Overview of Reservoir Simulation and Risk Assessment for WESTCARB's Kimberlina Phase III Pilot

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WESTCARB Annual Meeting
Anchorage, Alaska
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Outline

Part 1

- **Overview of reservoir simulation**
  - — **Geologic model**
  - — **TOUGH2/ECO2N**
  - — **Results**
  - — **Evolution of mobile fraction**

Part 2

- **Application of the Certification Framework (CF) to K3**
  - — **Characterization (surface, hydrology, geology)**
  - — **Reservoir modeling**
  - — **Likelihood of CO_2 and brine intersecting conduits**
  - — **CO_2 and brine leakage risk**

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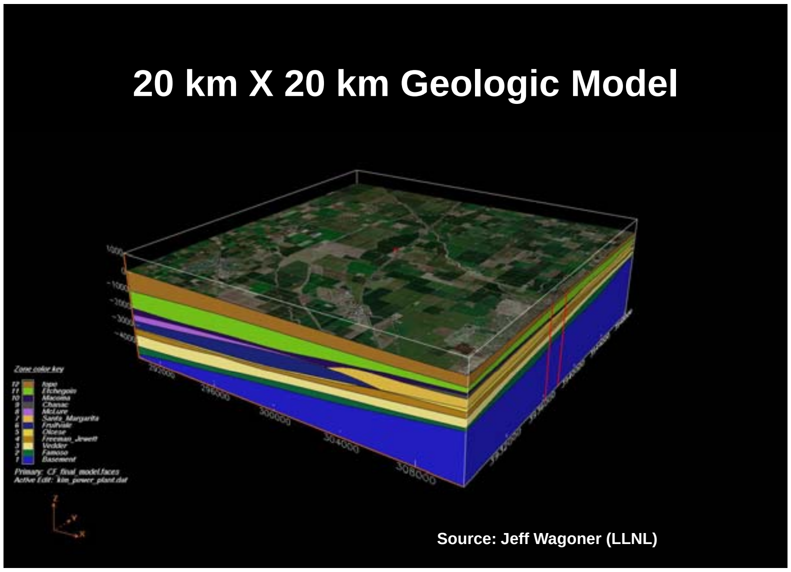
Geologic Model



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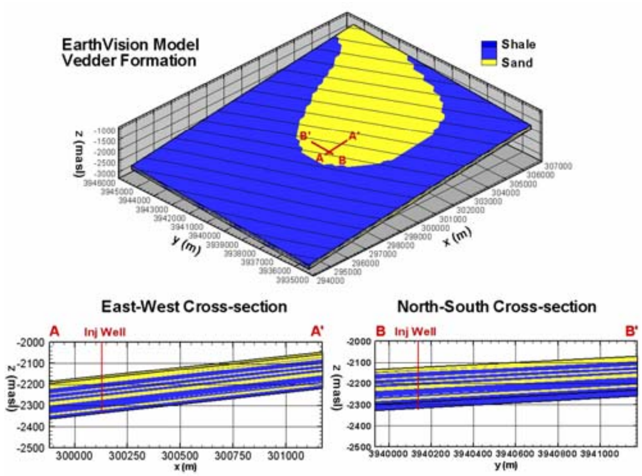
Geologic Model of Vedder



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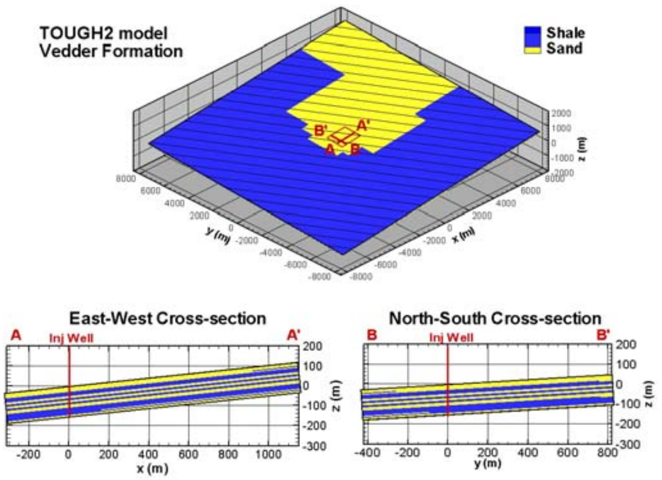
TOUGH2 Model of Vedder



TOUGH2 Model Development

- EarthVision model of Olcese and Vedder
  - 600 layers
  - 50 x 50 lateral cells
  - x: 250 m wide, y: 200 m wide
- TOUGH2 model
  - Vedder - 30 layers (6 EV layers combined to form each TOUGH2 layer)
  - Closed boundaries above and below Vedder
  - Constant-pressure boundaries at x extrema, closed at y extrema
  - Lateral grid spacing varies
    - 5 m at injection well
    - 55 m over region where CO_2 plume expected to go
    - Increasing to 2.5 km far from injection well
  - Earthvision facies assigned to TOUGH2 cells
  - Model is a tilted plane – good approximation to the nearly uniform dip observed in the EarthVision model. Dip angle is 7 degrees

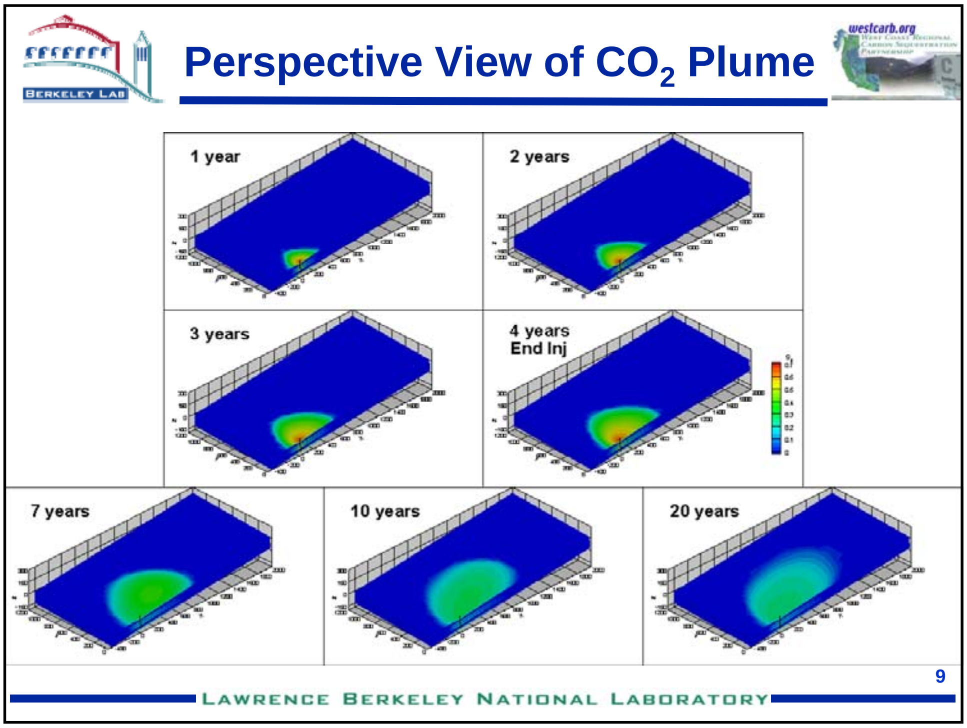
Model Parameters

Facies	Porosity	Horizontal Permeability	Vertical Permeability	Residual Liquid Saturation	Maximum Residual Gas Saturation
Sand	28%	200 md	20 md	0.2	0.28
Shale	15%	0.1 md	0.01 md	0.3	0.29

- **Residual gas saturation**
  - — **zero during drainage**
  - — **non-zero during imbibition, depends on saturation history**

CO_2 Injection in Vedder

- **Inject 250,000 t per year for 4 years**
- **Inject over entire thickness of Vedder (158 m thick)**
- **At injection location, about 50/50 sand/shale, so net sand thickness is about 79 m**
- **P = 220 bars, T = 81°C, density of CO_2 = 632 kg/m^3**


Perspective View of CO2 Plume
1 year
2 years
3 years
4 years
End Inj
7 years
10 years
20 years
9
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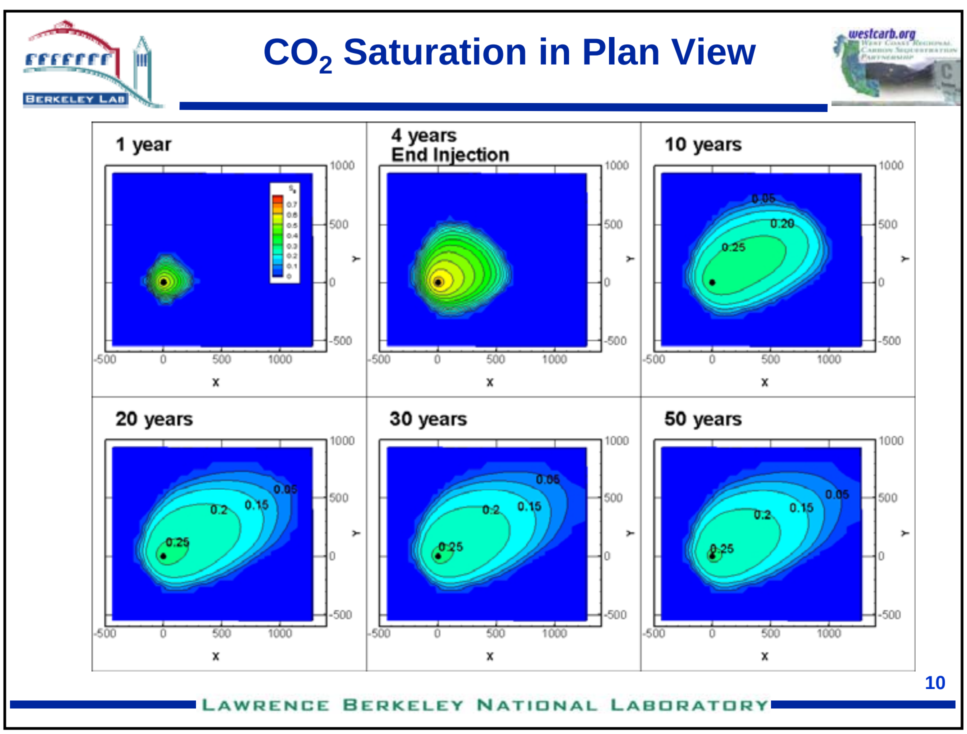
CO2 Saturation in Plan View
1 year
4 years
End Injection
10 years
20 years
30 years
50 years
0.05
0.20
0.25
0.2
0.15
x
y
-500
0
500
1000
10
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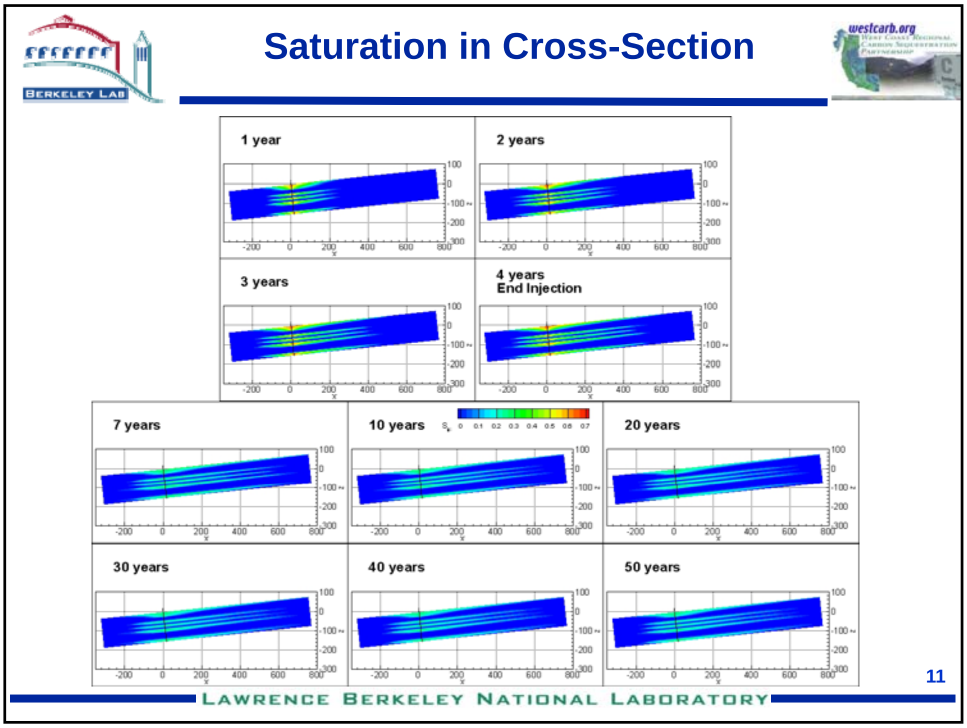
Saturation in Cross-Section
westcarb.org
1 year
2 years
3 years
4 years
End Injection
7 years
10 years
20 years
30 years
40 years
50 years
11
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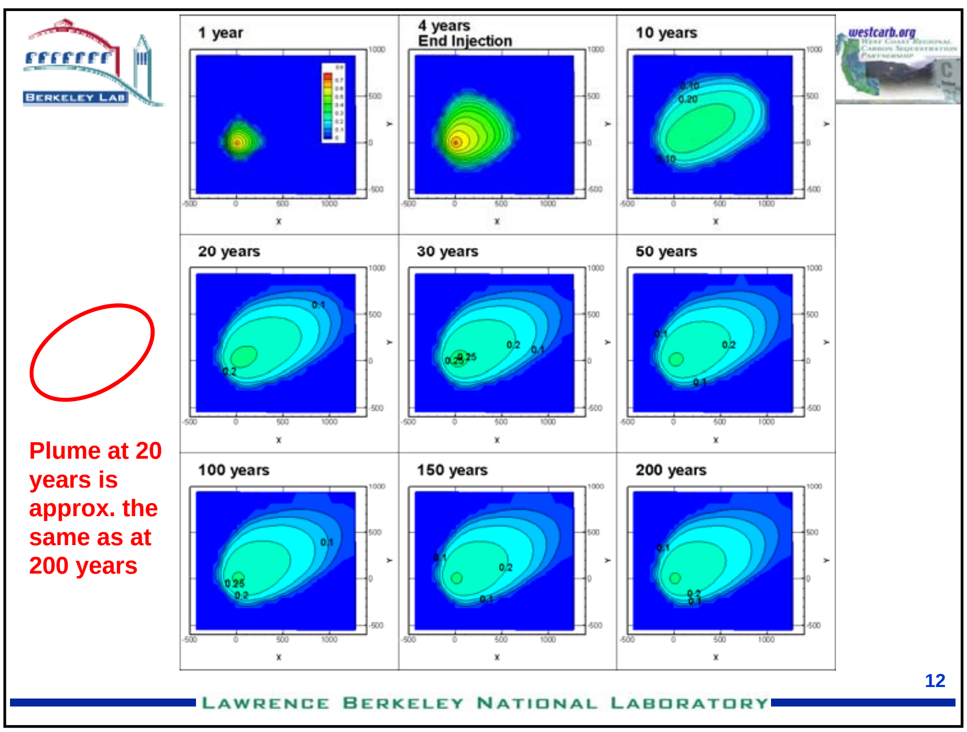
westcarb.org
1 year
4 years
End Injection
10 years
20 years
30 years
50 years
100 years
150 years
200 years
Plume at 20 years is approx. the same as at 200 years
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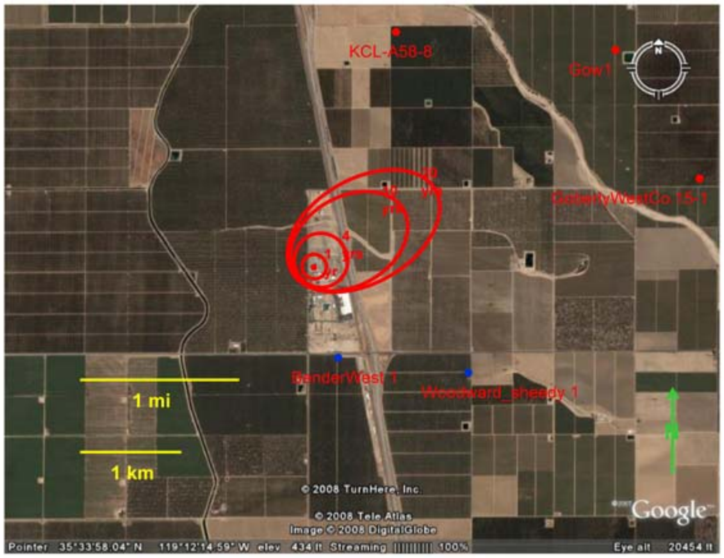
Plume and Wildcat Wells Near K3 Site



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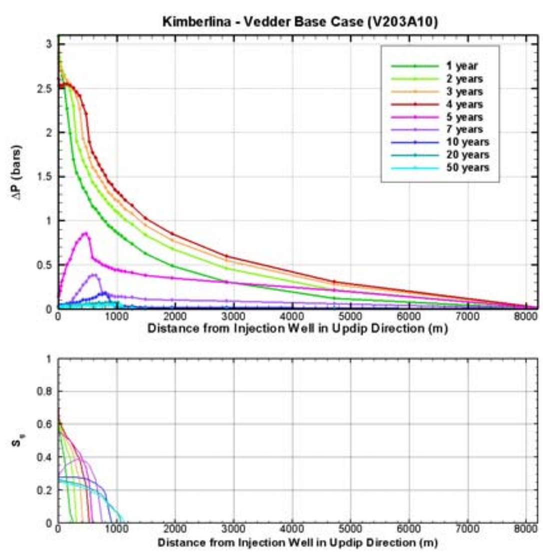
Evolution of Pressure and Saturation



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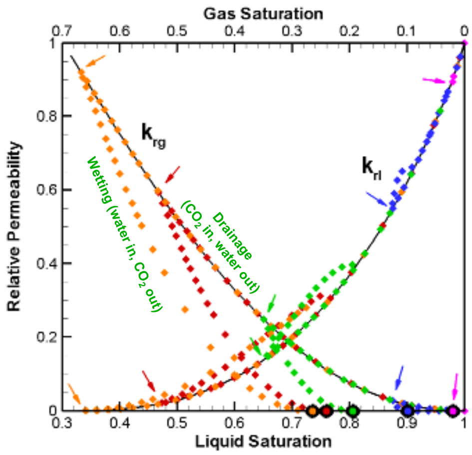
Residual Gas Trapping



Source: Chris Doughty (LBNL)

Hysteretic relative permeability

=> Permeability of each phase depends on its saturation change history.

Relative permeability of CO_2 is higher at given saturation if the region is being flooded with CO_2 (draining water).

When CO_2 migrates away, water comes back in (wetting), relative permeability of CO_2 is lower at a given saturation leading ultimately to residual gas trapping.

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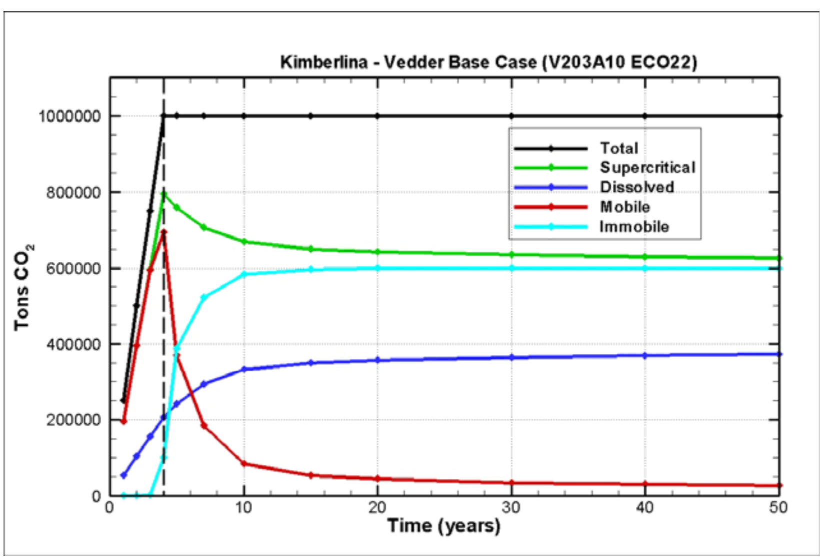
CO_2 Inventory Evolution



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Geological Carbon Sequestration
Certification Framework

Part 2: Risk Assessment for WESTCARB's Kimberlina Phase III Pilot

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Texas Bureau of Economic Geology

Mary Jane Coombs
UCOP

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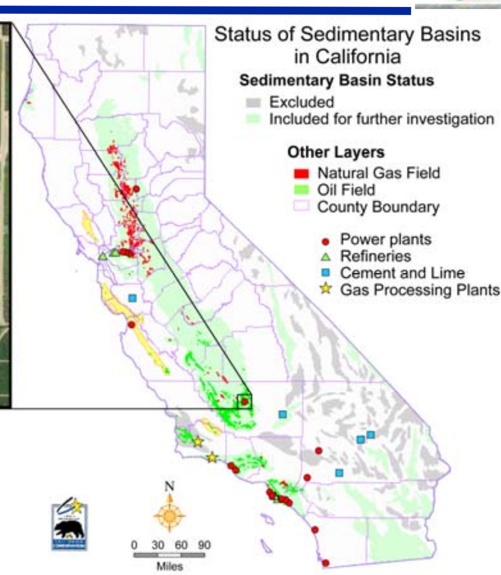
Kimberlina Phase III Pilot (K3)



250,000 t CO_2/yr for four years

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Oblique Low-Altitude Aerial Photo

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K3 Injection in a Nutshell

- CO_2 sourced from ~50 MW oxy-combustion power plant
- Inject 250,000 t CO_2 per year for 4 years at power plant site
- Inject over entire thickness of Vedder (160 m thick)
- At injection location, about 50/50 sand/shale => net sand thickness is about 80 m
- Top of Vedder is at a depth of 2300 m
- Vedder P = 220 bars, T = 80°C, density of CO_2 = 630 kg/m^3
- Cap rock is Freeman-Jewett shale (100 m thick)
- Overlying this is the Olcese sand (200 m thick)
- Cap rocks to Olcese are Round Mountain/Fruitvale, McLure, and Macoma (all shale aquitards) totaling 700 m of thickness

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Preliminary FEP Analysis

- Quintessa online FEP database
  - Features = characteristics such as geometry and flow properties
  - Events = abrupt changes in Features or Processes such as earthquakes
  - Processes = dynamics such as fluid flow or phase change
- 143 FEPs in Quintessa database
- We sorted FEPs into three groups
  - Group 3 = not relevant (78)
  - Group 2 = low probability or low impact or not in scope of K3RA (44)
  - Group 1 = very relevant (21)
- Screening done assuming K3 pilot parameters—not long-term GCS
- All Group 1 FEPs turned out to be either Features or Processes (no Events)

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Group 1 FEPs

Table 4-1. Important FEPs treated in this report.

R	Ca	Cl	FEP#	Category, Class, or FEP Description	Comments
1			2.2.5	Remedial actions	This topic is somewhat out of scope but a good site should have characteristics allowing for quick and effective remedial action. The limited number of deep wells suggests that it is manageable to retrofit them all in the unlikely case of leakage. Similarly, the small amount of CO_2 injected would make it relatively easy to pressurize the Olcese Sand and invert the pressure gradient.
1			3.1.1	Physical properties of CO_2	Injection depth is known. Temperature and pressure are extrapolated (see FEP# 4.1.13 and 4.1.14). The well-known and defensible code TOUGH2 is used (see Section 5.1)
1			3.1.2	CO_2 phase behavior	See FEP# 3.1.1
1			3.1.3	CO_2 solubility and aqueous speciation	See FEP# 3.1.1
1			3.2.1	Effects of pressurization of reservoir on caprock	Addressed in TOUGH2 modeling (see Section 5.1) - Maximum additional pressure due to injection is 3 bars (Figure 5-6) which is few percent of the local fluid pressure and unlikely to bring it to fracture pressure threshold.
1			3.2.5	Mechanical processes and conditions	fault reactivation, fracture creation unlikely – addressed in Section 5.1
1			3.3.1	Advection of free CO_2	Addressed by TOUGH2 modeling (Section 5.1)
1			3.3.2	Buoyancy-driven flow	Addressed by TOUGH2 modeling (Section 5.1)
1			3.3.6	CO_2 release processes	CO_2 release processes and impacts at the surface or shallow subsurface are treated in CF (Section 6)
1			4.1.3	Reservoir type	Injecting into a saline aquifer - see TOUGH2 results (Section 5.1)
1			4.1.4	Reservoir geometry	Specific geometric properties have been included into the TOUGH2 model (Section 5.1)
1			4.1.6	Caprock or sealing formation	Described in Section 3.2.1. Primary and secondary seals. Permeability and capillary entry pressure not known
1			*4.1.8.2*	Pore Architecture	Porosity and permeability are discussed in Section 5.1
1			4.1.10	Heterogeneities	Described in Section 3.2.4
1			4.1.11	Faults and fractures	Described in Section 3.2.3
1			4.1.12	Undetected features	Despite the lack of local data, area has been well studied because of the proximity of oil and gas deposits. Unexpected geologic structures are unlikely to be present. Fault distribution is addressed in Section 3.2.3
1			4.1.16	Petrophysical properties	Described in Section 5.1 (porosity, permeability, relative permeability curves, residual saturations) ; data extrapolated/interpolated from other wells and from expert knowledge
1			4.2.1	Fluid properties	CO_2 properties are addressed in FEP# 3.1.1 to 3.1.3. Generic brine properties are used in TOUGH2 simulations
1			5.2.4	Orphan wells	See Section 6.3
1			7.1.1	Loss of containment	Addressed in CF and on sections on seals (Section 6)
1			7.2.1	Contamination of groundwater	petrographic characteristics (FeOx, clay,feldspar) of aquifers given in Section 3.2.4 Elevated pressure area may not be sufficient for more saline water to reach overlying aquifers – See Appendix D

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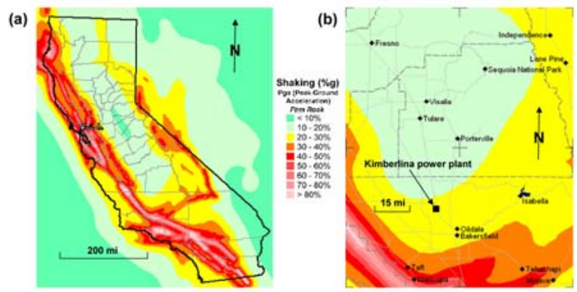
Some Group 2 FEPs

- Seismicity—relatively non-seismic area of CA
- Drilling activities—mostly for water much shallower than Vedder
- CO_2 composition—very pure CO_2 stream from CES plant
- Overpressuring—pressure buildup mostly during 4 years of injection
- Displacement of saline fluids—low-volume injection
- Induced seismicity—injection rate and injectivity compatible with small pressure buildup



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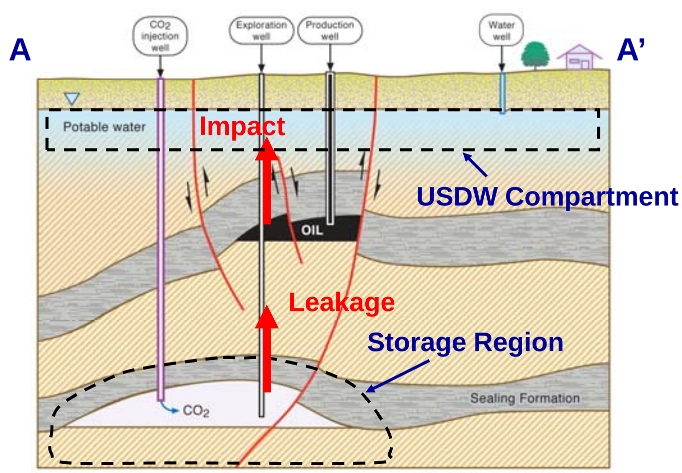
CF in a Nutshell



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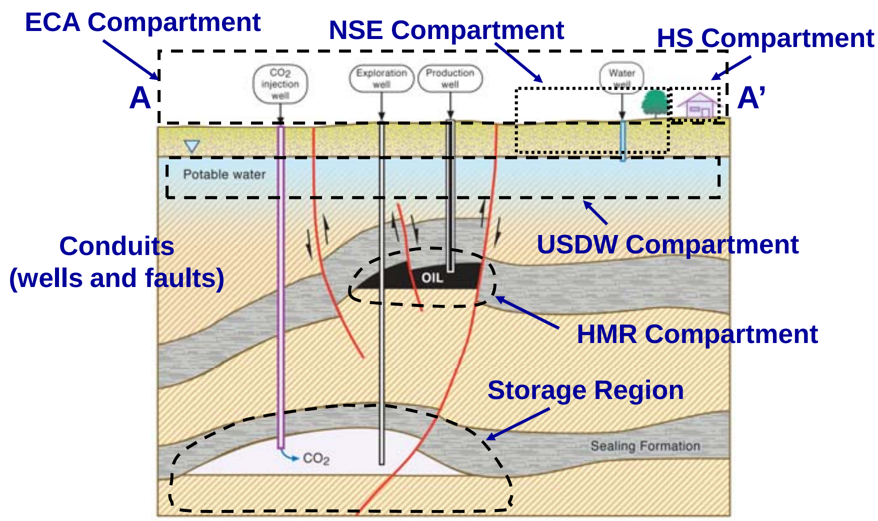
CF Compartments



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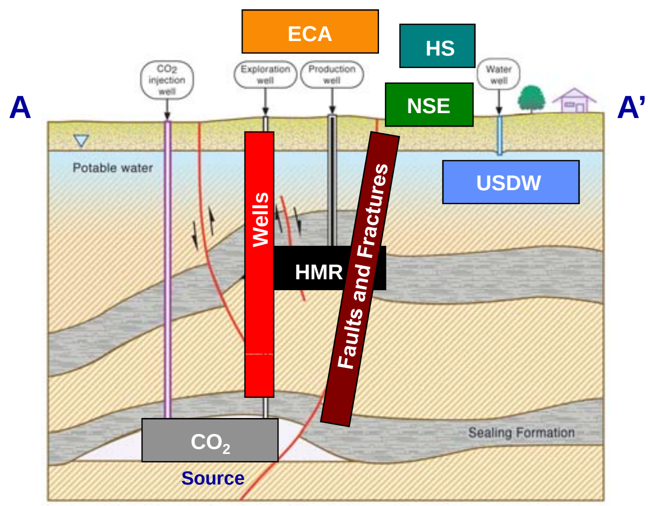
CF Conduits and Compartments



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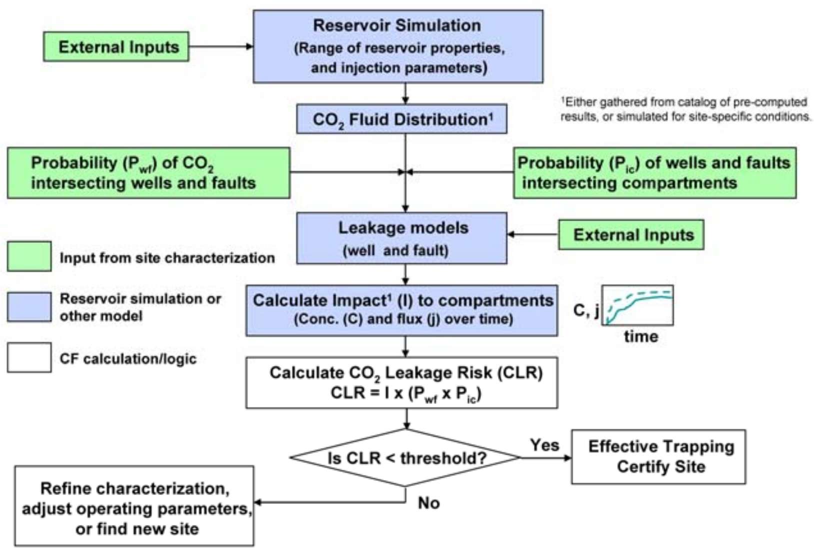
CF Logic



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CF Approach

- **Hazard**
  - **— CO_2 injection as a perturbation to the system**
- **Risk arises from**
  - **— Potential for CO_2 and brine leakage**
  - **— Potential for impacts due to leakage**
- **First step is to define the storage region**
- **Second step is to identify where impacts may occur**
- **Third step is to identify and characterize potential leakage conduits (wells and faults)**
- **Fourth step is to model CO_2 plume and pressure**
- **Fifth step is to evaluate potential for leakage and the associated impacts => calculate risk**

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1. Define Storage Region

First step is to define the storage region

- **— Vedder Formation from injection well to 10 km (6 mi) radius**

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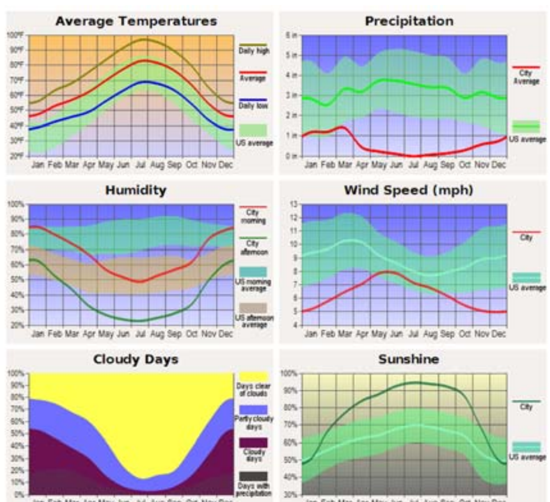
2. Define Vulnerable Entities

- **Topographic relief is minimal.**
- **Agriculture is primary land use (almond orchards).**
- **Site is adjacent to U.S. Route 99 and railroad.**
- **There are a few residences, closest one being 1 km to SW, but generally very sparsely populated.**
- **Calm conditions, inversion, tule fog in winter.**



Bakersfield climate

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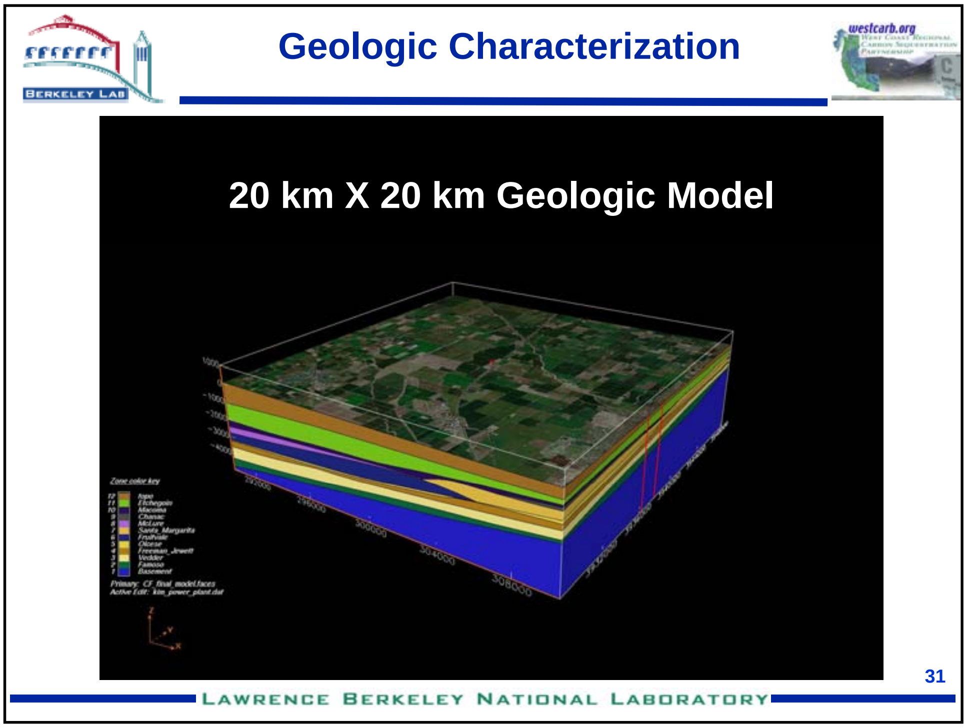
Geologic Characterization
westcarb.org
BERKELEY LAB
20 km X 20 km Geologic Model
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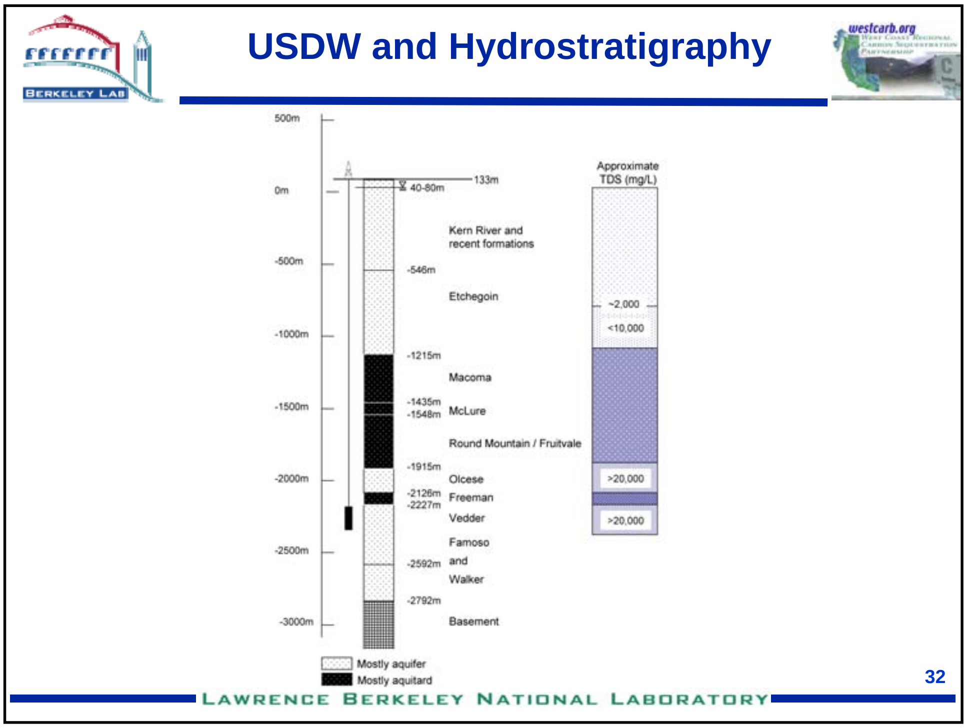
USDW and Hydrostratigraphy
westcarb.org
BERKELEY LAB
500m
0m
-500m
-1000m
-1500m
-2000m
-2500m
-3000m
133m
40-80m
Kern River and
recent formations
-546m
Etchegoin
-1215m
Macoma
-1435m
-1548m
McLure
Round Mountain / Fruitvale
-1915m
Olcese
-2126m
-2227m
Freeman
Vedder
Famoso
and
Walker
-2592m
-2792m
Basement
Approximate
TDS (mg/L)
~2,000
<10,000
>20,000
>20,000
Mostly aquifer
Mostly aquitard
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3a. O&G Wells in 20 km x 20 km Area

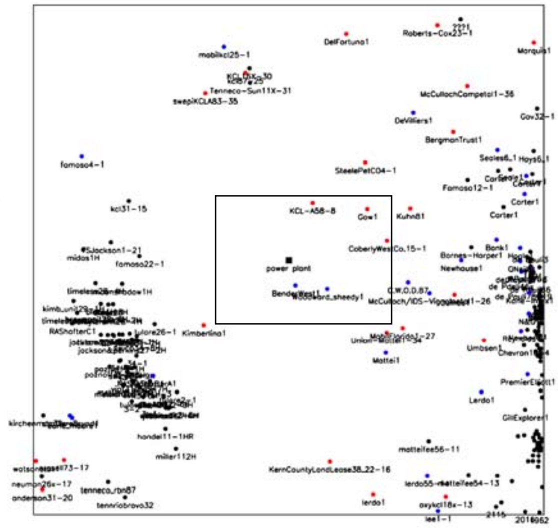
Third step is to characterize potential conduits
- **— wells**

Red => well penetrates top of Vedder

Blue => well terminates shallower than Vedder

Black => no depth data

Wells that penetrate the Vedder Formation



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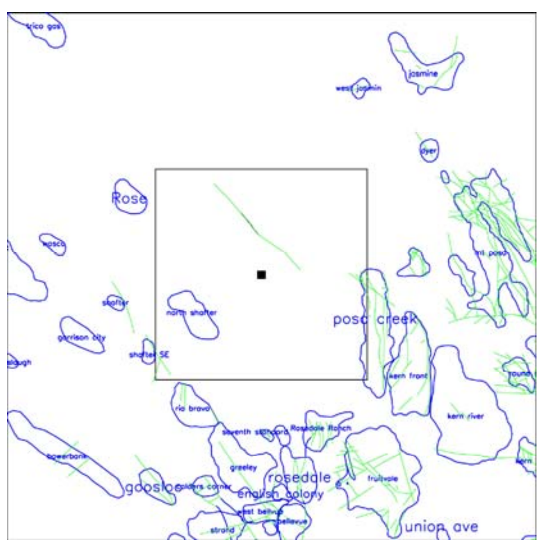
3b. Oil Fields and Faults Near K3 Site

Third step is to characterize potential conduits
- **— Faults (green)**



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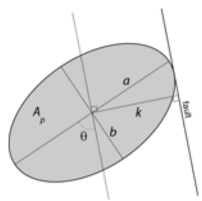
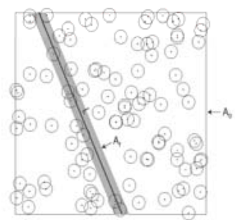
Faults

- There are no faults mapped at the K3 site
- Fundamentally, some concept of fault density is needed to develop a probability of the plume intersecting a fault.
- Faults occur over a wide range of scales => fault density concept requires specification of size of fault.
- In addition, relation between fault orientation and plume shape is important.
- Lacking site-specific fault data, we measured fault statistical properties determined at surrounding oil fields and assumed the same distributions apply at the K3 site.



(the approach described here was developed by Preston Jordan, LBNL)



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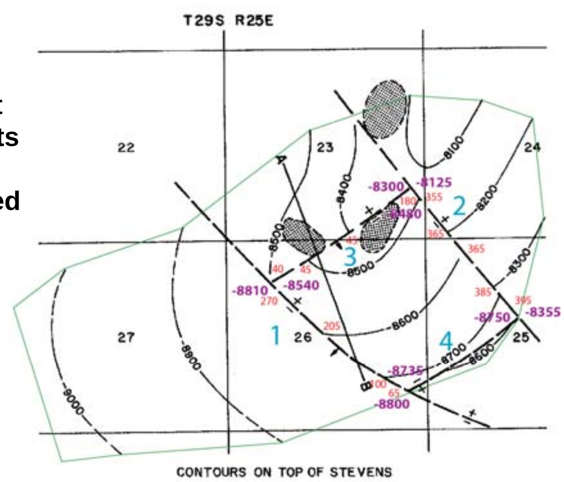
Example Fault Data

- 956 fault segments were measured



Structure Maps in DOGGR, 1998, CA Oil and Gas Fields, V.1

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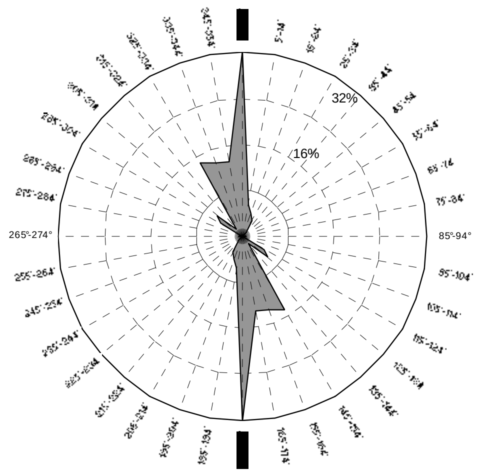
Near-Kimberlina Fault Orientation

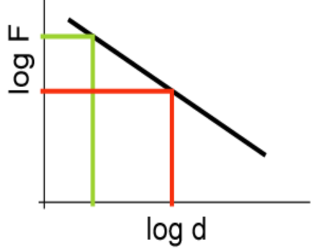


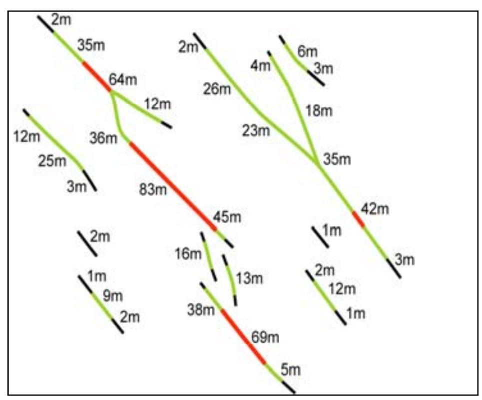
total fault length: 50 mi. (80 km)

Fault Density

$$F = Bd^{-C_d}$$

$$\log(F) = a - b\log d$$

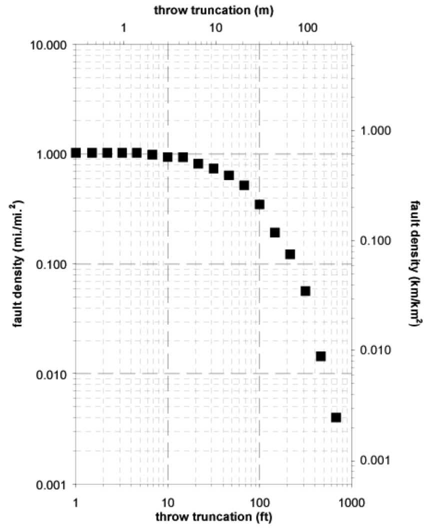




F is the length of fault in an area with greater than a given displacement (*d*)

(Watterson et al., 1996, for instance)

Near-Kimberlina Fault Density



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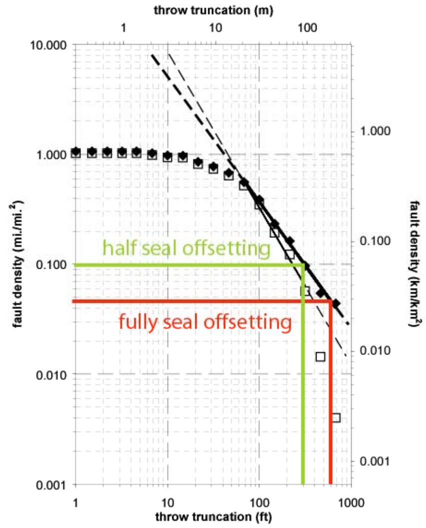
Near-Kimberlina Fault Density (cont'd)



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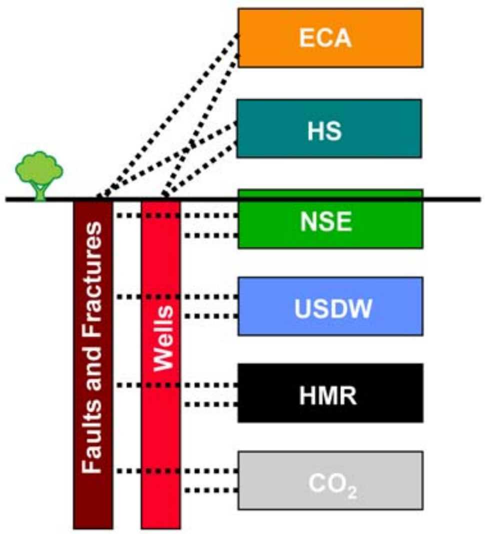
Potential Intersections



- **Emission Credits and Atmosphere**
- **Health and Safety**
- **Near-Surface Environment**
- **Underground Sources of Drinking Water**
- **Hydrocarbon and Mineral Resources**
- **CO_2 source**

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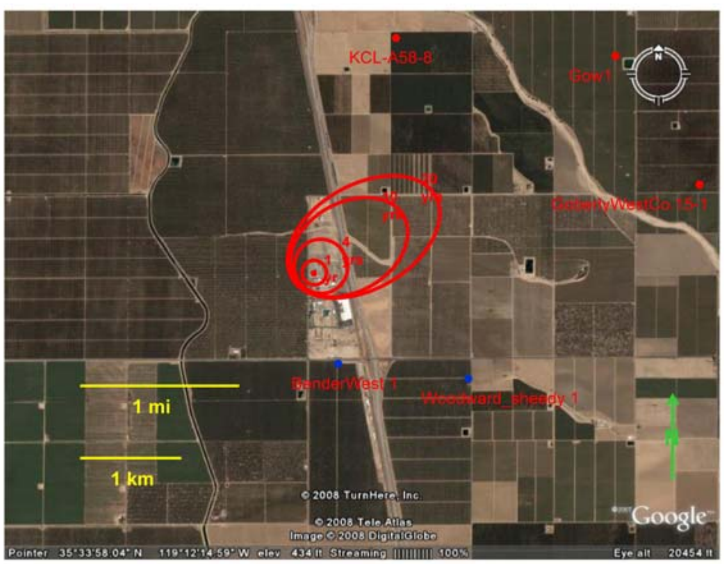
4. Model CO_2 and Pressure



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5. Evaluate Leakage Risk

- Sizes of perturbations
  - — CO_2 plume
  - — Pressure pulse
- Well and Fault intersection probability
  - — CO_2 plume
  - — Pressure perturbation
- Well and Fault flow potential
  - — Permeability
  - — Driving force
- Potential for impacts to compartments
- Overall CLR* and BLR**

*CLR = CO_2 Leakage Risk
**BLR = Brine Leakage Risk

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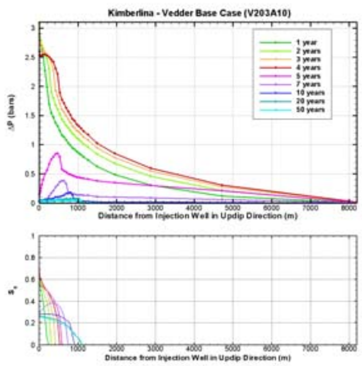
Sizes of Perturbations

CO_2 Plume

Plume is large relative to property lines, small relative to distance to wells and well spacing.

Pressure Perturbation



Pressure pulse is short-lived (<5 years)

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CO_2 Plume Conduit Intersection

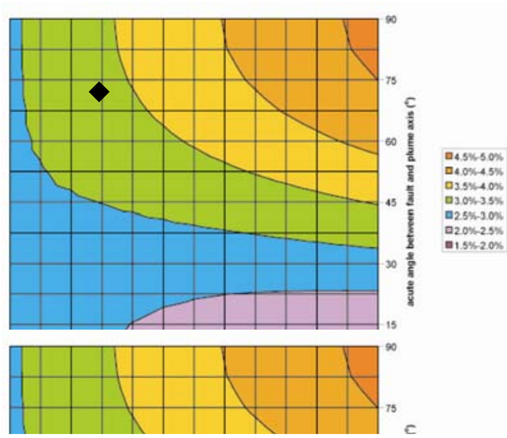
Wells

- Water wells are too shallow to intersect plume.
- Deep wells are sparse.
- CO_2 plume not predicted to intersect deep wells.

Caveats

- Could be unknown wells.
- Plume prediction could be wrong.

Faults



Probability that CO_2 plume will encounter a fault that fully offsets the seal.

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CO_2 Well and Fault Flow Potential

Wells

- Blowouts 1/15,000 over 20 yrs (Jordan and Benson, 2008).
- Most wells are filled with drilling mud or cement or have cement plugs.

Caveats

- Some wells could be open.

Faults

- Shale-gouge ratio (SGR) suggests seal-offsetting faults will be low-k features.

Caveats

- There are no data on faults at the K3 site.
- There is no oil or gas at the K3 site.
- Fault permeability is notoriously uncertain.

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Pressure Pulse Intersection

Wells

- **Multiple wells will be intersected by pressure pulse.**
- **Deep wells are sparse.**

Faults

- **Multiple faults will be intersected by pressure pulse.**

Caveats

- **Could be unknown wells.**
- **Pressure prediction could be wrong.**

Caveats

- **Could be unknown faults.**
- **Pressure prediction could be wrong.**

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Brine Well and Fault Flow Potential

Wells

- **Blowouts 1/15,000 over 20 yrs (Jordan and Benson, 2008).**
- **Most wells are filled with drilling mud or cement or have cement plugs.**
- **Elevated pressure does not necessarily lead to significant upflow.**
  - **Low k**
  - **Density stratified system**

Faults

- **Elevated pressure does not necessarily lead to significant upflow.**
  - **Low k by SGR**
  - **Density stratified system**

Caveats

- **Well properties are uncertain.**

Caveats

- **Fault permeability is notoriously uncertain.**

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Impacts

- **The impacts of potential leakage will be relatively small in this sparsely populated region (e.g., CO_2 discharging at the ground surface).**
- **Emphasis on likelihood of occurrence of low-impact events arises because it is hard to justify expending large resources on modeling low-probability, low-impact events.**
- **Conservative likelihood estimates are consistent with the sparse subsurface data available for the site.**

Table 6-1. Expectation terminology (modified from Hnottavange-Telleen, Schlumberger Carbon Services)

Occurrence expectation terminology	If there were 100 projects like the K3 pilot,
Improbable	…less than once in the 100 projects
Unlikely	…in 1 to 5 of the 100 projects
Somewhat likely	…in 6 to 10 of the 100 projects
Likely	…in 11 to 50 of the 100 projects
Very likely	… more than 50 times within the 100 projects

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Summary

- **We have used the CF approach (along with FEP analysis) to analyze CO_2 and brine leakage risk at the K3 site.**
- **We made use of 3D geologic model, and inventory of wells and associated data near the site.**
- **Lack of data on faulting inspired a novel approach to calculating the probability of encountering faults in a statistical sense.**
- **Numerical simulations with TOUGH2 and CMG-GEM provide defensible predictions of CO_2 plume migration.**
- **Based on these data, simulations, and analyses we find the leakage risk for the K3 pilot project to be de minimis.**
- **Additional data gathering, validation of the novel approaches used here, and modeling should be undertaken as the pilot project proceeds.**

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NETL   westcarb.org West Coast Regional Carbon Sequestration Partnership CO_2 Capture Project

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