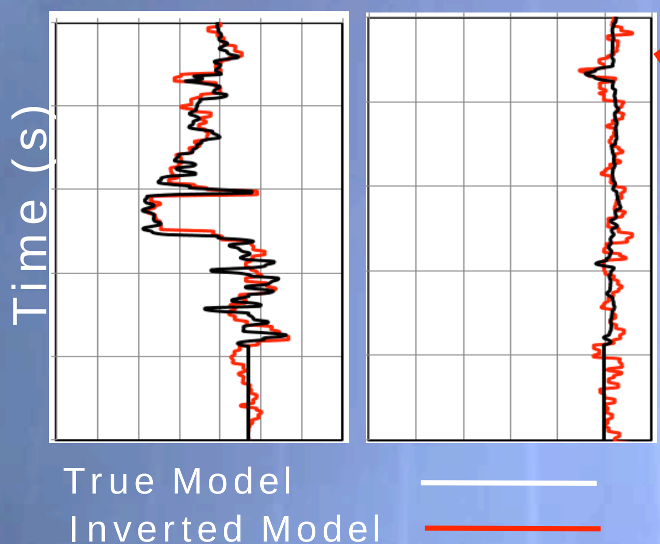
•PI: S. Mallick

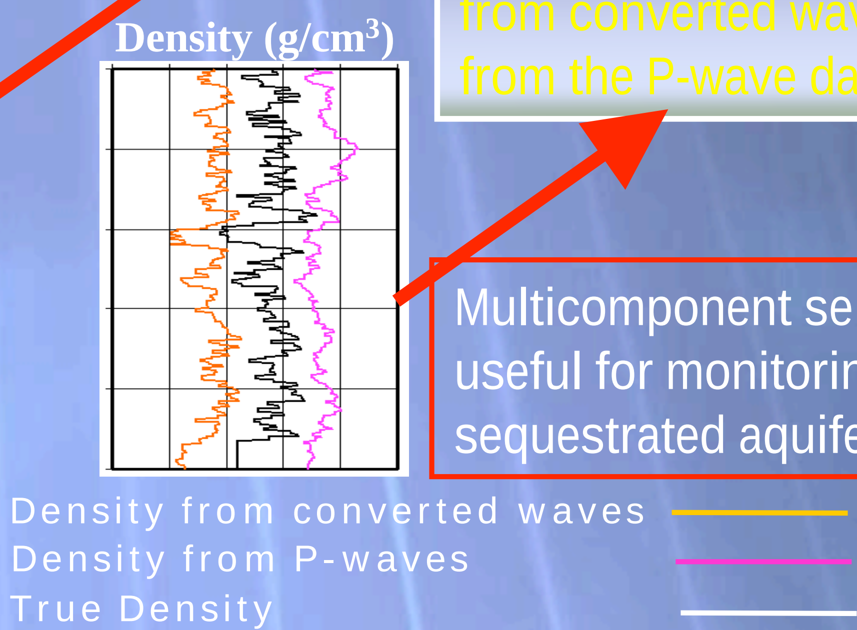


Density is more sensitive to the changes in CO_2 saturation in the aquifer than the Poisson's ratio

P-wave seismic data estimates the Poisson's ratio more reliably than the density

Density is more reliably estimated from converted wave data than from the P-wave data





Multicomponent seismic data is useful for monitoring carbon-sequestrated aquifers

Observations

- Tensleep/Weber, Madison, and Bighorn formations contain brine with > 10,000 ppm TDS
- Only 31 wells penetrate these deep intervals, minimizing potential leakage via wellbores
- Natural CO_2 in the Weber, Madison, and Bighorn formations, but not in shallower units, suggests that adequate seals and hydrologic isolation exist
- The Madison Limestone is thick (~300-800') with large storage capacity (Madison Limestone is receiving CO_2 near ExxonMobil's Shute Creek facility via AGI wells)
- The Tensleep/Weber is a thick (750') saline aquifer capable of holding commercial volumes of sequestered carbon dioxide
- The Bighorn Dolomite is most compatible with proposed rules for EPA Class VI geologic sequestration wells

Performance Assessment

- Performance assessment models help to predict the long-term migration of carbon dioxide and interactions with other fluids and solids in the subsurface. The accuracy of the models depends upon the detail of inputs such as formation thickness, porosity, permeability, heterogeneity are required
- Present sequestration demonstrations inject 1-3 M CO_2/year, which is roughly one-tenth of CO_2 generated by a typical coal-fired power plant
- Models substitute for actual experience

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Wyoming's energy and climate challenge…
…is also the nation and world's challenge

- Wyoming coal-fired power plants currently produce >42 million tons CO_2/yr.
- To meet "clean coal" standards, Wyoming must capture and store 18.5 million tons CO_2/yr.
- Equivalent to 37 Shute Creek-size sequestration sites
- Stricter emissions and/or expanded power generation will require additional sequestration.

- Geoscience educators can prepare professionals for carbon sequestration NOW.

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…there is one outstandingly important fact regarding Spaceship Earth, and that is that no instruction book came with it.

R. Buckminister Fuller (1895-1983)