Recommendations for Geologic Carbon Sequestration in California:
I. Siting Criteria and Monitoring Approaches,
II. Example Application Case Studies

Curt Oldenburg
Preston Jordan
Liz Burton

ARB GCS QM and PP Workshop
20170508
Careful site selection is the best way to ensure containment

- We recommend focusing site characterization and monitoring on the free-phase CO$_2$ plume and overlying area.
- Wells and boreholes are the main risk for CO$_2$ surface leakage.
- Areas with hydrocarbons discovered prior to 1921 in California have the highest likelihood of unknown wells.
- Uncased borings with no plugs in the primary seal create substantial risk due to lack of knowledge regarding the transmissivity of these features.
- Transmissive faults and fractures are best avoided by selecting sites with ductile seals.
- Sites with a pressure-dissipation interval between the storage zone and the base of underground sources of drinking water (USDW) reduce leakage risk and between the storage zone and the top of basement reduce seismic risk.
- A minimum injectivity is needed for any successful GCS site. This should be estimated during project design at a scale relevant to the proposed project.
- Sites in areas of low population density reduce the likelihood of impacts to people (e.g., from monitoring, pipeline transportation, injection, leakage).
Free Phase CO\textsubscript{2} Plume Area of Review (AoRc)

- Current plume extent, if any
- Best plume extent prediction, either final or interim
- AoRc for plume constrained by closed structure (buffer 0.1)
- AoRc for plume in 0-dip structure (buffer 2.0)
No “Early” Hydrocarbon Discoveries

California oil and gas agency established
No “Early” Hydrocarbon Discoveries

Average depth of deepest pool discovered prior to 1921
Uncased Borings Plugged In Seal

Deepest boring in each township and townships with a boring to basement prior to 1981
Wells/Uncased Borings Sealed In Seal

Installation date of deepest seal above the Vedder Formation

![Graph showing depth of deepest seal above the Vedder Formation versus TDS or NaCl concentration (parts per thousand).]

- **Minimum seal depth trend**
- **Safe Drinking Water Act takes effect** ~2,000 mg/L
- **Safe Drinking Water Act takes effect** ~10,000 mg/L

- **Deepest seal**
- **TDS**
- **NaCl**

- **Deepest seal in seal**
- **TDS**
- **NaCl**
Wells/Uncased Borings Sealed In Seal

Installation date of deepest seal above the Vedder Formation

- TDS or NaCl concentration (parts per thousand)
- Depth of deepest seal above the Vedder Formation (m)

Minimum seal depth trend

- ~2,000 mg/L
- ~10,000 mg/L

Safe Drinking Water Act takes effect

Deepest seal

TDS

NaCl

Wells/Uncased Borings Sealed In Seal
Seal with Low Brittleness

• Unconfined compressive strength less than twice normally consolidated unconfined compressive strength (little cementing or uplift)
• Unconfined compressive strength estimated from sonic velocity logs
• Normally consolidated compressive strength estimated from effective lithostatic stress

Seal with Low Brittleness

- Unconfined compressive strength less than twice normally consolidated unconfined compressive strength (little cementing or uplift)
- Unconfined compressive strength estimated from sonic velocity logs
- Normally consolidated compressive strength estimated from effective lithostatic stress

Or In Thrust Fault Stress Regime

- Vertical (lithostatic) effective stress less than horizontal stresses
- Opening fractures horizontal
- Shear fractures shallowly dip

http://www.naturalfractures.com/1.1.htm
Pressure Dissipation Interval Above

Aquifer

Dissipation Interval

Seal

Reservoir

Basement

CO₂

Water table

Base of protected groundwater
Pressure Dissipation Interval Above

Aquifer

Dissipation Interval

Seal

Reservoir

Basement

CO₂

Water table

Base of protected groundwater

Overpressure in leakage path
Pressure Dissipation Interval Above

Aquifer

Dissipation Interval

Seal

Reservoir

Basement

Water table

Base of protected groundwater

Secondary Accumulation

Overpressure in leakage path
Dissipation interval above both reduces leakage to receptors and provides a monitoring target.
Pressure Dissipation Interval Below

Dissipation interval below reduces seismic hazard
Pressure Dissipation Interval Below

- Water table
- Base of protected groundwater
- Dissipation Interval
- Seal
- Reservoir
- Seal
- Dissipation Interval
- Basement

CO₂

Overpressure cutoff along fault
• Injectivity test stressing one tenth of AoRc
Injectivity Management

- Injectivity test stressing one tenth of AoRc
- Backup injection interval
Injectivity test stressing one tenth of AoRc
Backup injection interval
Pressure management (fluid extraction)
Minimize Building CO₂ Injection Risk

- AoRc does not include any portion of a city
- The probability of an occupant experiencing a CO₂ well blowout into the building < one in ten thousand per project (<50% globally)
Negative accounting using monitoring results to quantify storage

- We recommend monitoring plans be developed to detect secondary accumulations, as well as surface leakage.
- We recommend quantifying the mass of CO₂ stored by subtracting either the detected leakage or the leakage detection limit from the mass injected.
- We recommend conducting three-dimensional (3D) time-lapse seismic at regular intervals using the same seismic network and monitoring for changes in pressure in the overlying dissipation interval.
Monitoring for **Quantification**

- **CO₂**
- **Aquifer**
- **Dissipation Interval**
- **Seal**
- **Reservoir**
- **Basement**

- **Water table**
- **Base of protected groundwater**
Monitoring for **Quantification**

- **CO₂**
- Aquifer
- Dissipation Interval
- Seal
- Reservoir
- Basement
- **Water table**
- **Base of protected groundwater**

“**Negative accounting**”
Monitoring for Quantification

“Negative accounting”
Monitoring for Quantification

"Negative accounting"

Two case studies demonstrate the approach

• In earlier studies by WESTCARB, four sites were screened for feasibility: King Island, Thornton, Kimberlina, and Montezuma Hills.
• King Island and Kimberlina emerged as the preferred sites.
King Island is a good prospect for GCS

- Unknown wells are unlikely.
- Seal appears to be sufficiently ductile to reduce fault and fracture transmissivity to preclude detectable leakage.
- A pressure-dissipation interval exists above and below the Mokelumne River target reservoir.
- Injectivity is likely to be sufficient.
- Unknown whether seal has sufficiently high capillary entry pressure or low permeability.
- There are shallow-plugged uncased borings that need to be evaluated and monitored.
- Free-phase CO₂ plume area may extend into city limits.
Kimberlina cap rock and injectivity need more analysis

- Dissipation intervals exist both above and below Vedder Formation storage target.
- While the seal has retained oil in fields surrounding the site at some distance, there are currently insufficient data to determine if the seal is ductile.
- Unknown whether seal has sufficiently high capillary entry pressure or low permeability.
- Area of review for the free-phase CO₂ plume may include a portion of an oil field with both known and unknown wells.
- There are shallow-plugged uncased borings that need to be evaluated and monitored as potential leakage pathways.
- Injectivity is limited, suggesting a project at this site would likely require pressure management by brine extraction.
Questions?