Evaluation of Carbon Sequestration in Kansas -- Update on DOE-Funded Project

U.S. DEPARTMENT OF ENERGY

W. Lynn Watney and Saibal Bhattacharya

Kansas Geological Survey
Lawrence, KS 66047

Kansas Next Step Conference
Aug 5, 2010, Hays, KS

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

Outline

Study Goal

Evaluate CO_2 Sequestration Potential in KS

- Deep Saline Arbuckle Aquifer in south-central KS

- Select depleted mature oil fields

Start Date - Dec 2009

No CO_2 will be injected in this 3-year project.

- **Overview - DOE-funded Project - Watney**
- **Subsurface fate of injected CO_2 - Saibal**
- **Update GeoModeling Studies – Watney**
- **Update Reservoir Simulation Studies - Saibal**

http://www.kgs.ku.edu/PRS/Ozark/index.html

"Evaluation of CO_2 sequestration potential in deep saline Ozark Plateau Aquifer System (OPAS) in south-central KS - *depleted oil fields and the deep saline Arbuckle aquifer*"
- American Recovery & Reinvestment Act (ARRA)

DOE Website

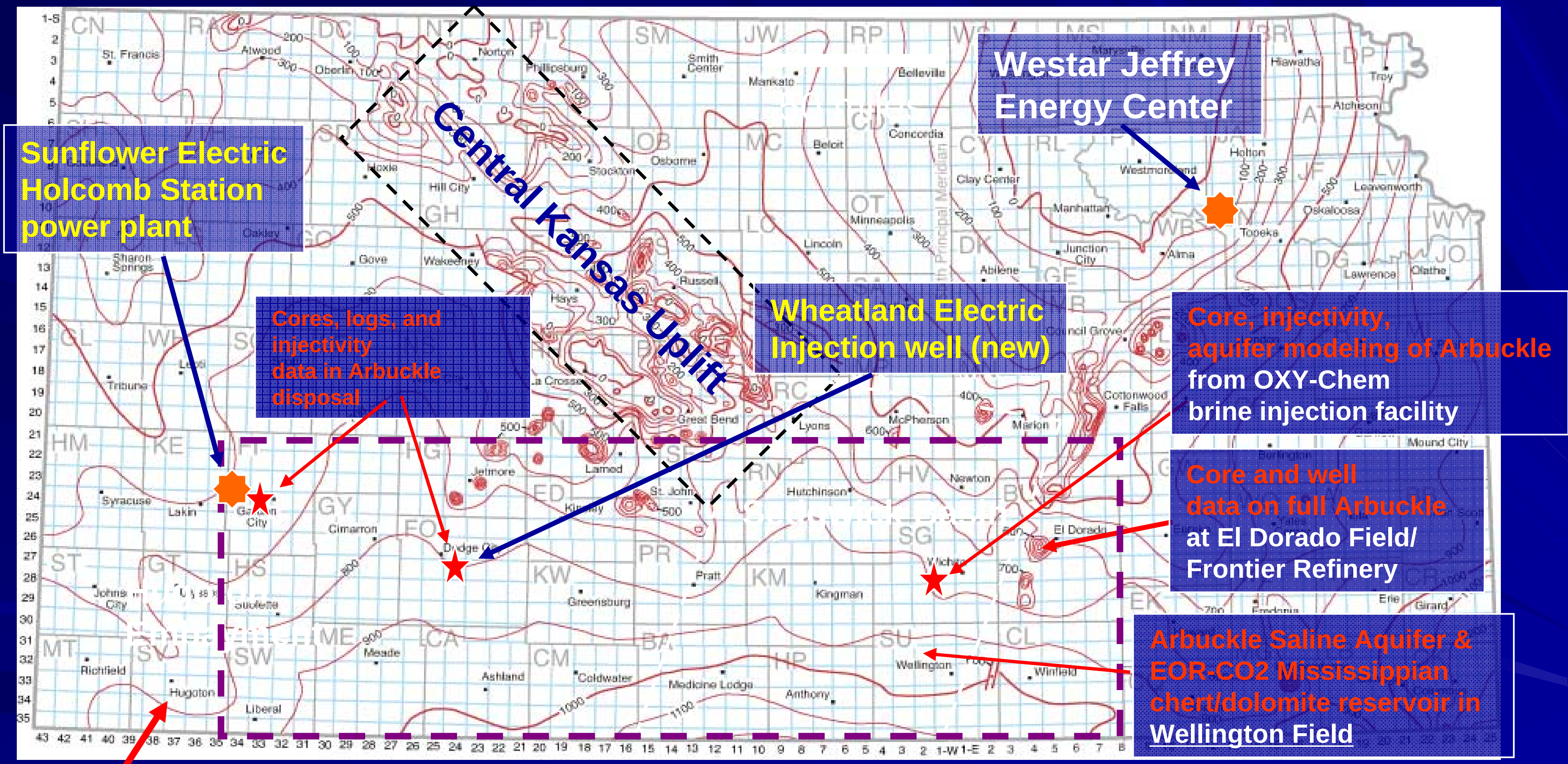
DOE share:
$4,974,352
Match by KGS and partners:
$1,251,422

Principal Investigators:
Lynn Watney & Saibal Bhattacharya

Duration:
December 8, 2009 to December 7, 2012

DOE-CO2 Project Study Area

Wellington Field (Sumner County) + 17+ Counties



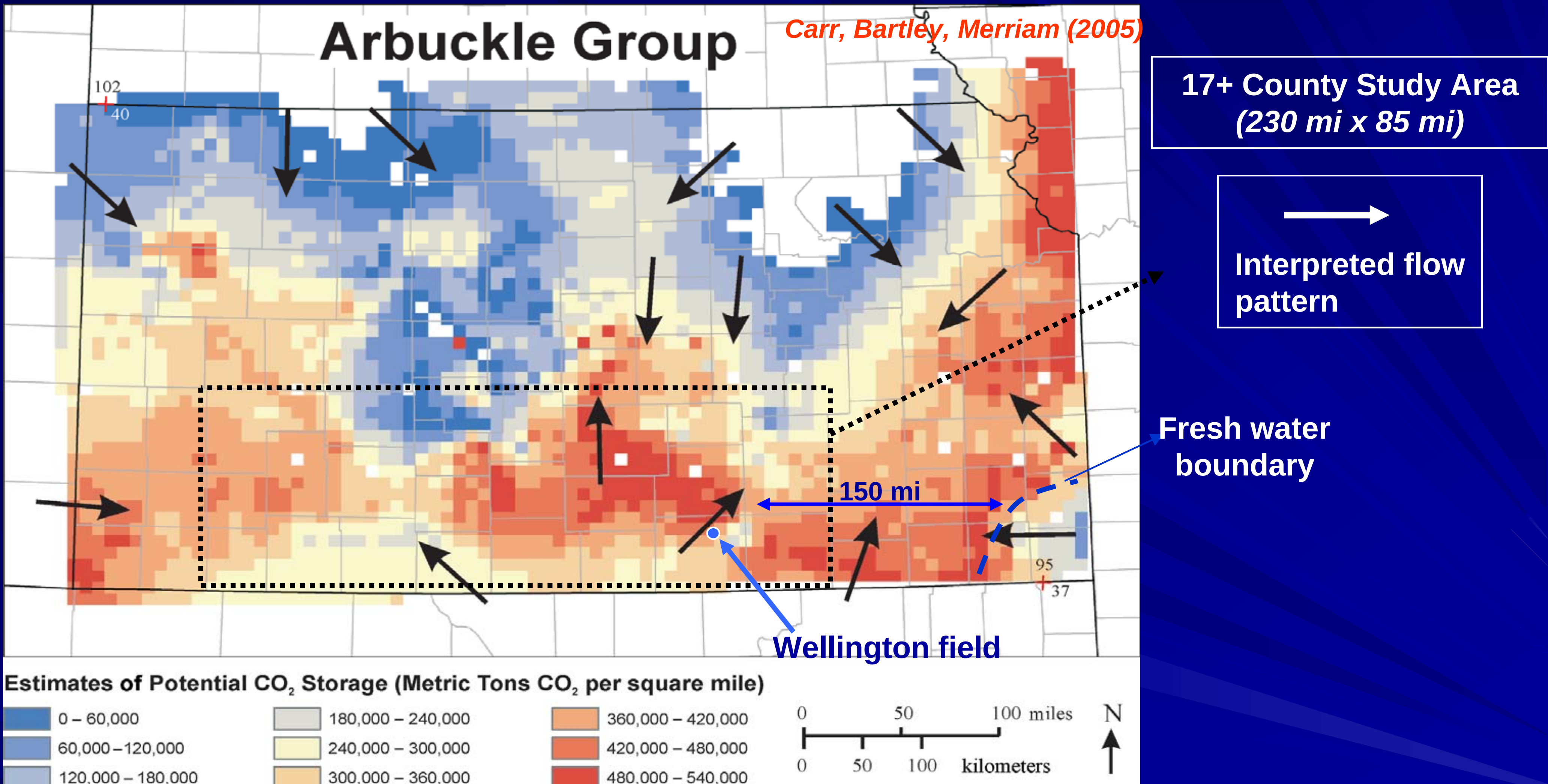
Contours = thickness of Arbuckle Group

Regional study → ~20,000 sq. miles

Relevance of CO_2 Sequestration in KS

- Coal-fired power plants to produce for years in Kansas
- DOE efforts to develop carbon capture and storage (CCS) infrastructure
- Initiatives of the *Midwestern Governors Association*
- CO_2-EOR – proven technology for EOR- select depleted oilfields
- Deep saline aquifers – potential to sequester large volumes of CO_2
  - Arbuckle deep saline aquifer underlies large areas in south-central KS
- KS centrally located to major CO_2 emitting states and cities
- CO_2 sequestration - potential to become a major industry in KS
  - Government incentives
  - Value of CO_2 as commodity
  - Infrastructure
  - Maturation of technology and regulations

CO_2 Sequestration Target
Arbuckle Saline Aquifer



Red Areas – Sequestration capacity - at least 480 thousand metric tons/mi^2

CO_2 emissions - US coal fired power plants 1,787,910 thousand metric tons DOE Report 2000.

Average coal plant of 1.3 million megawatt-hr/yr – 1.2 million metric tons CO_2/yr (≈ 3 mi^2)

Project Objectives

- Build 3 geomodels
  - *Wellington field (Sumner County)*
    - *Depleted Mississippian oil field*
    - *Underlying Arbuckle saline aquifer*
  - *Regional Arbuckle saline aquifer - 17+ counties (south-central KS)*
- Conduct simulation studies to estimate CO_2 sequestration potential
- Arbuckle saline aquifer - 17+ county area
  - Identify potential sequestration sites
  - Estimate sequestration capacity of Arbuckle saline aquifer in KS
- Risk analysis related to CO_2 sequestration
- Technology transfer

Subjects Outside the Purview of this Project

- CO_2 capture from point sources
- CO_2 transmission – from source to injection sites
- Who owns the pore space?
- CO_2 injection regulations
- Leakage monitoring
- Liability

Other DOE projects, ongoing and future, relate to CO_2 capture and transportation.

Newly funded DOE Project at KGS – "Prototyping and testing a new volumetric curvature tool for modeling reservoir compartments and leakage compartments in the Arbuckle saline aquifer: Reducing uncertainty in CO2 storage and permanence"

PIs: Jason Rush & Saibal Bhattacharya

Industry Partner: Murfin Drilling Co. (Wichita)

Project Time Line

	Year 1	Year 2	Year 3
Regional geomodel development of Arbuckle saline aquifer			
Collect, process, interpret 3D seismic data - Wellington field			
Collect, process, interpret gravity and magnetic data - Wellington field			
Drill, core, log, and test - Well #1			
Collect, process, and interpret 2D shear wave survey - Well #1			
Analyze Mississippian and Arbuckle core			
PVT - oil and water			
Geochemical analysis of Arbuckle water			
Cap rock diagenesis and microbiology			
Drill, log, and test - Well #2			
Complete Wellington geomodels - Arbuckle and Mississippian reservoirs			
Evaluate CO2 sequestration potential in Arbuckle underlying Wellington			
Evaluate CO2 sequestration potential in CO2-EOR in Wellington field			
Risk assessment - in and around Wellington field			
Regional CO2 sequestration potential in Arbuckle aquifer - 17+ counties			
Technology transfer			

Data Collection

CO_2-Seq Potential - Wellington

CO_2 Seq Potential - Arbuckle 17+ Counties

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DEPARTMENT OF GEOLOGY
KANSAS STATE UNIVERSITY

KU THE UNIVERSITY OF KANSAS Department of Geology

BEREXCO

PARAGON
GEOPHYSICAL SERVICES, INC

fairfieldnodal

noble energy

LOCKHART GEOPHYSICAL

ECHO GEOPHYSICAL CORPORATION
INTEGRITY-STABILITY-INNOVATION

HALLIBURTON

HEDKE-SAENGER GEOSCIENCE, LTD

Bittersweet Energy Inc.

Petrotek

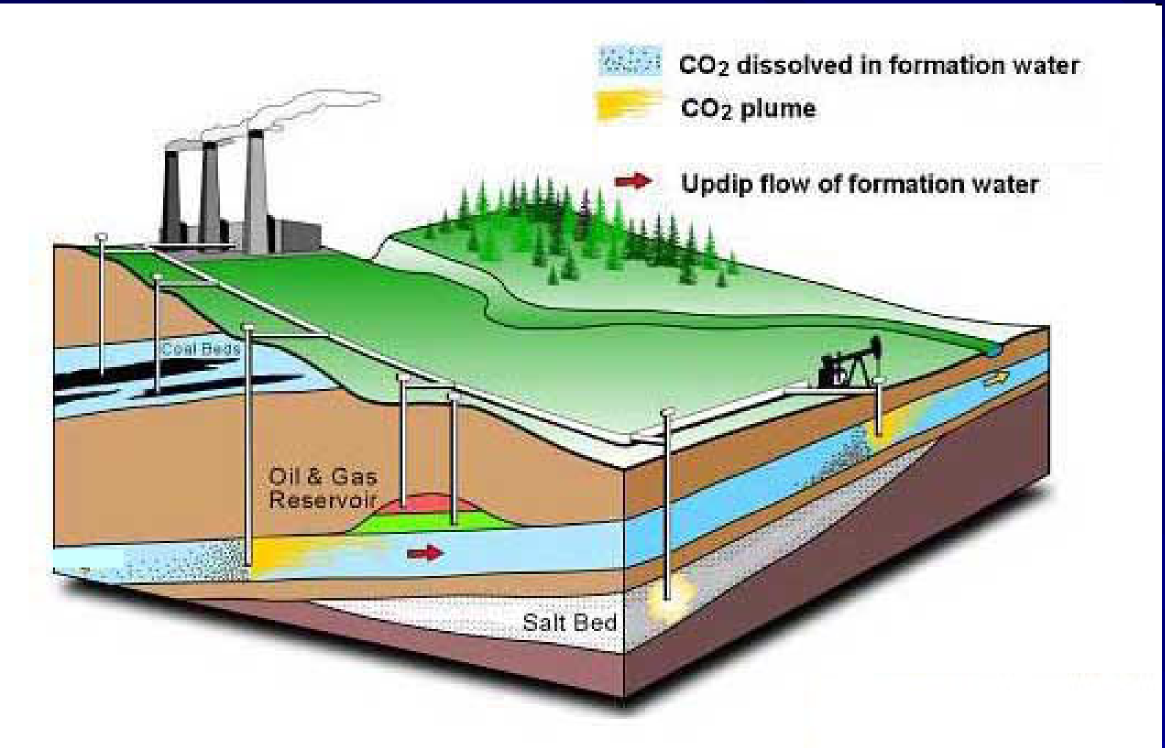
Charter Consulting
Integrated Geology & Geophysics

KOGER
REMOTE SENSING

LOGDIGI
A LEADING CONSULTING COMPANY

Subsurface fate of injected CO_2

Preeminence of Deep Saline Aquifer



Industry participation in infrastructure development possible if CO_2-EOR is viable

Global annual CO_2 emissions ≈ 8 * 10^9 tons

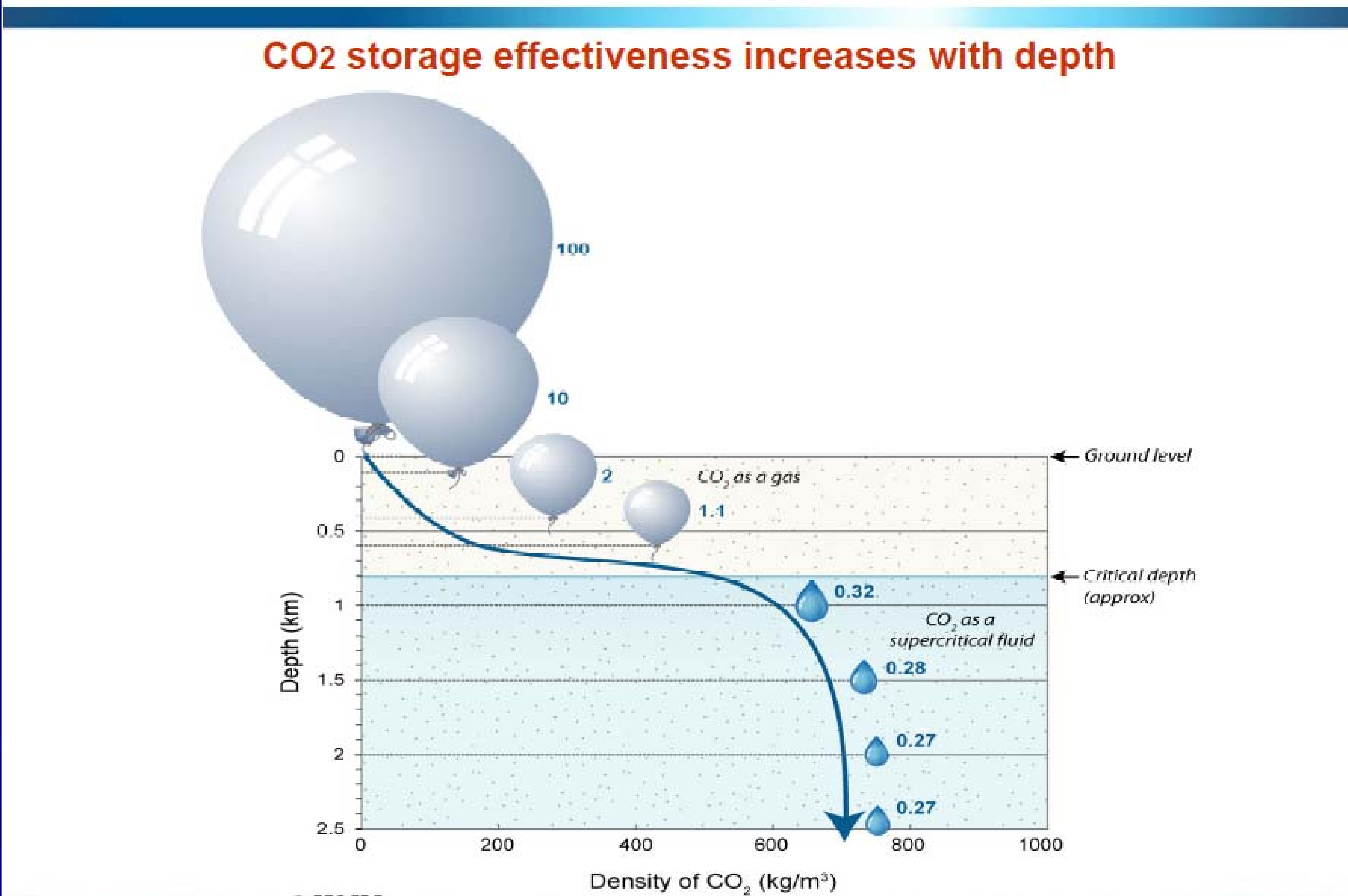
Earth Policy Institute

>400 yrs Current → Global emissions

Formation Type	*10^9 Metric Tons*	*%*
Saline Aquifers	3,297 – 12,618	91.8 – 97.5
Unmineable Coal Seams	157 – 178	4.4 – 1.4
Mature Oil & Gas Reservoirs	138	3.8 – 1.1
Total Capacity	3,592 – 12,934	100.0

DOE & NETL, "Carbon Sequestration Atlas of the US and Canada", 2008

Effectiveness of Injecting Supercritical CO_2



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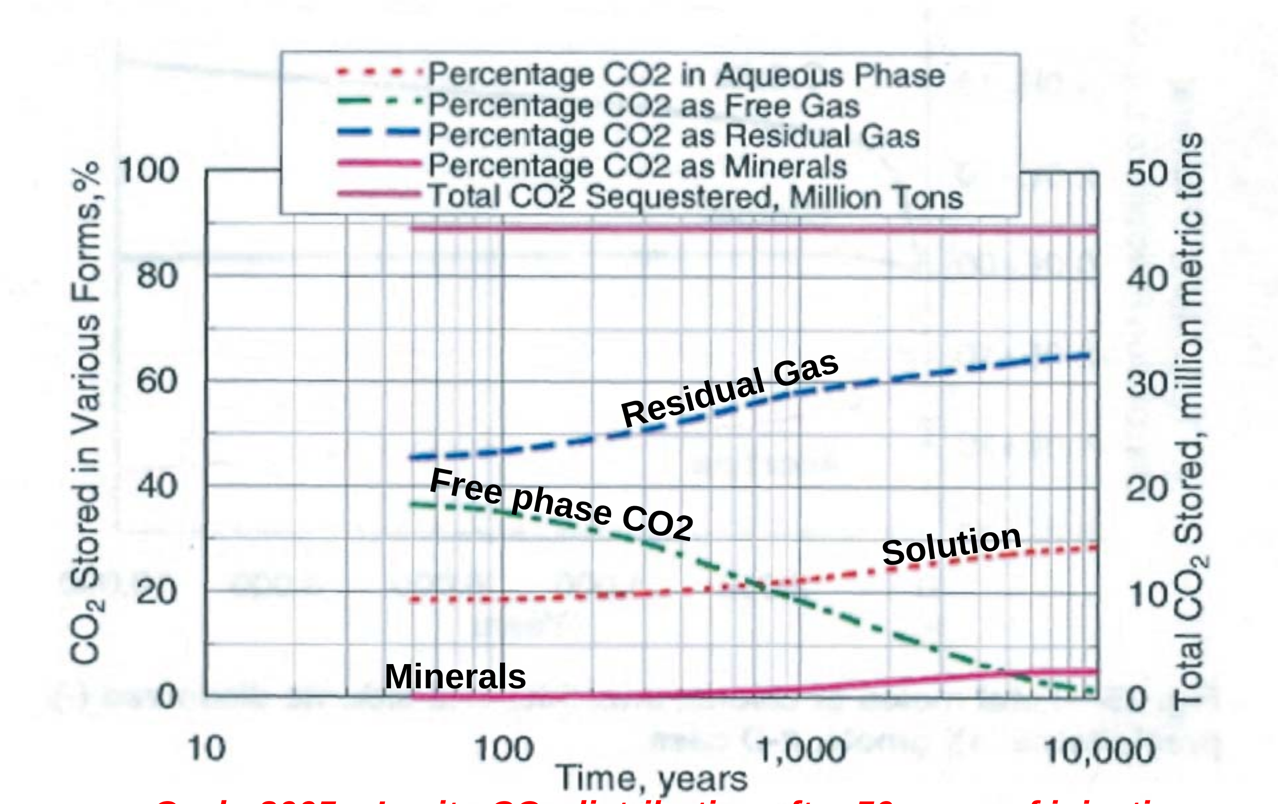
CO2CRC

In situ fate & entrapment of CO_2

Injected CO_2 entrapped in 4 different ways

- **some dissolves in brine**
- **some gets locked as residual gas (saturation)**
- **some trapped as minerals**
- **Remaining CO_2 – resides as free phase**
  - **Sub- or super-critical as per *in situ* conditions (depth/pressure and temperature)**



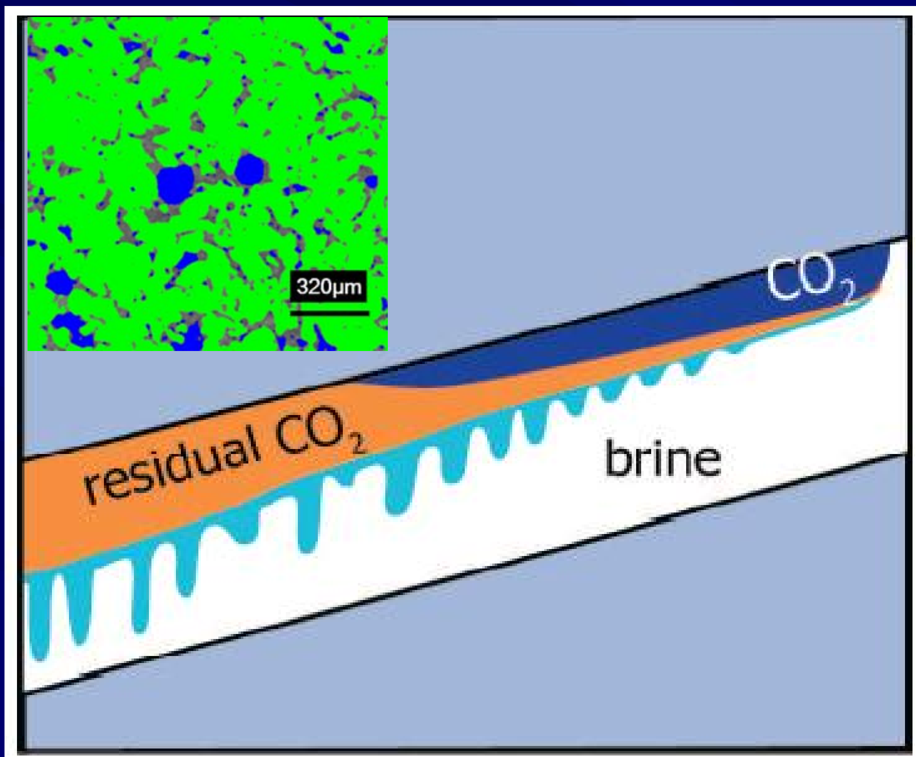
Ozah, 2005 – In situ CO_2 distribution after 50 years of injection

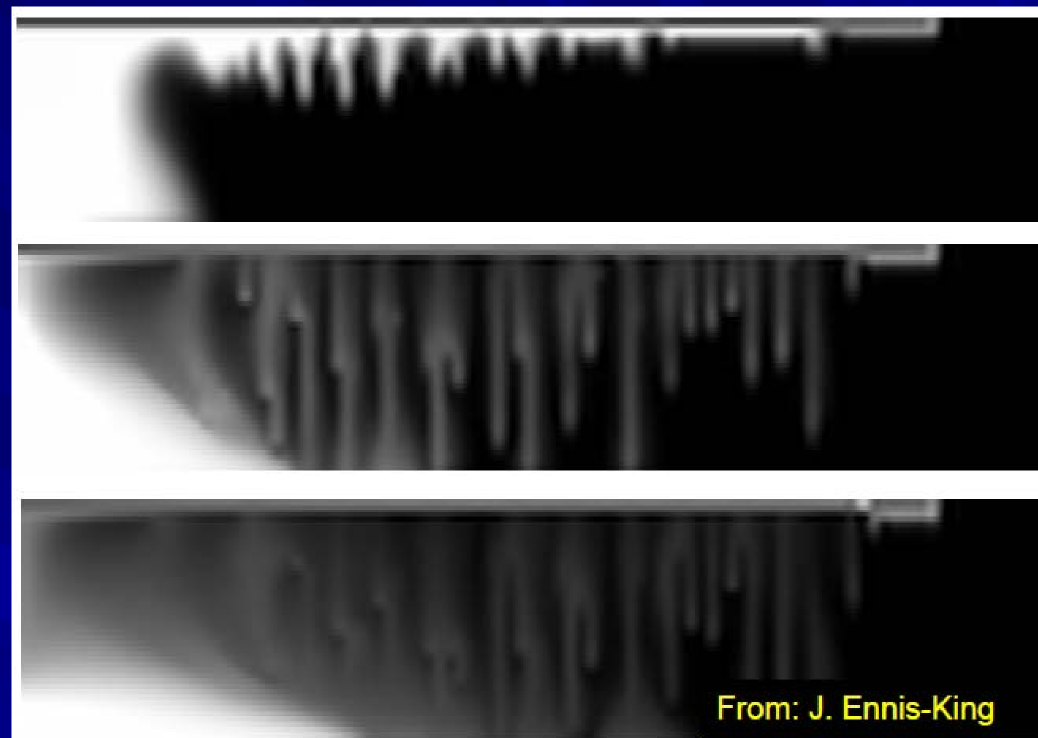
<u>CO_2 Entrapment Audit:</u>

1. ***Residual gas***
   - ***Start 45% to End 65%***
2. ***Solution***
   - ***Start 18% to End 28%***
3. ***Minerals***
   - ***Start negligible to End 5%***
4. ***Free Phase***
   - ***Start 37% to End 2%***

Dissolution of CO_2 in Brine

Convection Cycle increases entrapment





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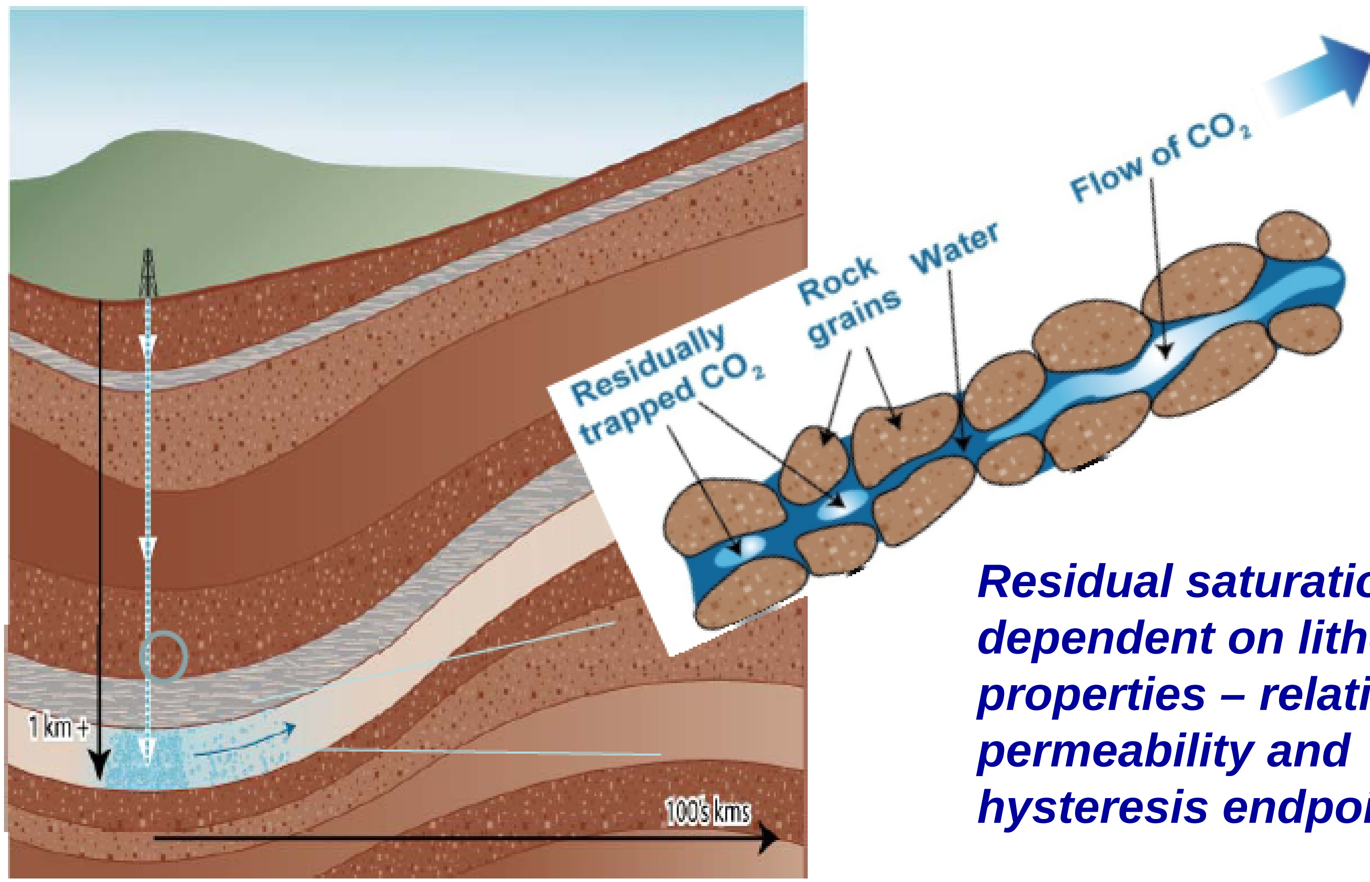
CO_2 Entrapment as Residual Gas

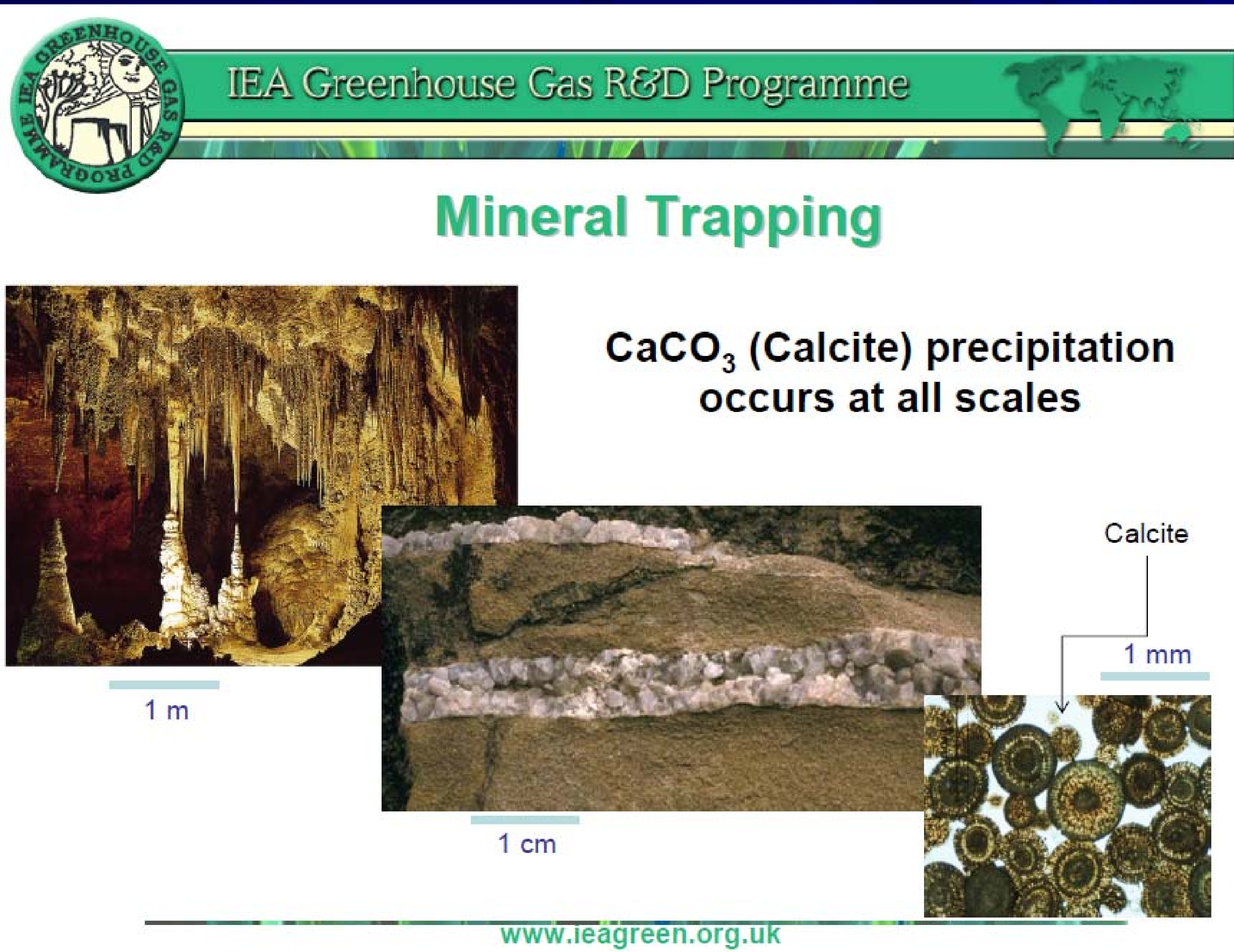
IEA Greenhouse Gas R&D Programme

Residual Trapping



Residual saturation dependent on lithofacies properties – relative permeability and hysteresis endpoints

CO_2 Entrapment as Minerals



Very slow process.

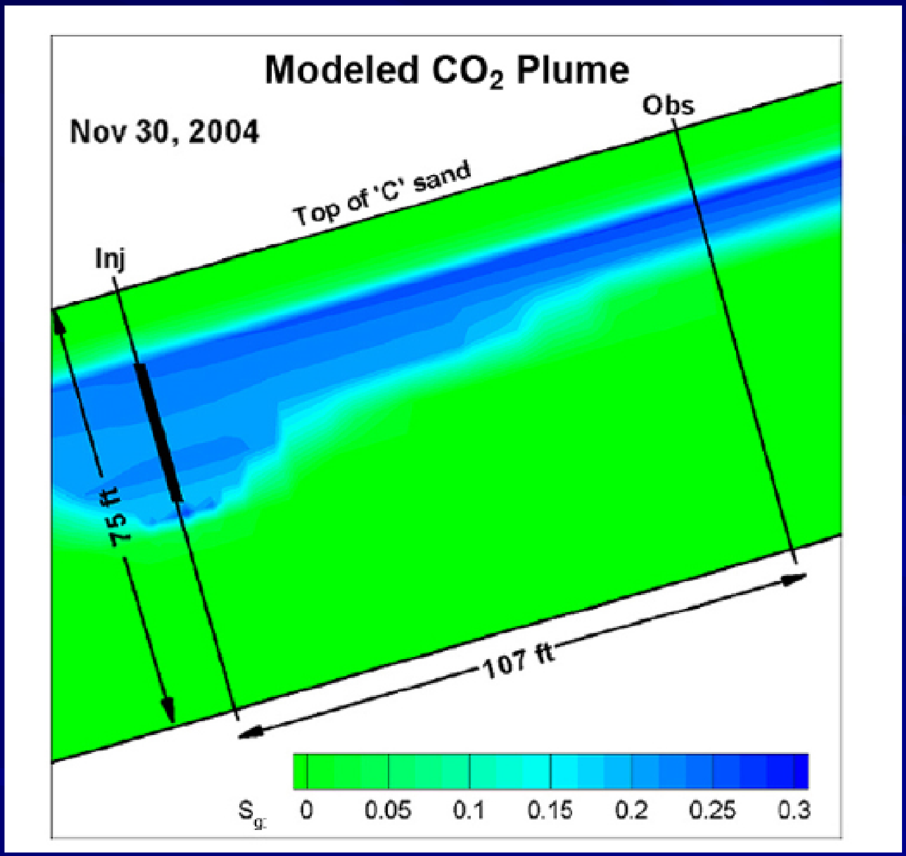
Important effects –

1) Precipitation leading to injectivity changes.

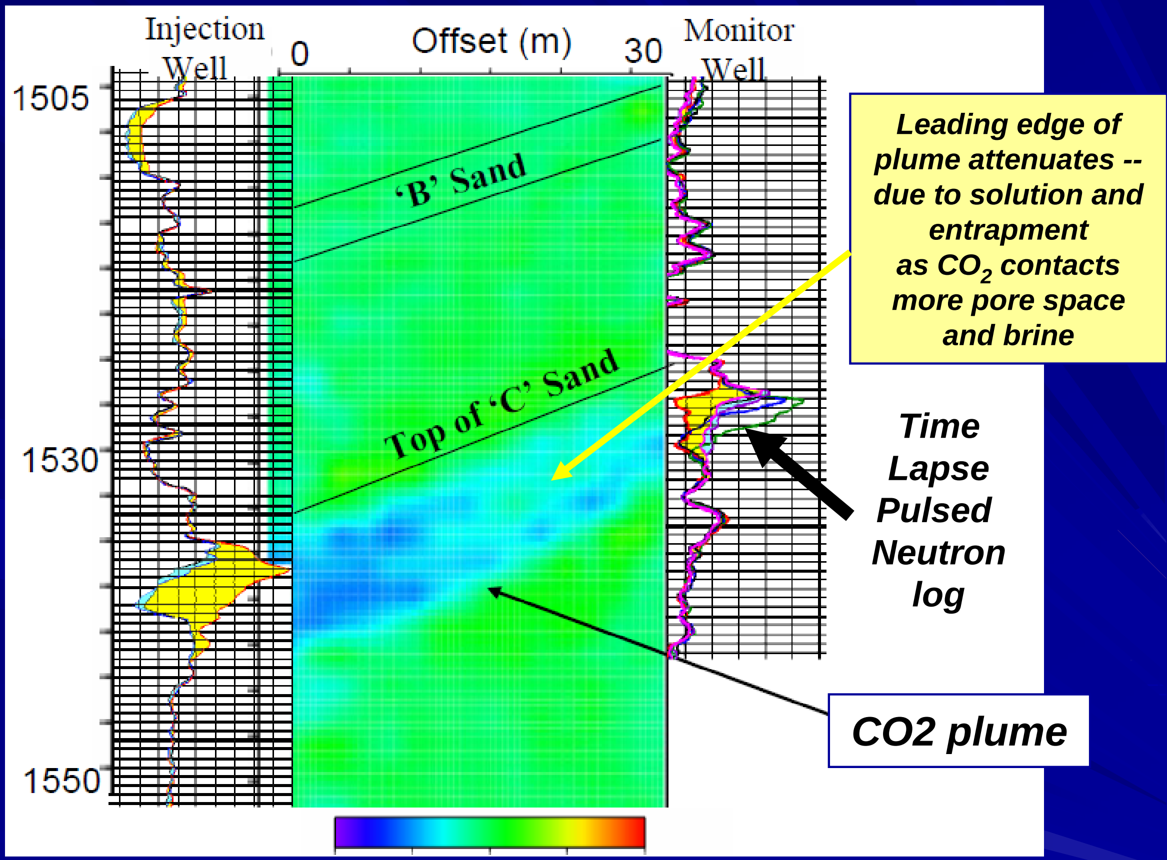
2) Dissolution and creation of cavities -- Adversely affect integrity of the caprock.

Frio Pilot Injection (Texas)
-- free phase supercritical CO_2 plume

Plume from Simulation



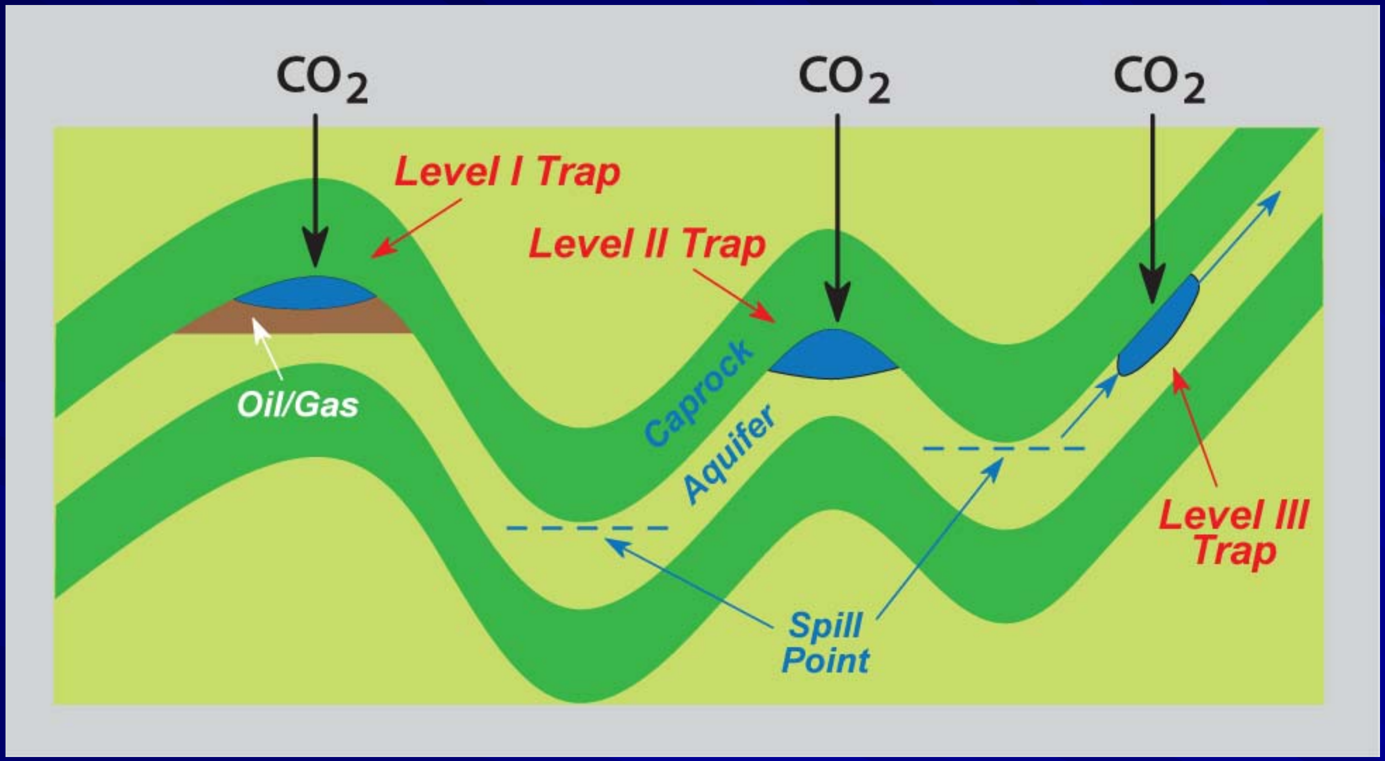
Plume from cross-well seismic tomogram



Current tools (geologic modeling, reservoir simulation, wireline logging, 3D seismic) are capable of tracking subsurface CO_2 migration.

Hovorka et al., 2006, 4-20-06 NETL Fact Sheet & Daley et al., 2007

CO_2 Injection Strategies

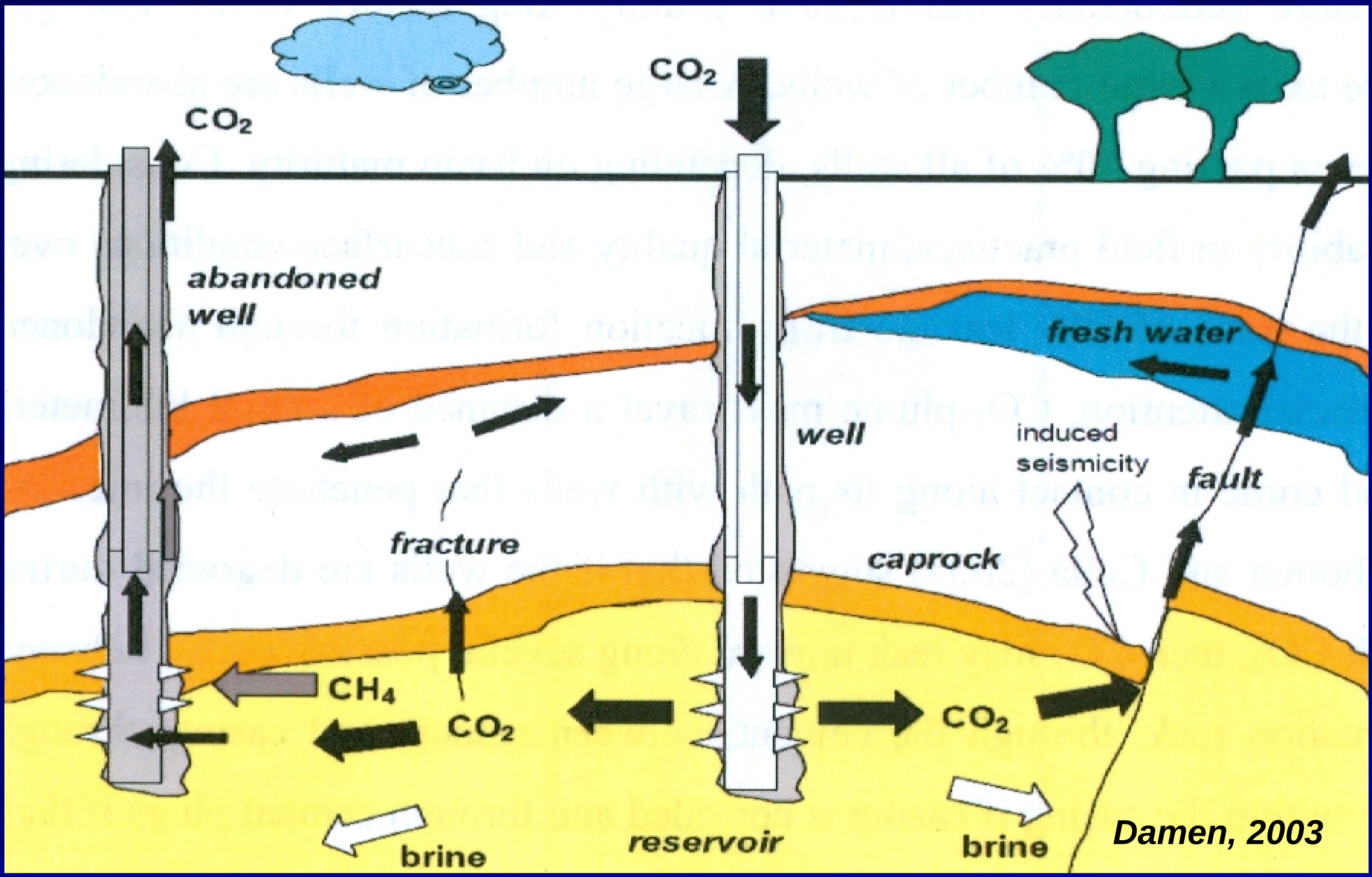


Level I Trap – solubility in oil and water, CO_2 pressure under cap rock, plume contained, CO_2 breakthrough at producing wells

Level II Trap – solubility in brine (convection), CO_2 pressure under cap, plume contained – HIGH RISK

Level III Trap – solubility in brine (convection), entrapment as residual gas, upward migration and dissolution of plume – LOWER RISK (in absence of conduits to surface)

Leakage Pathways
Conduits to the Surface

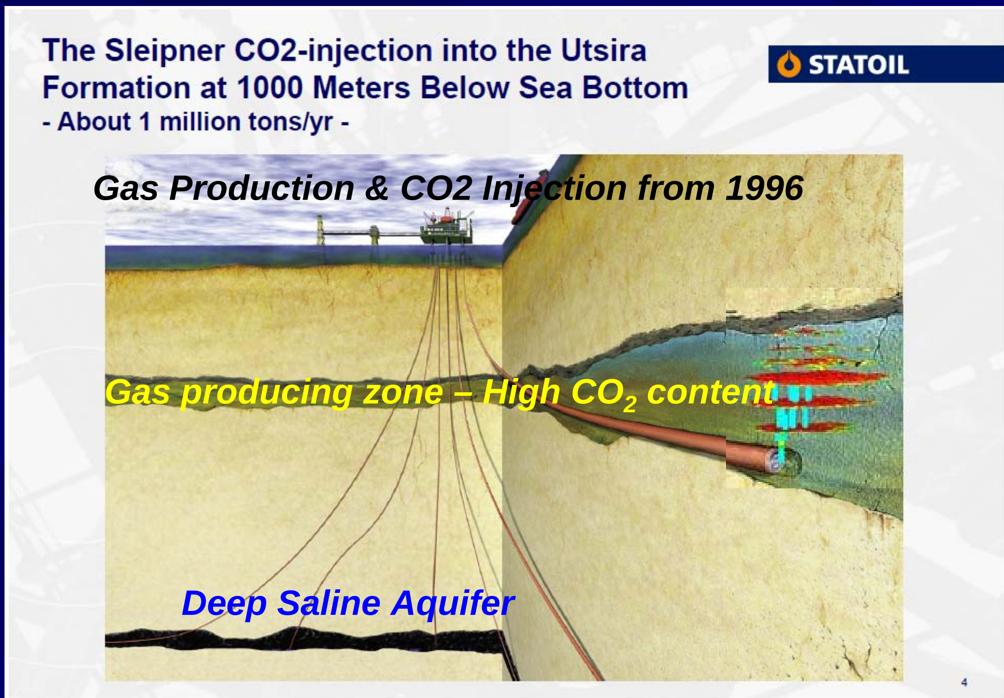


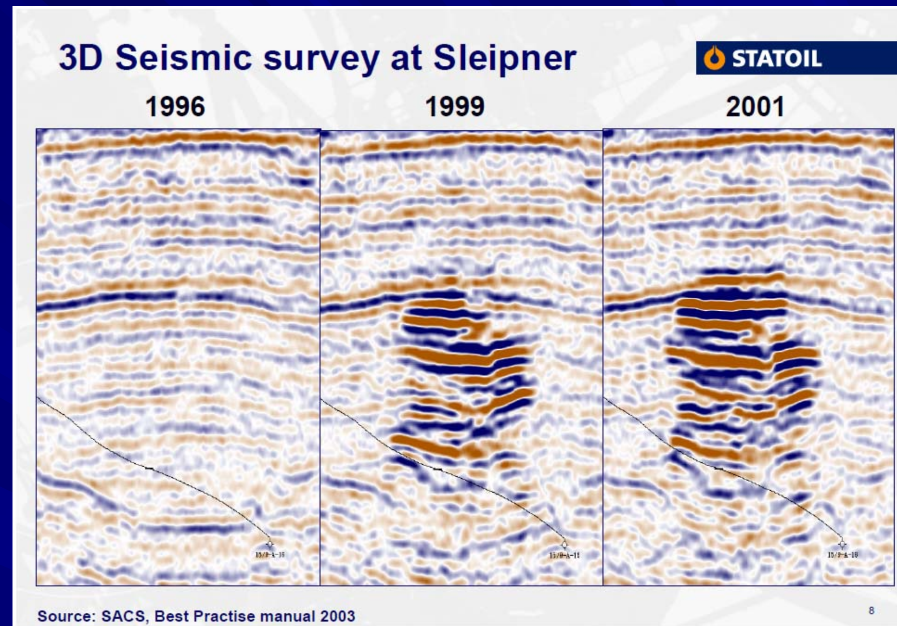
Faults and fractures will be mapped in the 17+ county study area:

1. **Satellite imagery**
2. **Gravity/magnetic**
3. **Structure, isopach, and petrophysical maps**

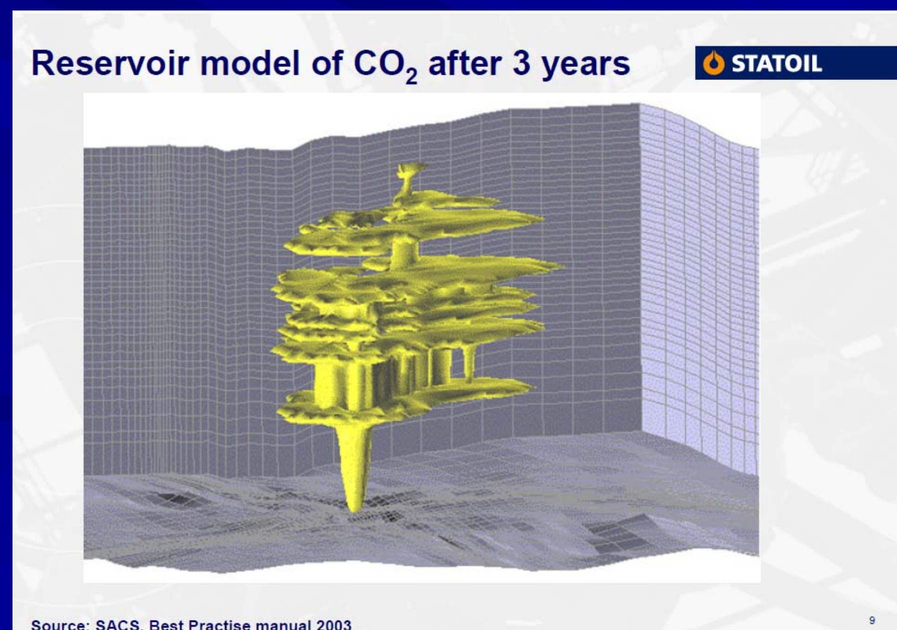
Site selection critical to minimize risks associated with CO_2 injection
Not all fractures/faults reach the surface – some do and need to be identified
Inventory of all plugged wells critical – REPLUG if needed.

CO_2 Sequestration in Heterogeneous Aquifer
Seismic Monitoring Results - Sleipner field (North Sea)





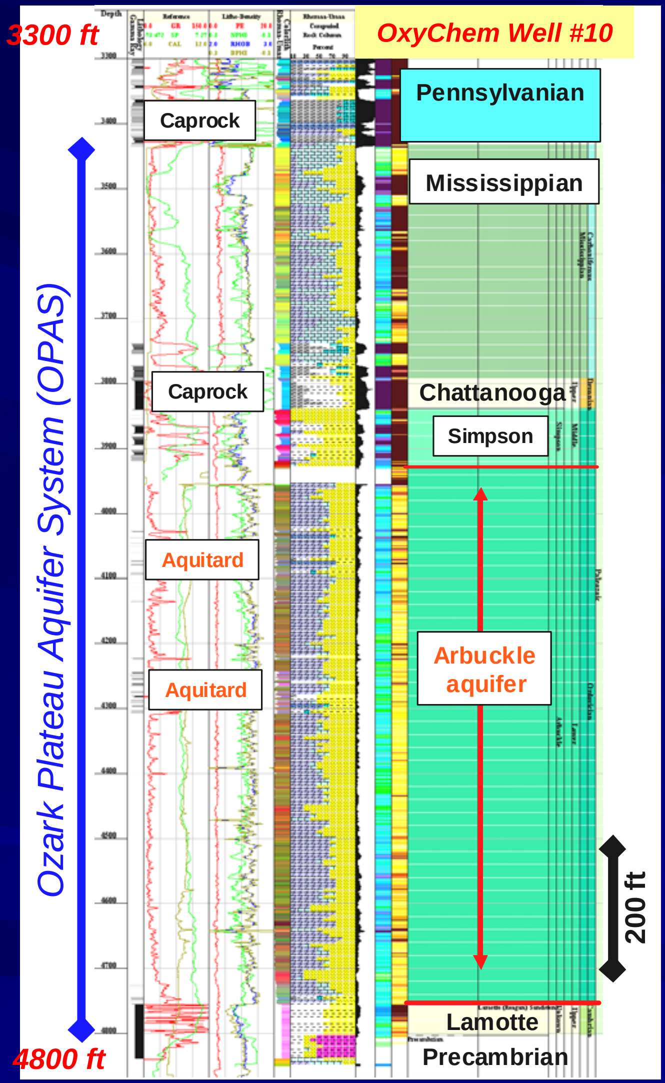
Every time the CO_2 plume meets a thin shale layer (< 5 m), it spread out laterally. This lateral dispersion results in additional sequestration and plume degradation - CO_2 dissolving into fresh brine and getting trapped in fine pores of the rock. *Torp & Gale, 2003*



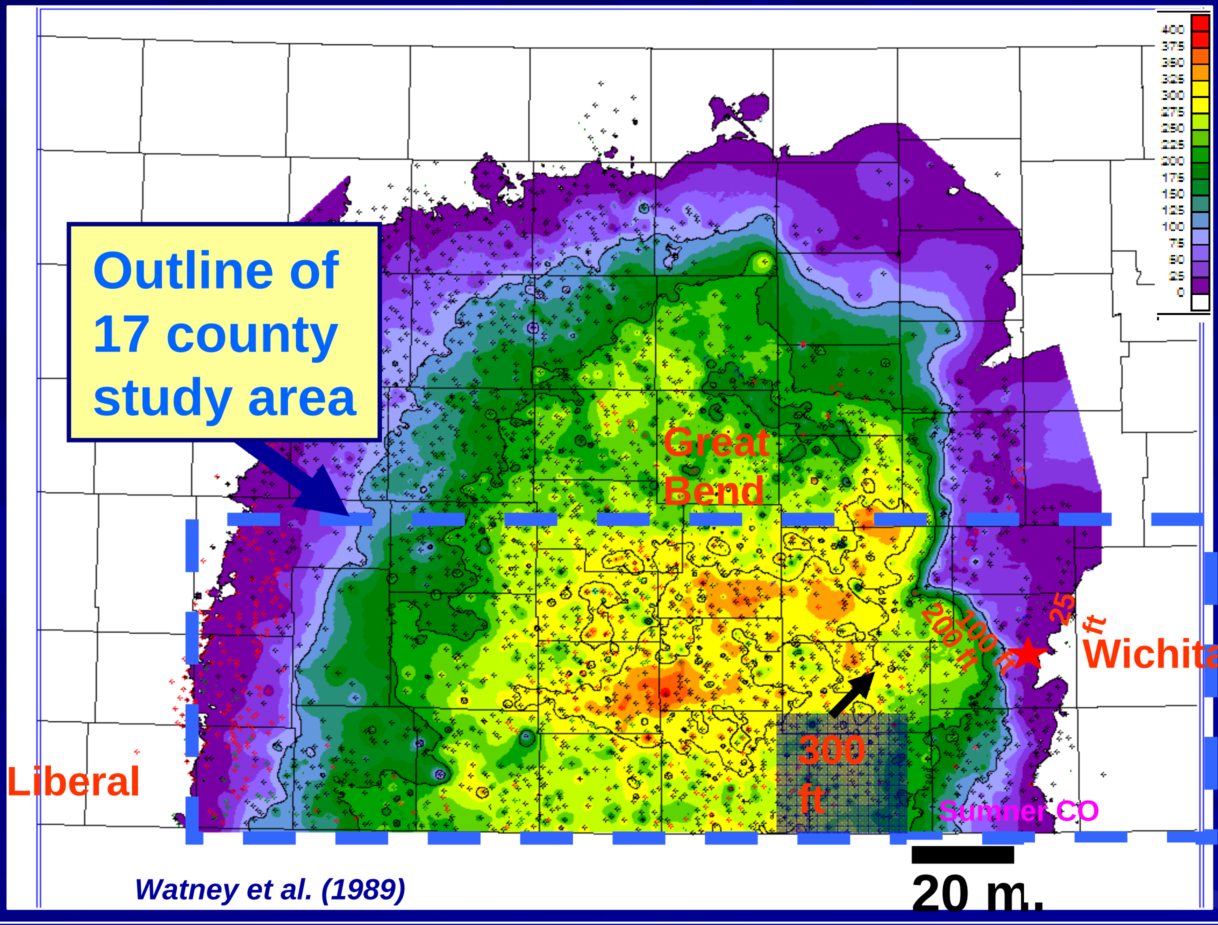
Shale layers (stratification) and aquitards – are present in the Arbuckle aquifer system.

Hydrostratigraphy – Project Study Area

Multiple Caprocks & Aquitards - Leakage Attenuation



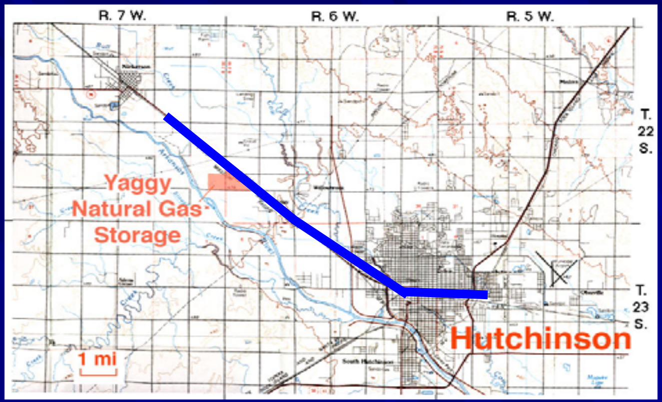
Net Halite (salt) Isopach (thickness), CI 100'

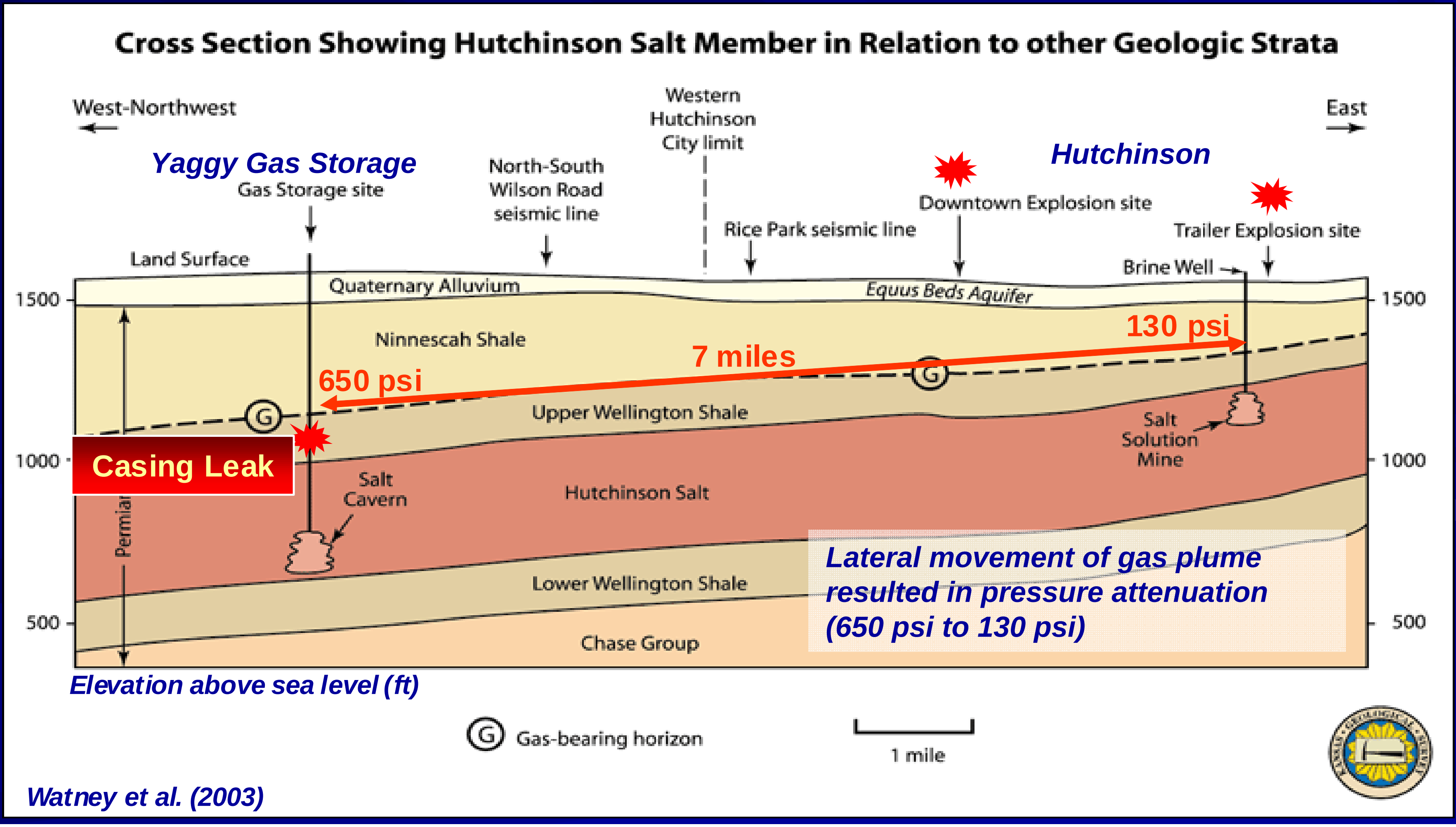


Total Permian evaporite thickness ranges from 400 to 2000' in south-central KS. These evaporites serve as ideal cap rocks being located between shallow freshwater aquifers and hydrocarbon bearing strata and deeper Arbuckle saline aquifer.

Yaggy Gas Storage Leak - 2001

Site selection for CO_2 sequestration CRITICAL, because all wells drilled in the area <u>have</u> to be accounted for and properly completed before onset of CO_2 injection.



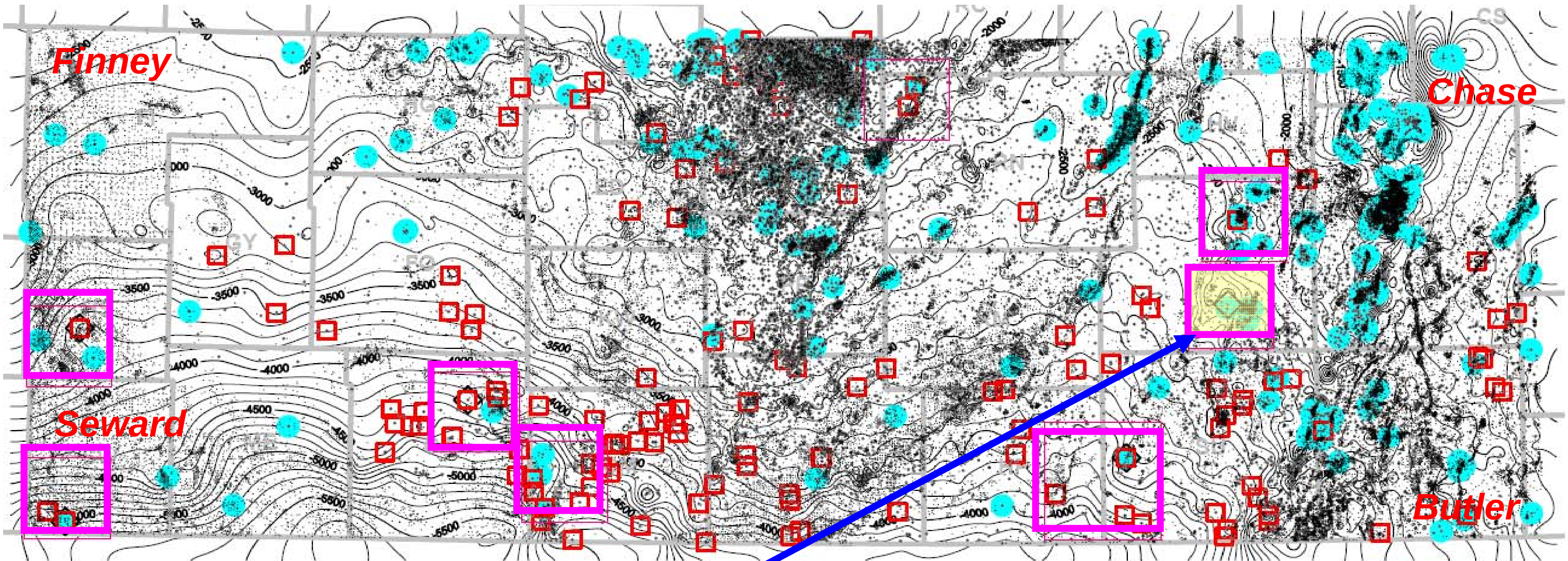


Update on Geomodeling Studies

Proposed criteria to select possible sites for saline aquifer sequestration :

- Precambrian test with log suite containing 3 porosity tools.
- Several wells that penetrate into the Arbuckle with good wireline log combinations.
- Top of the Arbuckle should have a synclinal or monoclinal structural attitude (*not anticlinal closure*).
- Continuity of strata and associated lithofacies.
  - Where stratigraphic truncations, faulting, or fracture systems not significant to disrupt flow units, aquitards, aquicludes, and caprock.
  - Eliminate indication of through going fault/fracture system
- Accommodate commercial quantities of CO2 (*30+ million tons/~510 BCF*)
- Contributions to regional study by Bittersweet subcontract team –
  - Tom Hansen, Paul Gerlach, Larry Nicholson, Ken Cooper, John Lorenz, and students

Areas of Interest
CO_2 sequestration in Arbuckle Saline Aquifer



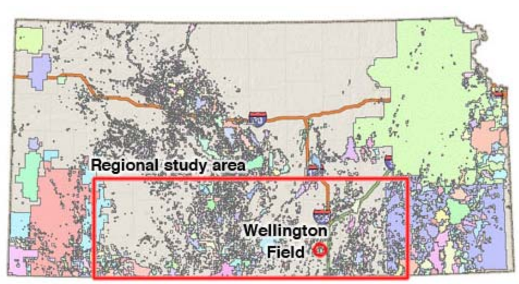
AREAS OF INTEREST

P-C Tests

Dens-Neu-Sonic Raster

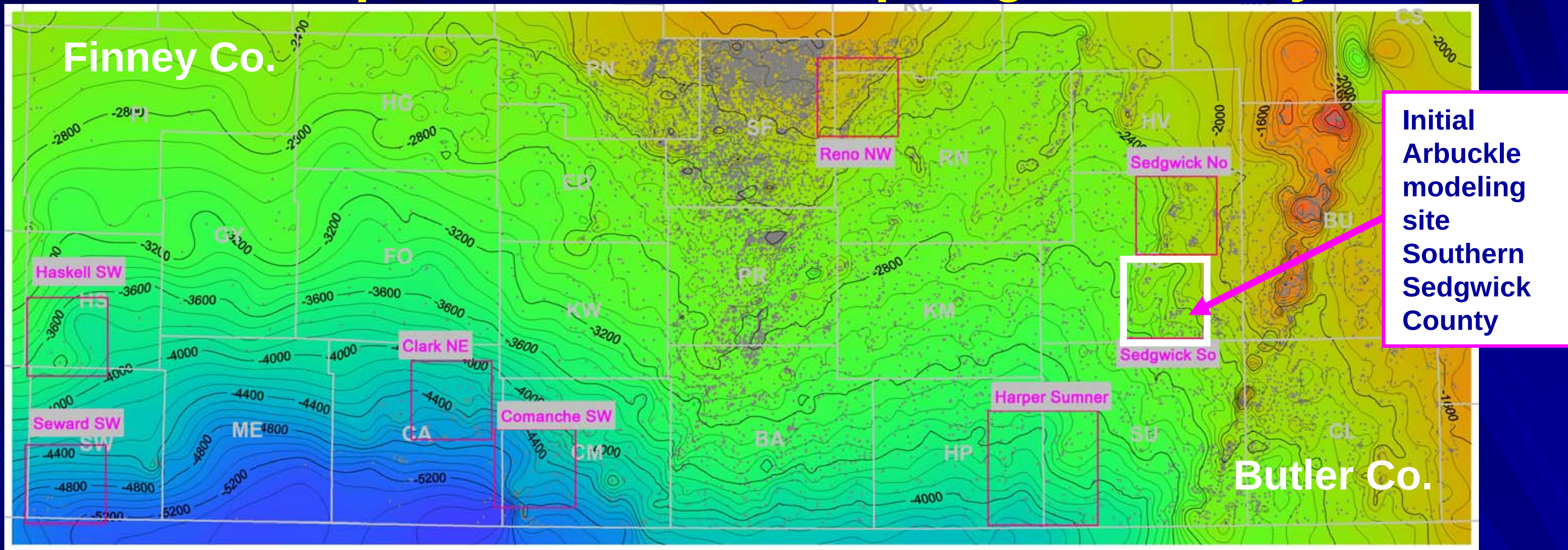
Dens-Neu-Sonic Vector

Initial Arbuckle modeling site -- southern Sedgwick County



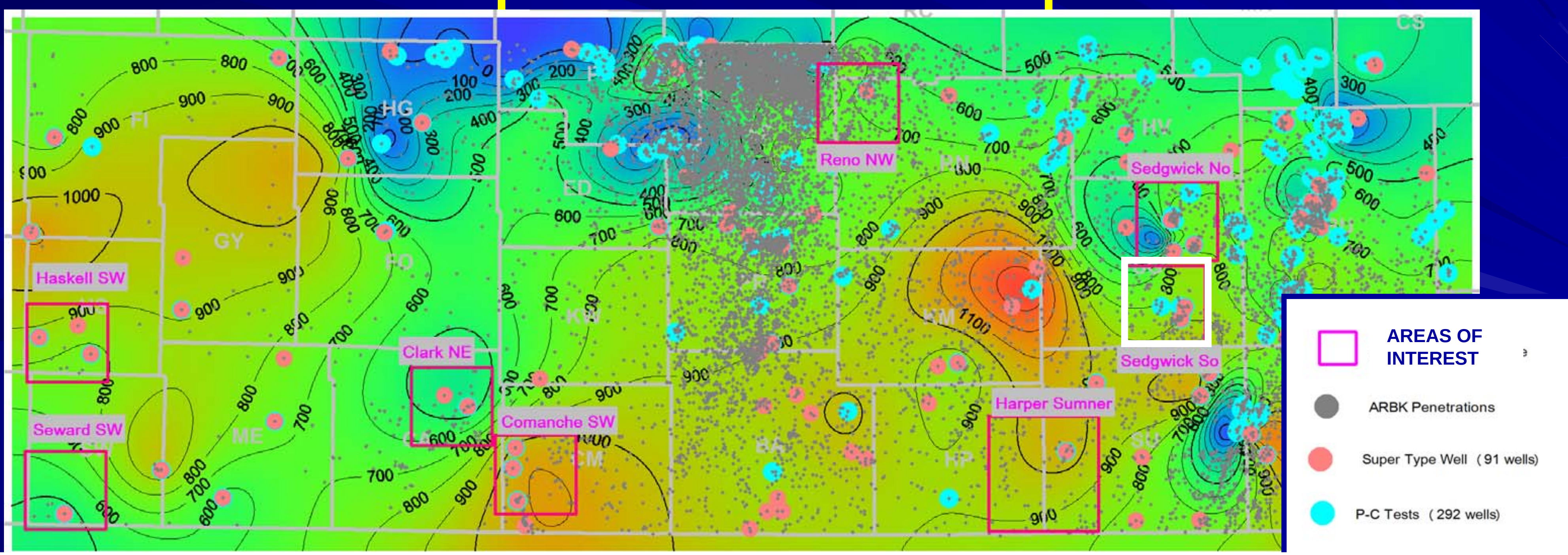
KGS CO2 PROJECT		
AREAS OF INTEREST		
Author: P Gerlach		Date: 7 May, 2010
	Scale: <scale>	

Structure top of Arbuckle Group, regional study area

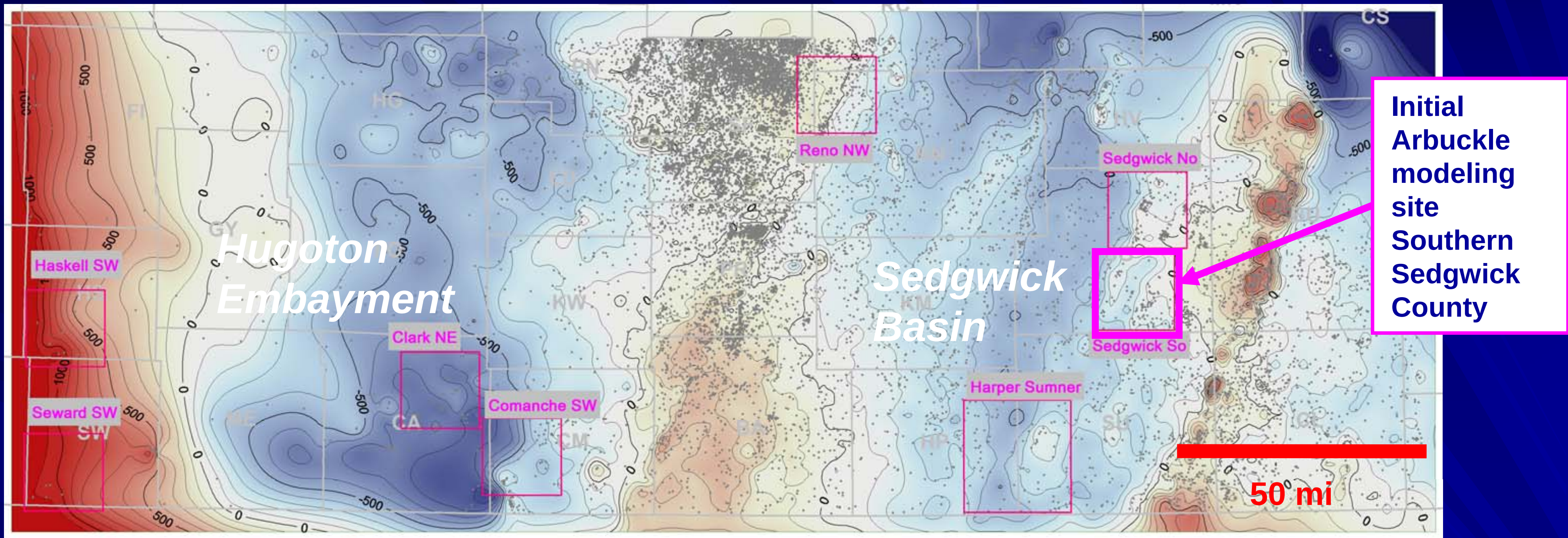


50 mi

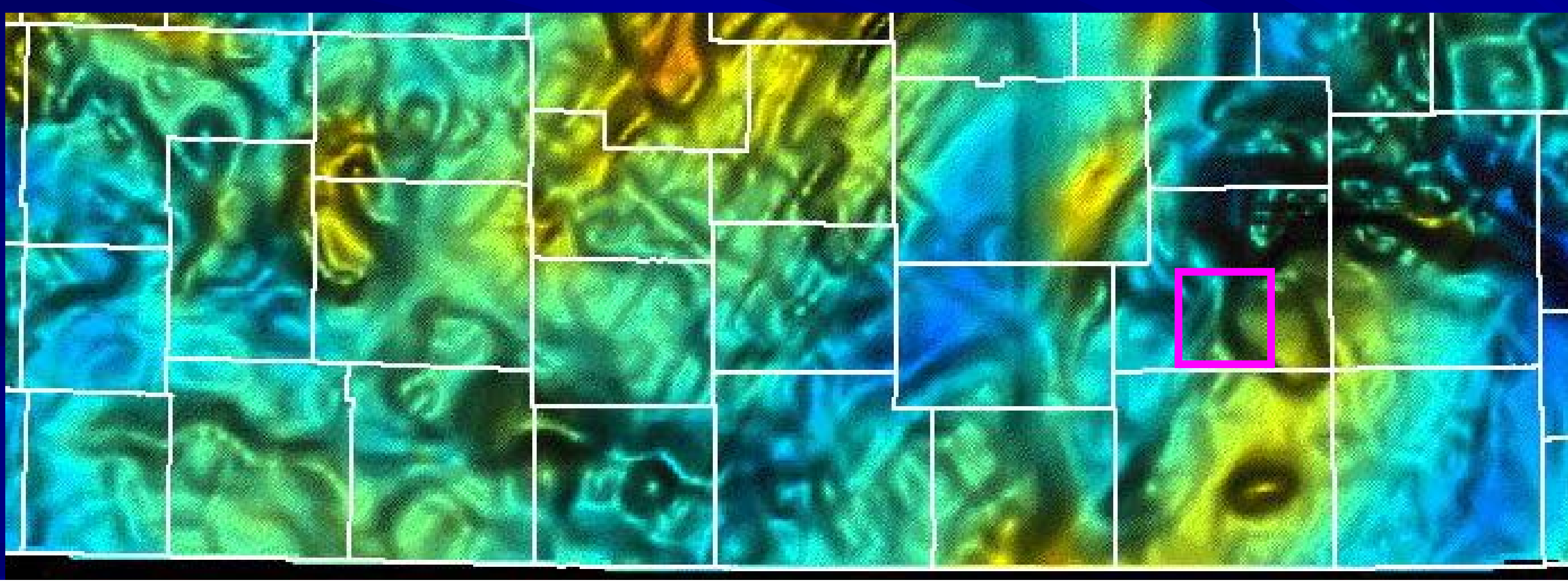
Isopach Arbuckle Group



3rd Order Structural Residual - Top Arbuckle



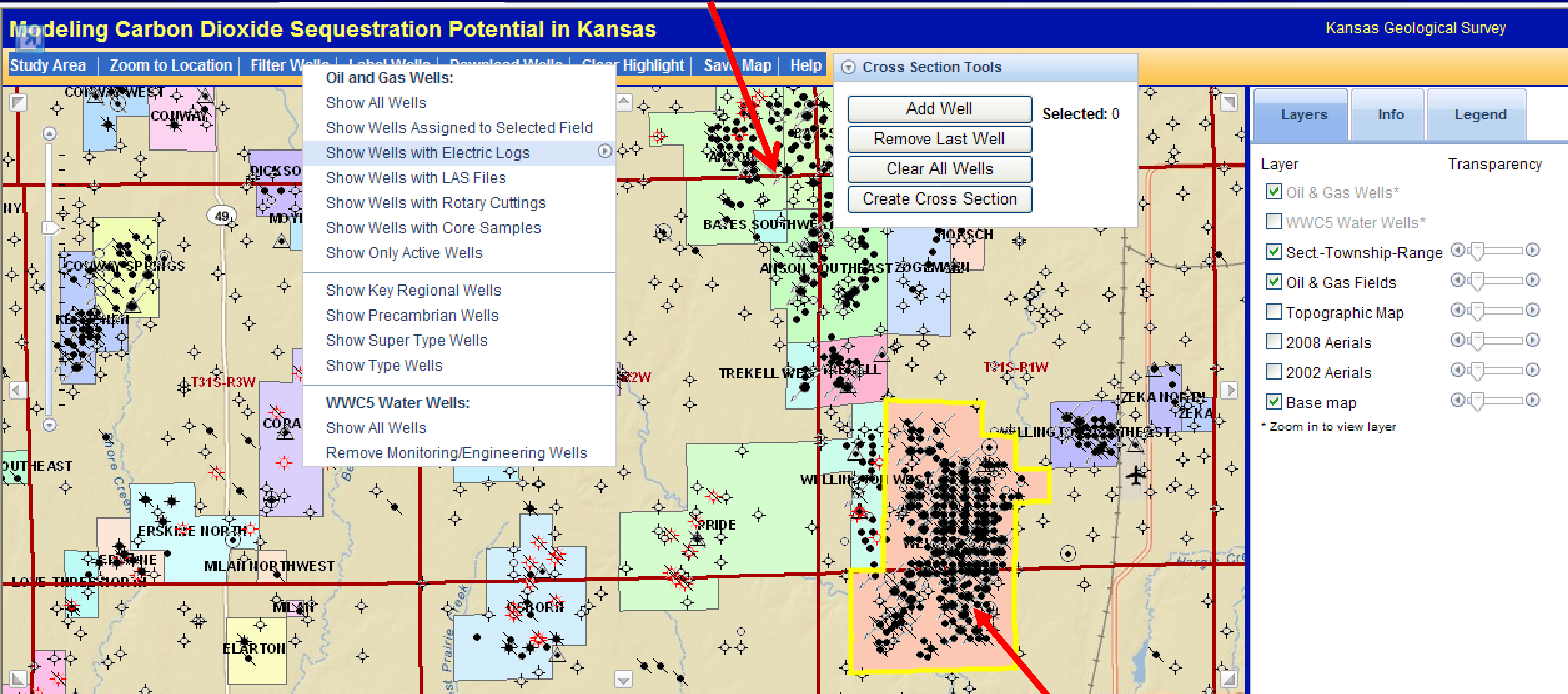
Color based on gravity, "relief" based on magnetics



Interactive Project Map Viewer

Well Data and Analyses, Georeferenced Maps, Cross Sections, Model Results

Anson-Bates Fields



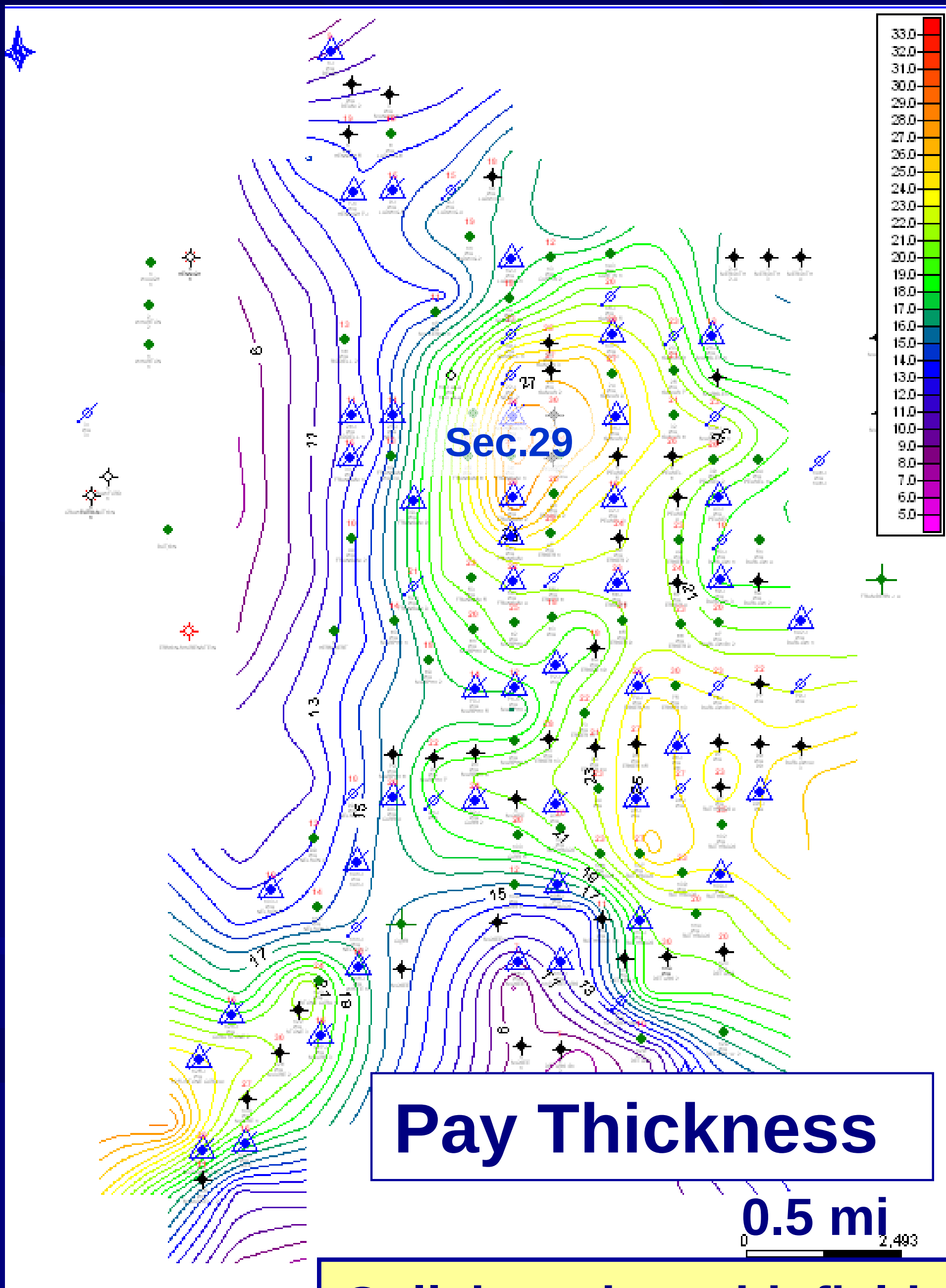
3 miles

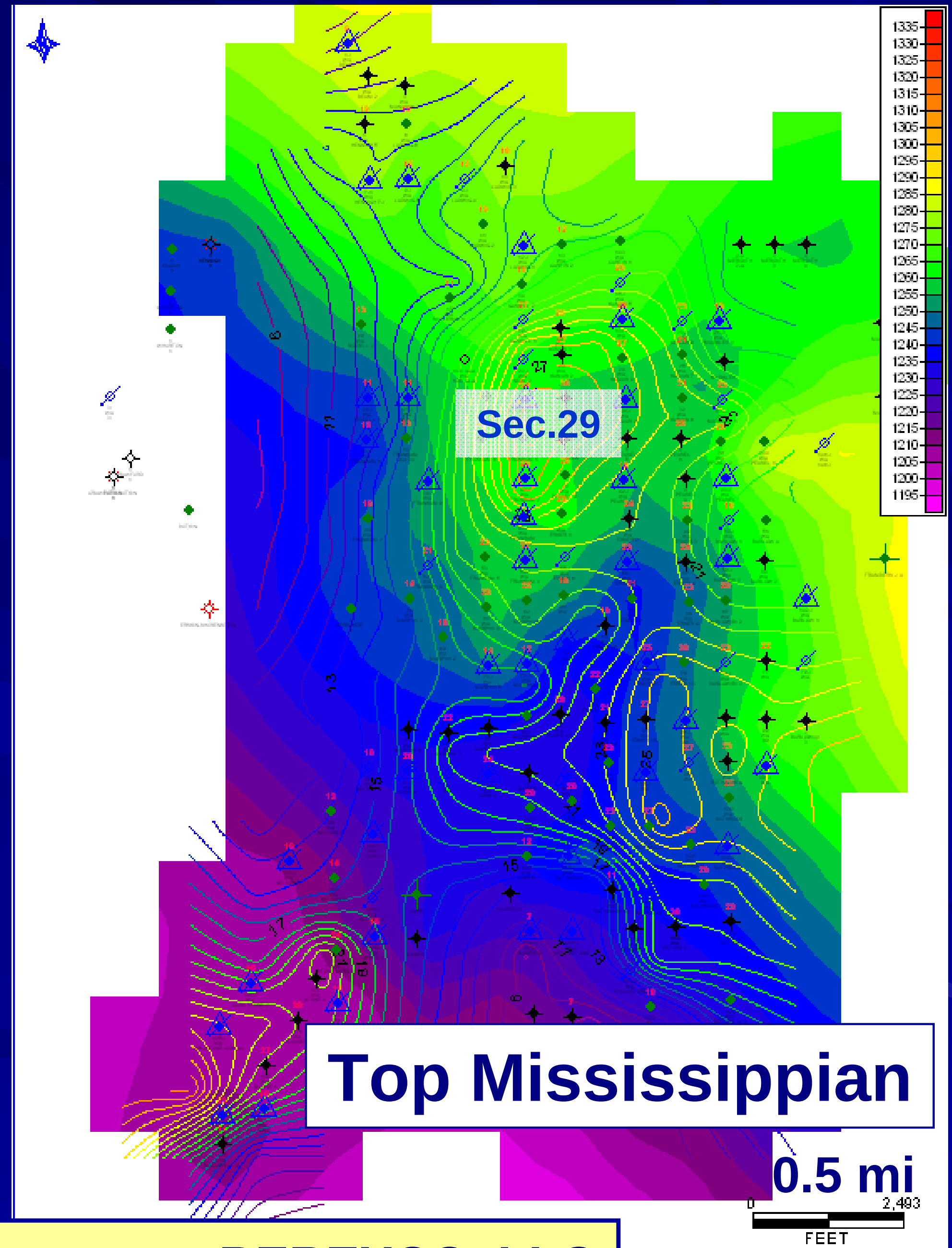
Wellington Field

http://maps.kgs.ku.edu/co2/?pass=project

Initial Mapping of Mississippian - Wellington

Depleted oil reservoir (chert/dolomite) - CO_2-EOR



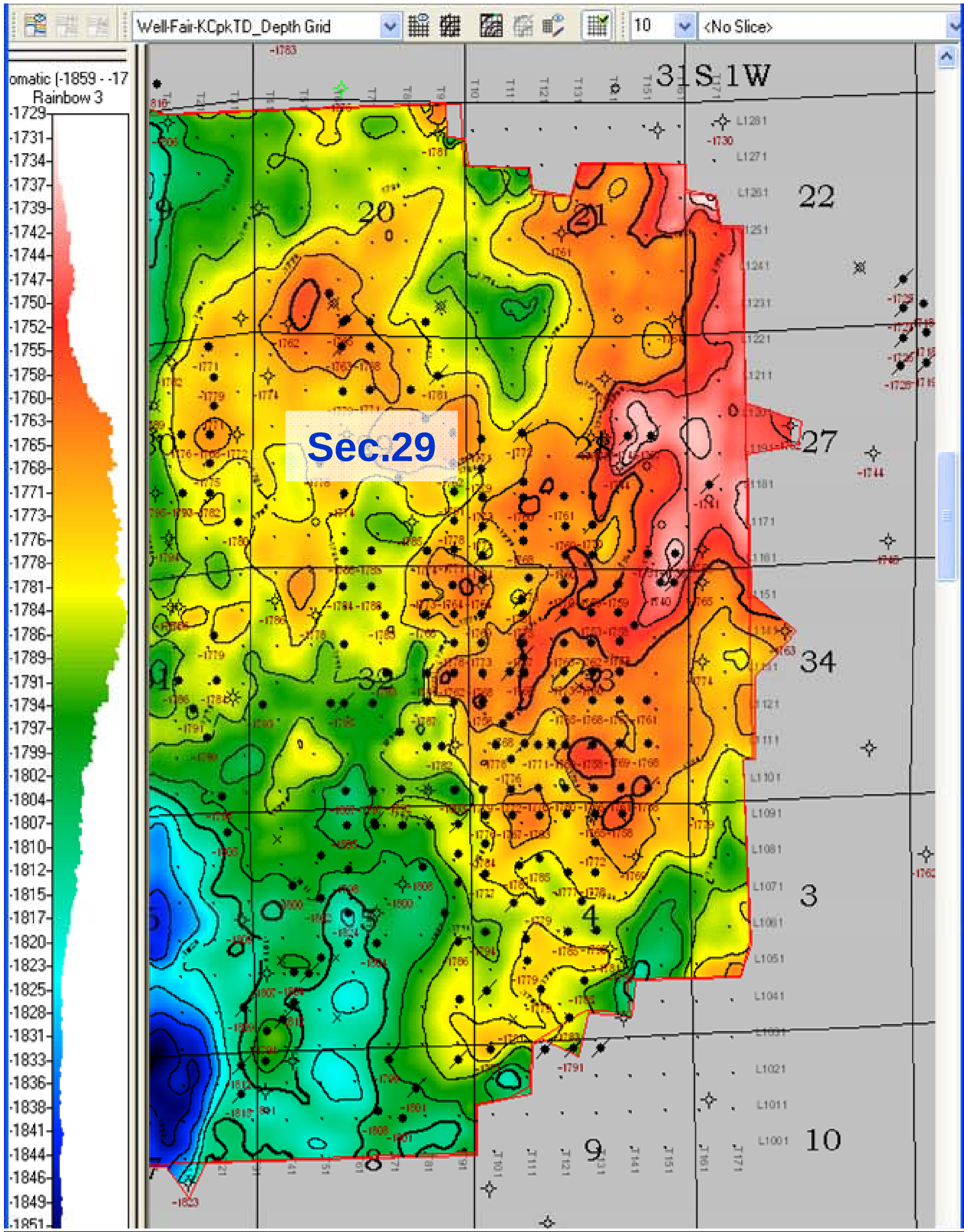


Collaboration with field operator – BEREXCO, LLC

Depth Converted Structure Comparisons

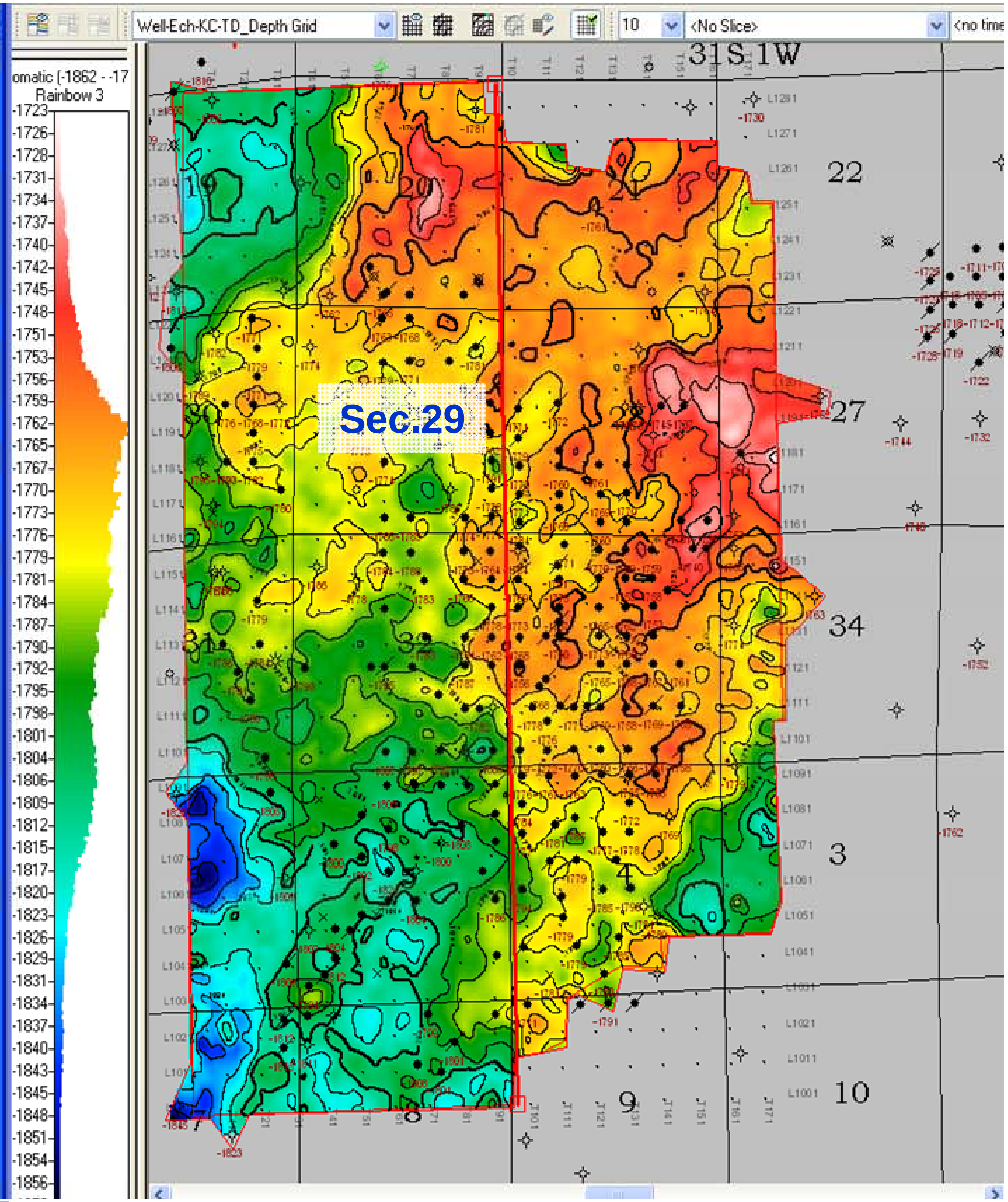
Drum/Dewey Limestone

Fairfield



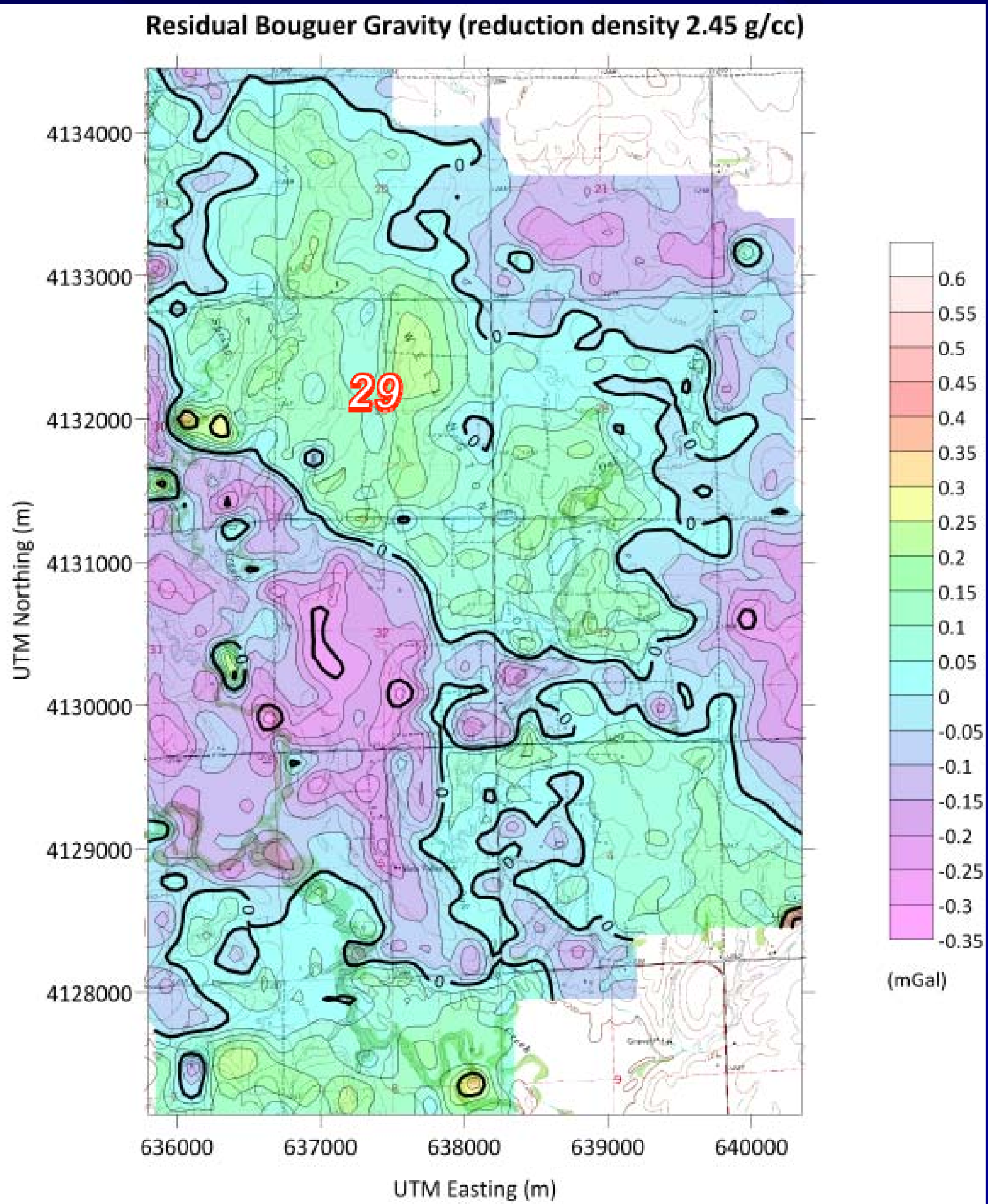
Dennis Hedke – preliminary analysis, July 2010

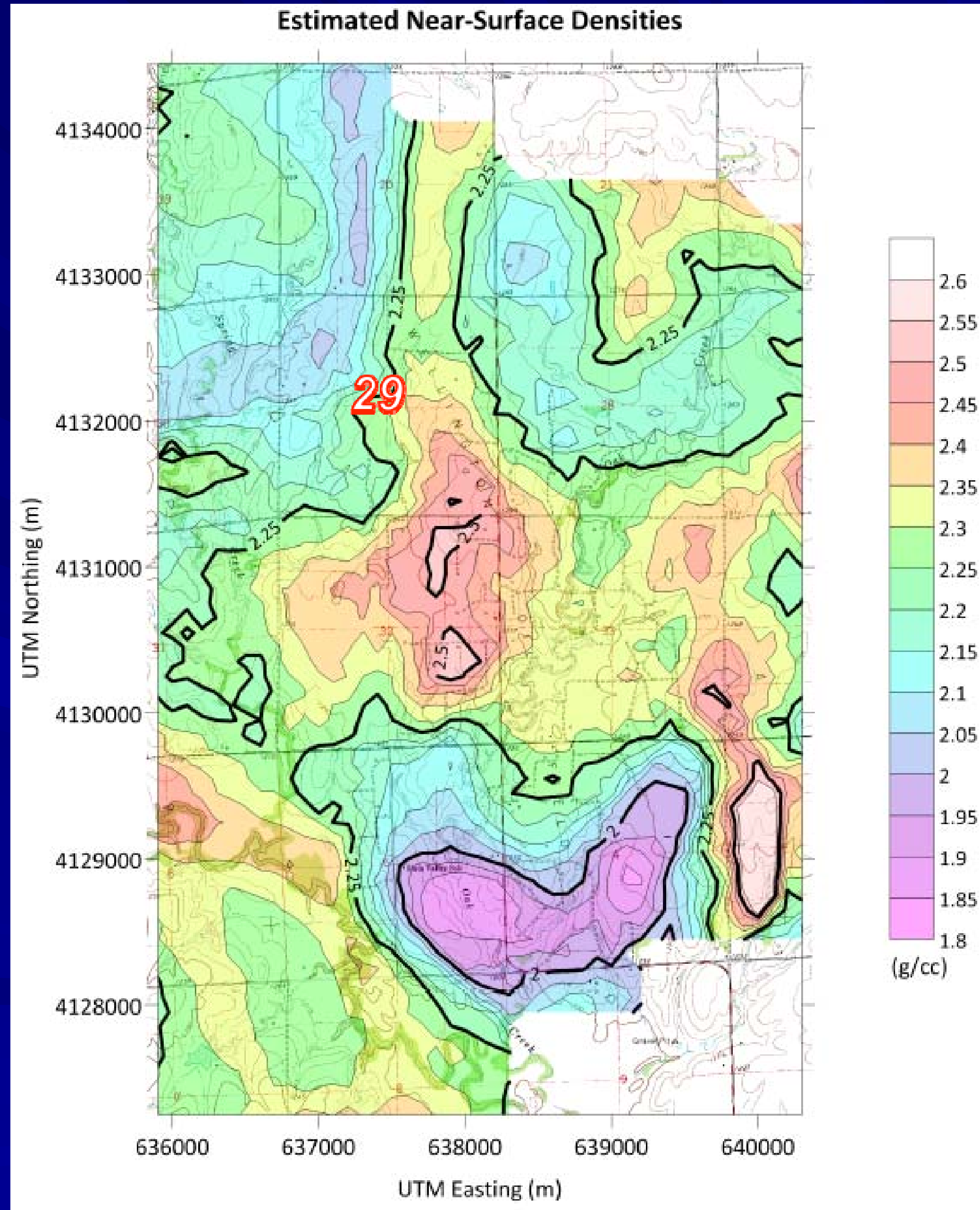
Echo



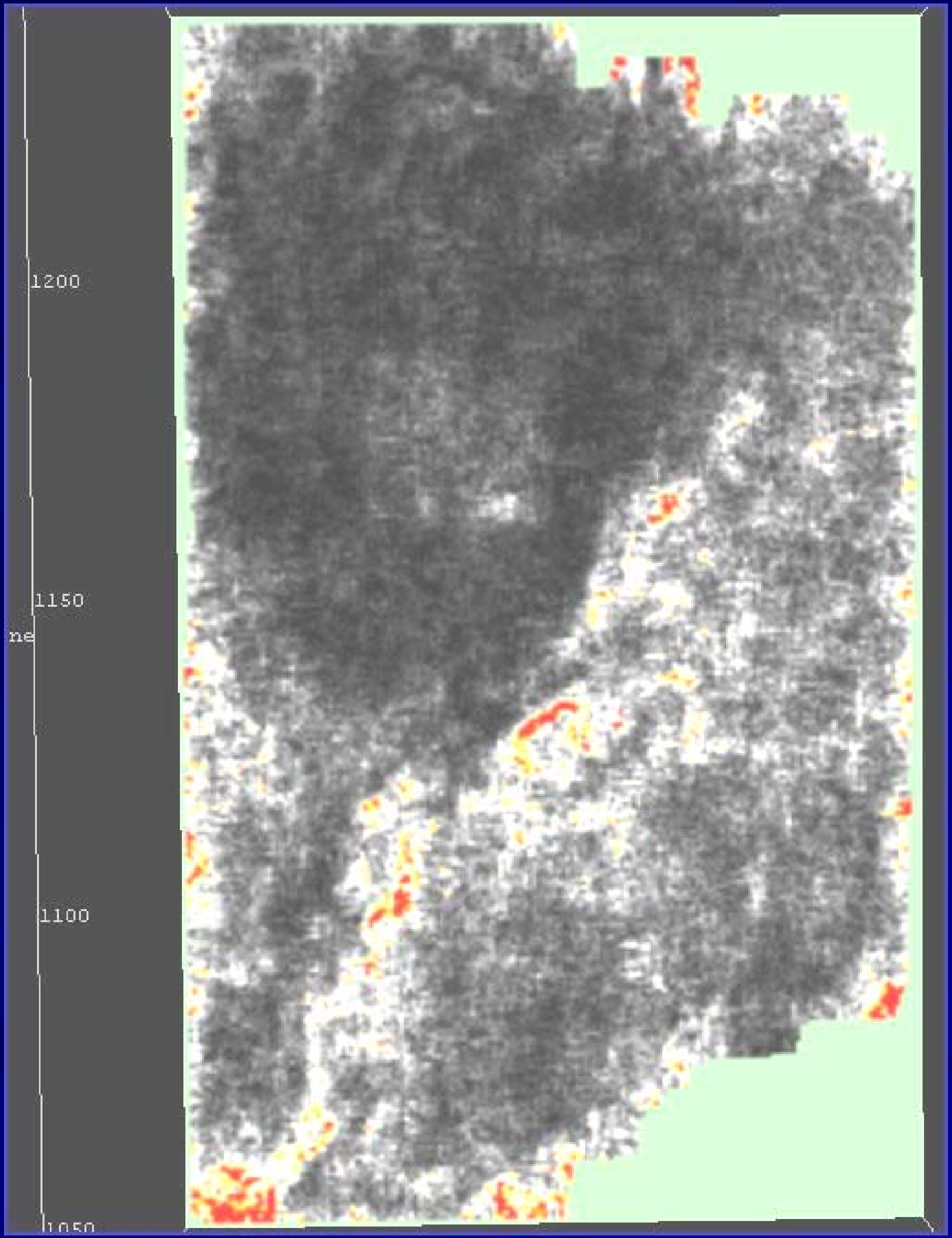
Multicomponent 3D seismic by Paragon

Gravity Data - Wellington Field
Aug. 2nd (Lockhart)



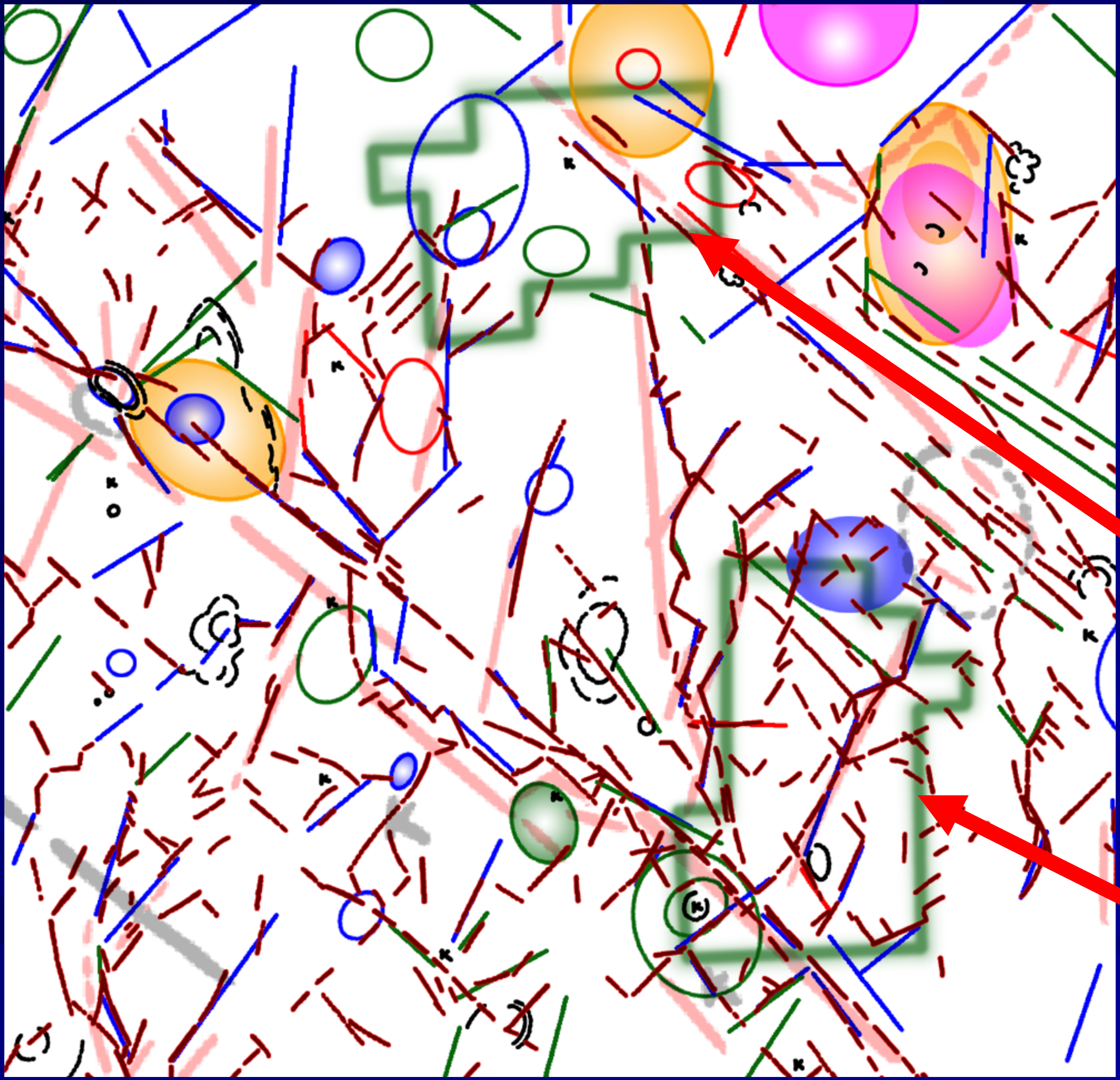


Coherency Attribute Time Slice
Possible structural/ stratigraphic anomaly - ??



Preliminary interpretation
A. Raef, KSU – preliminary analysis, July 28, 2010

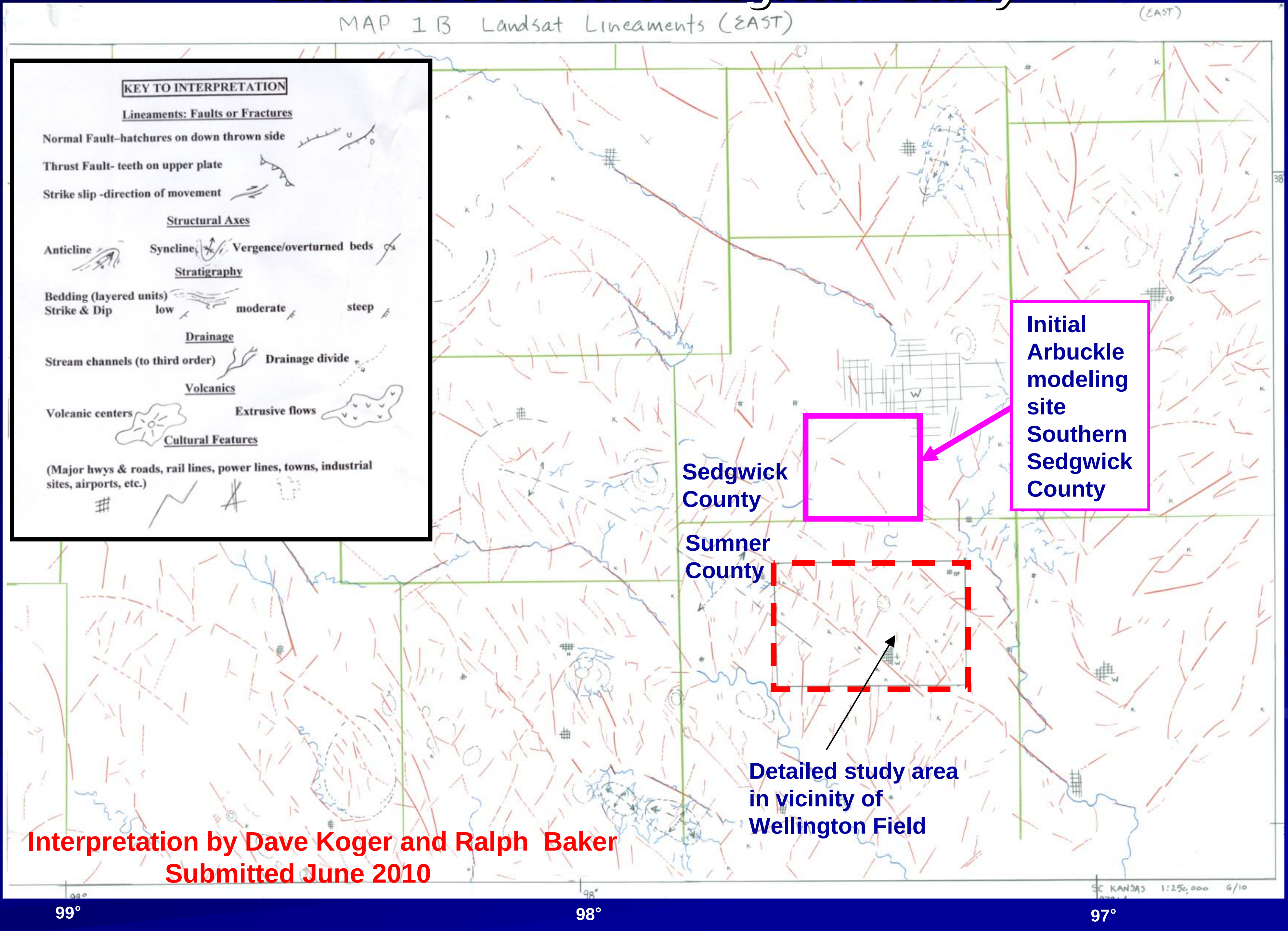
High-Resolution Landsat Interpretation
Wellington Field Area

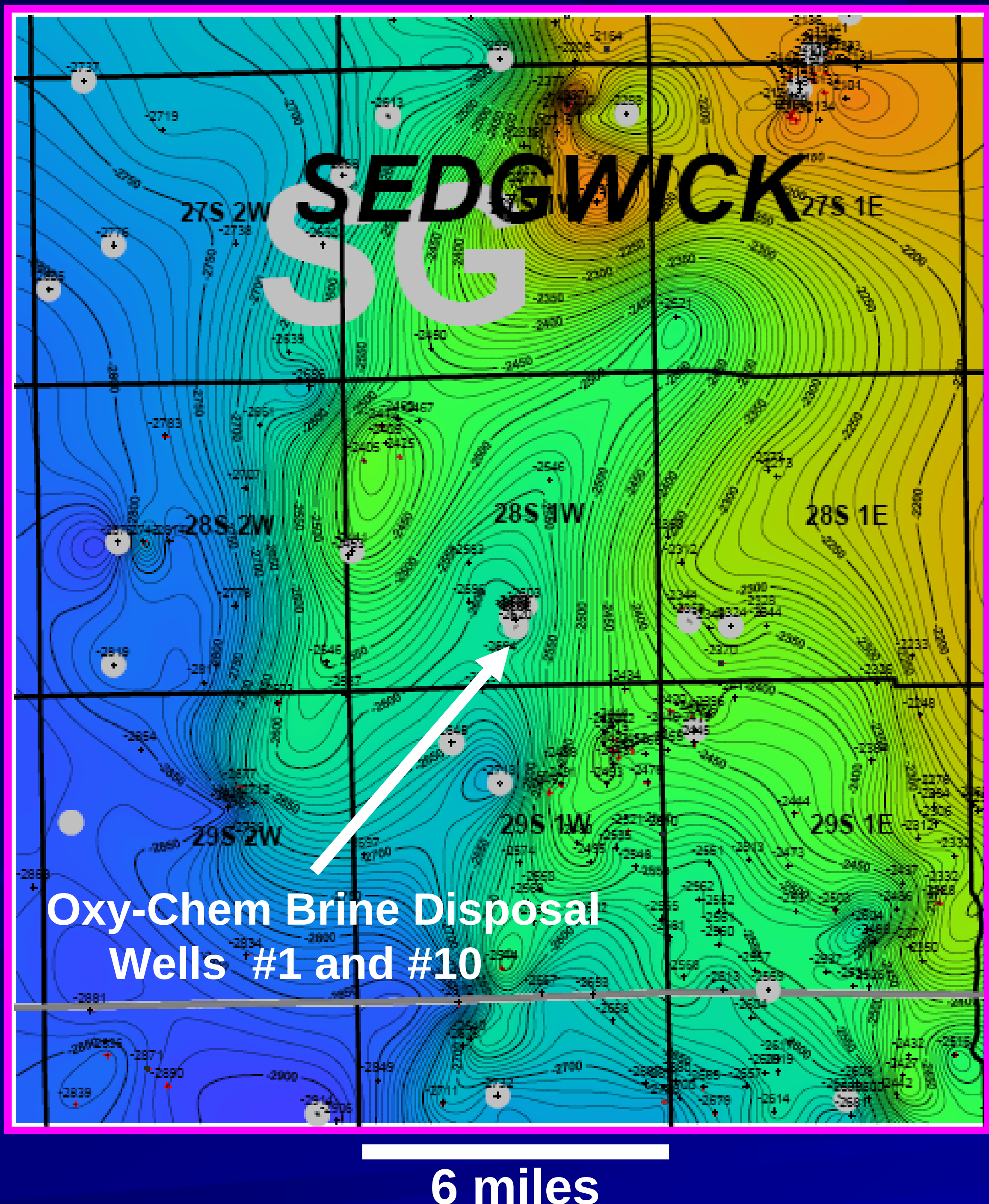


Thin lines = local lineaments
Thick lines = regional lineaments
Color ovals = subsurface fluids to surface?

Dave Koger & Ralph Baker – 8/3/2010

Draft Interpretation of Landsat Imagery
Eastern Section of Regional Study



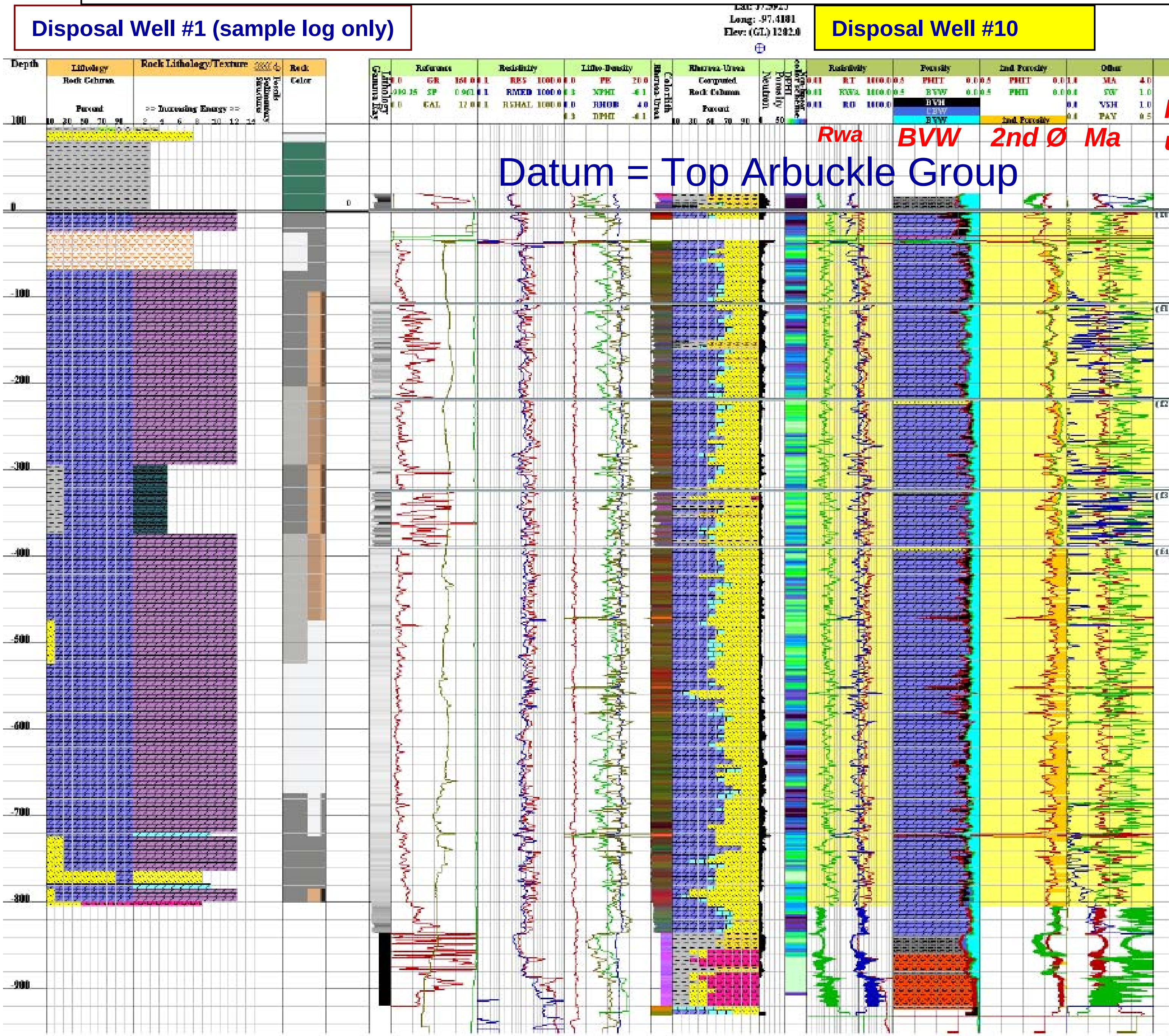


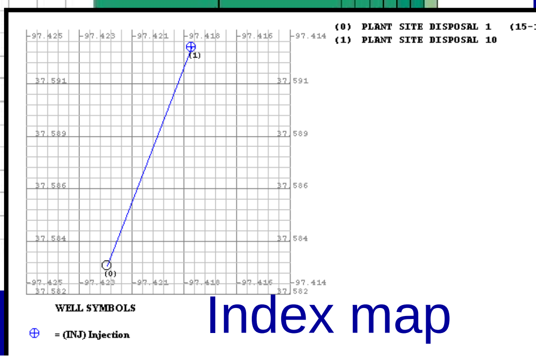
Simulation Model Area - Southern Sedgwick County

Arbuckle Structure of top flow unit JCC 4 (Layer L1 in simulation)

- **6 townships**
- **660 ft grid cells**
- **five flow units (*layers*)**

Stratigraphic cross section – Disposal well #1 to #10 – Oxy-Chem site south of Wichita
Integrated Lithologic/Petrophysical Interpretation of Flow Units – 5 LAYERS





Depth-constrained cluster analysis – Flow Unit Determination

Oxy-Chem Brine Disposal Well #10

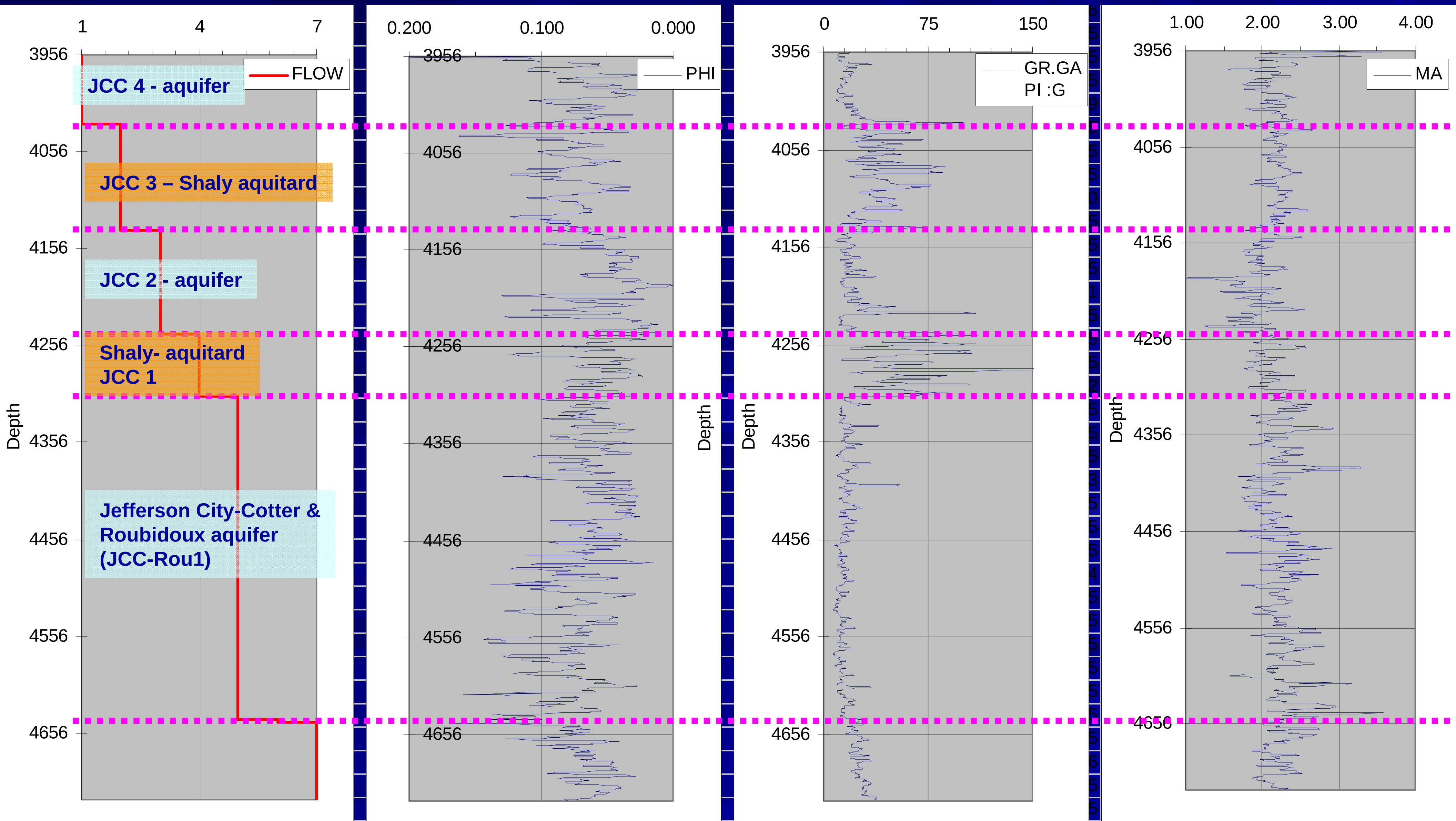
Cluster Analysis - Group Means					
Group	MinDepth	MaxDepth	Mov ave phi	GR.GAPI :	Ma
1	3956	4026.75	0.07	17.24	2.49
2	4027	4137.25	0.08	40.52	2.25
3	4137.5	4243.5	0.05	20.99	2.33
4	4243.75	4308.5	0.06	61.46	2.34
5	4308.75	4641.5	0.07	15.18	2.43
6	4641.75	4644.25	0.10	24.83	6.90
7	4644.5	4724.75	0.07	26.18	2.49

Cluster Analysis - Final Results

Number of clusters = 7

R-squared = 64.44%

OK



Flow Unit Analysis saved/archived as *LAS 3.0 file*

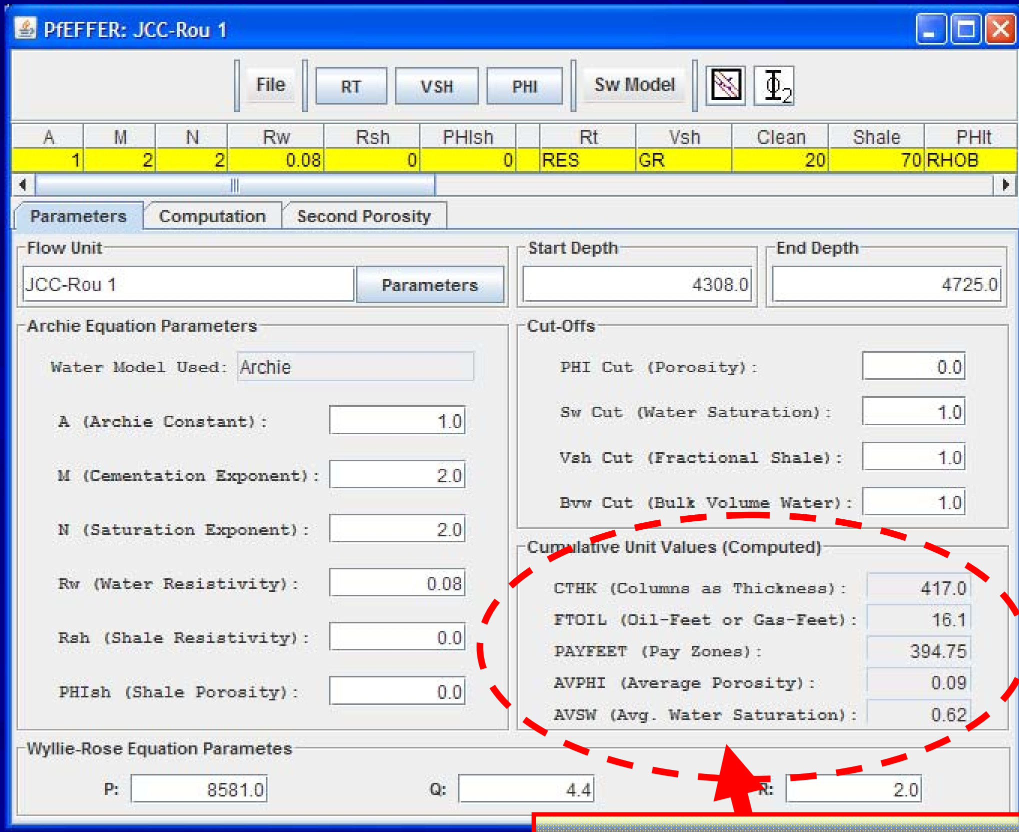
~IQ_Flow_Data | IQ_Flow_Definition
KEY ZONE STRT STOP ROCK H2O A M N RW RSH PHISH L_RT L_VSH CLEAN SHALE L_PHIT L_PHI1 L_PHI2 GRAIN FLUID PHI_VSH PHI_SH PHI_SH2 L_2ND 2_GRAIN 2_FLUID 2_VSH 2_SH C_PHI C_SW C_VSH C_BVW P Q R V_THK V_FT V_PAY V_PHI V_SW
"100727101550","JCC 4",3918.0,4027.0,"Dolomite","Archie",1.0,2.0,2.0,0.05,0.0,0.0,"RES","GR",20.0,70.0,"RHOB","RHOB","-999.25",2.8,1.0,"NO",0.0,0.0,"DT",47.5,185.0,"NO",0.0,0.08,0.5,0.3,0.08,8581.0,4.4,2.0,109.0,1533.58,42.5,36.14,0.39
"100727102039","JCC 3",4027.0,4137.5,"Dolomite","Archie",1.0,2.0,2.0,0.09,0.0,0.0,"RES","GR",20.0,70.0,"RHOB","RHOB","-999.25",2.8,1.0,"NO",0.0,0.0,"DT",43.5,189.0,"NO",0.0,0.08,0.5,0.3,0.08,8581.0,4.4,2.0,110.5,0.12,1.75,0.14,0.47
"100727103220","JCC 2",4137.5,4243.5,"Dolomite","Archie",1.0,2.0,2.0,0.05,0.0,0.0,"RES","GR",20.0,70.0,"RHOB","RHOB","-999.25",2.8,1.0,"NO",0.0,0.0,"DT",47.5,185.0,"NO",0.0,0.08,0.5,0.3,0.08,8581.0,4.4,2.0,106.0,0.65,9.5,0.12,0.41
"100727103920","JCC 1",4243.5,4308.0,"Dolomite","Archie",1.0,2.0,2.0,0.08,0.0,0.0,"RES","GR",20.0,70.0,"RHOB","RHOB","-999.25",2.8,1.0,"NO",0.0,0.0,"DT",47.5,185.0,"NO",0.0,8.0,0.5,0.3,0.08,8581.0,4.4,2.0,64.5,0.0,0.0,0.06,0.91
"100727105840","JCC-Rou 1",4308.0,4725.0,"Dolomite","Archie",1.0,2.0,2.0,0.08,0.0,0.0,"RES","GR",20.0,70.0,"RHOB","RHOB","-999.25",2.8,1.0,"NO",0.0,0.0,"-999.25",-999.25,-999.25,"NO",0.0,0.0,1.0,1.0,1.0,8581.0,4.4,2.0,417.0,16.1,394.75,0.09,0.62

Flow unit parameters

~IQ_Pfeffer_Parameter
#MNEM .UNIT VALUE : DESCRIPTION {FORMAT} | ASSOCIATION
IQKGS . : Profile Web App Saved Data Indicator {S}

~IQ_Pfeffer_Definition
#MNEM .UNIT VALUE : DESCRIPTION {FORMAT} | ASSOCIATION
FKEY . : Unique Identifier {S}
DEPTH .F : Depth {F}
THK .F : Thickness {F}
RT .OHM-M : Total Resistivity {F}
PHIT .PU : Total Porosity {F}
VSH .FRAC : V-Shale {F}
PHI1 .PU : 1st Porosity {F}
PHI2 .PU : 2nd Porosity {F}
RWA .OHM-M : Water Resistivity {F}
RO .OHM-M : Water Saturated Rock Resistivity {F}
MA .FRAC : Archie Cementation {F}
SW .FRAC : Water Saturation {F}
BVW .PU : Bulk Volume Water {F}
PAY .F : Pay {F}

~IQ_Pfeffer_Data | IQ_Pfeffer_Definition
FKEY DEPTH THK RT PHIT VSH PHI1 PHI2 RWA RO MA SW BVW PAY
"100727101550",3918.0,0.25,5.577,0.172,1.203,0.182,0.0,0.164,1.69,2.678,0.55,0.094,0.0
"100727101550",3918.25,0.25,5.405,0.179,1.175,0.174,0.0,0.173,1.56,2.722,0.537,0.096,0.0
"100727101550",3918.5,0.25,5.184,0.187,1.147,0.166,0.0,0.181,1.429,2.768,0.525,0.098,0.0
"100727101550",3918.75,0.25,5.012,0.195,1.125,0.158,0.0,0.19,1.314,2.818,0.512,0.099,0.0
"100727101550",3919.0,0.25,4.977,0.201,1.117,0.151,0.0,0.201,1.237,2.867,0.498,0.1,0.0
"100727101550",3919.25,0.25,5.153,0.203,1.121,0.145,0.0,0.212,1.213,2.906,0.485,0.098,0.0
"100727101550",3919.5,0.25,5.624,0.201,1.131,0.14,0.0,0.227,1.237,2.943,0.469,0.094,0.0
"100727101550",3919.75,0.25,6.523,0.195,1.138,0.137,0.0,0.248,1.314,2.979,0.448,0.087,0.0
"100727101550",3920.0,0.25,8.075,0.187,1.141,0.135,0.0,0.282,1.429,3.032,0.42,0.078,0.0
"100727101550",3920.25,0.25,10.605,0.177,1.143,0.134,0.0,0.332,1.595,3.093,0.387,0.068,0.0
"100727101550",3920.5,0.25,14.331,0.168,1.152,0.133,0.0,0.404,1.771,3.171,0.351,0.059,0.0

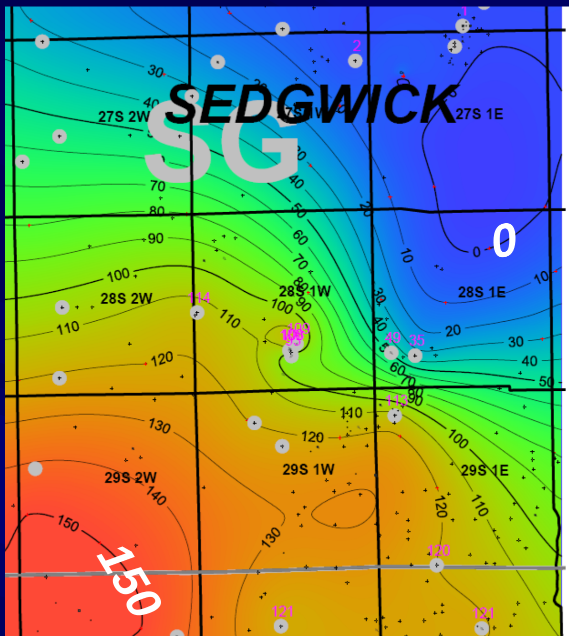


Cumulative & Average Properties

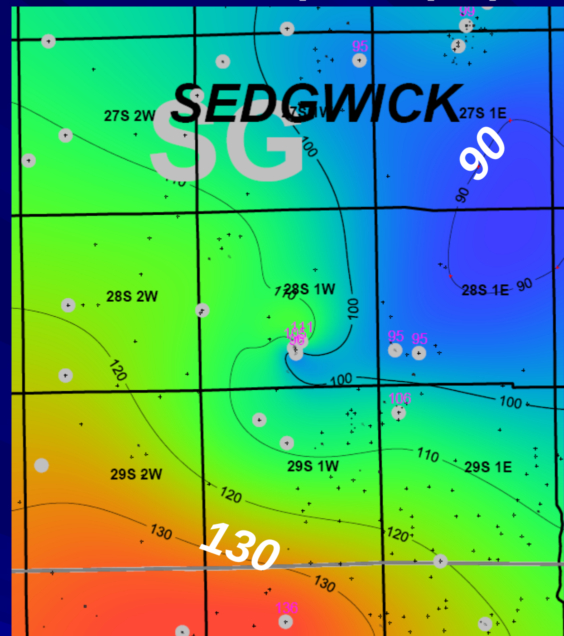
0.5 ft log analysis

Input to Simulation - Isopachs of Layers (Flow Units)

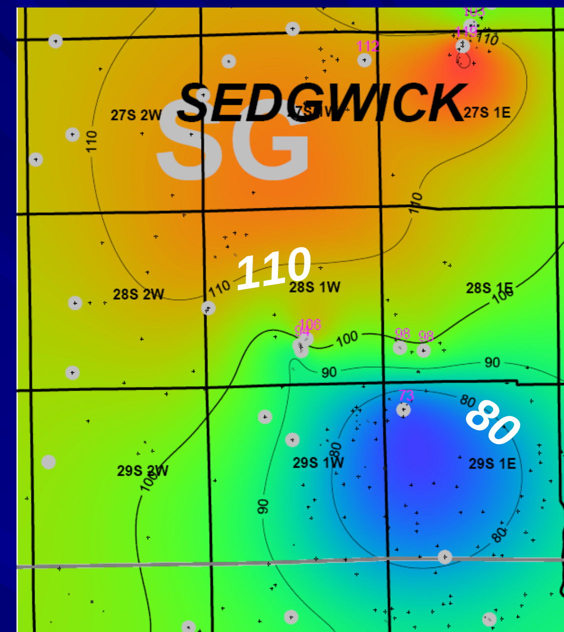
JCC 4 Isopach (L1)



JCC 3 Isopach (L2)

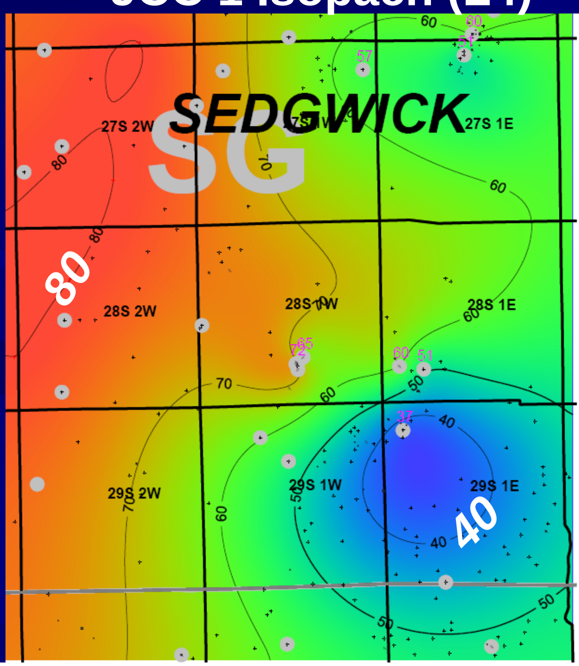


JCC 2 Isopach (L3)

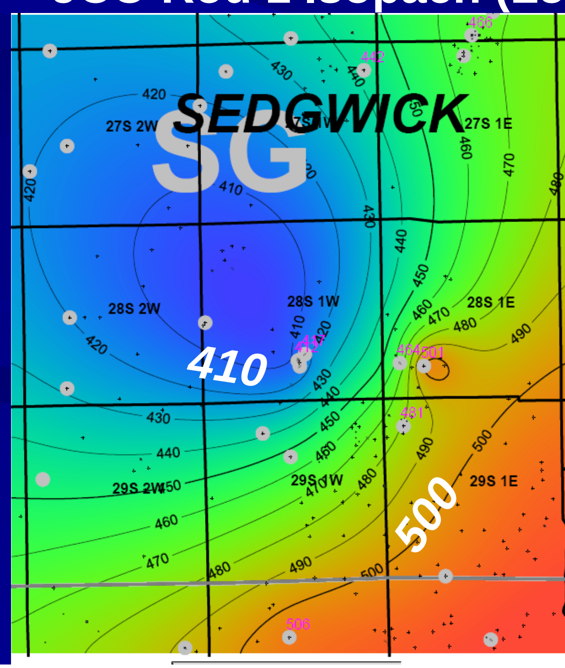


12 miles

JCC 1 Isopach (L4)



JCC-Rou 1 Isopach (L5)



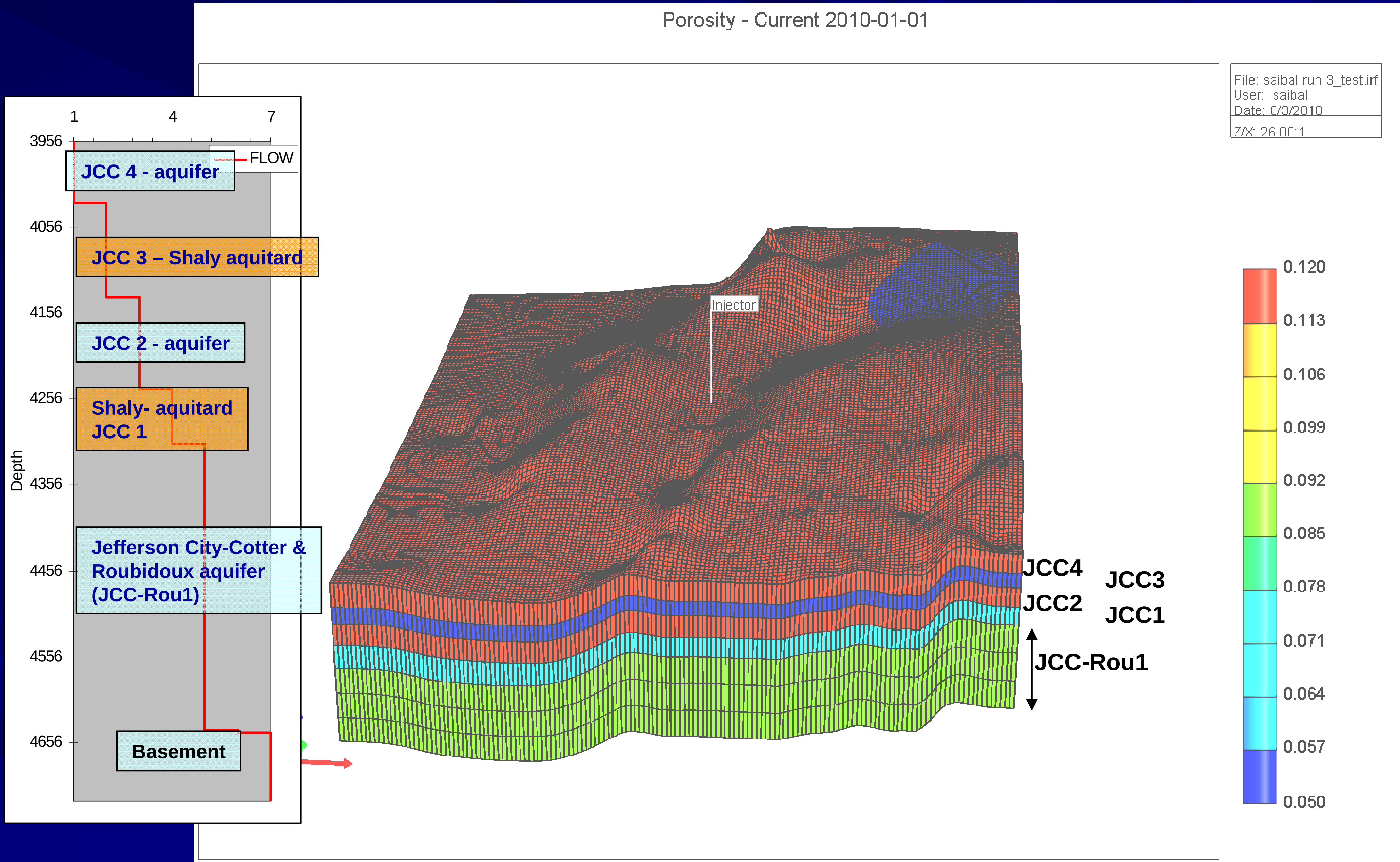
- *6 townships*
- *660 ft grid cells*
- *five flow units (layers)*

N

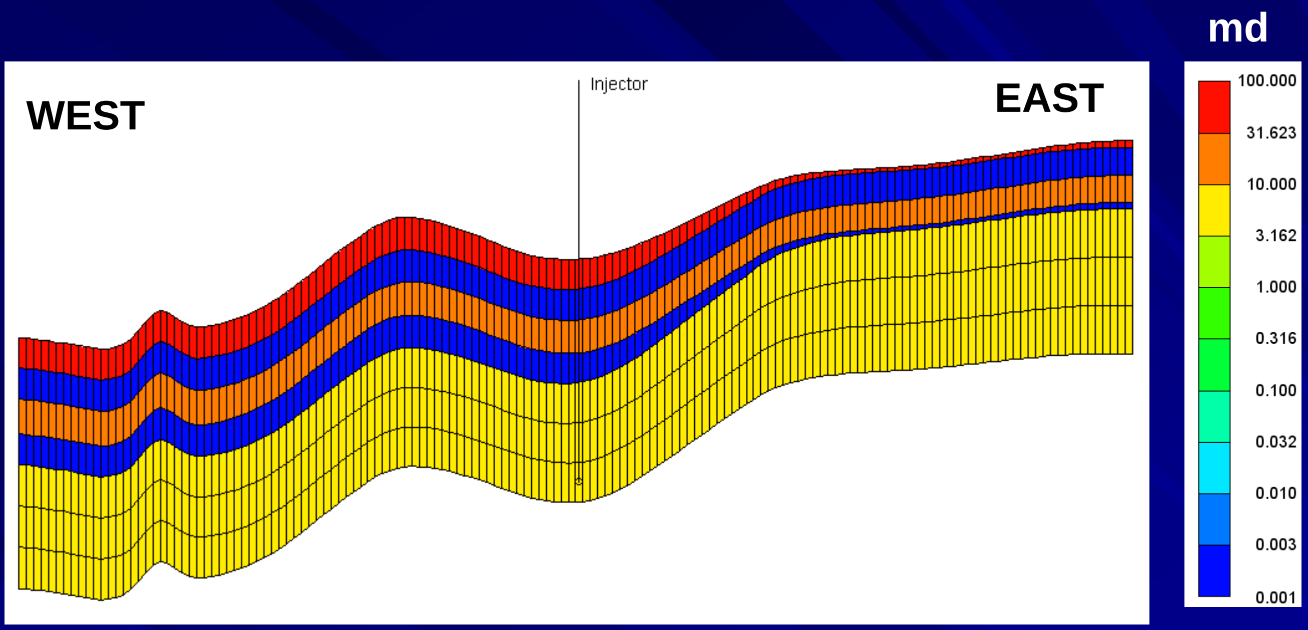
10 contour interval

Update on Simulation Studies

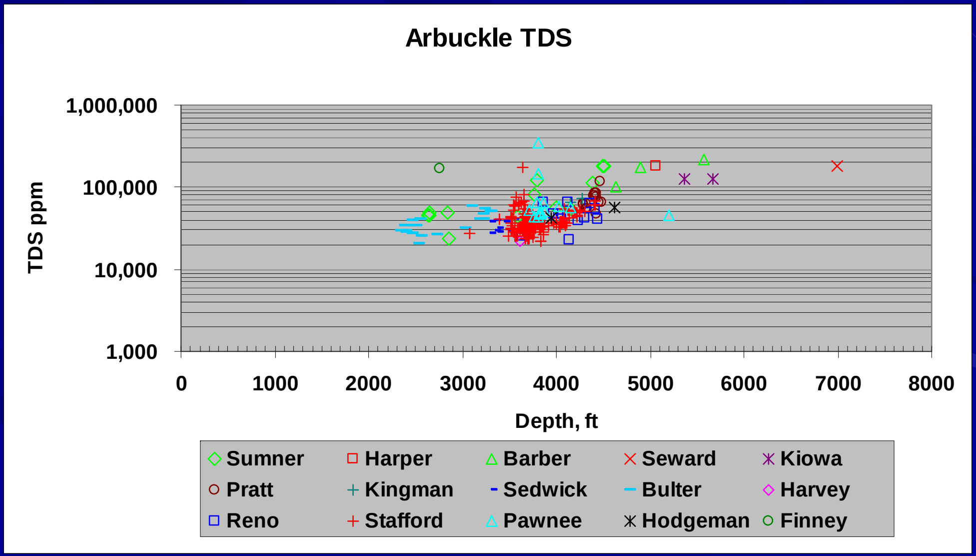
9 Township Model



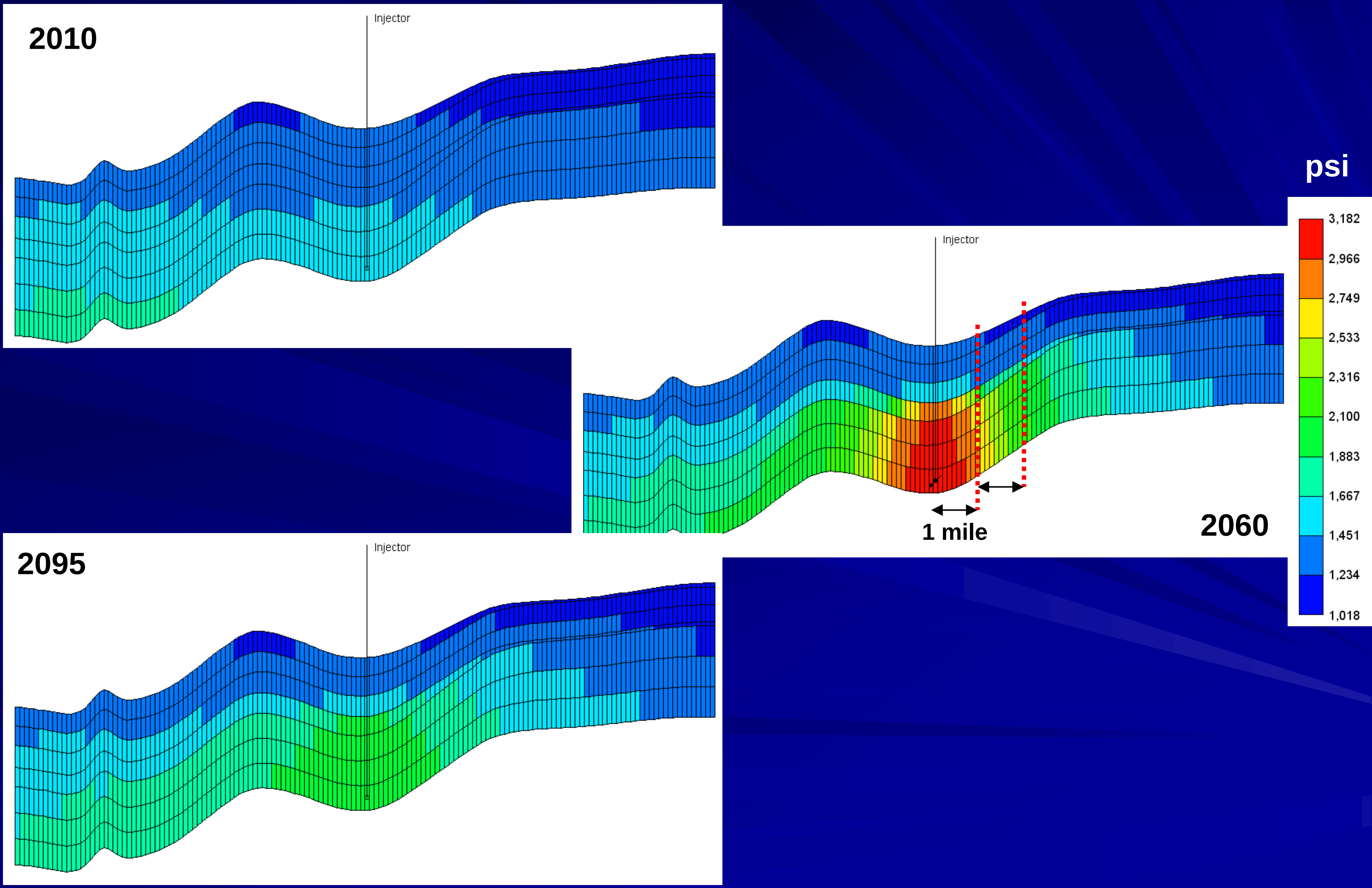
Simulation Inputs



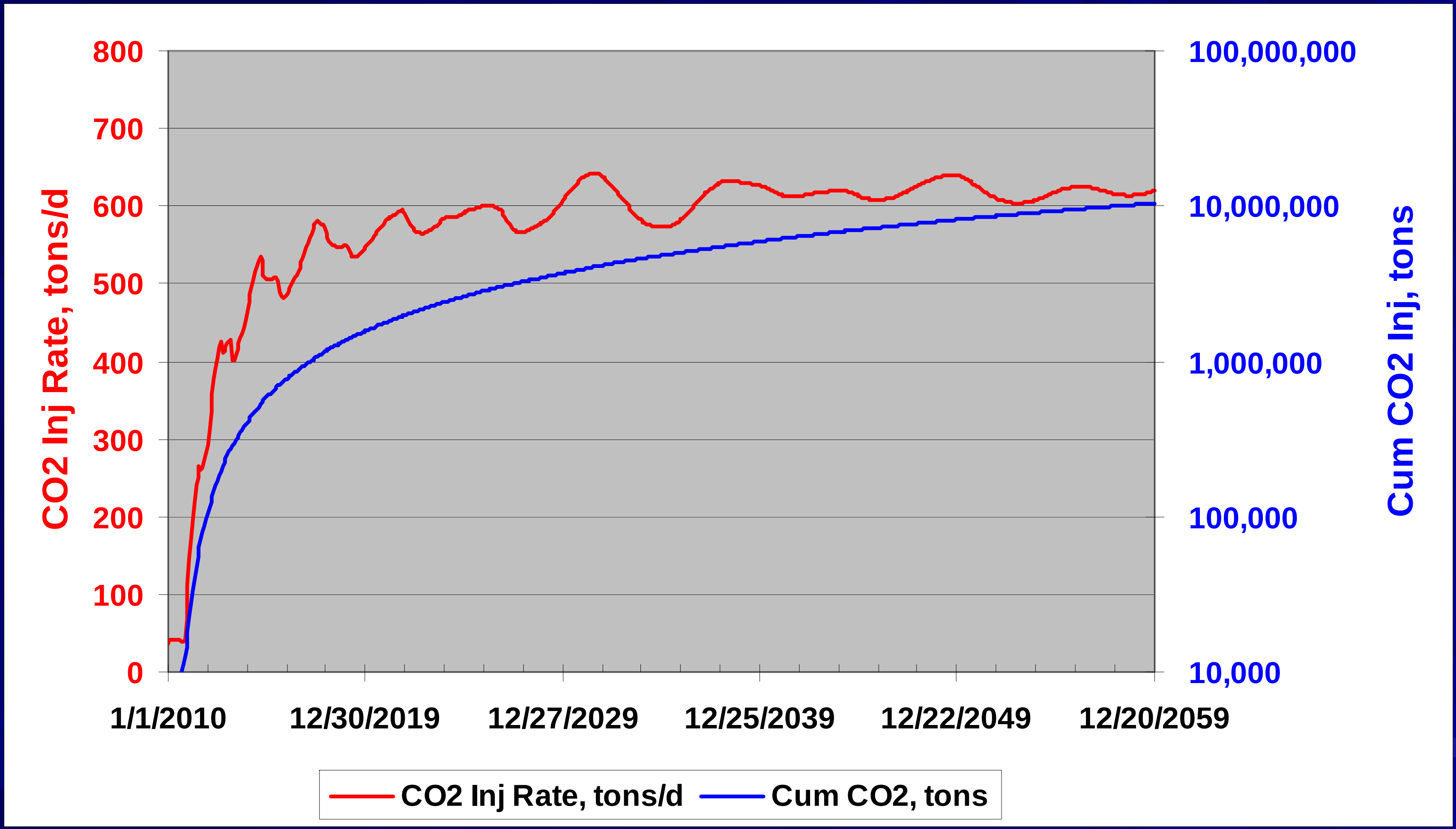
Layer	H, ft	Phi	K (md)	Pr, psi
L1	109	0.12	100	1288
L2	110.5	0.05	0.001	1337
L3	106	0.12	20	1386
L4	64.5	0.06	0.001	1424
L5	139	0.09	9	1470
L6	139	0.09	9	1532
L7	139	0.09	9	1595



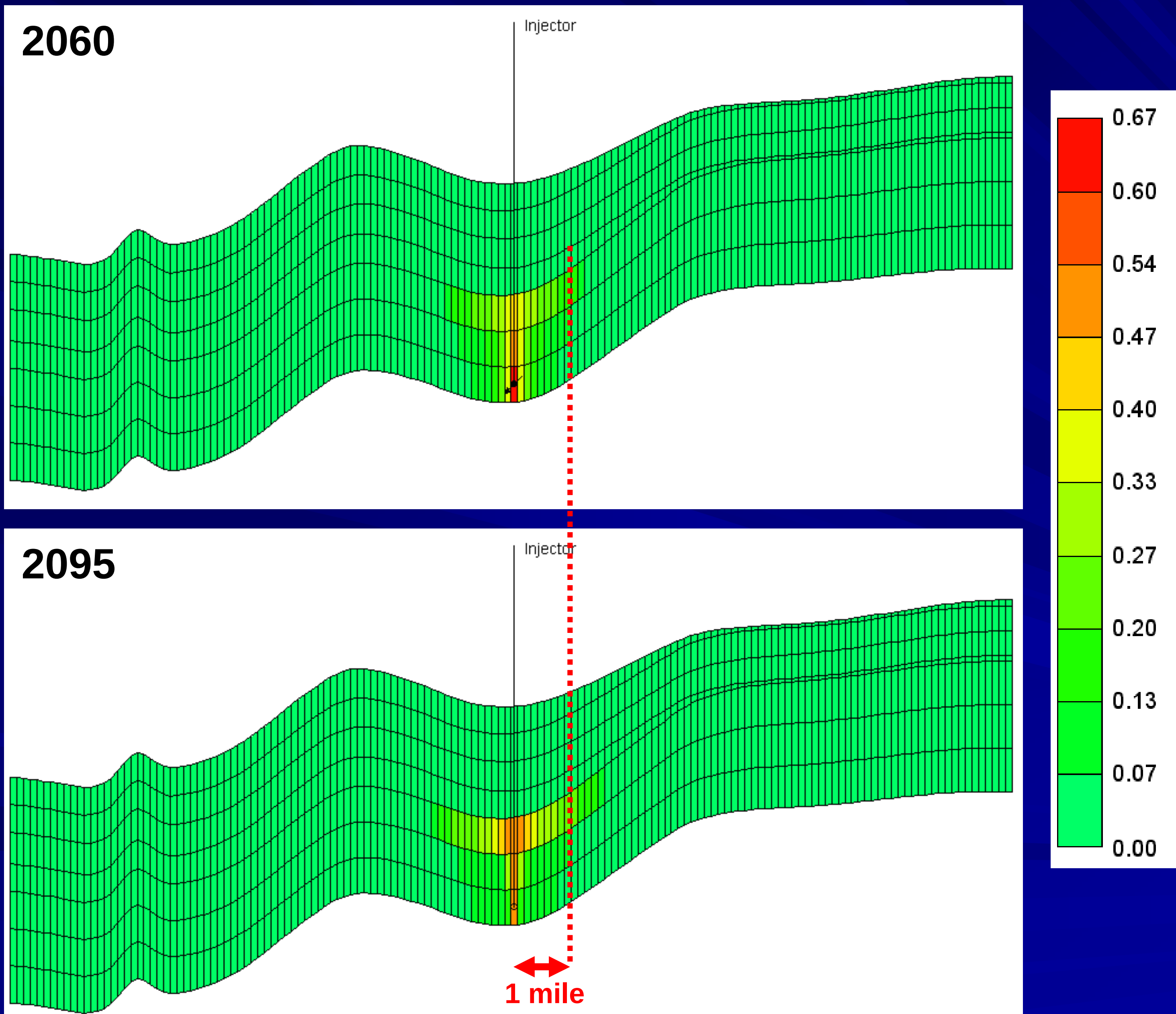
Pressure Change with Injection



CO_2 Injection Rate & Cum – 50 yrs



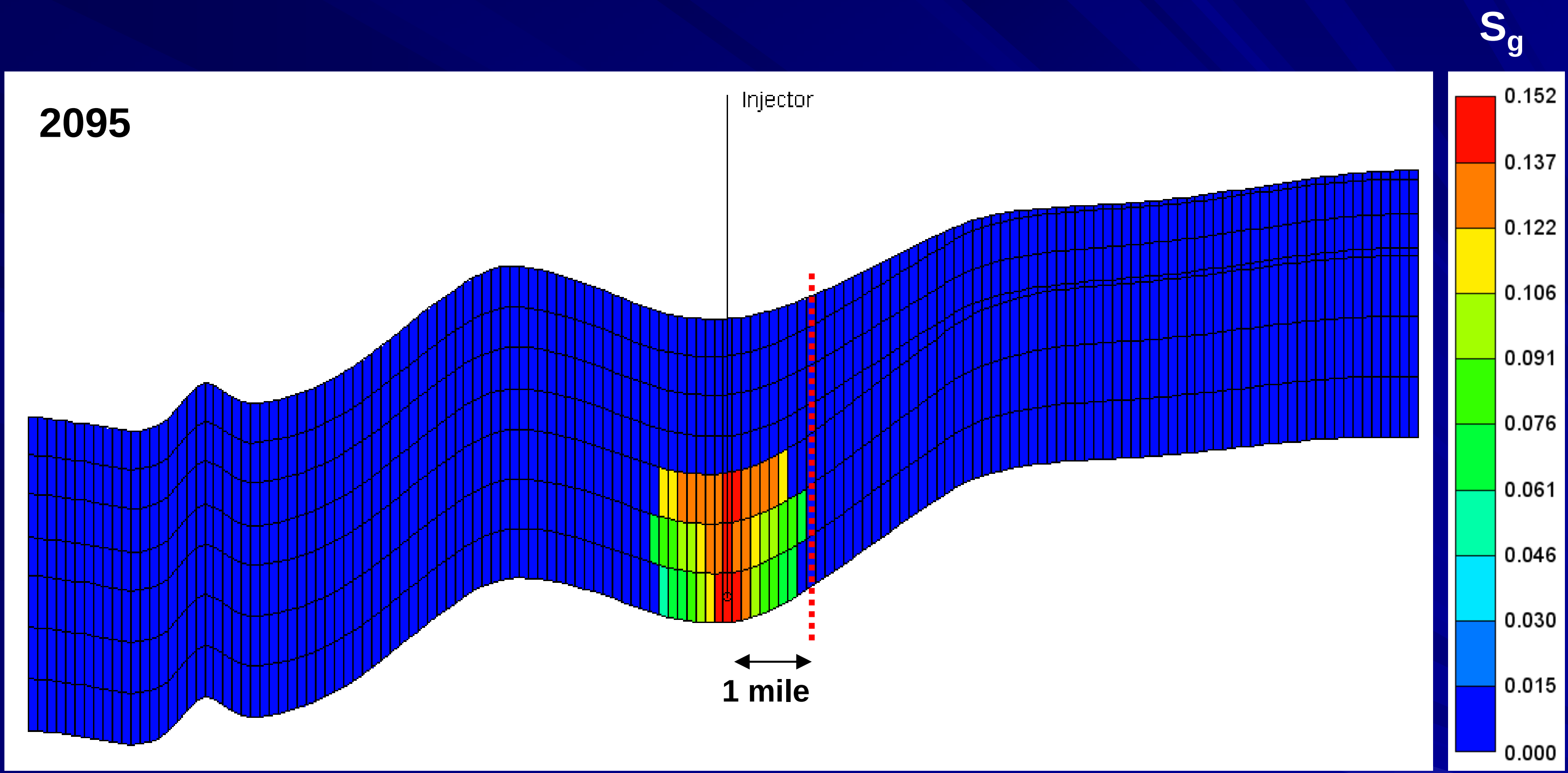
Free Phase Gas Saturation (Supercritical)



Greater vertical grid resolution required to model movement of free-phase CO_2 plume

Residual Gas Trapping – Hysteresis

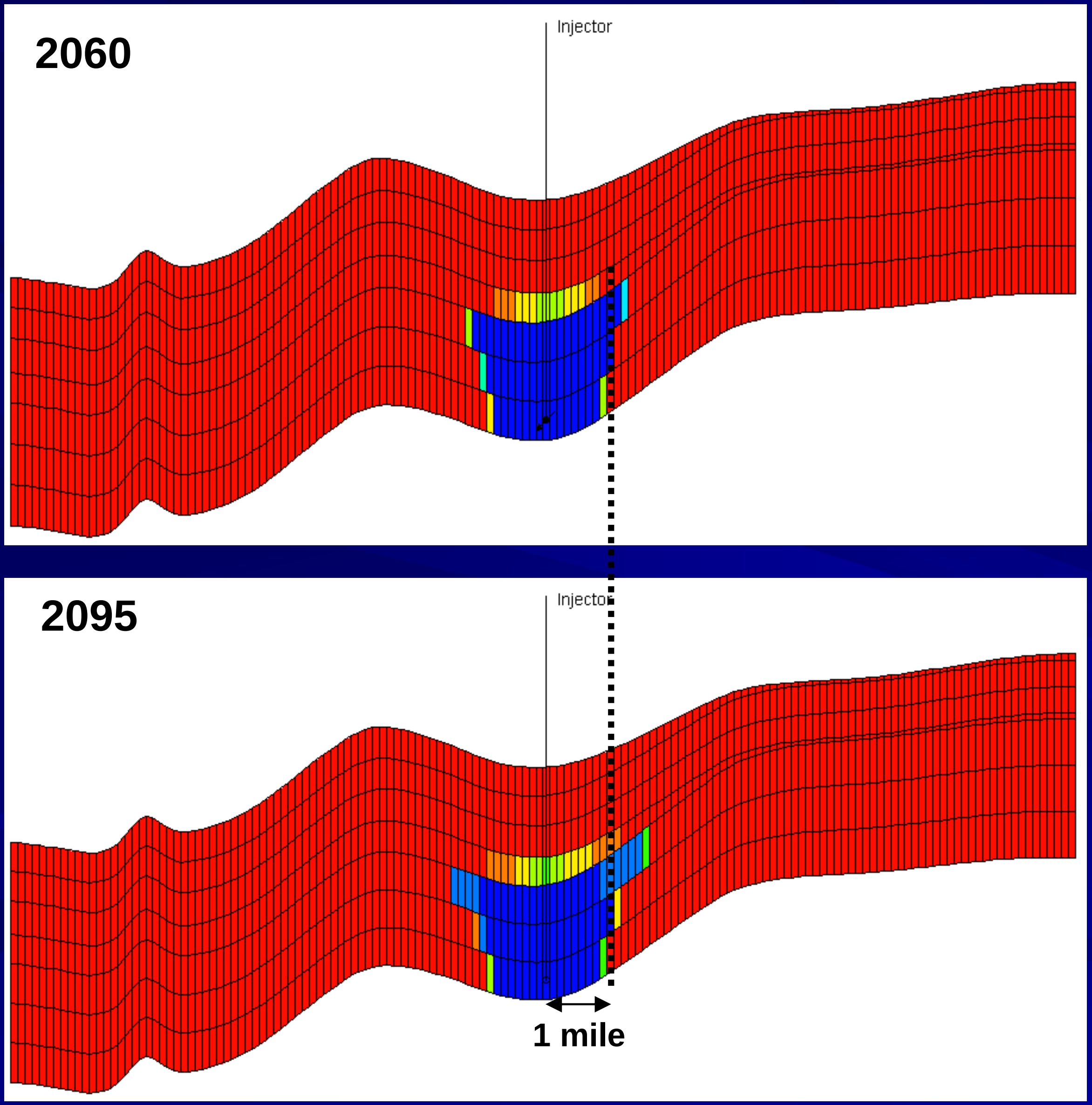
Dependent on input – Max Residual S_g

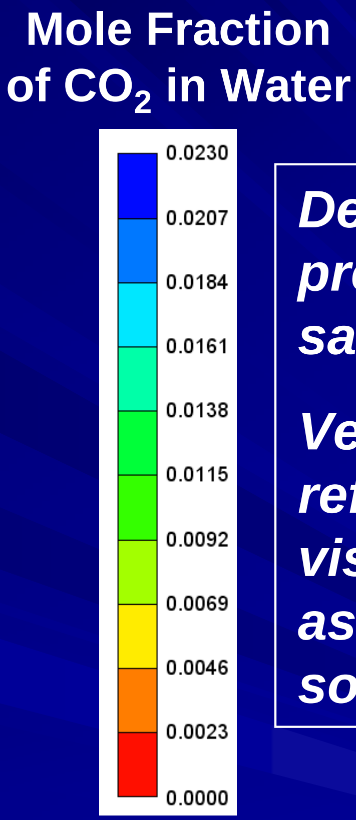


Hysterisis effect in K_{rg} modeled using maximum residual S_g = 0.25 (S_{gcrit} = 0.2)

Residual gas trapping increases: 1) WAG, 2) simultaneous water injection, 3) higher maximum residual S_g

Mole Fraction of CO_2 in Water - Solubility





Depends on pressure and salinity.

Vertical grid refinement - to visualize convection as a result of CO_2 solubility in brine.

Project Schedule

- **Sep 2010**
  - **Wellington field geomodel**
  - **Shoot two 2D lines – Wellington field**
- **Nov 2010 – 1st well drilled at Wellington**
  - **Drill to basement, core, & log**
  - **Case, perforate, and test Arbuckle – pr/fluid**
- **Feb 2011 – 2nd well drilled at Wellington**
  - **Drill to basement and log**
- **Apr 2011 – Core analysis data from lab**
- **May 2011 – Geochemical analysis from lab**
- **Jun 2012 – Reservoir simulation studies**

Thank you