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*

W. Lynn Watney & Saibal Bhattacharya
Kansas Geological Survey
Lawrence, KS 66047

Southwest Kansas Royalty Owners Association

April 24, 2010

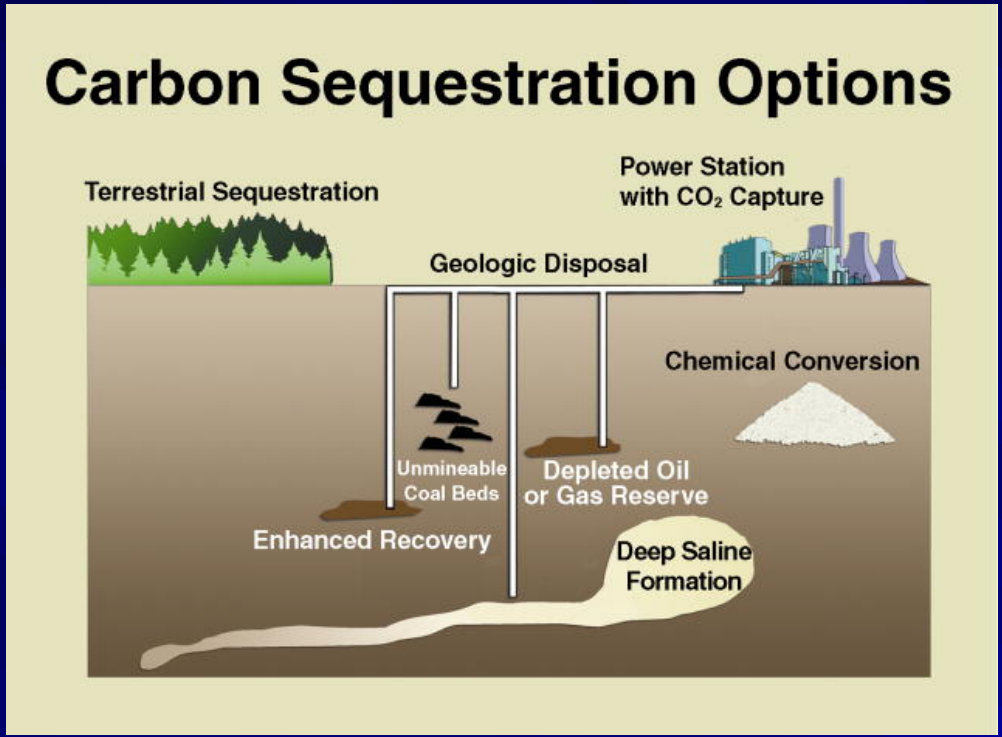
KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

U.S. DEPARTMENT OF ENERGY

Relevance of CO_2 Sequestration in Kansas

- Coal-fired power plants to produce for years
  - Need to address problem of CO_2 emissions
- DOE efforts to develop carbon capture and storage (CCS) infrastructure
- Initiatives of the *Midwestern Governors Association*
- CO_2-EOR – proven & reliable technology
  - Potential applications in many depleted KS fields
- Deep saline aquifers – has potential to sequester large volumes of CO_2
  - Arbuckle saline aquifer in KS
    - Is deep and thick
    - Underlies a large area in south-central KS
- Kansas centrally located to major CO_2 emitting states and cities
- With right incentives and government support CO_2 sequestration has the potential of becoming a major industry in KS

Geologic Sequestration of CO_2



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

Global annual CO_2 emissions ≈ 8 * 10^9 tons

Earth Policy Institute

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

Potential Sequestration of CO2 in Saline Aquifers

NatCarb
a national look at carbon sequestration
NETL

www.natcarb.org/Atlas/ims_map

American Recovery & Reinvestment Act

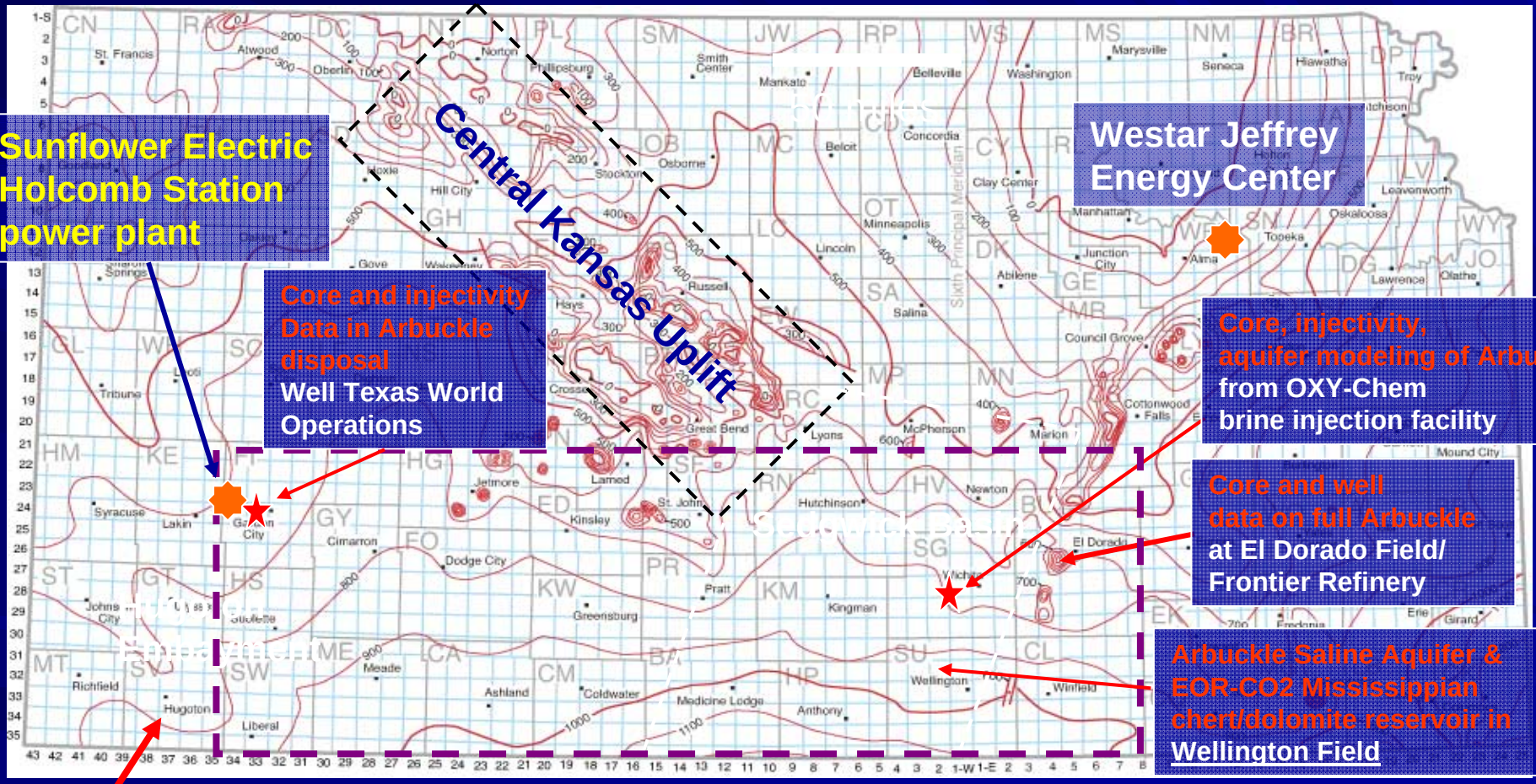
DOE share: $4,974,352
Cost match by KGS and partners: $1,251,422

Principal Investigators: Lynn Watney & Saibal Bhattacharya

Duration: December 8, 2009 to December 7, 2012

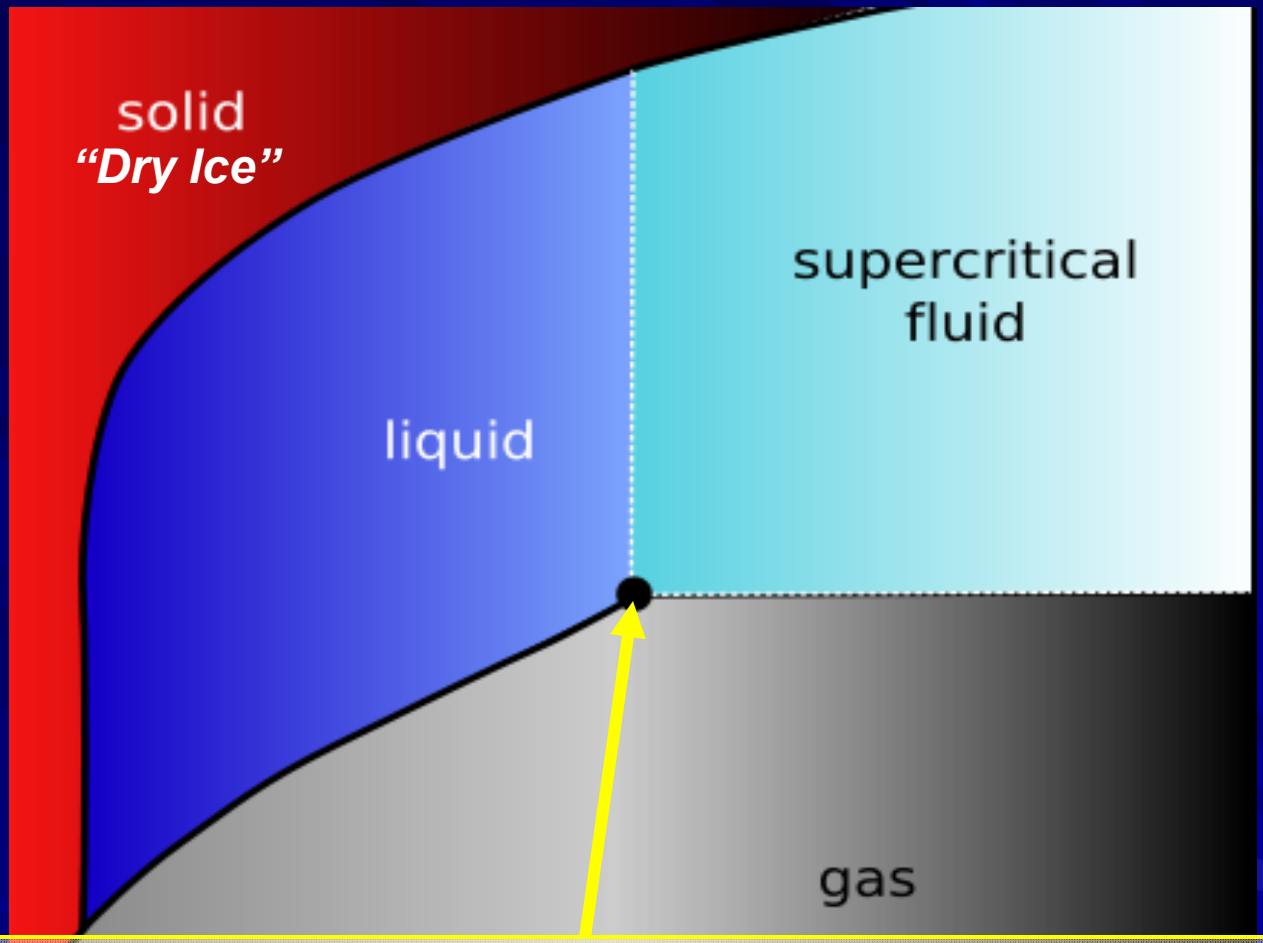
DOE-CO2 Project Study Area

Wellington Field (Sumner County) + 17 Counties



Contours = thickness of Arbuckle Group
thickest in southern Kansas

Saline Aquifer CO_2 Sequestration

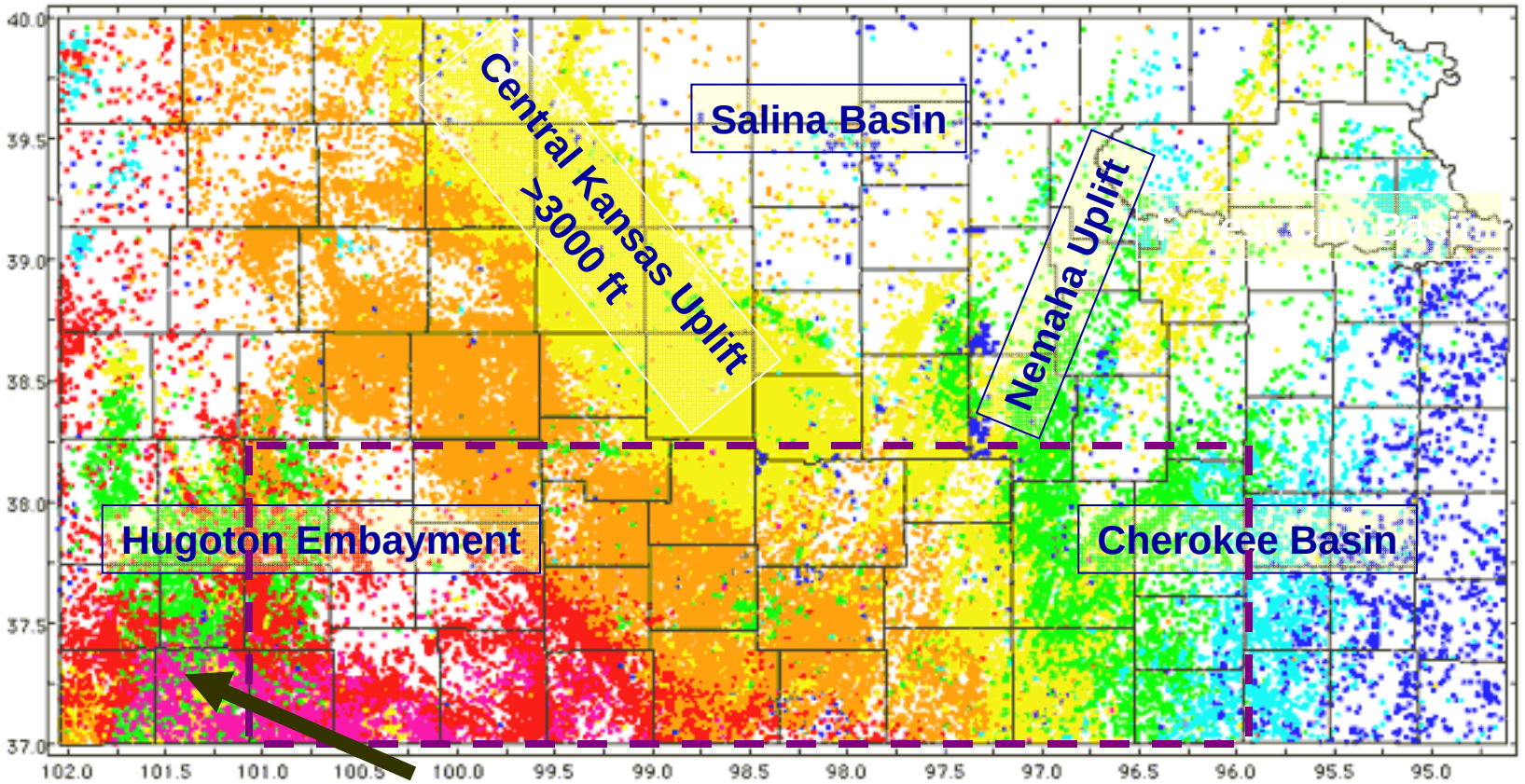


Pressure

@ depths >2200 ft (>1071 psi and 87.8°F) CO_2 becomes a supercritical fluid (3.6% volume of gas phase)

Temperature

Figure 1.--Map showing distribution of oil or gas well samples preserved in Kansas by total sample depth



Miscible displacement **of oil by CO_2 at depths greater than 2000 to 3000 ft (~950 to 1400 psi)**

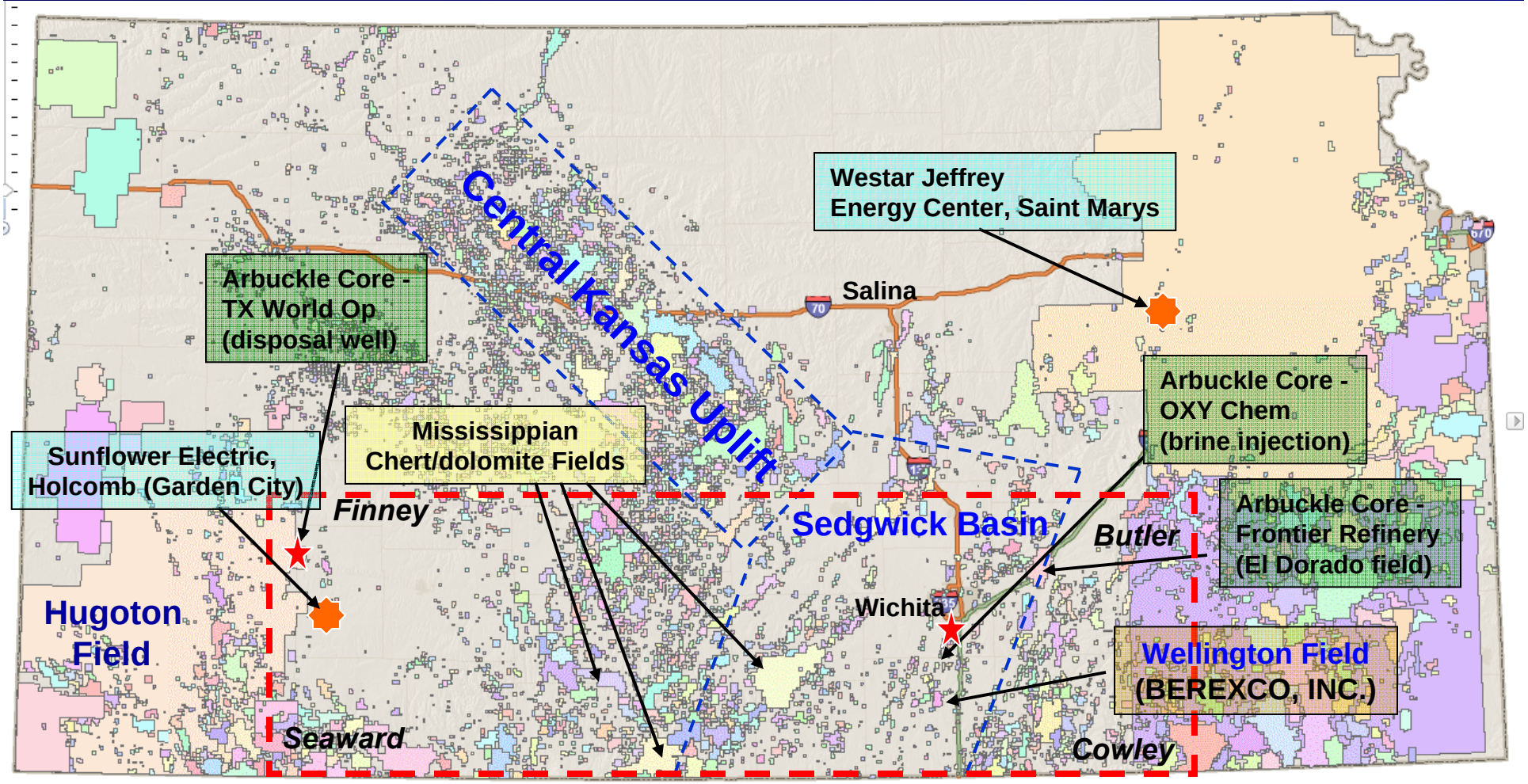
Minimum Miscibility Pressure

*** LKC oil @ Hall-Gurney = 1230 psi**

*** Arbuckle @ Bemis-Shutts ~ 1400 psi**

Project Study Area

Wellington Field (Sumner County) + 17 Counties



Regional study -> ~20,000 sq. miles

50 miles

Project Objectives

- **Build 3 geomodels**
  - ***Mississippian oil reservoir at Wellington field (Sumner County) - depleted***
  - ***Arbuckle saline aquifer underlying Wellington field***
  - ***Regional Arbuckle saline aquifer system over 17+ counties***
- **Conduct simulation studies to estimate CO_2 sequestration potential in**
  - ***Arbuckle saline aquifer underlying Wellington field***
  - ***Miscible CO_2 flood in Wellington field (along with incremental oil recovery)***
- **Identify potential sites for CO_2 sequestration in Arbuckle saline aquifer - 17+ county area**
- **Estimated CO_2 sequestration potential of Arbuckle saline aquifer – 17+ county area**
- **Risk analysis related to CO_2 sequestration**
- **Technology transfer**

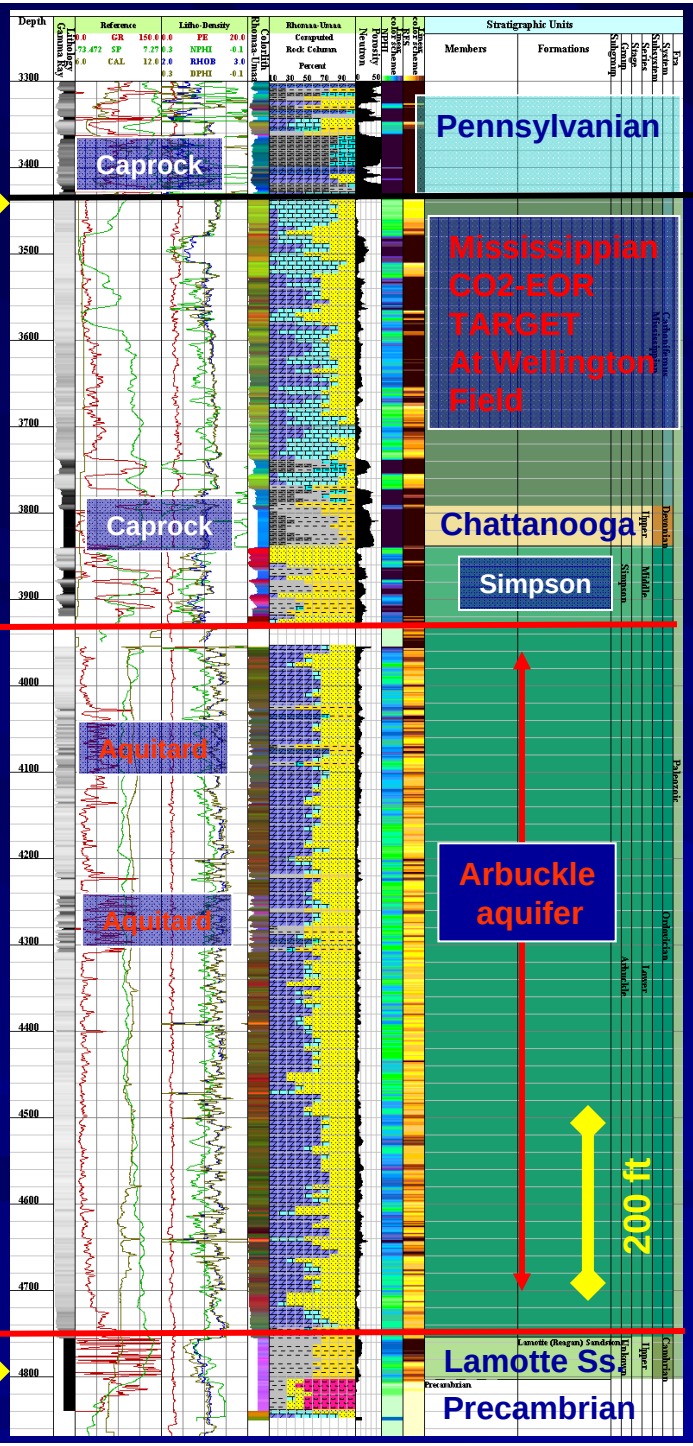
No CO_2 will be injected in this project

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.

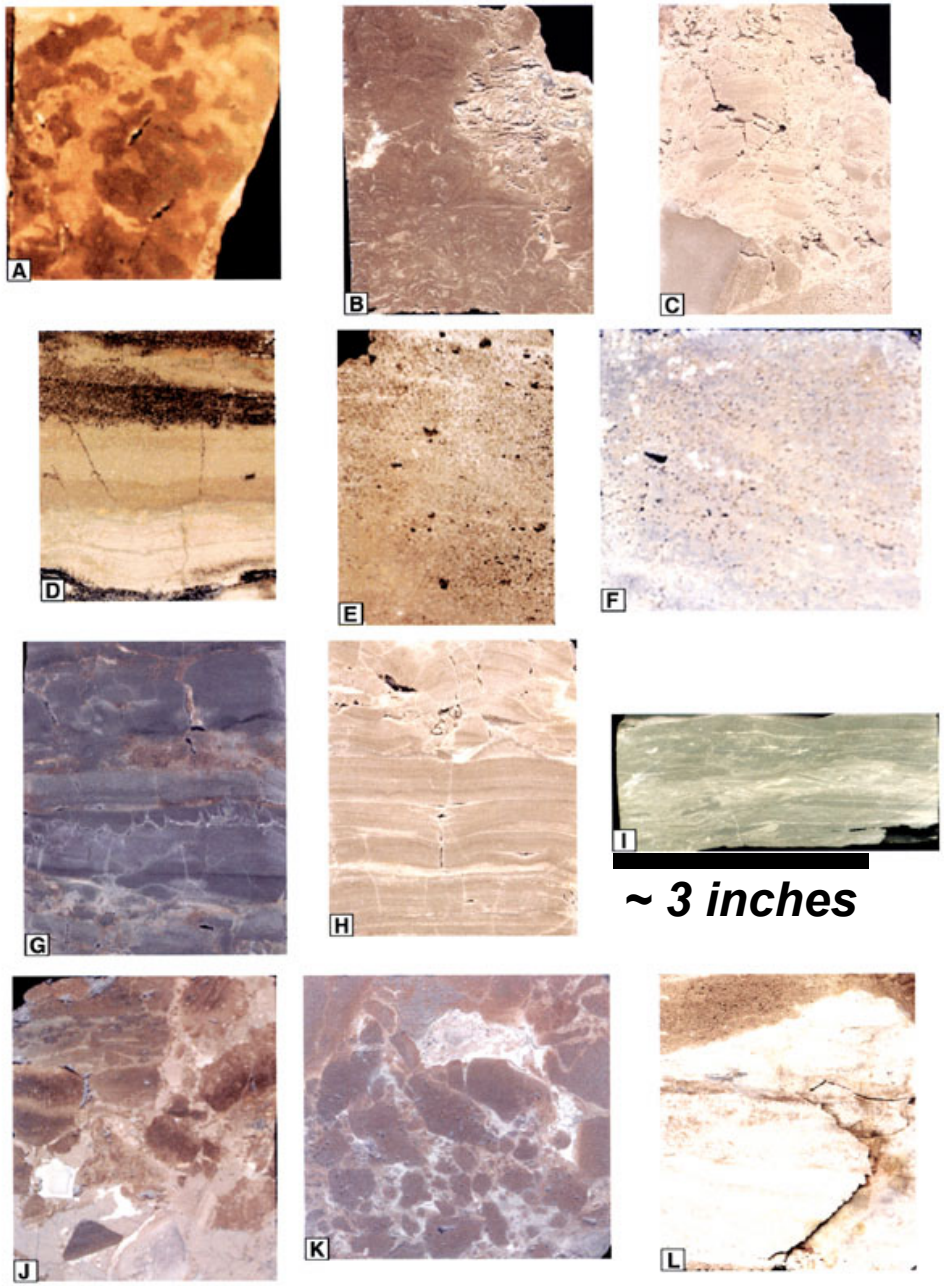
KS companies are working on proposals including demonstration projects related to CO_2 sequestration by CO_2-EOR and injection into underlying saline aquifers.



Color imaging log of deep Class 1 Arbuckle injection well #10 at the Occidental Chemical brine injection site south of Wichita

- High-volume injector (10's 1000's barrels/day, open hole completion in Arbuckle)
- Safe Injection since '50s
- Internal stratigraphic variation
- Role of fractures and compartments to be addressed
- Chattanooga Shale, serve as caprock/seal
- Mississippian chat reservoir interval

Flow units and seals/caprock

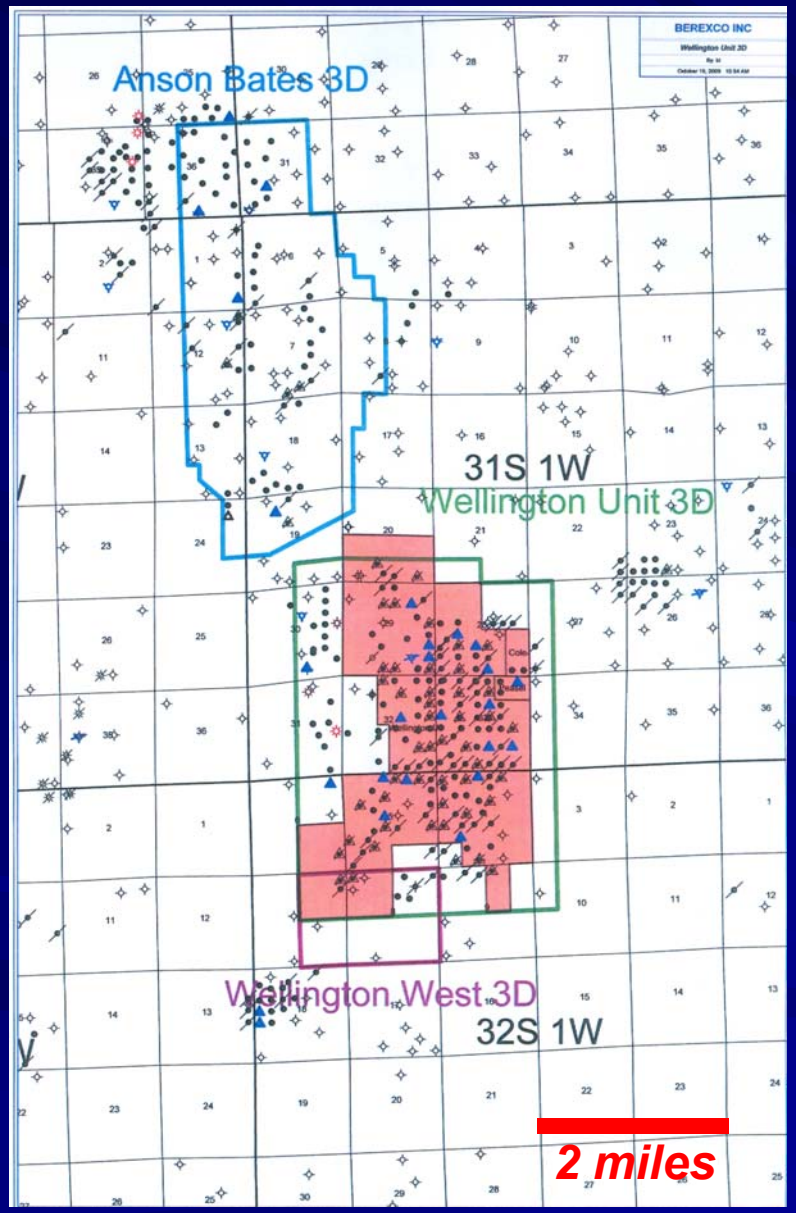


~ 3 inches

Some layers in Arbuckle are porous and act as flow units/aquifers while others have very low permeability and serve as retardants to flow (aquitards)

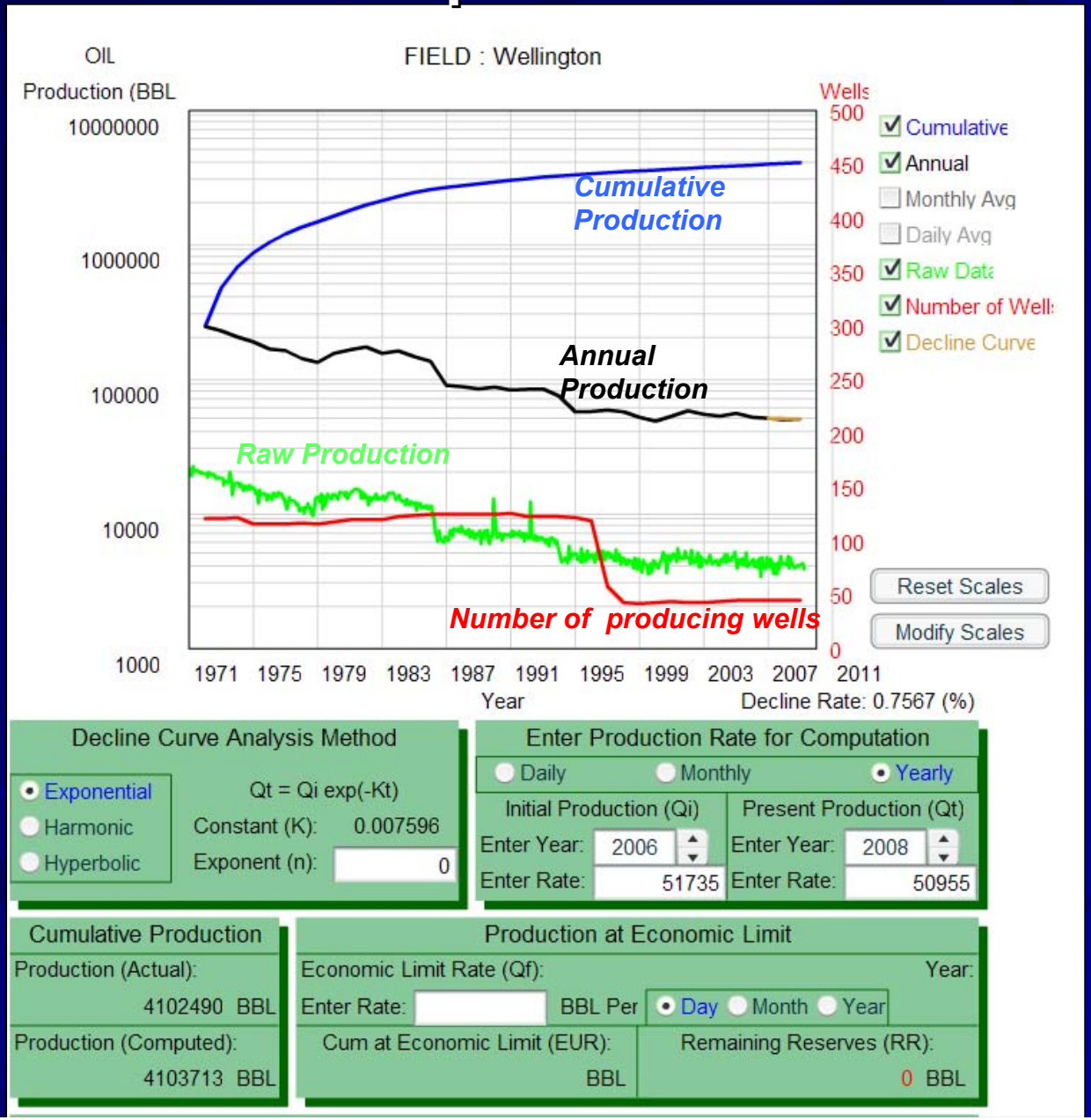
Caprock = thicker shales e.g., Chattanooga Shale

Wellington field, Sumner County, KS



- Discovered in 1922 (134+ total wells)
- 44 active wells, 20.5 MM bbls (oil)
- Field owned by BEREXCO – unitized
- Excellent waterflood performance (no gas) – great CO_2-EOR candidate
- Arbuckle aquifer – ~1000 ft thick (Mississippian top ~ 3650 ft, Arbuckle top ~ 4150 ft, Granite wash ~ 5100 ft)
- Considered for CO_2-EOR using CO_2 from Coffeyville plant
- Adjacent field - Anson and Bates – 6 MM bbls oil (Mississippian Chat), 3D seismic donated by Noble Energy Corp
- All three fields together could sequester ~ 30 MM tons of CO_2

Survey website – lease and field production for Kansas



WELLINGTON FIELD

Total cumulative is 20.5 million bbls. – BEREXCO

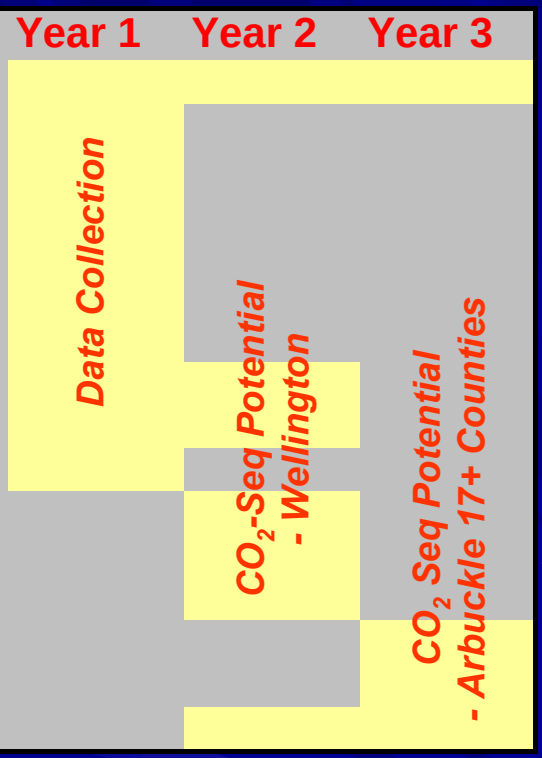
Single pay – Mississippian chert and dolomite

Data Collection & Analysis

- Geophysical surveys at Wellington field
  - *3D multicomponent seismic, 2D shear seismic, & High Res. Gravity/Magnetic*
- Drill, core, log, and test Well #1 to basement – Wellington field
  - *Collect and analyze water samples from different Arbuckle intervals*
- Drill, log, and test Well #2 to basement – Wellington field
  - *Collect water samples from different Arbuckle intervals*
- Analyze Mississippian and Arbuckle core (Well #1) & PVT
  - *Integrate core data with previously taken cores*
- Geochemical studies on Arbuckle water – **KSU Geology Dept.**
- Analysis over 17 county area – Regional geomodel of Arbuckle system
  - *Satellite imagery*
  - *Gravity and magnetic*
- Cap rock integrity and micro-biological studies – **KU Geology Dept.**

Project Time Line

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



No CO_2 injection will take place in this project

Participants

KANSAS GEOLOGICAL SURVEY
The University of Kansas

U.S. DEPARTMENT OF ENERGY

PARAGON GEOPHYSICAL SERVICES, INC

BEREXCO

noble energy

DEPARTMENT OF GEOLOGY
KANSAS STATE UNIVERSITY

KU THE UNIVERSITY OF KANSAS
Department of Geology

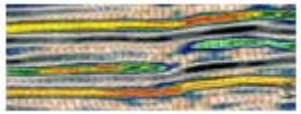
fairfieldnodal

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

Participants

Kansas Geological Survey, Univ. of KS, & KS. State Univ.

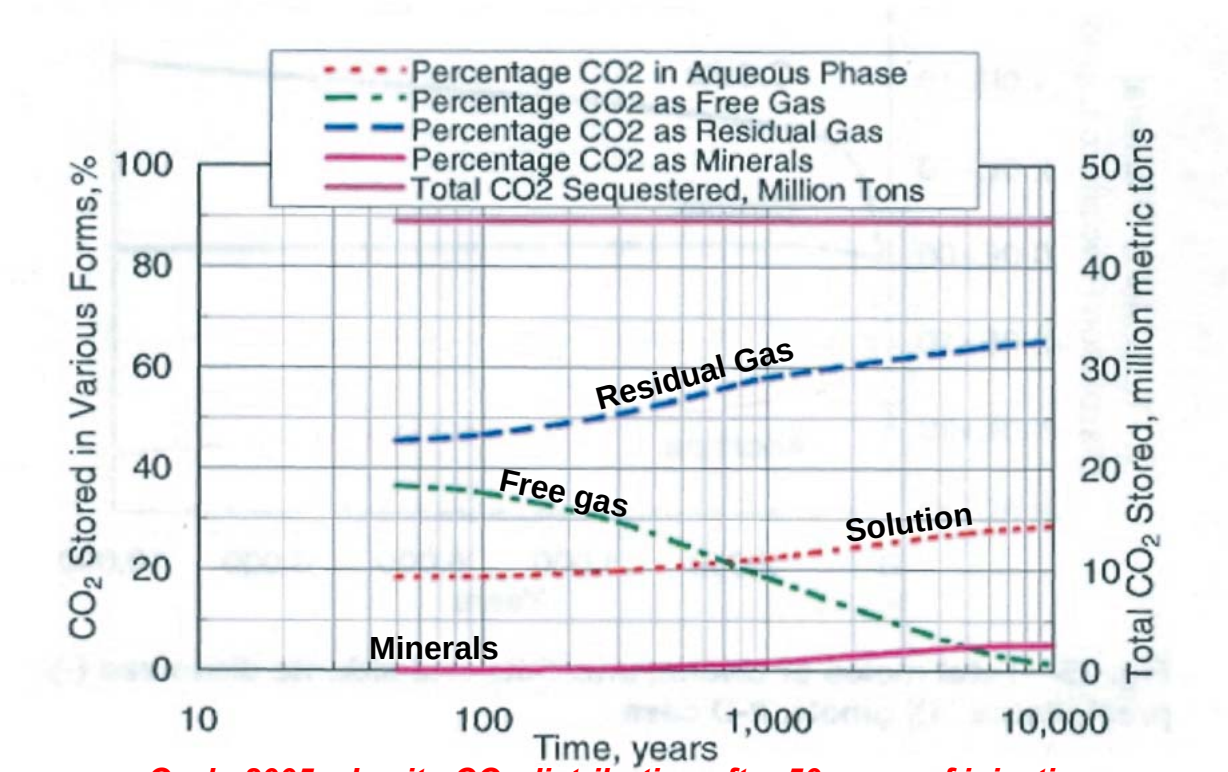
- **Project Manager & PI – Dr. Lynn Watney**
  - **Geologist** - 33 yrs experience in KS geology
- **2nd PI – Saibal Bhattacharya**
  - **Reservoir Engineer** – 12 yrs reservoir simulation experience in KS fields
- **Other KGS Co-PIs**
  - Dr. D. Newell – Structure & diagenesis
  - J. Rush – Petrel geomodeling and data integration
  - Dr. R. Miller – Seismic interpretation
  - Dr. J. Doveton – Log petrophysics and core modeling
  - Dr. J. Xia – Gravity-magnetic modeling and interpretation
  - Dr. M. Sophocleous – Aquifer modeling and well testing
  - **Others**
    - **J. Victorine – Java web application**
    - **D. Laflen – core curation**
    - **M. Killion – ESRI GIS**
    - **K. Look, G. Gagnon, D. Suchy, D. Stewart – manage data**
- **Department of Geology – University of KS**
  - Dr. E. Franseen – Stratigraphy & diagenesis
  - Dr. R. Goldstein – Cap rock integrity (Fluid inclusions and diagenesis)
  - Drs. Roberts & Fowle – experiments in microbial-CO_2 interactions
- **Department of Geology – Kansas State University**
  - Dr. S. Datta – Aquifer geochemistry
  - Dr. A. Raef – Seismic analysis and modeling

Participants

Industry & Consulting Partners

- **BEREXCO INC. – owner/operator of Wellington field**
  - Dana Wreath – Divisional Engr – Supervise all field operations
  - Randy Koudele – Reservoir Engr
  - Bill Lamb – Petra database management and data transfer
  - Evan Mayhew – Operations Engr – drilling, completion, and well testing
  - Robert Hefner – Geophysicist – 3D acquisition, processing, and interpretation
  - Phyllis Shahin – Landman – landowner negotiations and contracts
  - Charles Spradlin – VP and Land Manager
  - Adam Beren – President
- **Hedke-Saenger Geosciences Ltd. – Seismic acquisition & initial interpretation**
  - Paragon Geophysical, Lockhart Geophysical, Fairfield, Echo, Geotextures & Susan Nissen
- **Bittersweet Energy Inc. – Geological Consultants (17+ county regional geomodel)**
  - Tom Hansen – Supervise regional study, Arbuckle aquifer geomodeling
  - Ken Cooper – Arbuckle aquifer simulation and coring
  - John Lorenz – Fracture characterization
  - Paul Gerlach - Arbuckle aquifer geomodeling
  - Larry Nicholson - Arbuckle aquifer geomodeling
- **Weatherford Laboratories - Routine & Special core, Rock Mechanics, PVT**
- **Computer Modeling Group**
  - Bob Brugman – Simulation Engineer – CMG WINPROP & GEM-IMEX simulation
- **David Koger – Satellite imagery analysis – surface lineaments and fractures**
- **Noble Energy – 3D seismic donation (Anson Bates field),** David DesAutels, contact
- **LogDigi – Log digitization**
- **Halliburton – Well logging**

In situ entrapment of injected CO_2



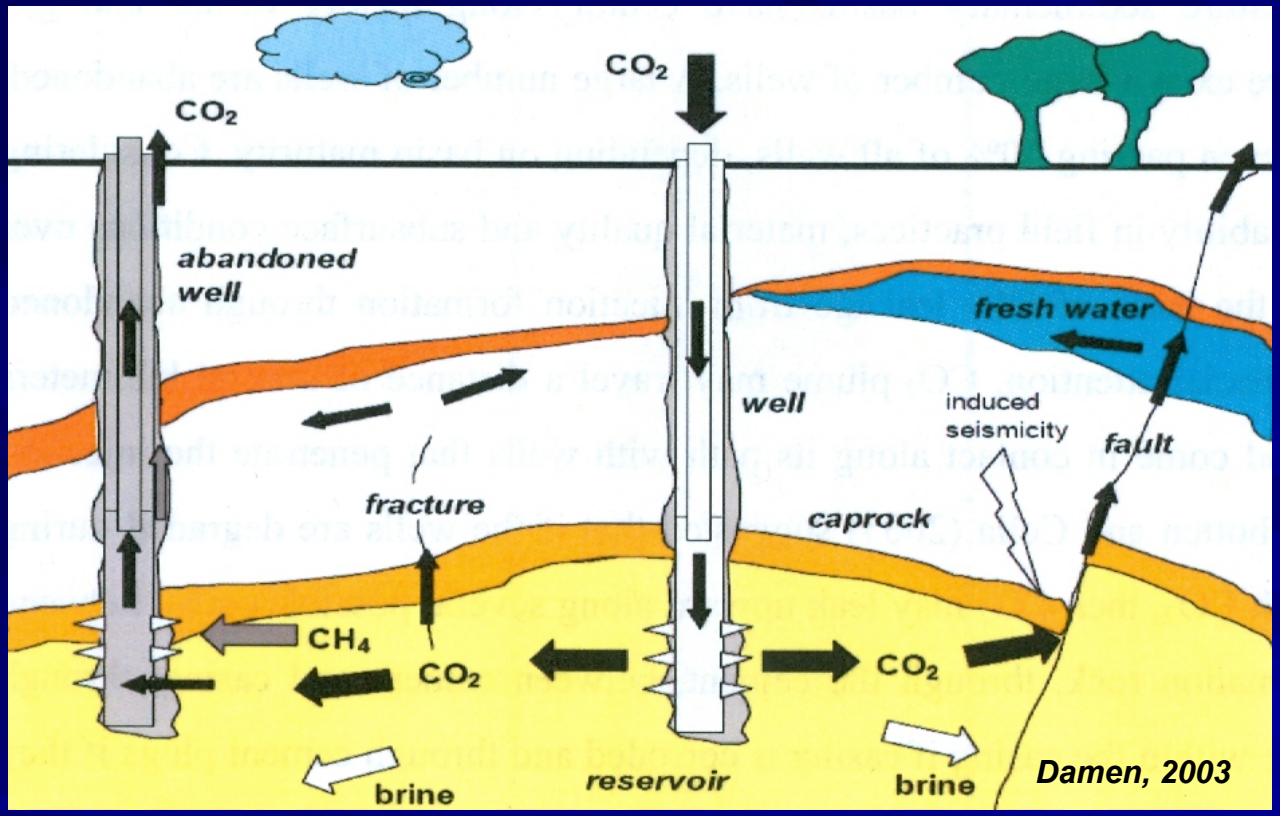
Ozah, 2005 – In situ CO_2 distribution after 50 years of injection

Our study will estimate the amount of CO_2 (tons) that will sequestered in various states using **site-specific geology, rock, and water properties**

Majority of injected CO_2 gets trapped as residual gas saturation followed by CO_2 dissolved in brine solution.

CO_2 mineralization is a slow process.

Risk Analysis – Potential leakage pathways



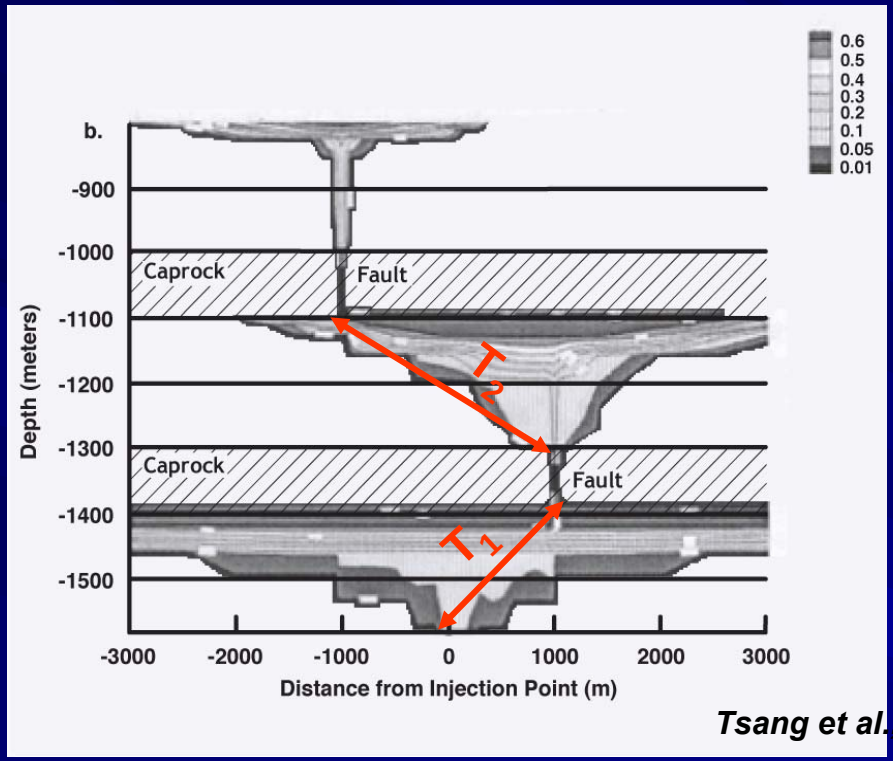
Faults and fractures will be mapped in the 17+ county study area:

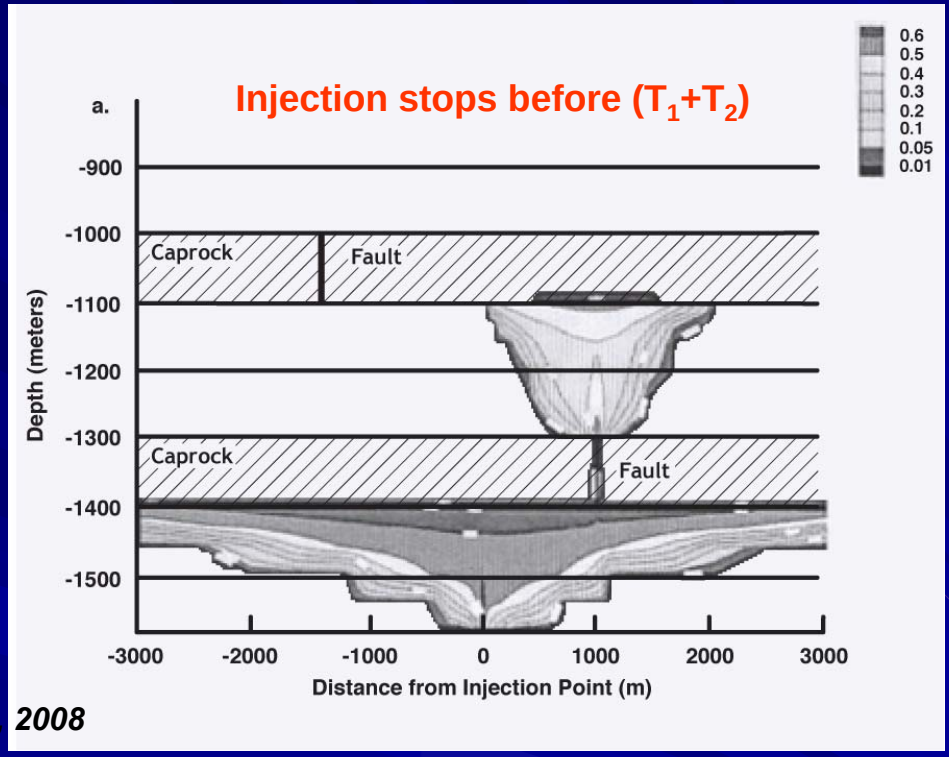
1. **Satellite imagery**
2. **Gravity/Magnetic**
3. **Structure maps**

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.

Risk Analysis

Plume Breaches Cap Rock via Fault/Weak zone





Tsang et al., 2008

Simulated plume after breach smaller and has lower pressure.

If injection stops before plume reaches fault – then no leakage occurs.

What are the chances that the plume will breach successive cap rocks?

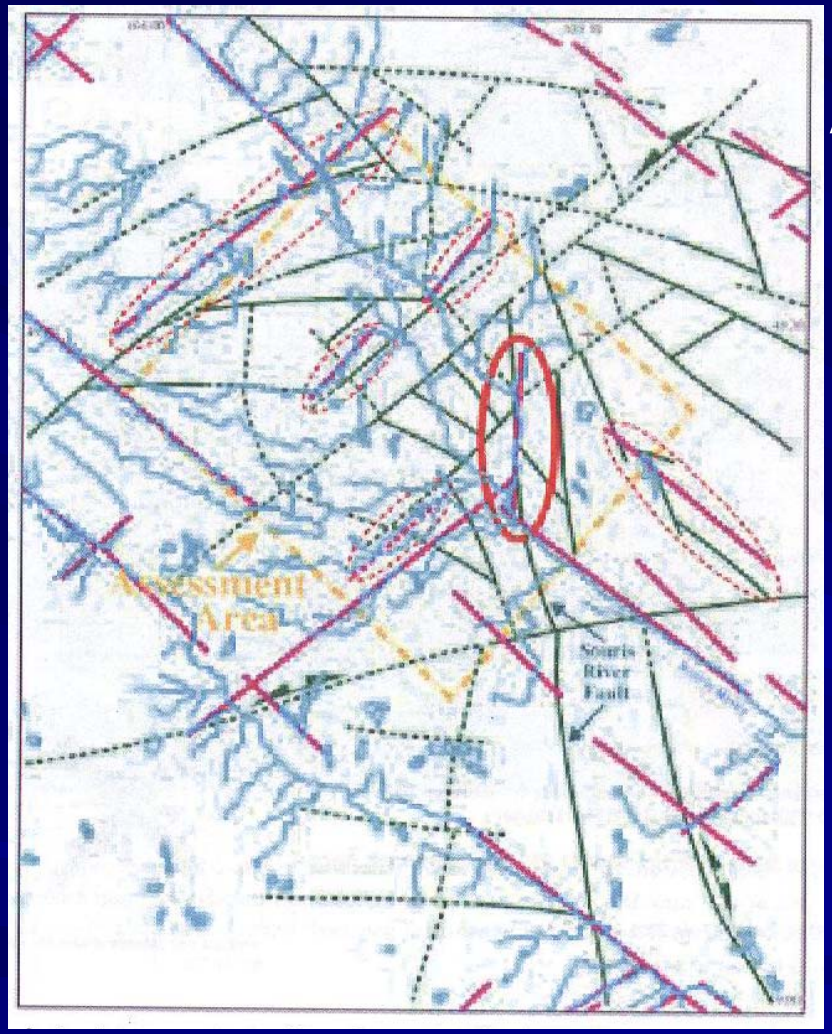
Is CO_2 sequestration tonnage economic before plume reaches fault?

Weyburn CO_2-EOR - Canada

- **September 2000** – CO_2 from coal gasification plant (N. Dakota) transported by 350 km pipeline & injected into Weyburn oilfield (Saskatchewan, Canada)
  - Weyburn – 50 yr old depleted oil field
- Expected performance of CO_2-EOR **by 2035**
  - 155 million gross barrels of incremental oil recovery
  - Sequestration of 30 million tonnes of CO_2
- **October 2005** – CO_2 injection began at adjacent Midale oilfield
  - Expect 45-60 million barrels of incremental oil recovery

http://www.netl.doe.gov/publications/factsheets/project/Proj282.pdf

Weyburn CO_2-EOR - Canada



IEA GHG Weyburn Summary Report 2000-04
~20 miles across base of map

Analysis of Natural Faults and Fractures

***Solid Green** – fault trends from seismic & HRAM (high resolution aeromagnetic)*

***Broken Green** – trends from HRAM*

***Purple** – surface lineaments*

***Red oval** – Souris Valley fault (fault identified by seismic and HRAM coincide)*

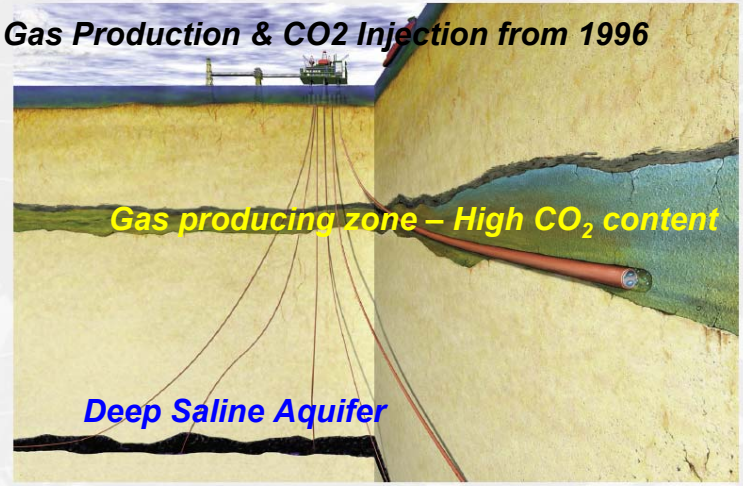
***Broken Red** – weak correlations between data sets*

Not all sub-surface faults/fractures reach the surface

Risk Analysis
Seismic Monitoring Results - Sleipner field (North Sea)

The Sleipner CO2-injection into the Utsira Formation at 1000 Meters Below Sea Bottom
- About 1 million tons/yr -

STATOIL



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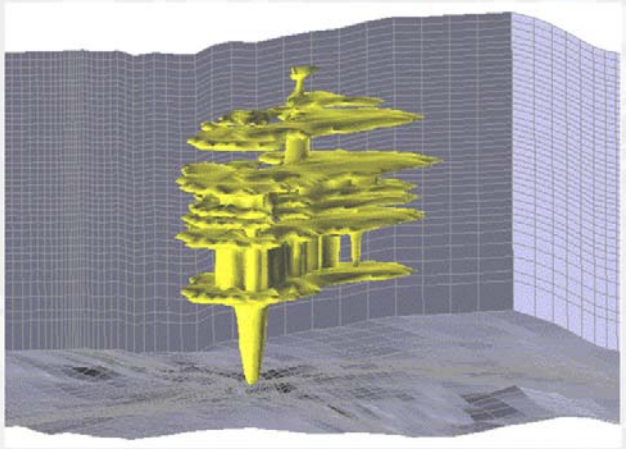
Reservoir model of CO_2 after 3 years

STATOIL



Source: SACS, Best Practise manual 2003

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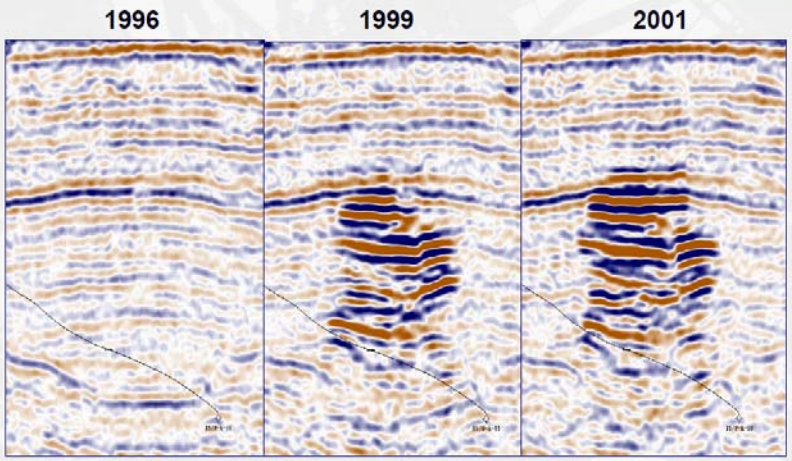
Every time the CO_2 plume meets a thin shale layer, it spread out laterally. This lateral dispersion results in additional sequestration and plume degradation - CO_2 dissolving into fresh brine and getting trapped in fine pores of the rock. *Torp & Gale, 2003*

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

3D Seismic survey at Sleipner

STATOIL



Source: SACS, Best Practise manual 2003

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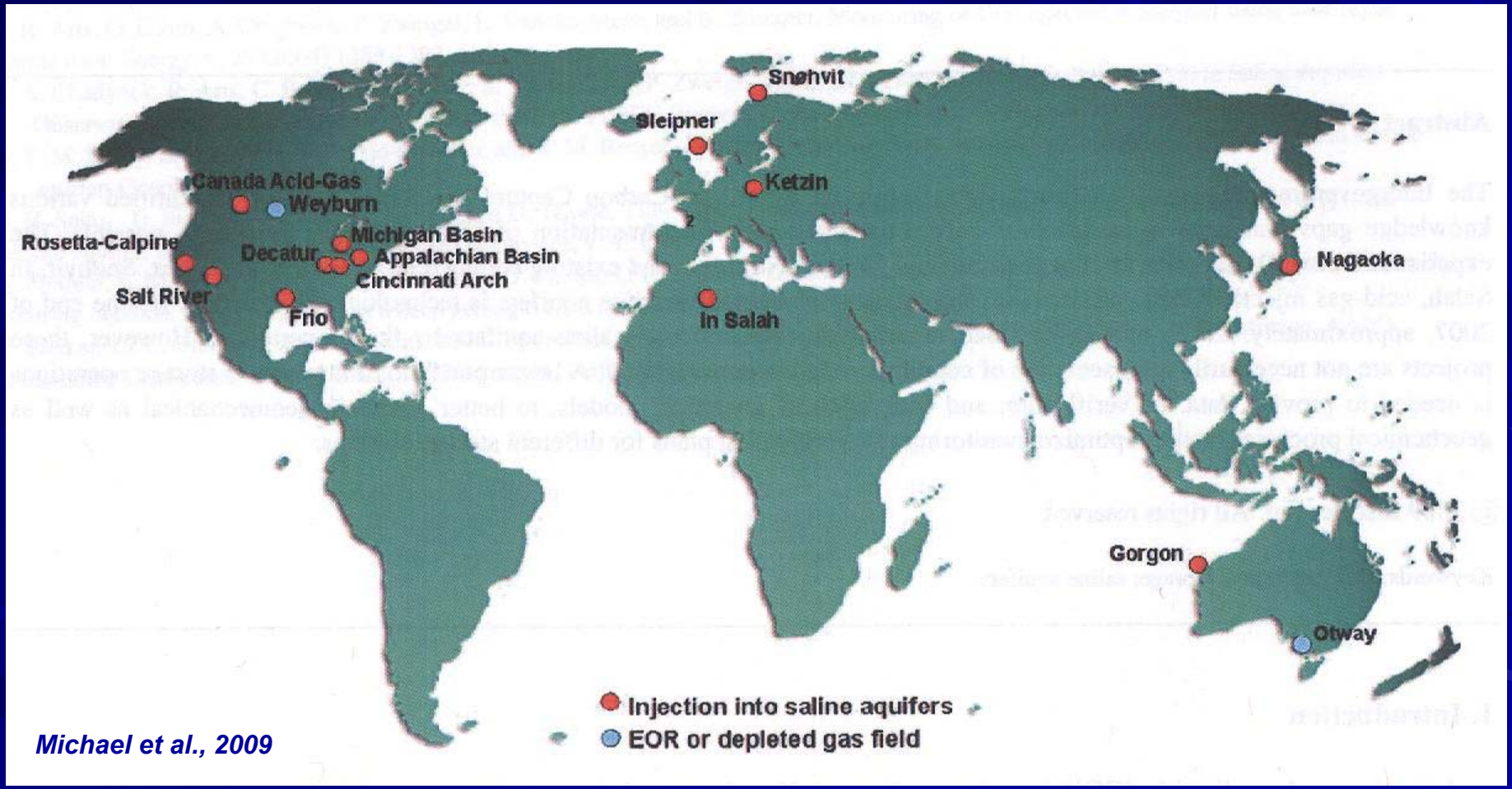
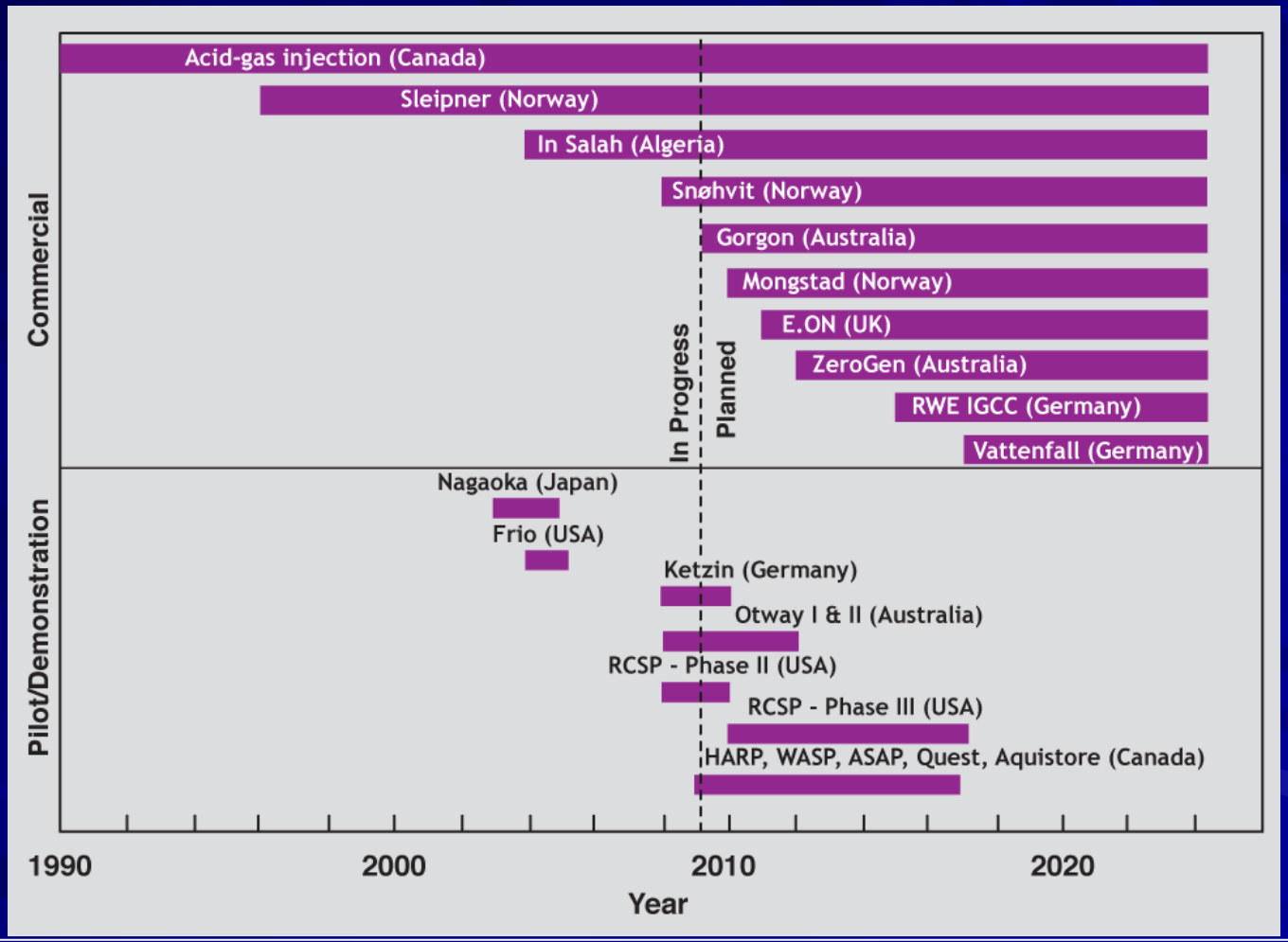
CO_2 Sequestration Projects Worldwide
Deep Saline Aquifers



Michael et al., 2009

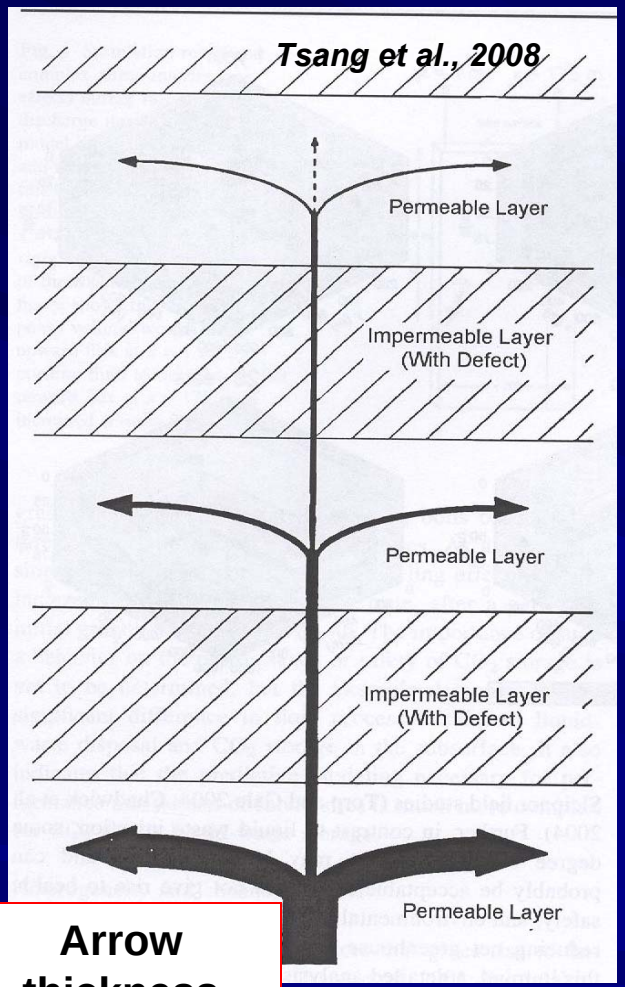
CO_2 Sequestration Projects Worldwide
Deep Saline Aquifers

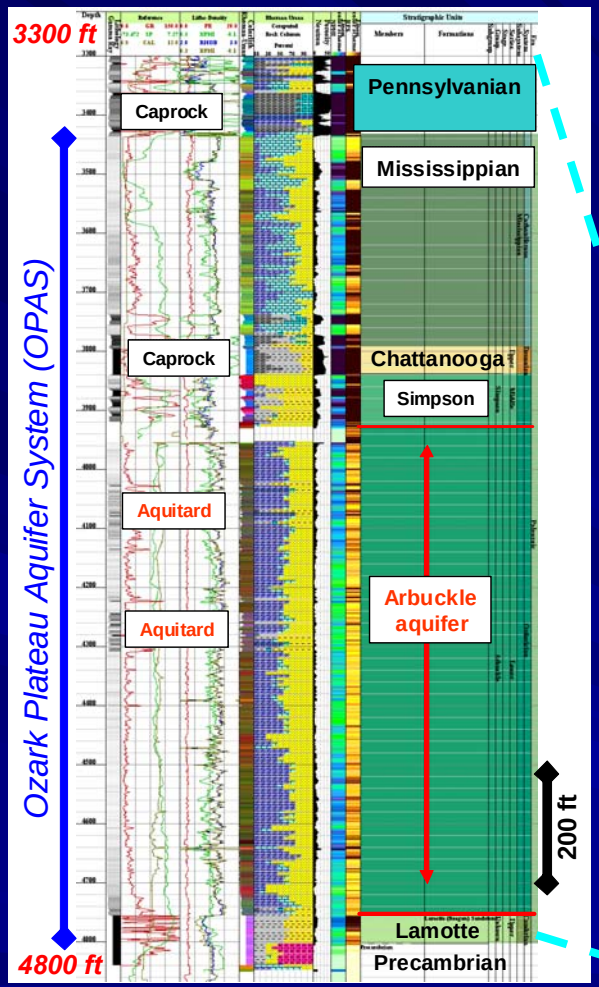


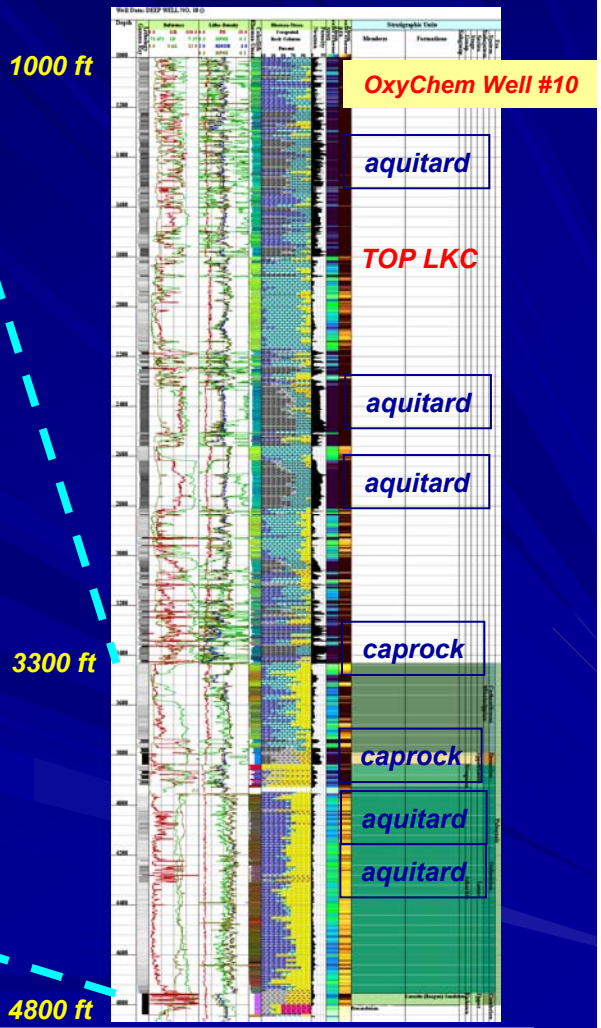
Univ. of Utah *(SW Regional Sequestration Partnership)* & Cap CO_2 have submitted a proposal to DOE for field scale CO_2-EOR on Apr 15 2010 - KGS is a partner

Risk Analysis

Leakage Retardation – Multiple Caprocks & Aquitards



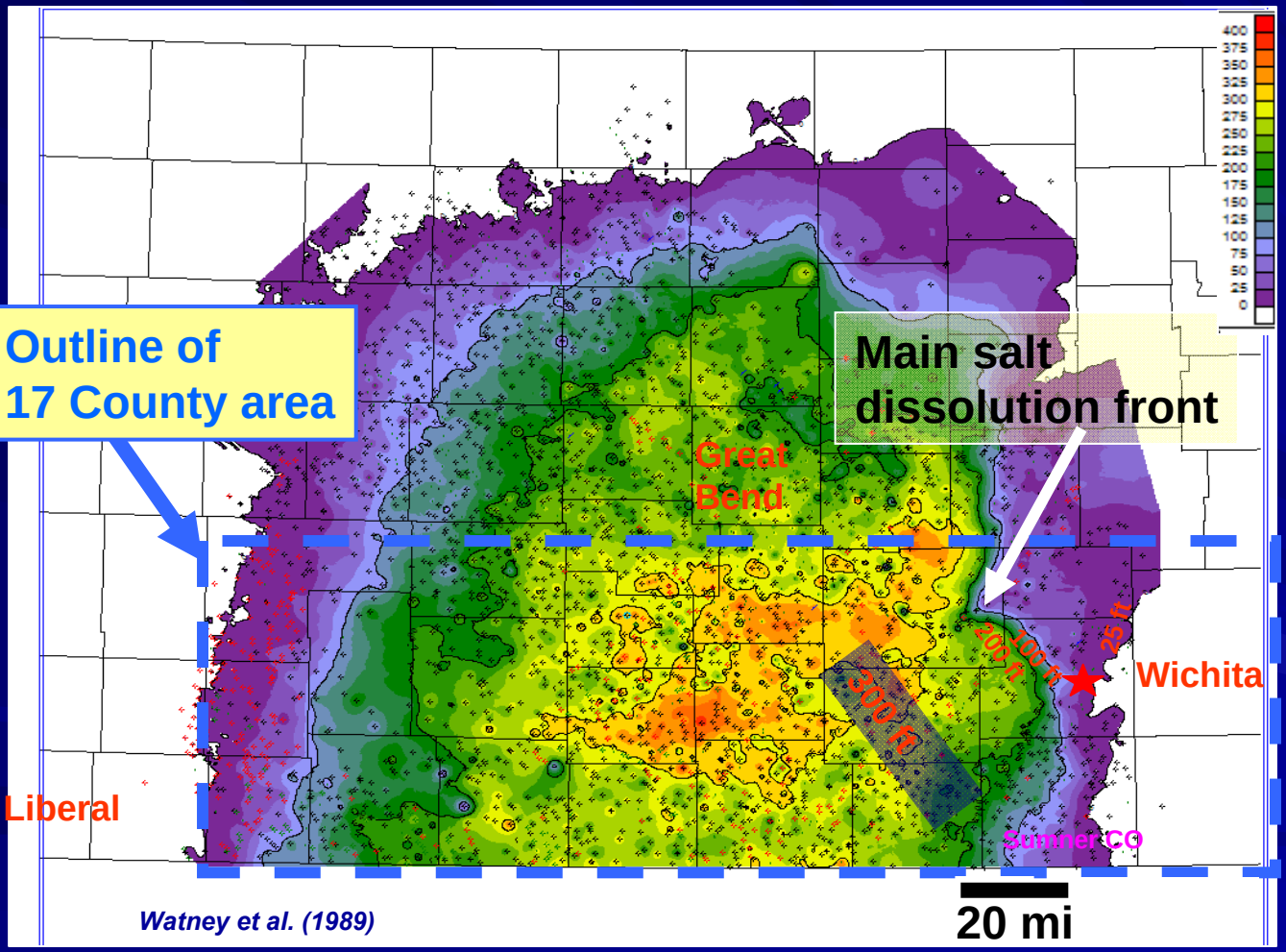




Arrow thickness -Relative amount of flow

CO_2 plume undergoes pressure reduction upon breaching cap rock. Also additional CO_2 gets trapped in the fine pores of aquitards.

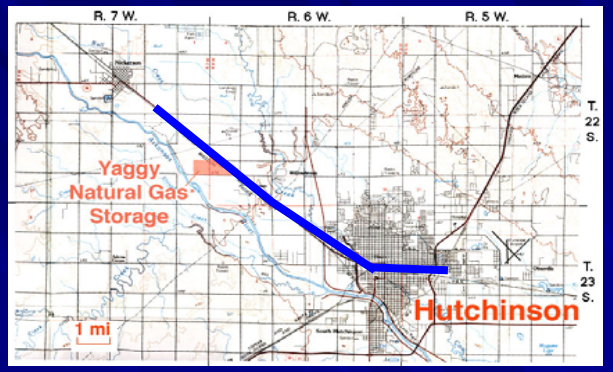
Net Halite (salt) Isopach (thickness)

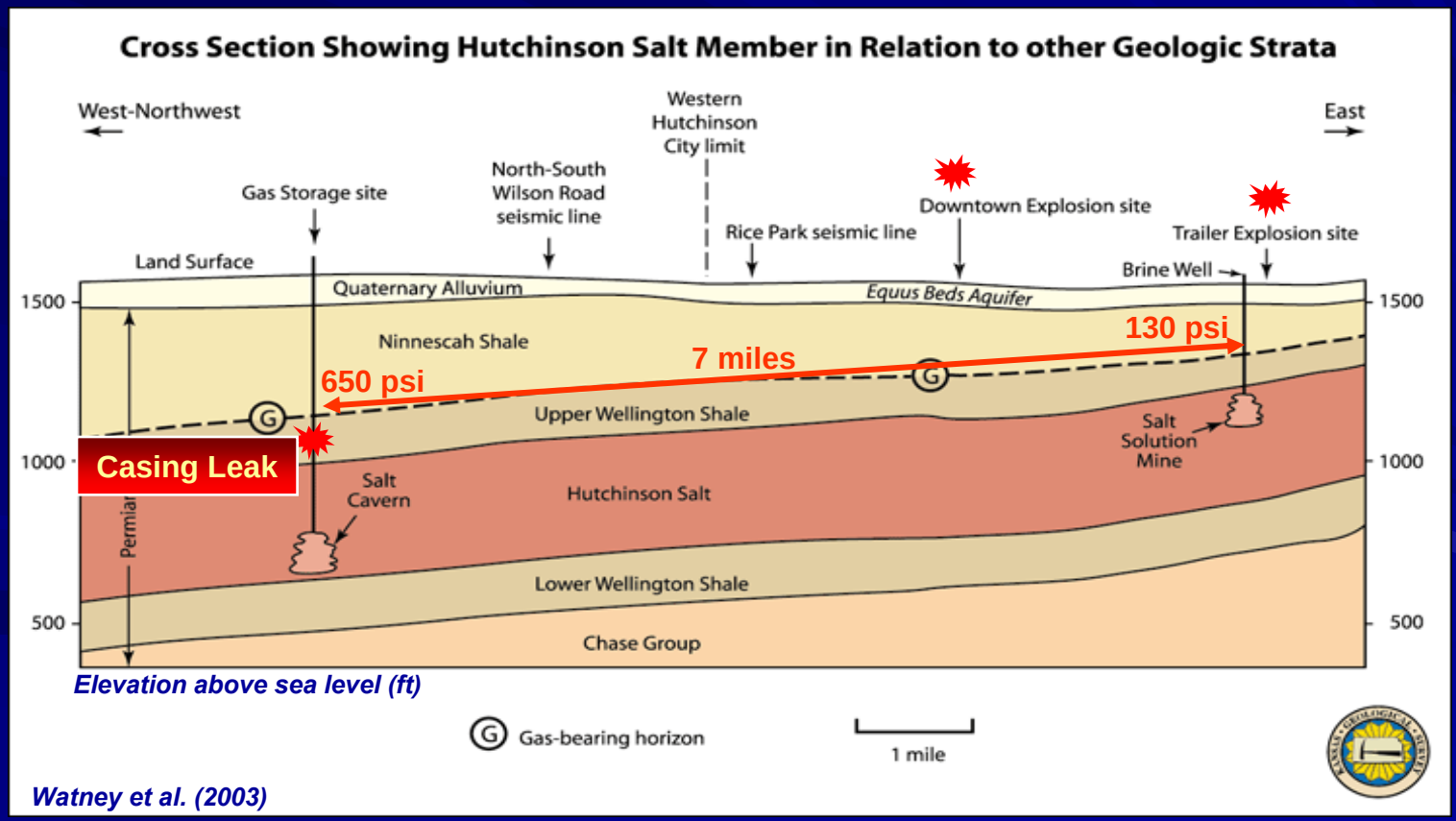


Additionally, KGS maps show that total evaporite thicknesses range from 400 to 2000 ft in south-central KS. These evaporites serve as ideal cap rocks.

Yaggy Gas Storage Leak - 2001

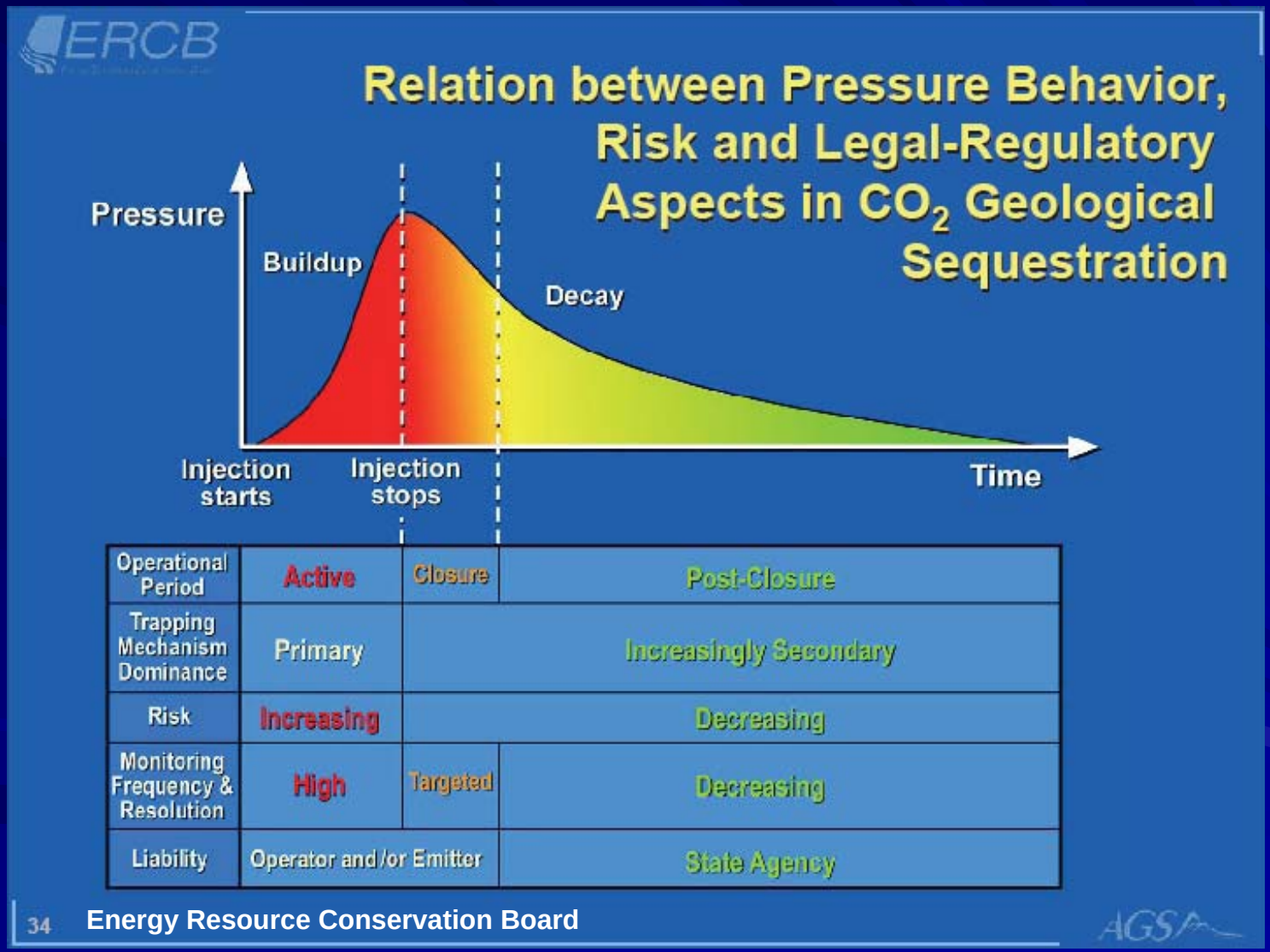
Site selection for CO_2 sequestration CRITICAL, because all wells drilled in the area have to be accounted for and properly completed before onset of CO_2 injection.





Watney et al. (2003)

Saline aquifer CO_2 sequestration



2 x 750 MW coal-fired power plant → *10 million tons CO_2 per year*

South-central Kansas CO_2 Project
Kansas Geological Survey

Project Overview

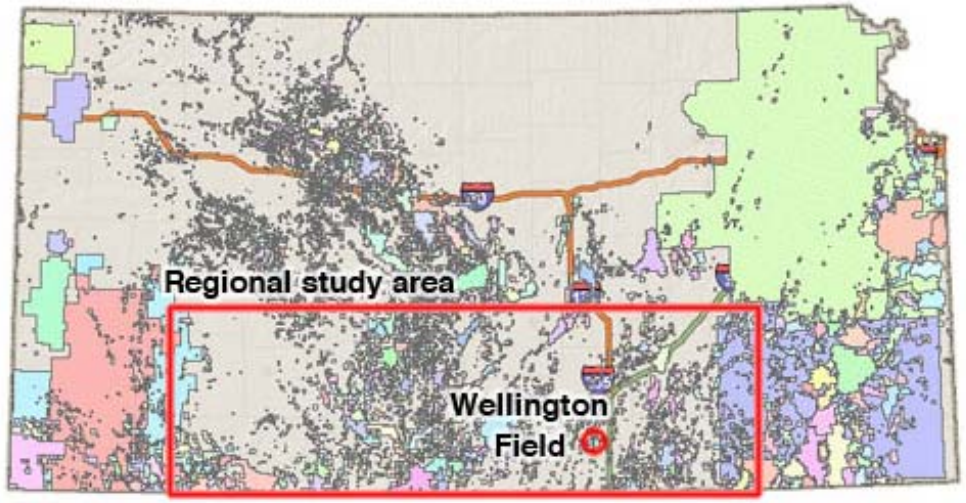
March 2010

Abstract

The proposed study will focus on the Wellington Field, with evaluation of the CO_2-EOR potential of its Mississippian chert ("chat") reservoir and the sequestration potential in the underlying Cambro-Ordovician Arbuckle Group saline aquifer. A larger geomodel study of the Arbuckle Group saline aquifer will then be undertaken for a 17+-county area in south-central Kansas to evaluate regional CO_2 sequestration. This study will demonstrate the integration of seismic, geologic, and engineering approaches to evaluate CO_2 sequestration potential.

Project Area

March 2010



About...

South-central Kansas CO_2 Project is a DOE-funded project of the Kansas Geological Survey. More ...

Topics...

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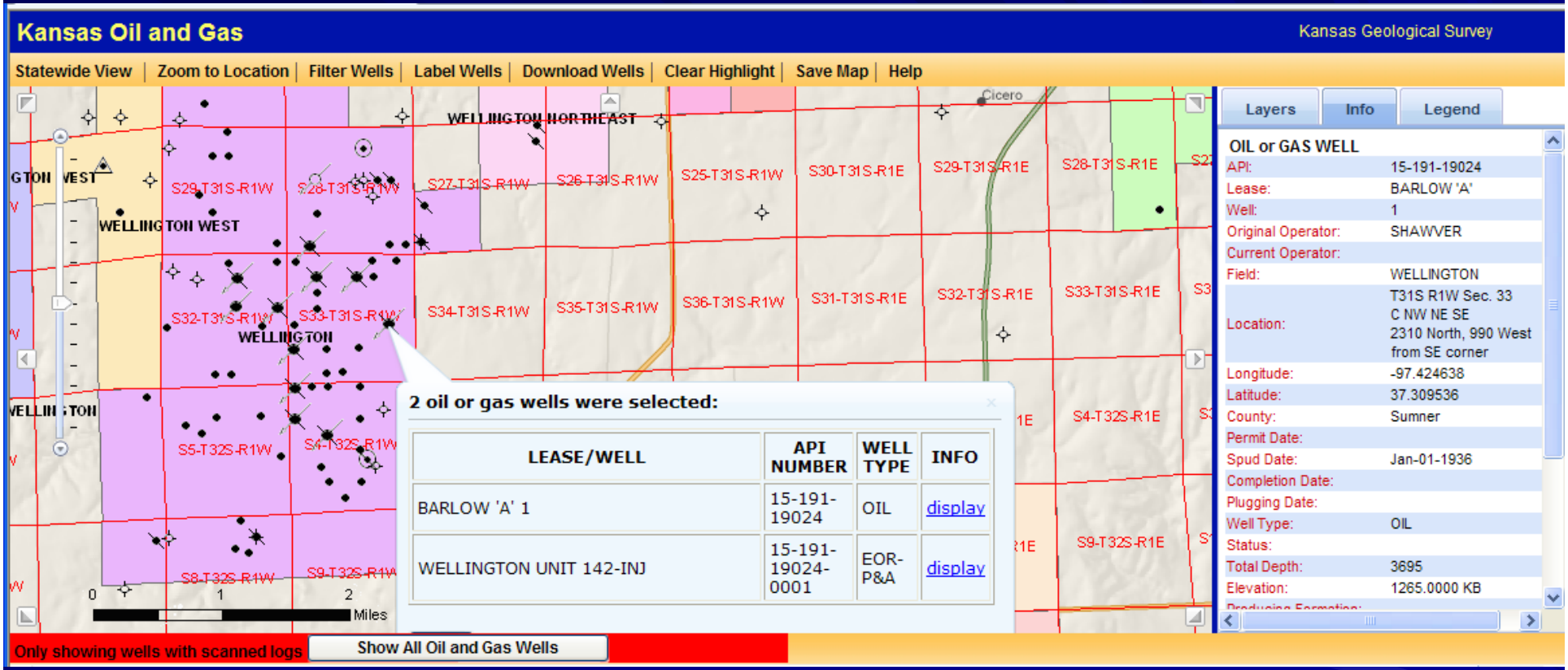
Publications

People

www.kgs.ku.edu/PRS/Ozark

Interactive Map Viewer

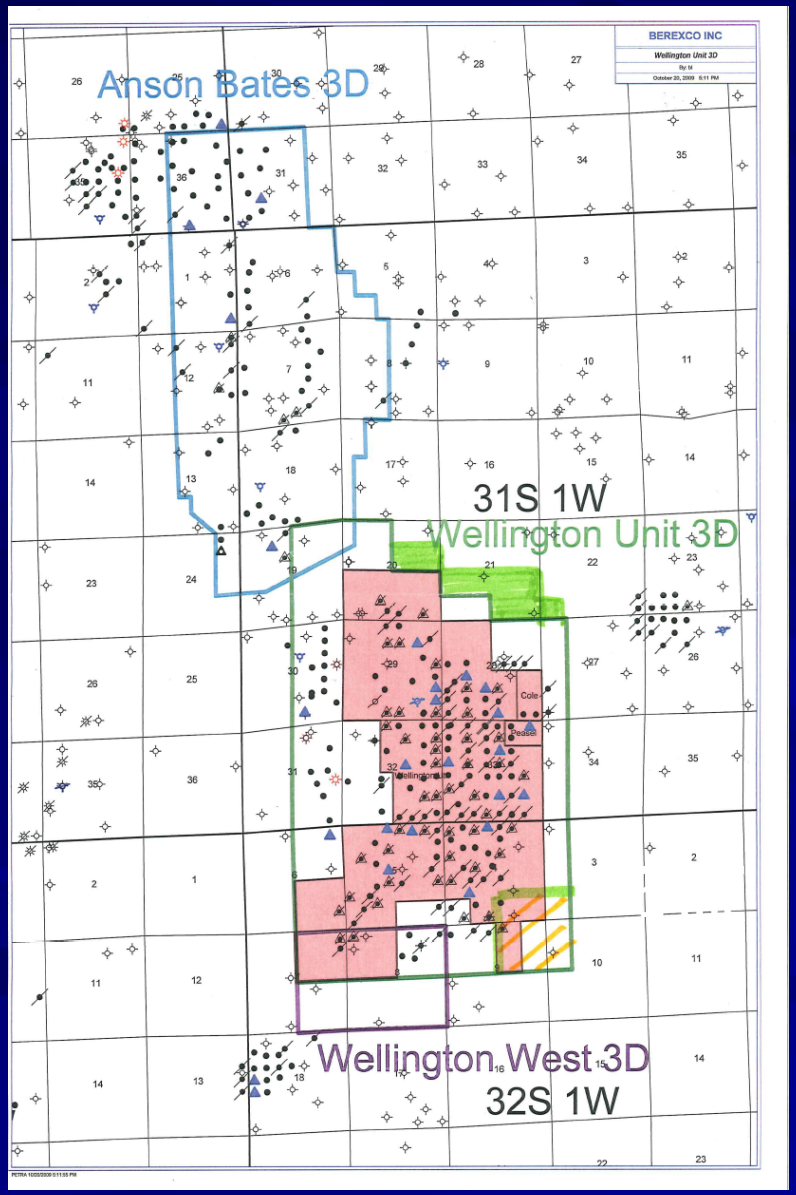
Interface for public to access data and interpretations obtained from project

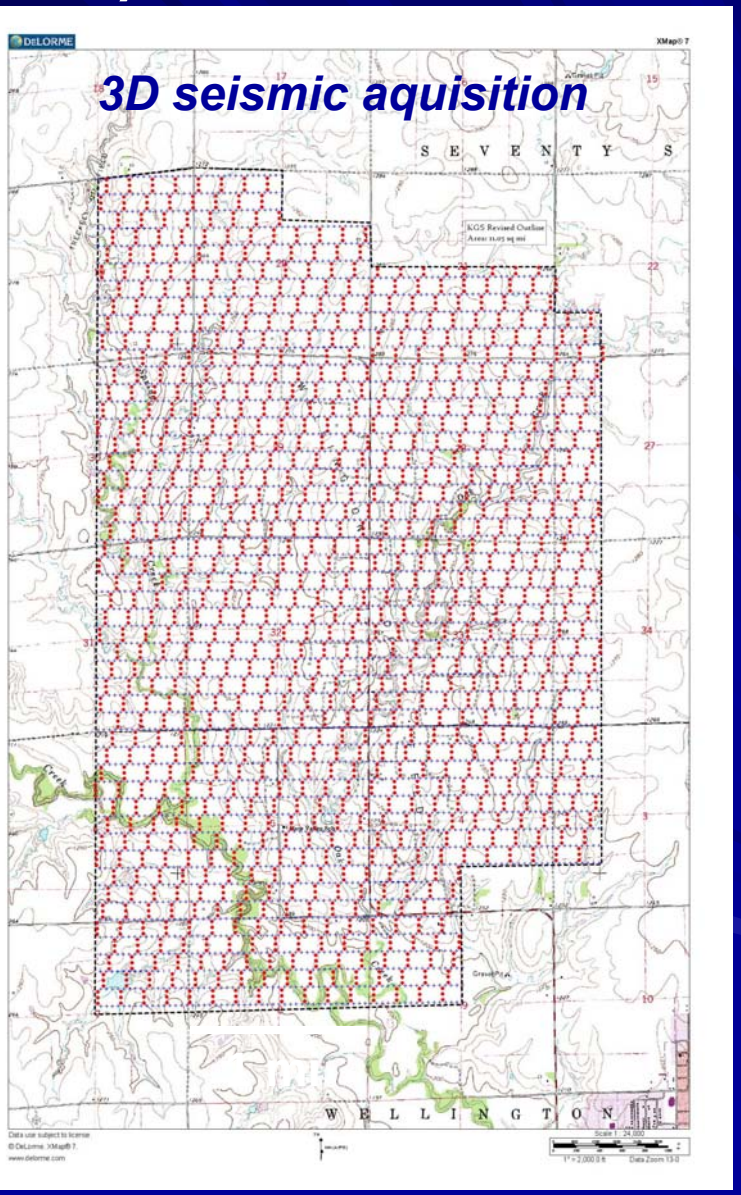


KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

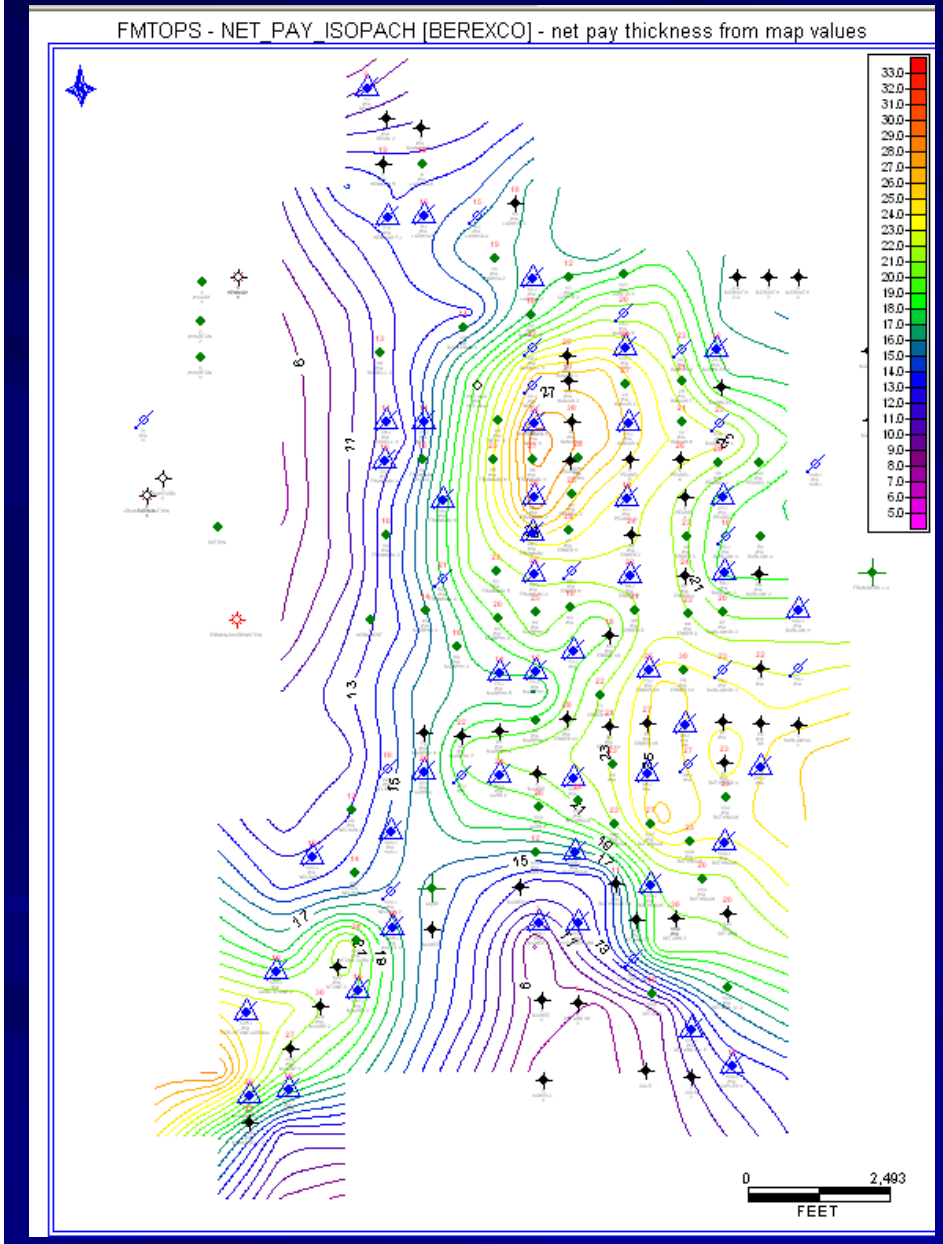
- *Identify wells (click and link to complete information including lease production)*
- *Filter wells (e.g. wells with scanned logs)*
- *Overlay aerial photos & topographic maps*

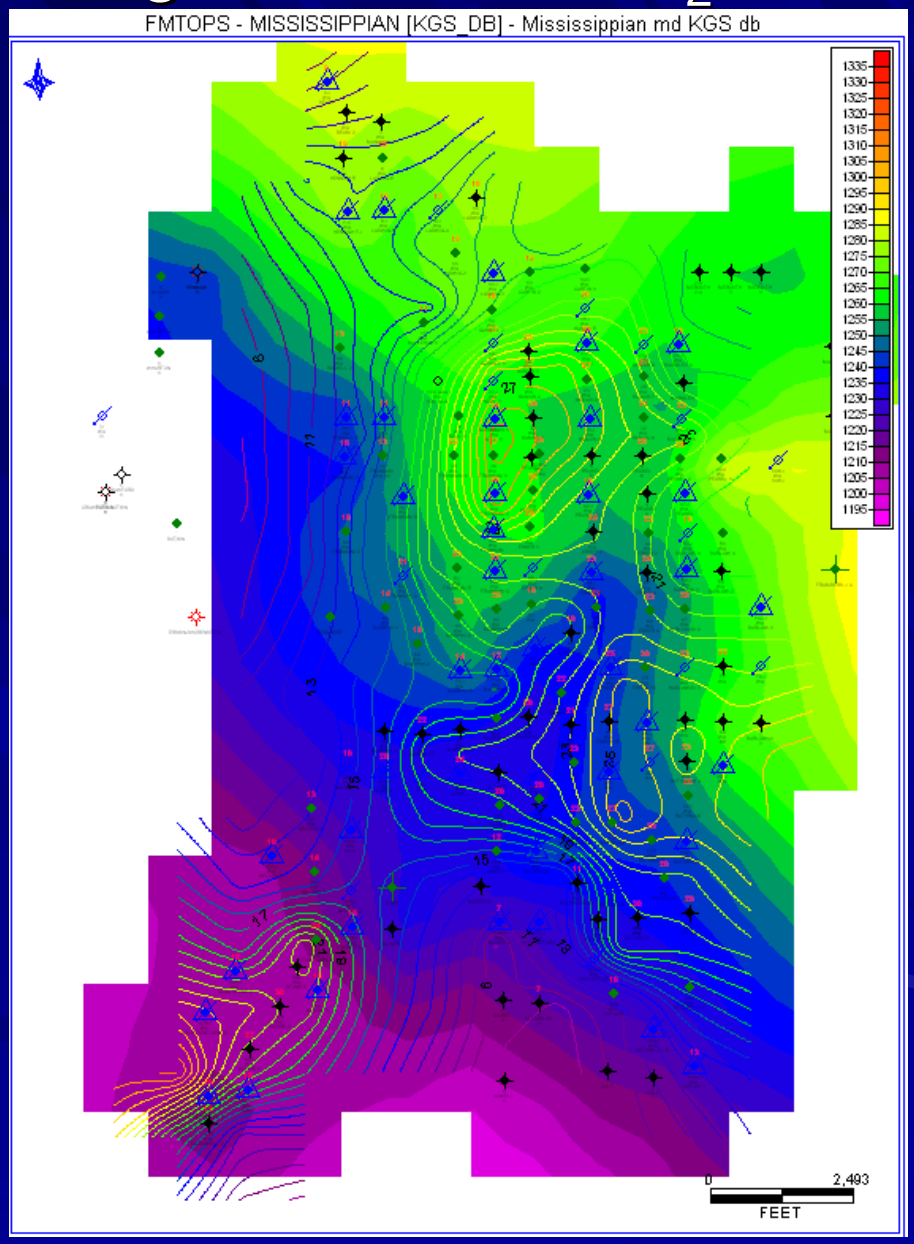
3D seismic acquisition complete (Paragon) – April 10, 2010
High Resolution Gravity/Magnetic acquisition (Lockart) - by June, 2010
2D shear wave seismic (Lockhart) – June, 2010



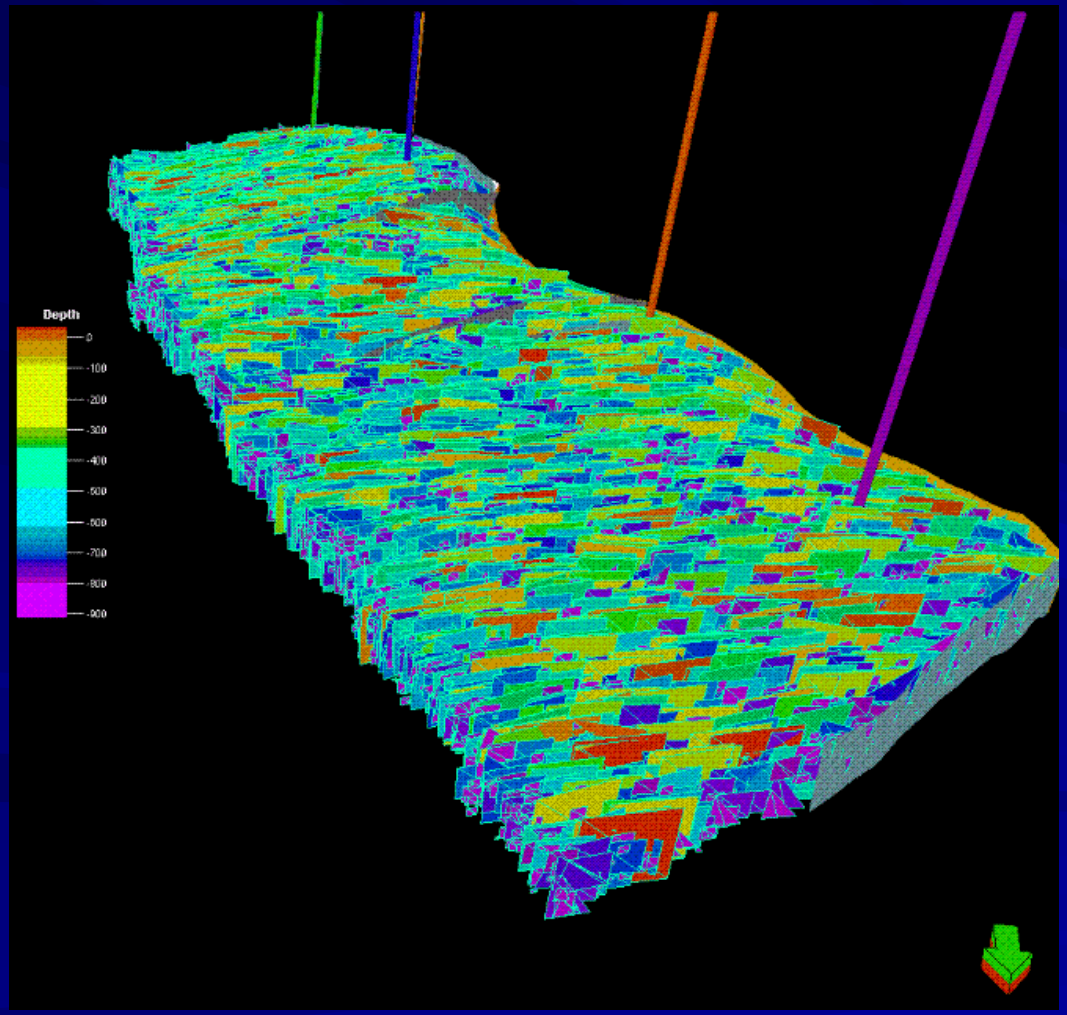


Initial Wellington mapping of Mississippian chert/dolomite oil reservoir being studied for CO_2-EOR





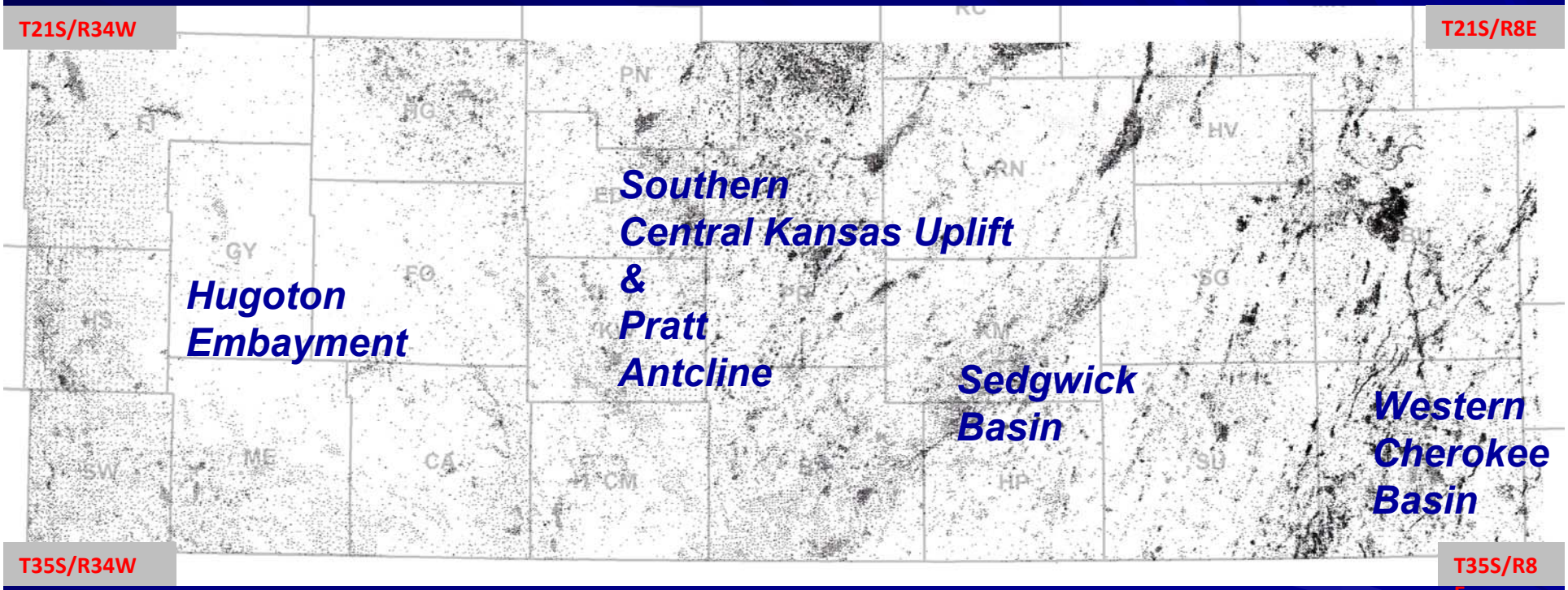
Eventually – build 3D geomodel using *Petrel* for Wellington field and compartments at regional scale, which will be input into CMG-GEM simulator



Discrete fracture network showing fracture size as an attribute.

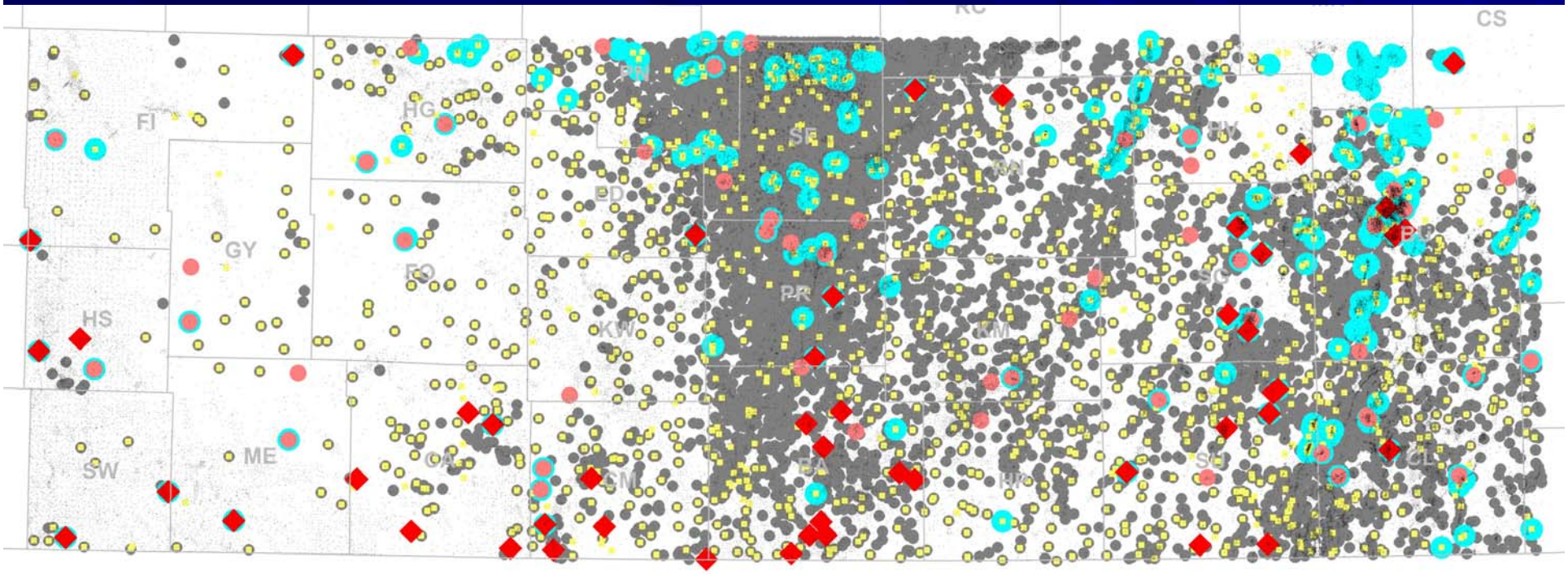
Courtesy - Schlumberger

Well Count – Regional 17+ County Area



All Wells / All Counties
95,117 wells

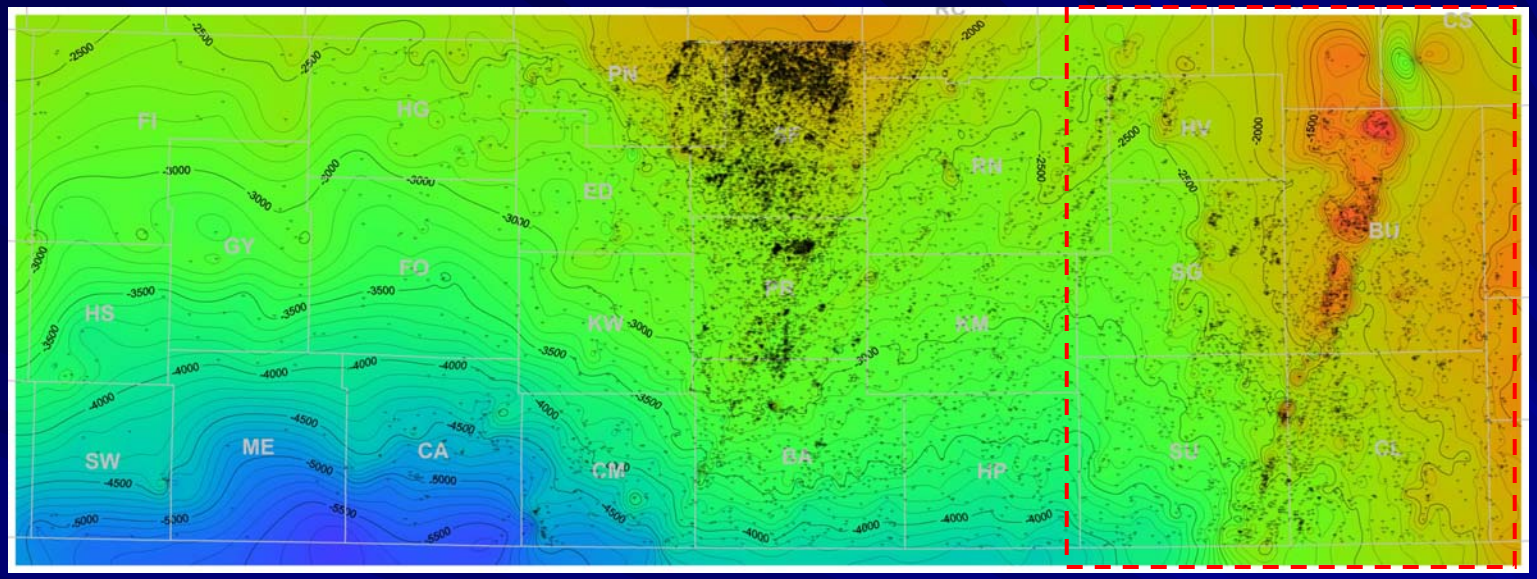
Current Well Distribution
Regional Mapping & Log Analysis



- Pre-Cambrian Wells = 292
- Arbuckle Wells = 14,105
- Type Wells (>200’ into Arbuckle) = 1,417
- Super Type Wells (>400’ into Arbuckle, 1980 or later) = 91

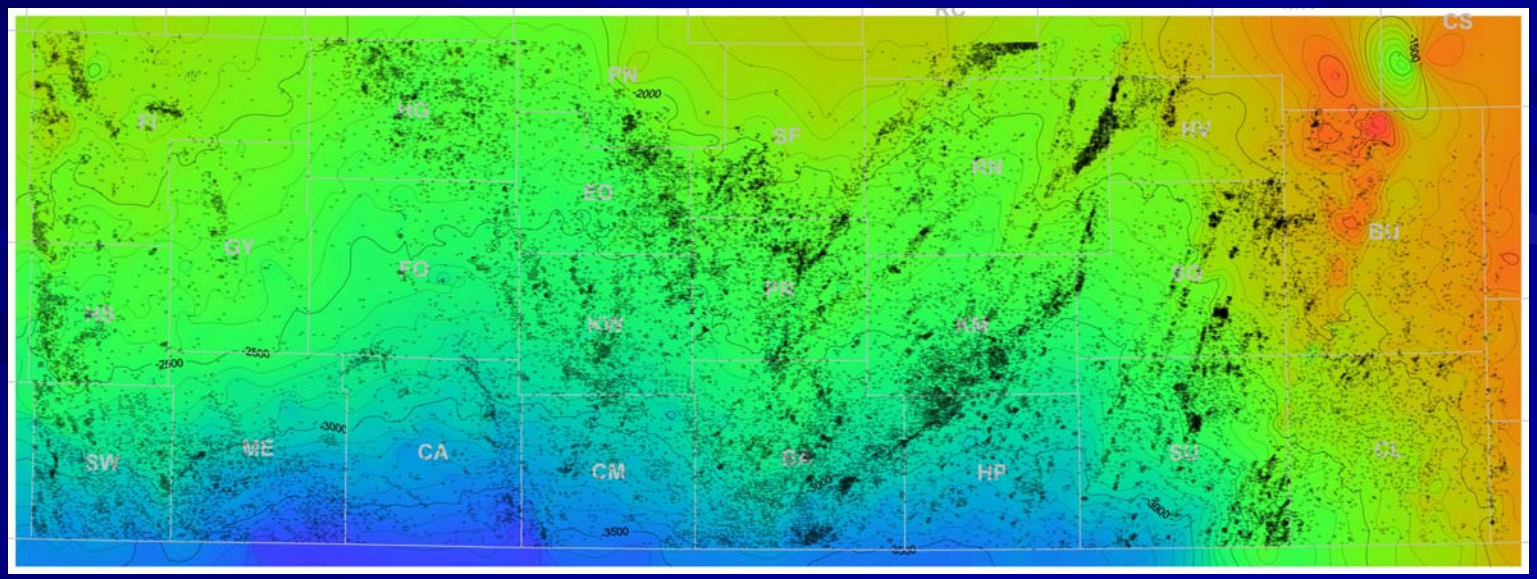
LAS Files 48 wells (to date)

Top of Arbuckle Structure



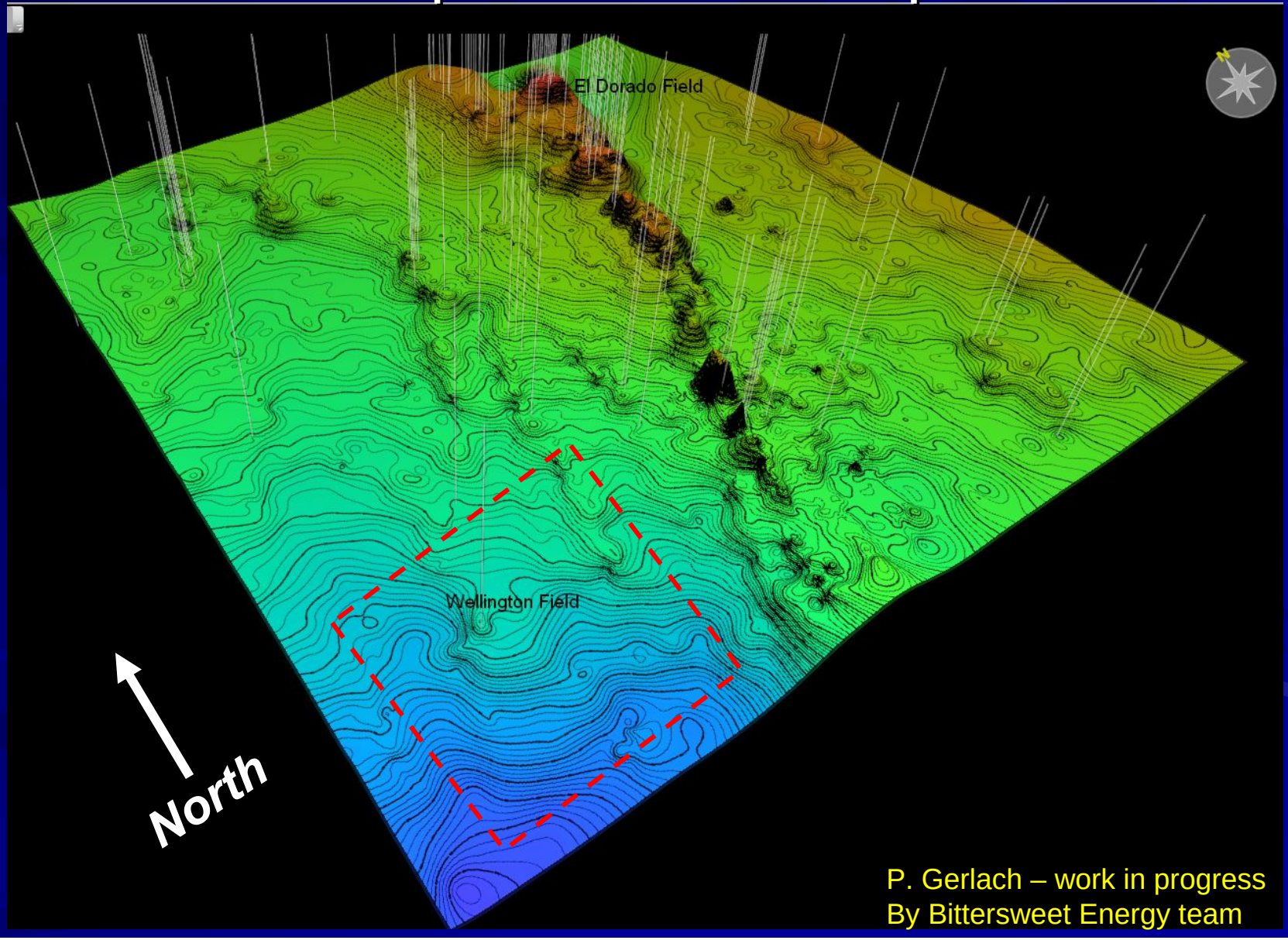
14,105 wells

Top of Mississippian Structure



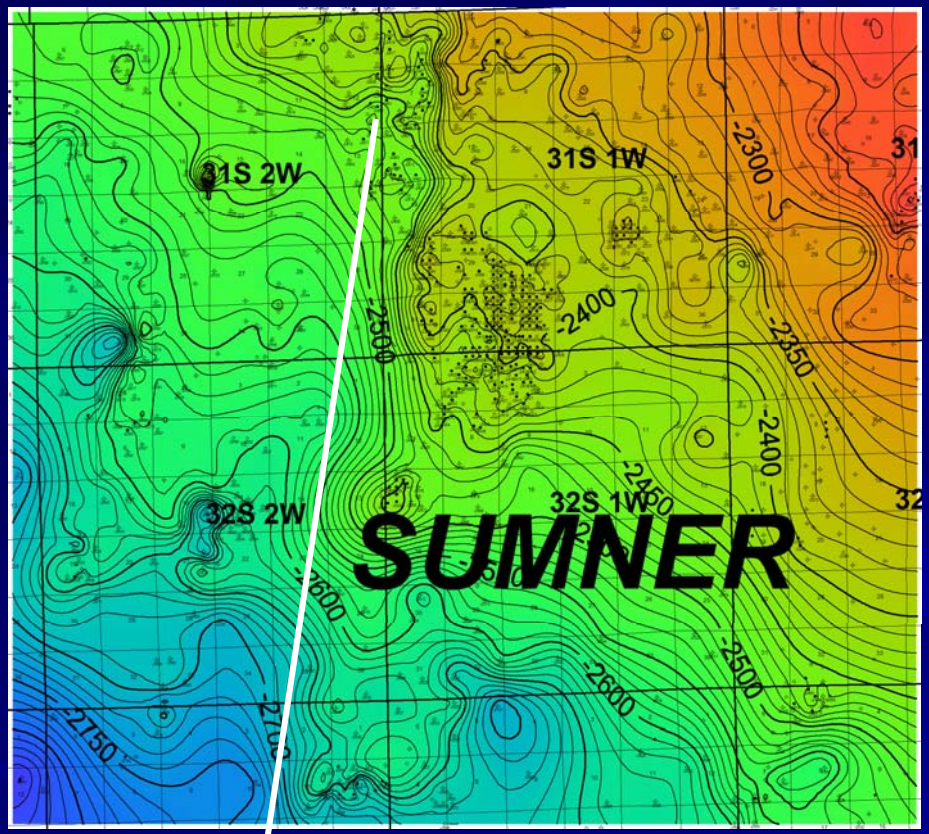
35,415 wells

East side of regional study area
Top Arbuckle Group



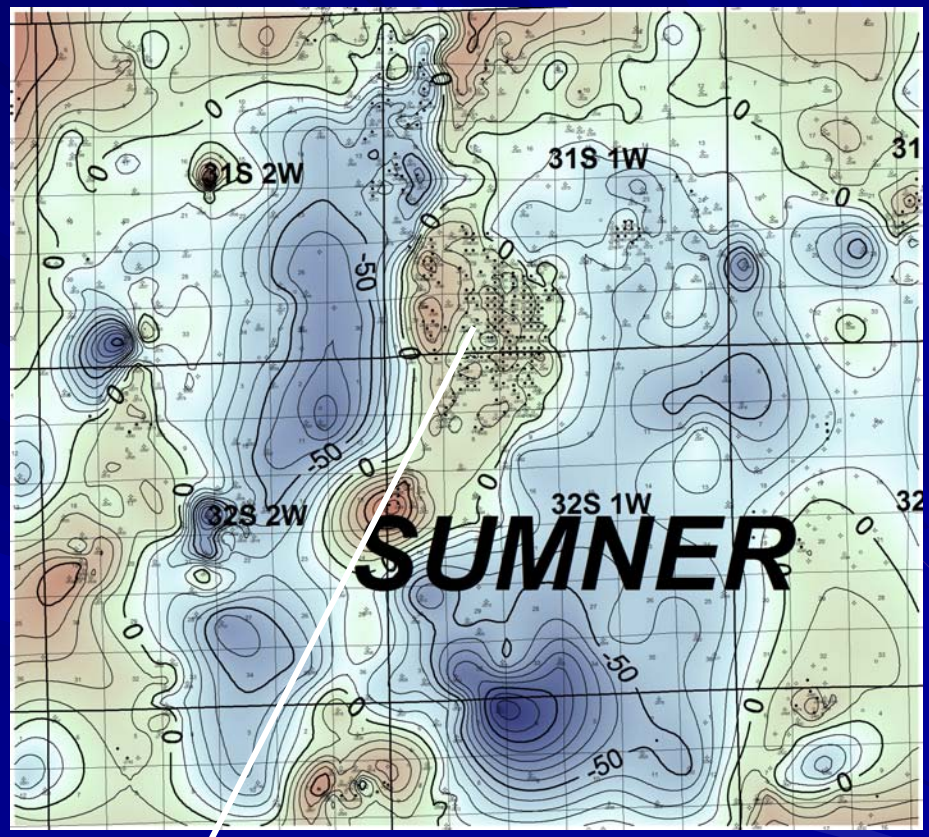
P. Gerlach – work in progress
By Bittersweet Energy team

Mississippian Subsea
25 ft C.I.



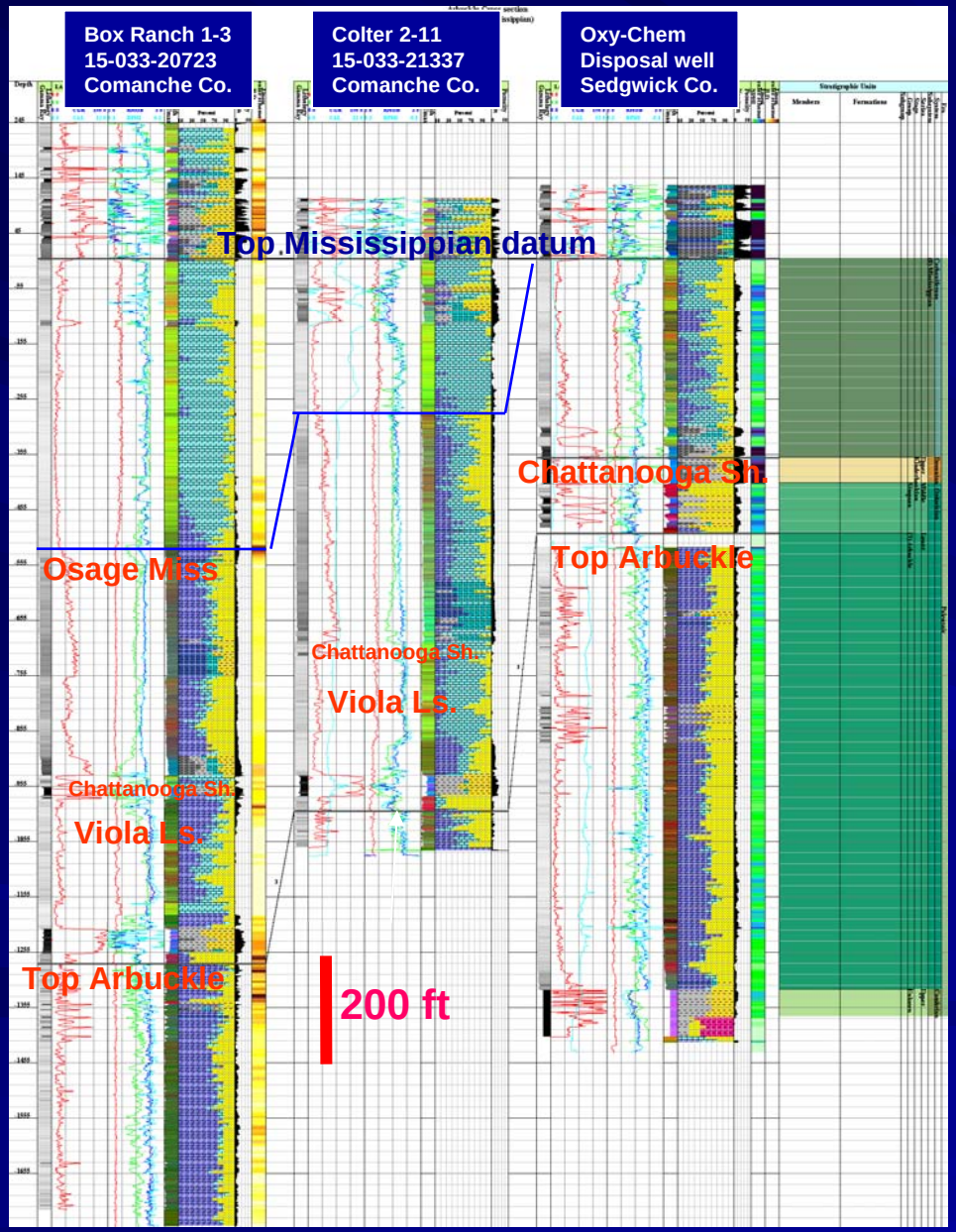
Southern part of Anson-Bates field

3rd Order Residual of
Mississippian Subsea
25 ft C.I.



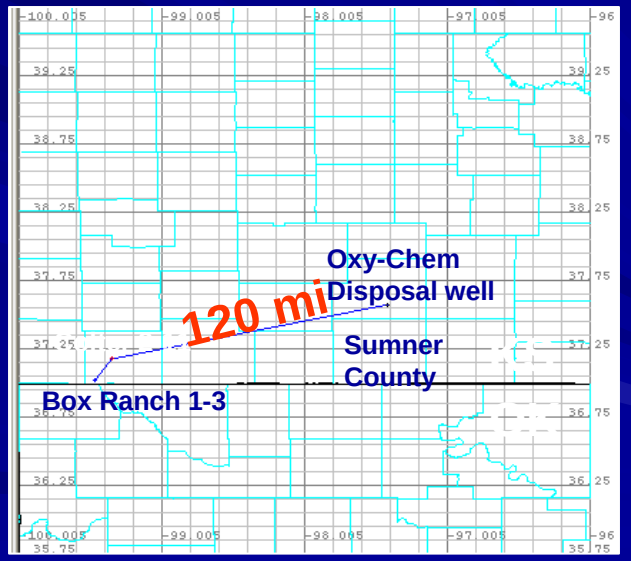
Wellington field

KGS Developed Web-Tool - Well Profile & Cross Section
Input Data – LAS files & Digitized



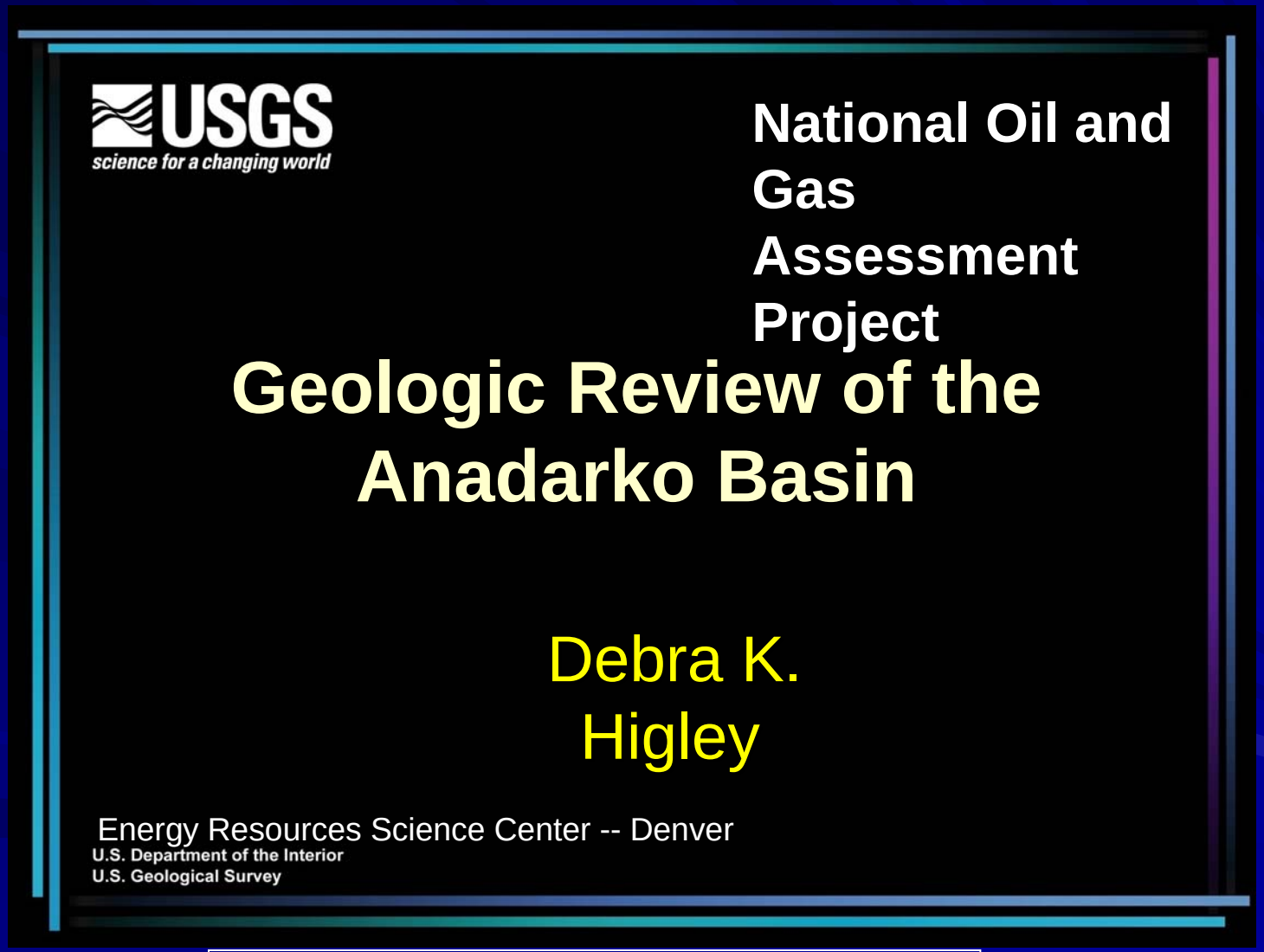
<u>Three well stratigraphic cross section with datum on top of the Mississippian carbonates</u> showing color images of gamma ray (gray scale), lithology track (multicolor image column), and color lithology percentage.

Index map, South-Central KS & North-Central OK



All well data saved in <u>LAS 3.0 format</u>

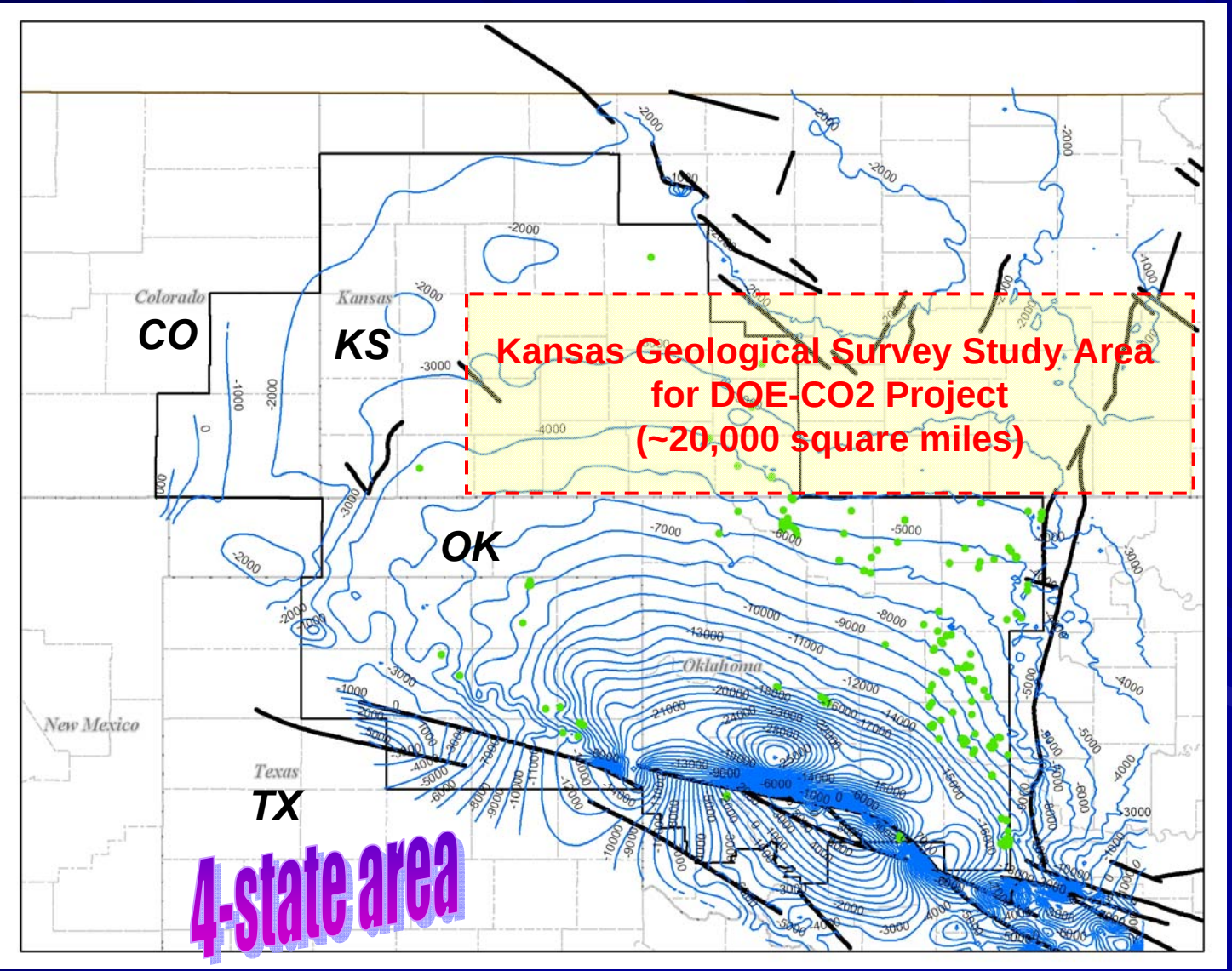
KGS's Geomodel will utilize data from USGS's Anadarko Basin Resource Assessment

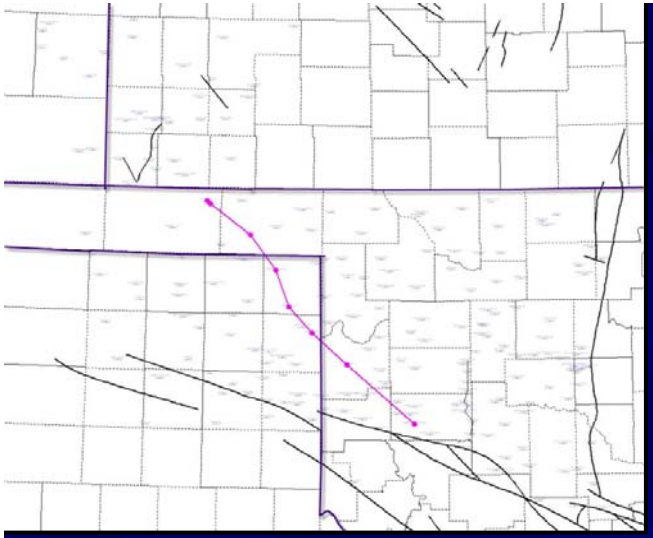


USGS Project – Completion mid-2010

Top Simpson Group Structure Map

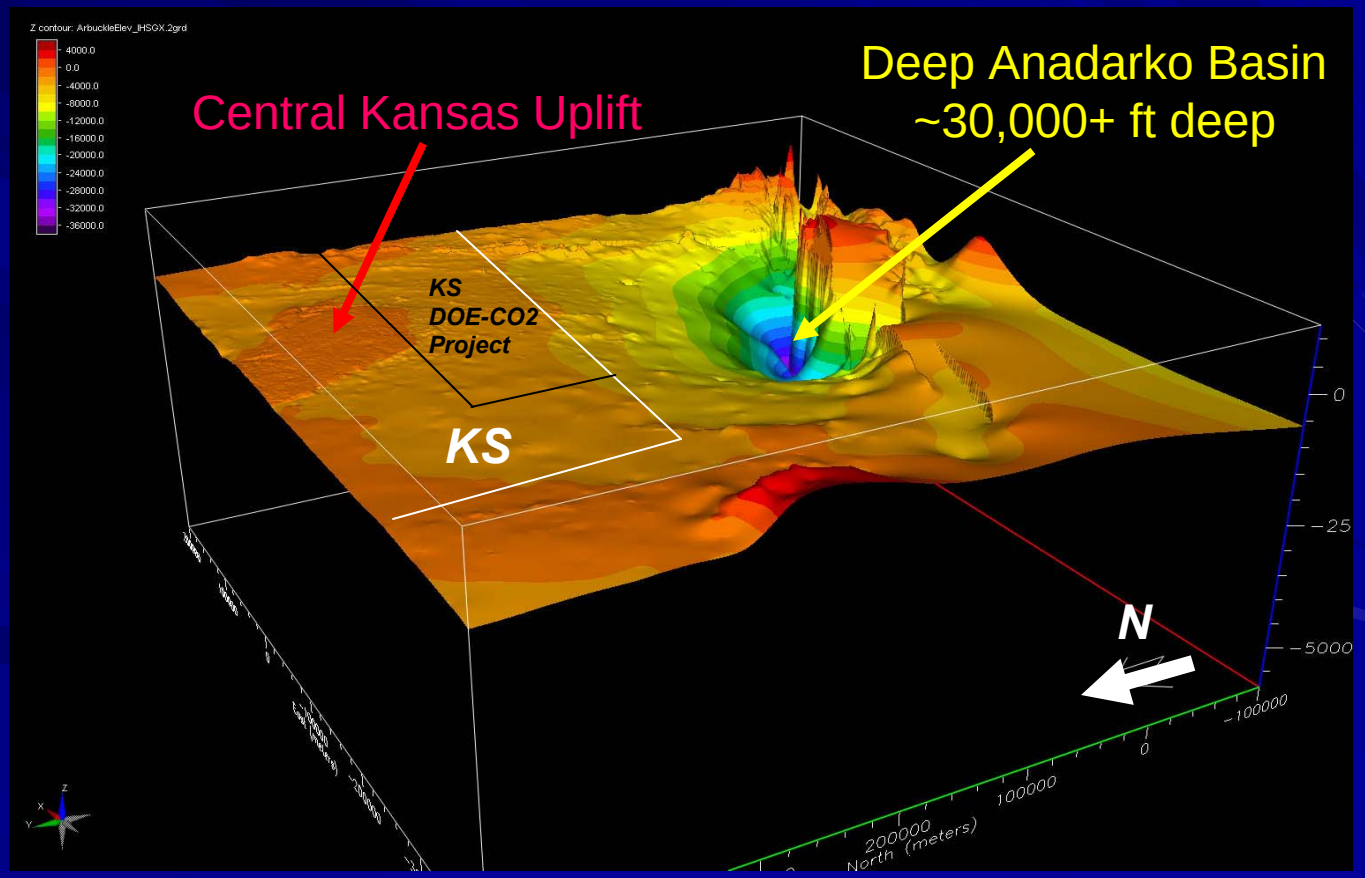
From USGS Anadarko Basin Resource Assessment Project





USGS's Anadarko Basin Project

Top of Arbuckle Group



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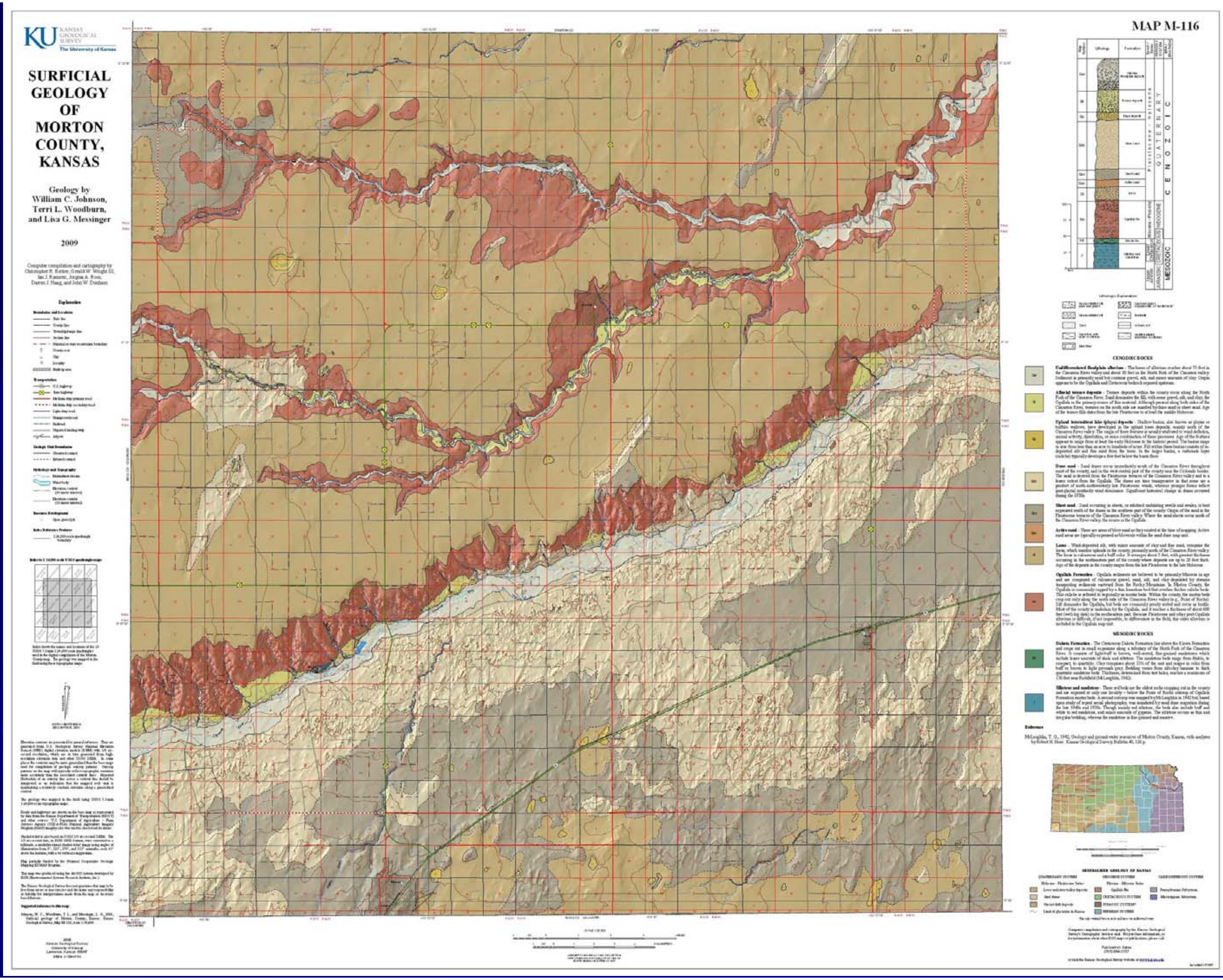
  - Positions Available
  - News

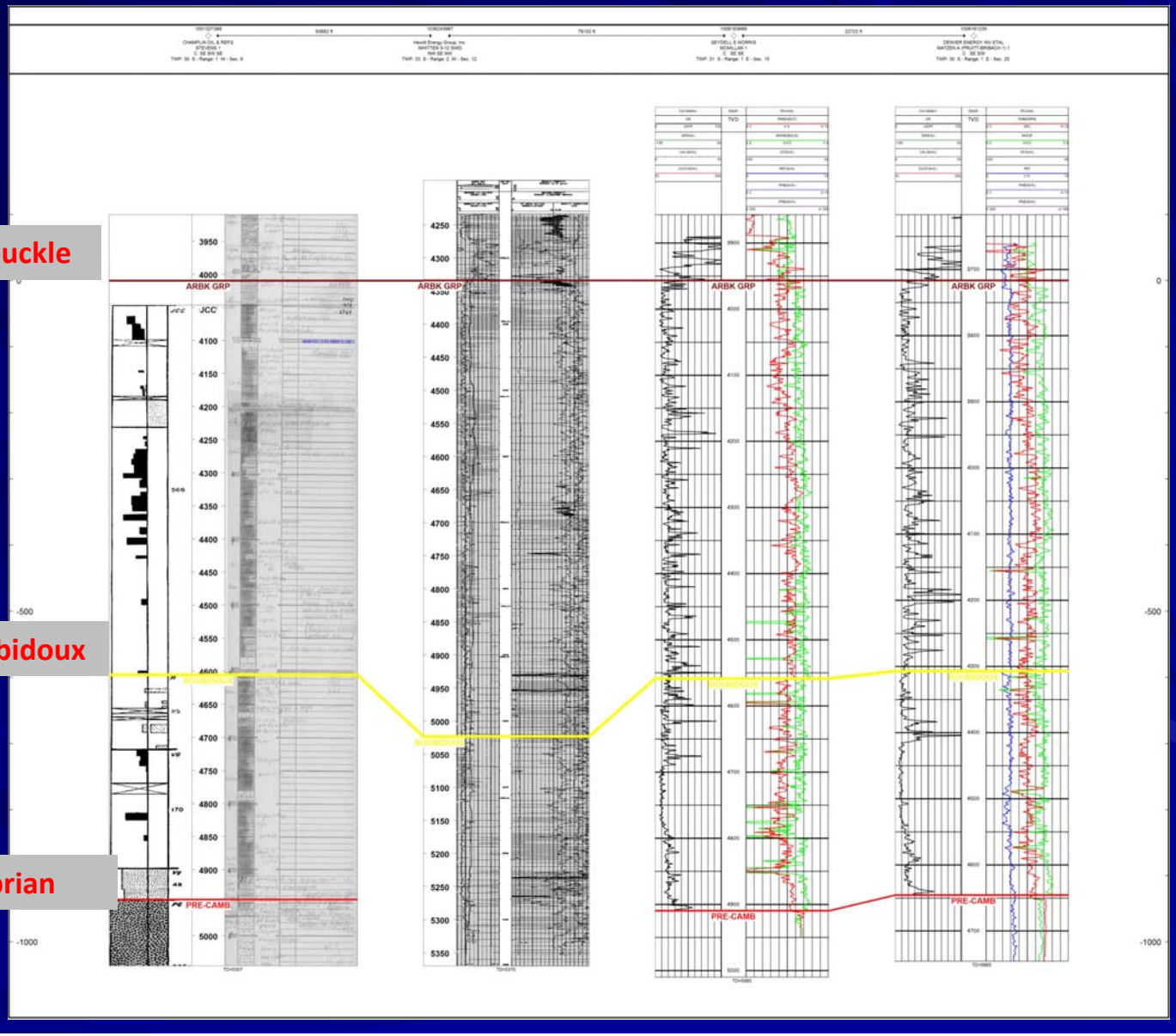
Office Locations

- Lawrence office
  - Data Resources Library
- Wichita Well Sample Library

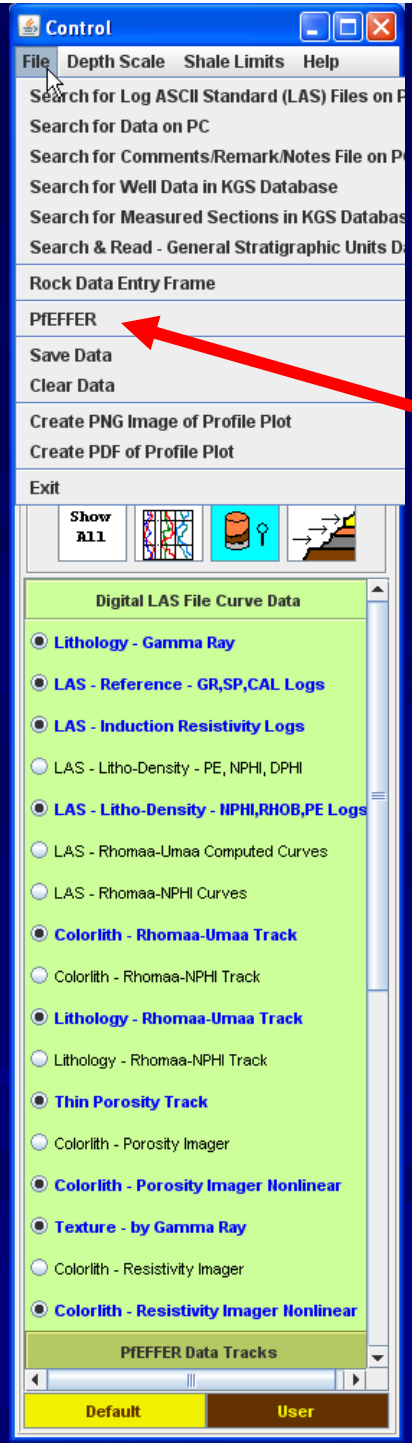

KU KANSAS GEOLOGICAL SURVEY
The University of Kansas
SURFICIAL GEOLOGY OF MORTON COUNTY, KANSAS
Geology by
William C. Johnson,
Terri L. Woodburn,
and Lisa G. Messinger
2009
MAP M-116
CENOZOIC ROCKS
MESOZOIC ROCKS

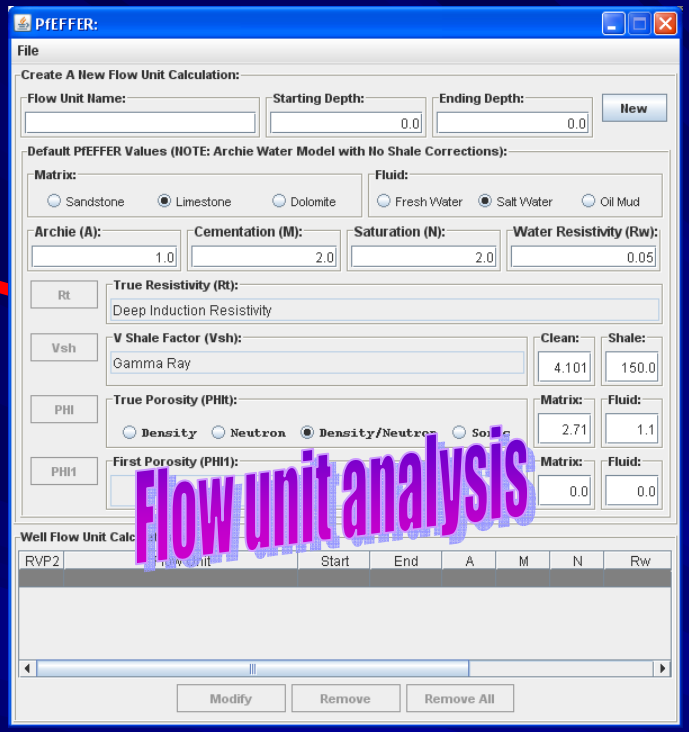
Integration of Well data – different vintages

Detailed Stratigraphic Analysis

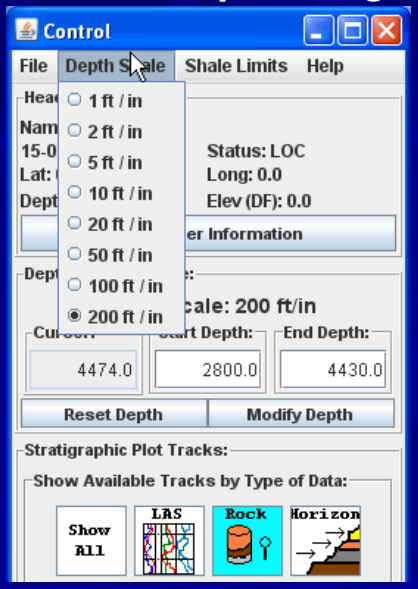


KGS's – Web-based Log Analysis Tool

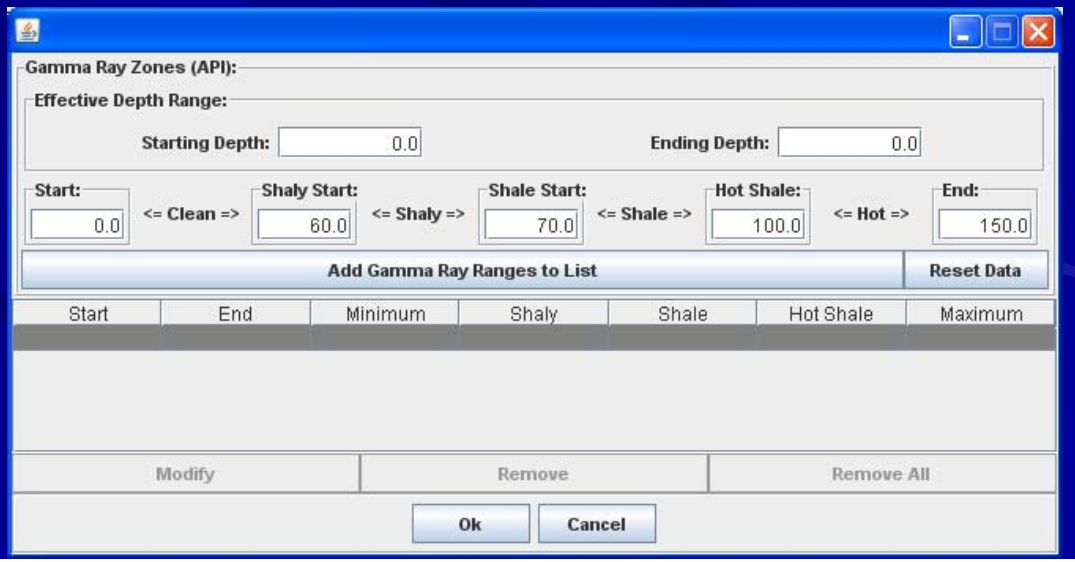




Scales & depth ranges

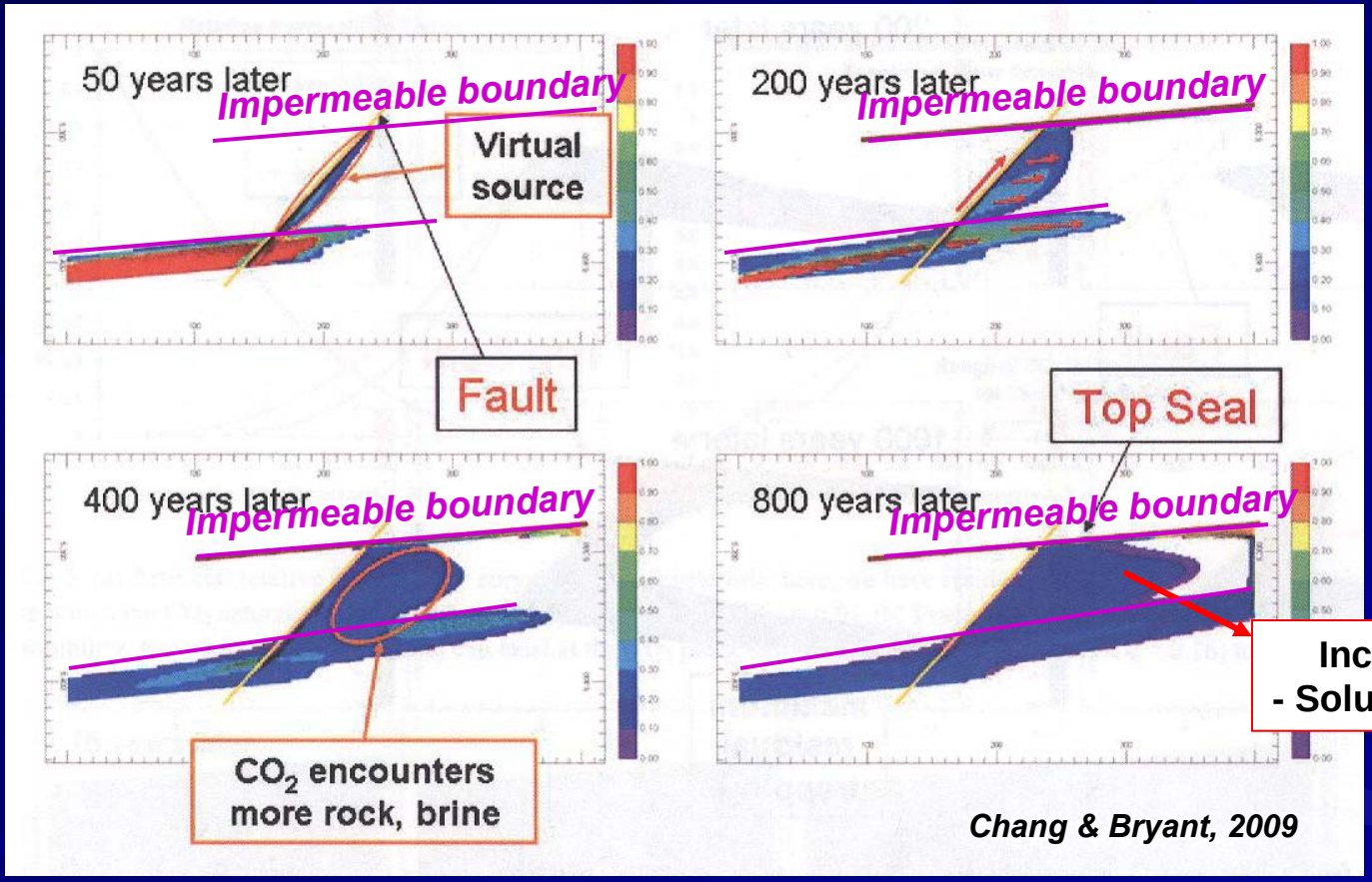


Handling un-scaled GR



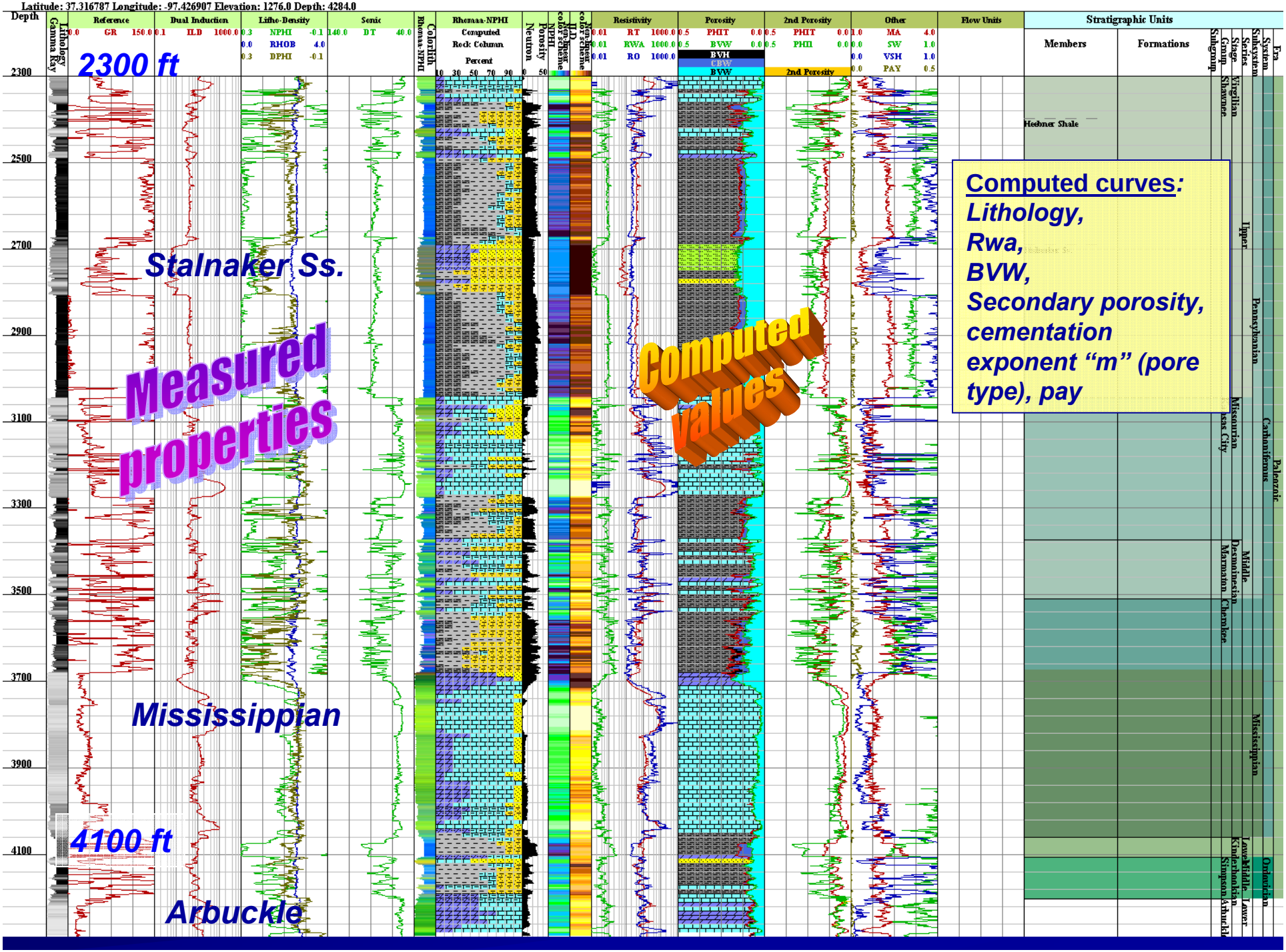
Risk Analysis

Plume Intersects Inclined Fault – does not extend to surface



CO_2 leaks into fault and creates a "virtual CO_2 source".

CO_2 migrates updip and gets attenuated – additional trapping in solution and as residual gas


WELLINGTON UNIT, was PEASEL 1 144 (15-191-20789) T: 31S R: 1W S: 33
Latitude: 37.316787 Longitude: -97.426907 Elevation: 1276.0 Depth: 4284.0
Depth
Lithology
Gamma Ray
Reference
GR
Dual Induction
ILD
Litho-Density
NPHI
RHOB
DPHI
Sonic
DT
Rhomaa-NPHI
ColorHth
Computed
Rock Column
Percent
Neutron
Porosity
NPHI
color scheme
Nonlinear
ILD
color scheme
Resistivity
RT
RWA
RO
Porosity
PHIT
BVW
BVH
CBW
BVW
2nd Porosity
PHIT
PHIE
2nd Porosity
Other
MA
SW
VSH
PAY
Flow Units
Stratigraphic Units
Members
Formations
Era
System
Subsystem
Series
Stage
Group
Subgroup
Paleozoic
Carboniferous
Pennsylvanian
Upper
Virgilian
Shawnee
Missourian
Lansas City
Middle
Desmoinesian
Marmaton
Cherokee
Mississippian
Lower/Middle
Kinderhookian
Simpson
Ordovician
Arbuckle
Heebner Shale
2300 ft
Stalnaker Ss.
Measured properties
Computed values
Mississippian
4100 ft
Arbuckle
Computed curves: Lithology, Rwa, BVW, Secondary porosity, cementation exponent “m” (pore type), pay

Budget

$ 4,974,299.00	$ 1,359,020.00	$ 6,333,319.00

	Budget - DOE	Match	Total
Berexco - Drilling (2 wells)	$ 1,659,895.00	$ 288,000.00	$ 1,947,895.00
Berexco - Geophyscics	$ 624,687.00	$ 175,305.00	$ 799,992.00
Berexco - Logging (2 wells)	$ 207,240.00	$ -	$ 207,240.00
Berexco - Coring (1 well)	$ 272,000.00	$ 10,000.00	$ 282,000.00
Weatherford - Core Analysis	$ 365,873.00	$ 105,015.00	$ 470,888.00
KS State	$ 225,167.00	$ 82,966.00	$ 308,133.00
CMG	$ 212,432.00	$ 152,108.00	$ 364,540.00
Bittersweet	$ 703,900.00	$ 70,096.00	$ 773,996.00
Log Digi	$ 38,000.00	$ -	$ 38,000.00
Noble Energy	$ -	$ 274,856.00	$ 274,856.00
Remote Sensing	$ 41,000.00	$ -	$ 41,000.00
KGS	$ 383,490.00	$ 159,265.00	$ 542,755.00
Others - Supplies & Travel	$ 55,470.00	$ -	$ 55,470.00
GRA Tuition	$ 21,355.00	$ -	$ 21,355.00
KU - F&A	$ 163,790.00	$ 41,409.00	$ 205,199.00

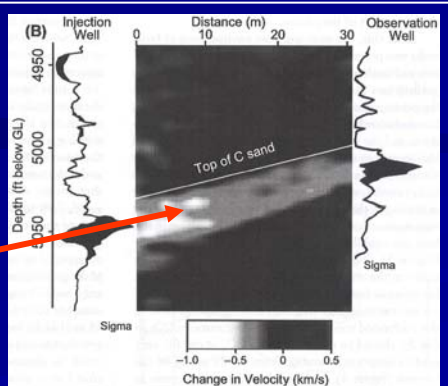
What happens when super-critical CO_2 is injected into a saline aquifer?

1. Part of the injected CO_2 dissolves in the surrounding brine under pressure – **solution (20 to 30% over time)** *- Ozah, 2005*
2. Part of injected CO_2 remains as **free-phase (gas) CO_2 (35 to < 5% over time)**

   - Free-phase (gas) CO_2 rises to the top of the flow unit (being lighter)
3. As free-phase (gas) CO_2 rises, additional CO_2 gets trapped in fine pores in the rock – **residual gas saturation (45 to 65% over time)**
4. Natural movement of water in the aquifer **dilutes** CO_2 in solution and in free phase
5. Over long term (100s and 1000s of years), some of the injected CO_2 gets trapped as **mineral precipitates** in the aquifer **(< 5%)**

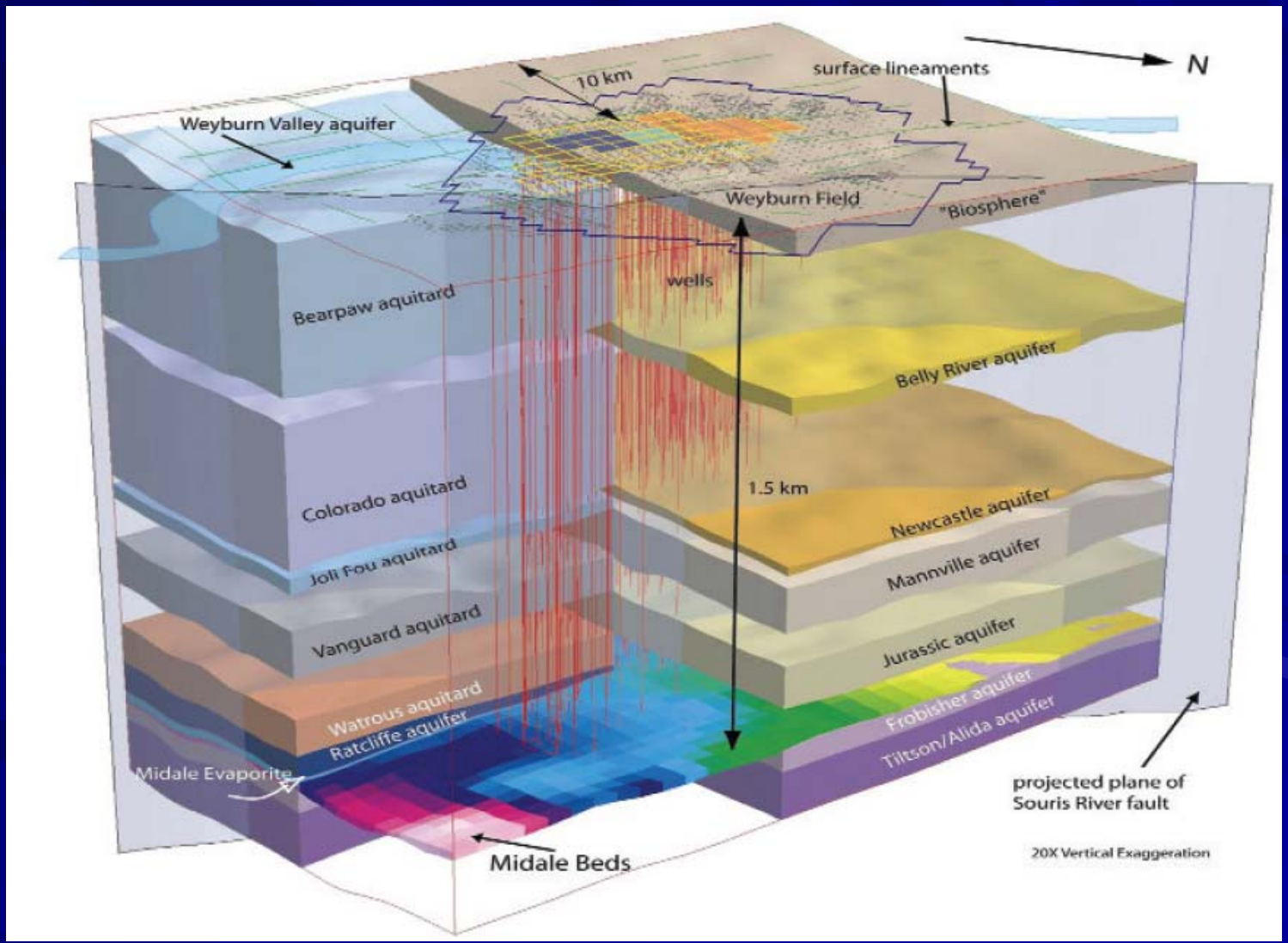
Frio Pilot CO_2 injection Project, Texas

CO_2 plume visualized by cross-well seismic tomogram

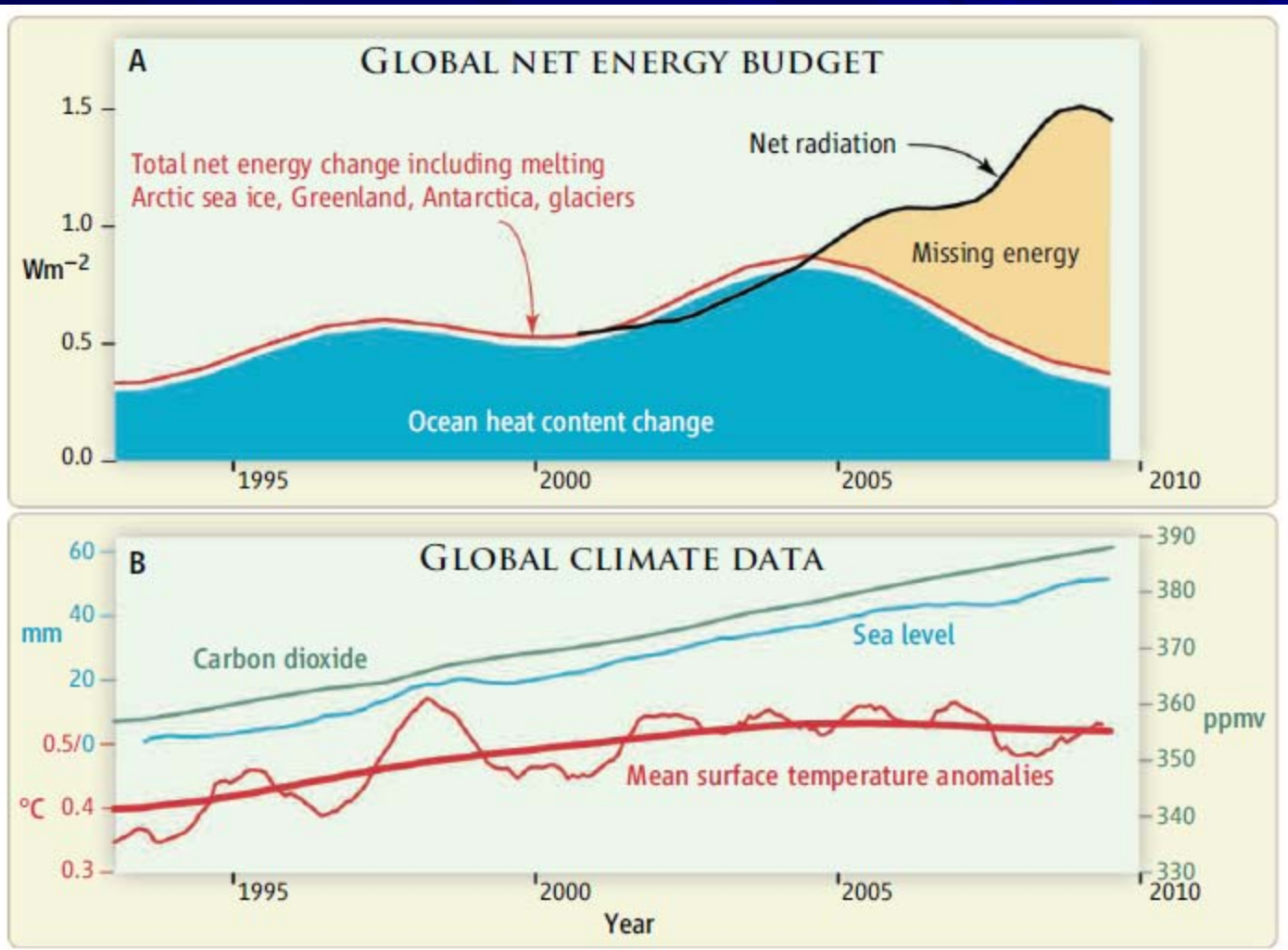


Because of heterogeneity, not all injected CO_2 ends up as free (gas) phase in the saline aquifer.

Weyburn


N
10 km
surface lineaments
Weyburn Valley aquifer
Weyburn Field
"Biosphere"
wells
Bearpaw aquitard
Belly River aquifer
1.5 km
Colorado aquitard
Newcastle aquifer
Joli Fou aquitard
Mannville aquifer
Vanguard aquitard
Jurassic aquifer
Watrous aquitard
Ratcliffe aquifer
Frobisher aquifer
Midale Evaporite
Tilston/Alida aquifer
projected plane of
Souris River fault
Midale Beds
20X Vertical Exaggeration

Tracking Earth's Energy
CLIMATE CHANGE
Kevin E. Trenberth and John T. Fasullo
16 APRIL 2010 VOL 328 SCIENCE



Where does the energy go? (**A**) Estimated rates of change of global energy. The curves are heavily smoothed and somewhat simplified. From 1992 to 2003, the decadal ocean heat content changes (*10*) (blue), along with the contributions from melting glaciers, ice sheets, and sea ice and small contributions from land and atmosphere warming (*7*), suggest a total warming (red) for the planet of 0.6 ± 0.2 W/m² (95% error bars).